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AN INTERDISCIPLINARY APPROACH FOR THE STUDY AND THE VALORIZATION OF THE ROMAN THEATRES OF CRETE

Ph.D. Thesis

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ABSTRACT

This thesis is the result of an interdisciplinary study that has involved disciplines as architecture, archaeology, acoustics and computer science. The main challenge have been to demonstrate how these disciplines can collaborate in order to achieve new information about ancient buildings that are now almost completely destroyed, and how they can improve the valorization of these monuments.

There are three research questions. The first one is: **what do we know about the architecture of the Roman theatres of Crete?** All the available documents (ancient plans, descriptions, archaeological reports, aerial pictures, geophysical anomalies) related to the twelve Roman theatres of Crete have been examined. It has been discovered that there are several lacunae about these monuments, above all due to their bad state of preservation, and that an overall study about the Roman theatres of Crete is missing. So, the second question has arisen: **In which way we can obtain information about the architecture of monuments that are scarcely preserved?** A new methodology has been developed consisting in the use of 3D models of the hypothetical reconstructions of the original aspect of the theatres, 3D visibility analysis and virtual acoustics analysis. It has been demonstrated as 3D models are useful to carry out analyses and then to obtain additional info, and that the 3D visibility analysis and the virtual acoustics analysis can produce interesting results useful to formulate or to verify hypothesis about the architecture of the theatres. The interpretation of the results obtained from the afore mentioned methodology, applied to seven of the Roman theatres of Crete (Aptera, Hersonissos, Gortyna acropolis, Gortyna Pythion, Gortyna Kazinedes, Koufonissi and Lissos), has brought to new conclusions: the Roman theatres of Crete seem to have preserved some characteristics belonging to the architecture of the Greek theatre. Then, a new question has been formulated: **How to spread the information obtained through the accurate examination of the monuments and how to valorize the Roman theatres of Crete?** Two different solutions has been thought, one dedicated in particular to the specialists and another one addressed to the general public. The first solution is a web database containing all the information about the Roman theatres of Crete, including

the acoustics values of the parameters examined; it is possible to filter the results according to the name of the theatres, to the name of the scholars who documented it, and according to the architectural data. The second solution is a VR application for head-mounted display, where the user is virtually transported inside each theatre; he/she can choose a seat and listen to the auralized files as if he is attending an ancient performance, and he can interact with several icons in order to have information about the theatres. These two solutions intend to facilitate and improve the study of the Roman theatres, and to bring the general public closer to Cultural Heritage.

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1. INTRODUCTION

1.1 Cultural Heritage and Digital Media

The sector of **Cultural Heritage** has always being characterized by the interaction of several disciplines. We cannot obtain a thorough study of a monument if we do not consider its historical context, its architecture, and its graphical representation. As well as we cannot completely understand an archaeological site if we do not take into account its geographical context, its history, its artefacts, and its social and religious functions. History, architecture, history of art, geography, sociology, anthropology and theology are only some of the disciplines that all together contribute to a better and deeper knowledge of what we now consider symbols of the past representing our culture.

In the last two decades, a new bailiwick has been involved in the field of Cultural Heritage: the information technology (IT). Virtual analyses, 3D modeling, virtual reality and digital media are some of the very useful instruments borrowed from the technological sector and applied to the field of Cultural Heritage, above all to archaeology.

The first examples originated by the combination of these different disciplines, dated in the '80s, are the virtual reconstructions of the temple precinct of Roman Bath and the Roman legionary bathhouse at Carleon, in Wales[1], [2]. In 1987 the first virtual animated tour was shown at the British Museum and it was about the reconstruction of the Saxon minster of Winchester[3].

The collaboration between archaeology and information technology is so substantial that a new expression was coined by Paul Reilly already in 1991, "virtual archaeology": "What does the term virtual archaeology mean here? The key concept is virtual, an allusion to a model, a replica, the notion that something can act as a surrogate or replacement for an original. In other words, it refers to a description of an archaeological formation or to simulated archaeological formation"[4]. The University of Southampton, in 2013, uploaded the animation made by Reilly in

1991[1], where a solid model of an excavated area is shown. His aim was "to demonstrate that archaeologists can produce realistic records of the data they inevitably destroy in the course of excavation"[4]. Indeed, the animation shows a 3D model of a complete archaeological stratigraphy, together with sections and plans of the represented stratigraphy. Layers can be removed or placed again in order to reproduce the temporal sequence of natural and anthropic events, features and objects can be isolated to let better understand their shape and their characteristics, and the real position of the objects within the stratigraphy can be visualized. Through this kind of visualization the archaeologists can better explain "how their interpretation derives from the data"[4]. It is an instrument to present results of research in a very clear and intuitive way and, above all, to keep analysing the data also when they are not available anymore, having been destroyed by the excavations.

It is evident, since the very beginning of the birth of virtual archaeology, the fundamental importance of 3D models in archaeology. "Archaeological 3D modelling is basically the recreation of landscapes, architecture, and objects by digital means based upon the current state of the salvaged monuments integrated with the data coming from historical and archaeological researches using software for developing 3D models"[5]. Therefore, a 3D model is the result of the transformation of digital information collected during the research into one or more solid shapes visible on a display. These shapes obviously have an aspect recognizable by people because "the purpose of model of an entity is to allow people to understand the structure or behaviour of the entity"[6], "a model is a simplification of something more complex to enable understanding"[7].

The most powerful aspect of virtual archaeology is the possibility to disseminate virtual reconstructions of the past through **digital media** and therefore to easily and quickly reach the general public.

Nowadays, the digital media used in Cultural Heritage are numerous and everyone satisfies different demands, but their common aim is educational. Through the years

[1] http://eprints.soton.ac.uk/353058/

they have been improved in order to increase the feeling of presence and immersion in the virtual place.

Already in 1993, a Reality Theatre was included in the Reality Centre in Theale (England); generally, these kind of theatres are rooms with a curved screen where the images are projected. The CAVE has a similar function but the images are projected on each wall of the room, not on a screen. These ambiences are very evocative for people and also music plays an important role to let the spectators get lost in the virtual world as much as possible.

Another very powerful instrument to communicate virtual archaeology's visualization is the virtual museum. The aim of this instrument is to let the users to interact actively with the virtual exhibitions online, allowing him/her to click on the objects and to choose different options, as reading information about them, or rotating and manipulating 3D models, or visualizing images and videos; the result is a very educational tool. A good example in this case is represented by the Virtual Museum of Iraq, promoted by the Italian National Research Council and the Italian Ministry of Foreign Affairs. It is possible to explore virtual rooms since the prehistory till 762 A.D., year of the foundation of Baghdad[2].

Another way to catch people's interest are serious games. They probably have a more explorative feature than the other applications: the user can choose where to go, what to look at, sometimes it is also possible to interact with animated character and to "grab" objects and playing with them[8]. The characteristic of serious games is not only to entertain the user, but to teach and to let the user easily assimilate the fundamental aspects of several past cultures[3].

More recently, with the circulation of modern smartphones and tablets, applications of augmented reality (AR) have been developed. The expression "augmented reality" comes from the addition of virtual objects to the real world. In the field of Cultural Heritage, the purpose of augmented reality applications is to virtually show 3D reconstructions of monuments and/or sites (or only part of them) that are not visible

[2] http://www.virtualmuseumiraq.cnr.it/prehome.htm

[3] For an overview about serious games in Cultural Heritage: [9].

anymore, in the real context where they were located in the past. The result is the visualization in real time of not existing ancient buildings within modern towns and landscapes. Alternatively, it is also possible to visualize 3D objects, pointing the device (smartphone or tablet) towards a compatible image representing the monument, as it is shown for the amphitheatre of Lecce[4].A good example of augmented reality on-site is given by the project ARCHEOGUIDE, which improves the visiting experience of the archaeological site of Olympia with the visualization of virtually reconstructed monuments and the presence of avatars representing athletes competing in the ancient stadium[10].

One of the very last innovation in the field of digital media for Cultural Heritage is the use of Head-Mounted display, as Oculus Rift, Samsung Gear, HTC Vive and Google Cardboard. All of them are headset devices for immersive and interactive virtual reality applications. Google Cardboard is a cheap and simple version of Oculus and all you need is a smartphone, provided with a gyroscope and a VR application installed on it. One of the first VR applications showing reconstructed monuments has been developed by Fabola *et al.*[11]which aim is to guide tourists within the site of Saint Andrews Cathedral in Scotland. 3D objects, audio narratives, videos included into the application, enhanced the multiple views of the virtual cathedral.

"As a way of influencing large number of people, computer visualization is a potentially powerful tool. On the one hand it can give large numbers of people access to the past, but on the other hand it gives tremendous power to the custodians of the heritage"[12]. For this reason, there are some rules that everyone who wants to work on a project of virtual Cultural Heritage and virtual archaeology should follow, in order to offer a scientific and valuable result.

The London Charter has been elaborated in 2006 with the purpose to provide a guideline for the use of 3D visualization in the research and communication of

[4] http://vcg.isti.cnr.it/LecceAR/

Cultural Heritage in a systematic way[5]. The last draft is dated to 2009 and it has six principles which invite to have a scientific documentation as base of a project, to well analyse this documentation and to transmit it to the community, along with the explanation about why we use 3D methods to illustrate the research, what exactly we want to show with the 3D visualization and how we obtained the three-dimensional model. Furthermore, the London Charter suggests to plan strategies for the "sustainability of cultural heritage-related computer-based visualization outcomes and documentation" and it underlines the importance of improving the access to Cultural Heritage through computer-based visualization.

In 2007, the second principle of ICOMOS Charter for the Interpretation and Presentation of Cultural Heritage[6] repeats that scientific documentation is necessary and that all the information sources have to be documented, as the London Charter states, but, in addition, "alternative reconstructions" are required. This is an important aspect because what the specialists show through the virtual representation of an object or a building or a monument is only an interpretation. As such, the interpretation can also be the result of mistakes and we never have the certainty of accuracy of our reconstruction (unless we are reconstructing something that is still visible). Presenting only one version of the model, there is the risk that people accepts that model as the only right one, activating in this way the circulation of a possible wrong reconstruction of the culture[7].

In 2009, the Seville Charter has been conceived in order to establish principles for being applied to virtual archaeology[14]. The last draft is dated to 2011 and the principles are the following: interdisciplinarity, purpose, complementarity, authenticity, historical rigour, efficiency, scientific transparency, training and

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[5] http://www.londoncharter.org/

[6] http://www.enamecharter.org/principles_2.html

[7] An alternative to the presentation of two or more versions of the model is to create a code of accuracy for the project as for example we can see in *Aquae Patavinae* VR project. Here, the scholars use different number of stars for indicating different level of certainty: "evocative", "possible", "probable"[13].

evaluation. The Seville Charter is much more focused on the needs of the archaeological world and everyone who works in this context should follow these rules in order to achieve reliable results, useful for future researches, for other scholars and for the community.

1.2 Research questions

The interdisciplinarity characterizing the new bailiwick of Cultural Heritage and digital media, makes not easy the choice of an exact research question. The study needs to satisfy the requirements of two different fields: how this research enhances the world of cultural heritage and the one of digital media? Then, it is obvious that the research questions can be various.

The first question is: **what do we know about the architecture of the Roman theatres in Crete?**

Only very recently some of the Roman theatres in Crete have been analysed thoroughly, but unfortunately their remains are very scarce and therefore it is often challenging to imagine their architectural structure, even for the archaeologists. Furthermore, only single and unconnected studies have been carried out, without taking into account possible regional similarities. It is surprising to think that the first attempt to group the Roman theatres of Crete together has been made by the Italian physician and traveller Onorio Belli, in the XVI century. He drew the remains of seven of the Roman theatres of Crete (the one in Chania, the one in Hersonissos, the one in Lyttos, the two at Gortyna and the two at Ierapetra) and he sent these plans, along with a couple of letters, to his uncle in Italy. Since then, no one else[8] dedicated a thorough study to the architecture of several Roman theatres of Crete[9]. All of them have been mentioned, and some of them have been described, by Ian Sanders[16], but

[8] Except for Falkener and Spanakis, which researches are actually based on Belli’s plans and they add very little.

[9] Valentina Di Napoli has studied the Roman Theatres in Crete and she has considered them as an ensemble but mainly from a topographical and ornamental point of view [15].

his study was not focused on the Roman theatres of Crete only, rather it is a wider research which includes all the Roman structures in Crete[10].

This study aims to fill the gap of information about the architectural structures of the Roman theatres in Crete. In addition, the theatres want to be analysed as a set, in order to verify the contingent presence of patterns and if it is possible to identify a category typical of the Roman theatres of Crete.

The established Roman theatres in Crete were twelve, today only eight are still partially visible. Unfortunately, for many theatres we have very poor information and sometimes not even that. The theatre of Chania is destroyed. The theatre of Kissamos (Chania) and one of the theatres in Ierapetra are buried under modern buildings. The theatre of Littos (Heraklion) is recognizable only by the shape of the terrain where it used to lay on. The small theatre of Ierapetra has just been partially revealed.

The cases study of this research are the seven theatres of which there are enough archaeological data to enable analysis and a deeper study: the theatre of Aptera, the theatre of Chersonissos, the theatre of Koufonissi, the three theatres of Gortyna, and the theatre of Lissos. Actually, as it is possible to read in the case study chapter (chapter n. 5), the theatre of Lissos is very badly preserved but I attempted to analyse it anyway, also to use it as a comparison for the efficacy of the methodologies applied.

The second question is: **in which way I can obtain information about the architecture of monuments that are scarcely preserved?**

Obviously, the first thing to do is to examine the available documentation: archaeological reports, descriptions from old travellers, results from the geophysical prospection, remains, maps, plans; but, as aforementioned, the information we have is very few. When the helpful data are not enough to answer our questions, information technology often comes to our aid.

[10] More information can be found in the third chapter of this thesis which is dedicated to the state of art of the Roman theatres in Crete.

Two basic analyses have been employed during this research in order to know more about the architecture of the studied theatres.

The first one is the **3D visibility analysis**. As Pappalardo[17] underlined, the Greek word *θέατρον* (theatre) comes from the ancient Greek verb *θεάομαι* which means to see, to watch, so it is possible to assume that the visibility had a great relevance in the ancient theatres. Through the use of GIS, it is possible to verify the visible area from selected locations. In this case, an innovative methodology has been applied in order to check the visibility of the actors on the stage from the spectators' positions in the cavea. Some architectural elements (as the converging walls of the *analemma*), together with the height and the position of the stage, influenced the level of visibility of the performances. 3D visibility analysis allows to know if, and which, spectators could actually see the actors, and it also indicates which elements obstacle the visibility. Being the sight one of the fundamental aspects of a theatrical performance, we can assume that everyone, or almost everyone, was able to watch the actors playing. Therefore, we can use the results obtained by the 3D visibility analysis to validate or not the hypothesized theatres' architecture, and to propose new interpretations.

Of course, in the analysis of the reconstruction's hypotheses, it is essential to take into account also the other important sense that it is involved during a theatrical performance: the hearing[11], as it is suggested by the Latin word used for theatre, *auditorium,* which comes from the verb *audio* that means to listen[19]. **Virtual acoustics analysis** is the second instrument used in order to better understand the architectural structure of the Roman theatres in Crete. Acoustics software can measure the impulse response of virtual receivers (placed in spectators' positions) and give the values of important parameters related to the quality of the acoustics in a room. Architecture influences in large part the quality of the acoustics and the thorough study of François Canac[20] revealed which architectural elements have a

[11] As stated by Wheatley[18], it is important not to favour the sight over the other senses during an archaeological examination.

stronger influence and how they improve and worsen the comprehension of the sound.

The very convenient aspect of these tools is the possibility to work with 3D models, in a whole virtual environment. It is then possible to analyse buildings that are not entirely preserved and that could not being investigated otherwise, and moreover to test different hypotheses.

The third question is: **how to spread the information obtained through the accurate examination of the monuments and how to valorise the Roman theatres of Crete?**

Nowadays, the most efficient way is through digital media. The market of smartphones, tablets and laptops, plus the continuous evolution and creation of applications for such devices, are a clear evidence of how much our life depends on digital technologies. The sector of Cultural Heritage is finally aware of that, so more and more specialists decide to diffuse the results of their research through digital media, mainly for two reasons. First of all, as it has been stressed before, almost everyone has a smartphone or a tablet that uses daily, therefore it is very easy and fast disseminating information through and for these systems, above all thanks to the social media where it is possible to share news, ideas and links, with hundreds of people. Second, our Cultural Heritage showed through digital applications looks much more attractive, especially for the non-experts of the sectors. Digital media allow the presentation of appealing images, videos, audios and 3D reconstructions, which help the spectator to empathize with that context and consequently to memorize it. Often, it is possible to directly interact with the objects represented through the digital media, and to experience a sensation of immersion, that increase the entertainment and the learning process[21].

In particular for this research, hypotheses about the possible original aspect of the theatres will be visualized by creating realistic texturized 3D models through modelling software, as 3D Studio Max. These 3D reconstructions are used in two different applications, useful for deeper and future studies about the Roman theatres in Crete (and not only) and to share the acquired knowledge with the general public too, attracting it towards Cultural Heritage.

A **web database** has been created, with the collaboration of the laboratory of Geophysical-Satellite Remote Sensing and Archaeo-environment (GeoSat ReSeArch Lab) of F.O.R.T.H., to store and share all the information collected about these theatres. The innovative aspect of this database is not only the content, but also that it is possible to search for information about the theatres according to several scholars and that some queries can be formulated in order to list theatres with similar characteristics.

In addition, a **VR application for head-mounted display** has been developed, thanks again to the collaboration with the laboratory of Geophysical-Satellite Remote Sensing and Archaeo-environment (GeoSat ReSeArch Lab), where the user can, not only be transported within each theatre, but he/she can also experience an ancient Greek performance from several seats in the cavea, observing the different acoustics characteristics.

The scientific contribution given by this research is the following: enlarging knowledge about Roman theatres, demonstrating the precious collaboration between Cultural Heritage and information technology, and the creation of an application that can let people experience one of the main activity of the past.

2. SIMILAR RESEARCHES

3D reconstructions of Greek and Roman theatres are numerous, but many of them only aim to show the original appearance of the monuments, without additional information and without interaction from the users. It is possible to give as example the virtual reconstruction of the Roman theatre of Catania which is really well elaborated (based on laser scanner survey and old documents) and very high quality, but it is limited to the visualization and it is disseminated by a video[12][22].

The topic of this Ph.D. is to acquire more information about the Roman theatres in Crete by means of 3D modelling, and transmit these data to both expert and non-expert public. In order to involve the user and consequently to make easier the learning of new information, a VR application has been chosen as the medium, which will contain information, images, audios and the user will go through an interactive experience. In addition, a web database will be elaborated in order to store and show all important information useful to compare the theatres among them, and to help other scholars to improve their own research about Roman theatres and to motivate them expanding the database by adding new data (expert crowdsourcing).

A previous research, involving several ancient theatres, where 3D models are complete with information, images, virtual interactions and audios is the project called THEATRON.

THEATRON has been developed by King's Visualization Lab, at King's College London, specialized in visual representation for archaeology, historic buildings, cultural heritage organizations, and academic research. THEATRON is an architectural and textual resource online, which main aim is to provide a new instrument to study the theatre history in Europe[13]. It consists of 15 theatres, dated since the Greek time to the 20th century, spread all over Europe. The monuments can be selected according to time (chronological order), geography (dislocation on a

[12] The trailer of the virtual reconstruction of the Roman theatre of Catania is available here: https://www.youtube.com/watch?v=J52H5SLUcEM

[13] http://www.theatron.org/index.html

map), topology (shape of the theatre) and alphabetical order (fig. 1). Each theatre has its own non-textured 3D model which is possible to investigate in real time, from different points of view. Each point of view presents a description of what the user is looking at, plus some images of ancient drawings and reconstructions, recent pictures and text of sources useful to understand the history and the structure of the theatre. Four of the theatres contain also audio files that are convolved files reproducing the sound how it was listened within those theatres and at different locations (seats).

Figure 1 Map with selectable theatres according to their position, their age and their shape.

THEATRON has been then evolved into THEATRON 3. The latter is an online teaching application that takes advantage of virtual environment in Second Life[14] in order to improve teaching and learning skills[15][23]. Ten of the texturized 3D models of the theatres included in THEATRON project have been uploaded in Second Life. The avatars can walk or fly inside and outside the 3D models of the theatres, take a sit on the seats or stand on the stage. Second Life gives the possibility to add a new

[14] Second Life is an online platform reproducing a virtual world. It is possible to visit several regions and different realities, socialize with other users and made several activities, through a tridimensional avatar.

[15] http://www.theatron3.cch.kcl.ac.uk/index.php?id=88&type=signup

theatre in the “Theatres Island”, and also to book a virtual theatre in order not to have other avatars around (this is particularly convenient for teachers and students). Unfortunately, it is no longer possible to explore the theatres of THEATRON 3 in Second Life, because of lack of funding to maintain the subscription to the platform.
Among the other theatres, THEATRON includes the one of Pompey (in Rome), whose reconstruction has been realized once again by the King’s Visualization Lab. The Pompey Project is a very accurate work of research aiming to give the correct reconstruction of the first permanent theatre in Rome. Several documents have been consulted for its reconstruction: results of early excavations, fragments of the *Forma Urbis Severiana*[16], ancient plans of the remains and old drawings representing hypothetical reconstructions. The combination of these documents allow the architects to realize several 3D models of the theatre of Pompey as much accurate as possible, in order to know more about its original architecture. The sources used by the scholars and the 3D reconstructions are on a website platform freely accessible[17]. The multidisciplinary team that worked at this project, stressed once again the importance of 3D implementation, and more specifically of virtual technology, in the sector of Cultural Heritage, not only to stimulate the imagination of the visitors, but also to verify different hypotheses [24][25]. This is the appropriate direction to reconstruct and visualize ancient monuments, and it has been adopted to recreate the plausible original aspects of the Roman theatres in Crete.

The large part of the Greek and Roman theatres are included in several databases. The most valuable ones include The Ancient Theatre Archive of Whitman University, and Theatrum created by Direktion Landesarchäologie of Mainz. These can be considered as the main databases containing a variety of information of a large number of ancient theatres.

[16] The *Forma Urbis Severiana* is a plan of the town of Rome with its monuments, carved into several slabs of marble put all together, dated to the first half of III century, and wanted by the emperor Septimius Severus.

[17] http://www.pompey.cch.kcl.ac.uk/index.htm

The Ancient Theatre Archive mentions 119 theatres in the area of the Roman Empire[18]. It provides ancient name, modern name, location, date, cavea width in meters, orchestra width in meters, capacity (max), facing direction, renovation dates. Seventy one entries are accompanied by pictures, detailed descriptions and their localization on a map. However, it does not mention any of the theatres in Crete.

The German website Theatrum has been constructed to easily provide basic information about all the known Greek and Roman theatres[19]. The information provided includes dimensions, construction inscriptions, inscriptions of the theatres, sources, description, equipment, literature and events. Theatrum is mainly focused on the ancient sources related to these monuments. In this case, all the Roman theatres in Crete are mentioned, but the theatre at Gortyna, in locality Kazinedes, is still indicated as an amphitheater which is the old and wrong interpretation.

The mayor of the town of Locroi (Italy) and the director of the museum chose a virtual reality application in order to disseminate the knowledge they have about the Greek-Roman theatre of the town. The company digi.Art, with the collaboration of archaeologists, has developed a VR app for Google Cardboard, in order to give a reliable reconstruction of the theatre. The application enables the user to move within the area of the monument, to interact with some of the structures as the *velarium* covering the seating area and the mechanisms of the stage to activate the mobile scenography that was used during ancient performances. A voice narrates the history of the theatre and provides several info in different points of the theatre.

This short review is useful to understand the main innovations of this research.

The aim of this Ph.D. is to enrich our knowledge about Roman theatres in a part of a specific province of the Roman Empire, Crete[20], by mean of technologies that ease understanding, interpretation, research and diffusion.

Theatron is an excellent project but it has few limitations:

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[18] https://www.whitman.edu/theatre/theatretour/home.htm

[19] http://www.theatrum.de/home.html

[20] Crete was part of a larger province called “Crete and Cyrenaica”.

1. Real time navigation is no longer possible because of lack of fundings to pay again the subscription to Second Life platform.
2. The real time navigation through Theatron website does not show rendered and texturized 3D models; it is only possible to visualize some images with texture.
3. Audio files are not available for all the theatres and for none of the ancient ones.

The Ancient Theatres Archive and Theatrum are very informative databases with a user-friendly interface, but they allow a restrictive kind of research. The first allows to select theatres by name and by location, the second one only by name. The database I will present at the end of the Ph.D. will permit to enlarge the quality of the research. It will be possible to select theatres by name obviously, but it will be possible also to select the scholars which investigated the monuments, one by one, in order to read their descriptions of the theatres and to see other data according to each specific author. This will facilitate other scholars making their own research, it will be an instrument to comprehend the history of the monuments, and it will help interpretation comparing different information. In addition, the database will enable searching based on specific architectural data: it will group all the theatres according to the dimension of the cavea and/or orchestra, the number of sectors of the cavea, and the typology of the construction of the cavea. This will facilitate to make comparisons among the listed theatres.

Furthermore, among the other information (location, orientation, dimension, capacity, info about the architecture, etc.), the values of the parameters about acoustics quality, measured through virtual acoustics analysis, will be also inserted.

The VR application that shows the 3D reconstruction of the ancient theatre of Locri is the very first one, and at the moment the only one, that has been implemented with Google Cardboard system. Google Cardboard is a kind of “surrogate” of the more expensive Oculus Rift. The convenience of Google cardboard is certainly that a large number of people can afford to buy it being very cheap (about 15 euros), allowing a very large spreading of the applications developed for it. However, it is important to stress that Oculus Rift has a much better quality producing a much more enjoyment and stronger feeling of presence in the virtual world. In addition, an application created for Oculus, can also be exported to Samsung Gear VR, the price of which is more affordable (about 100 euros) but it is still a high quality device. The application that will be created during this Ph.D., as visualization tool of the 3D models of the theatres realized, will be developed for Oculus Rift, therefore it can be used in museums or archaeological sites, but it will still have the possibility to be used in any other location with the Samsung Gear option available.

The VR application of the Roman theatres of Crete will contain several information about the history of the monuments, but above all it will be possible to listen audios, reproducing a short extract of an ancient drama, exactly how it should had been listened in that space and in those seats in the past. The listening of the audio will produce even a greater sense of immersion and it will enable the user to verify and compare the quality of the acoustics of the past at different seats.

Summarizing, the innovation that this research will bring, includes the following:

1. A detailed study about all the Roman theatres in Crete and, more specifically, about their architecture. 3D visibility analysis and virtual acoustics analysis will be two further instruments, in addition to the more traditional ones (take as example the Pompey Project aforementioned), that will help to provide a higher level of accuracy to the 3D reconstructions.
2. A web database that will contain all the information about the Roman theatres in Crete. It will enable the user to group theatres according to their architectural similarity, to read the data collected by singular scholars and to know some of the acoustics characteristics of the theatres.
3. A virtual reality application that will transport the user within the theatres of Crete during the Roman time and will allow the listening of an ancient performance.

3. STATE OF ART OF THE ROMAN THEATRES IN CRETE

For a long time the Roman theatres in Crete have been neglected, while large part of the attention was addressed towards the rich Greek past of the island. This initial attitude of the archaeologists in Crete might surprise considering that the relevance of several Roman remains (including theatres) was already witnessed at the end of XVI century.

The first documents that refers to the information about some of these theatres are a couple of letters written by Onorio Belli to his uncle Valerio Barbarano in 1586.
Onorio Belli was a physician from Vicenza who was sent to investigate the island of Crete, at that time under the control of the Republic of Venice[21]. His main aim was to study the flora of the area but he was also really interested in collecting antiquities that he could send to Venice. During his surveys, Belli made drawings of the remains he found, among which there were eight theatres. These drawings were included in his work called "*Honorii Belli medici vicentini rerum creticarum observations variae, continents diversos actus, aedifici, inscriptions, etc.*" that unfortunately is lost. Luckily, some of the information contained in his work, are also included in other texts: the two aforementioned letters in which Belli attached six of the drawings of the Roman theatres plus their descriptions; his autograph work "*Descrittione geografica dell'isola di Candia di H. Belli*" dated to 1598; some extracts collected by Apostolo Zeno in the first half of XVIII century[22]; and comments about the lost work by intellectuals that had the possibility to read it (Scipione Maffei and Filippo Pigafetta).
The two letters containing the drawings of the six theatres that have been published the first time by Antonio Magrini[27] on the occasion of the wedding of Dr. Antonio Zanella and Laura Turra in 1847, and a second time by Lionello Puppi[28] in 1973[23].

[21] For further information about the life and the activities of Onorio Belli cf. Beschi[26].

[22] The extracts Mss. It. CL. X. 345=7162 are kept at the Biblioteca Marciana in Milan.

[23] The letters of Onorio Belli have been also published and translated in Greek by Spanakis[29] in 1968.

In 1999 Luigi Beschi[26] published the manuscript letters preserved in the letter book of Valerio Barbarano.

The remaining drawings of Belli represent the plans, with scale annexed, of the following theatres: theatre of Hersonissos, large theatre of Gortyna, small theatre of Gortyna, large theatre of Ierapetra, small theatre of Ierapetra and theatre of Littos.

These documents can be judged of great importance, considering that Belli had the opportunity to see the monuments when they were in a better preservation state than what they are now. Nevertheless, a critical approach is necessary in order to understand Belli's intent and capabilities, and consequently the reliability of his drawings.

Belli states that, having time, he used a great diligence to make these plans, and that he put all his efforts in order to find the truth[24]. Pigafetta[25][30] and Maffei[26][31] had the chance to read his work and they agreed about its great value because they considered it to be written with erudition and diligence, and it shows considerable knowledge of geography, antiquities and architecture.

Nevertheless, it is important to remind that he was a physician and not an archaeologist, so he might not had full capacities to completely understand the remains. In addition, it is necessary to consider that Belli belonged to the entourage of Andrea Palladio[27]: his interpretation of ancient remains might have been influenced by this cultural context which was inspired by the classicism of the ancient times.

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[24] "*Io nel levar queste et altre piante ho usato gran diligenza perché havevo tempo et comodità [...] Ma io, che più di una volta ho cavalcato tutta l'isola et ho fatto cavar molte statue et colonne in molte delle sue città rovinate, et dilettandomi non poco del studio di geografia, mi sono affaticato con tutto il mio poter di rintracciare il vero*".

[25] "*è scritta con grande diligenza e ricerca, e con considerevole conoscenza della geografia, antichità ed architettura*".

[26] "*L'opera è scritta con erudizione e con senno, e non si ha sopra quel paese alle stampe cosa di gran lunga paragonabile*".

[27] Andrea Palladio was an architect of XVI century, who was greatly influenced by the Greek-Roman architecture and above all by Vitruvius.

In the midst of 1800, the architect Edward Falkener[32] studied the documents left by Belli and he formulated his own interpretation about the remains of the theatres described by the physician. For each theatre, Falkener elaborated two plans: one plan has half part representing the foundations of the theatre and the other half representing a facsimile of Belli's plan (who probably drew foundations and elevated parts together); the second one is a plan re-elaborated by Falkener according to his own knowledge regarding architecture and according to the information Belli gave in his descriptions[28]. It is possible to notice some differences between Belli's plans and Falkener's plans, such as the division of the cavea in sectors, the number of rows of seats, the diameter of the columns, and even more. Falkener also underlined the peculiarity of these theatres with respect to the depth of the *postscaenium*, the existence of magnificent porticos behind the scene, and the location of stairways for the access to the cavea. In addition, he compared the Roman theatres in Crete with some others theatres built in the rest of the Empire.

Onorio Belli is certainly the only traveler that left us such an accurate documentation for several Roman theatres in Crete, but he has not been the only traveller to give testimony of these monuments.

Since XV century, numerous Europeans decided to visit Greece. Many of them passed by Crete on route to other destinations toward Near East, while others were sent to Crete by their motherland for socio-political reasons. Their travel diaries can be a valiant resource because they describe landscapes that have been severely changed or modified during the centuries and sometimes monuments or archaeological remains, that are now disappeared, were present at that time. It can be very useful to carry out a careful analysis of these documents, but always keeping a critical approach and considering that often who provided these descriptions was not an expert archaeologist or architect, so it is important always to compare this data with other recent information gained in a more scientific way.

[28] Falkener noticed some incongruities in the work of Belli between plans and descriptions regarding the same building.

Except for Belli, the rest of the travelers were not particularly interested in the Roman theatres of Crete and this is the reason why there are only sporadic information about these monuments in their diaries, or trip's reports.

One of the first documents about some of the ruins of Crete is the *Descriptio Insulae Cretae* by the Italian geographer Cristoforo Buondelmonti during his journey at the beginning of XV century[33]. He described the island through several maps and drawings, and one of this reproduces the town of Gortyna with its remains (fig. 2).

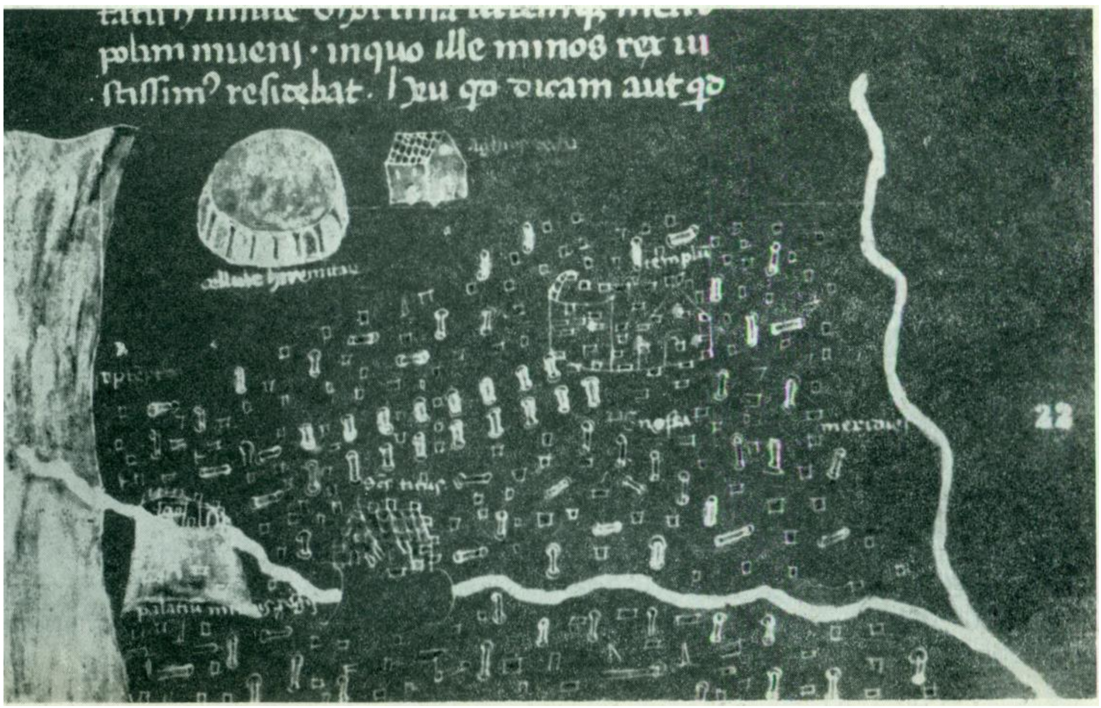

Figure 2 Ruins of the town of Gortyna by Cristoforo Buondelmonti.

At the beginning of 1700s, the king of France sent J. Pitton de Tournefort[34] to Crete in order to obtain a naturalistic study of the island. The traveller also dwelled on the ruins that he found in the areas he investigated. His painting of the landscape of Gortyna is significant (fig. 3), as it seems possible to recognize some of the buildings and monuments of the site. Immediately to the left of what appears to be the bridge above the river Letheus, there are some walls that could be part of the *postscaenium* of the large theatre of the acropolis. In the middle of the painting, in foreground, we can see the façade of a building that seems to be half-circular, sustained by arches, and it could be correlated to the small theatre, the one next the temple of Apollo Pythion. Close to the representation of the village of Agoi Deka, a half round or ellipsoidal ruin is represented and it could be identified as the amphitheater (found not many years ago exactly under the modern residential area) or as the Roman theatre that has been localized not far from the particular location.

Figure 3 Landscape with the ruins of Gortyna by J. Pitton de Tournefort.

Since the middle of 1700 till the second half of 1800, three of the several British travelers who have undertaken personal voyages in Near East, gave descriptions with many historical, geographical, cultural and social details of each place they visited during their trip, among which they included Crete.

In the work of Richard Pococke[35], there are references to the Roman theatre at Gortyna, in locality Kazinedes, that has been recently identified: till some years ago it was supposed to be an amphitheater, as Belli suggested first. Actually, Pococke expressed his doubt regarding its original function mentioning that those ruins (whereof he reported measures, construction material and architectonical description) could pinpoint a theatre as well as an amphitheatre, but in the end he, as many others, was inclined to think it was a theatre.

Robert Pashley[36], in the first half of 1800, clearly recognized the theatre of the ancient town of Aptera and he underlined it was made out of stone, rather than dug in the rock according to the Greek tradition. Unfortunately, he does not give any other information about this theatre, that it is still visible, and neither for any other Roman theatre of Crete.

There are more data in the report of the trip of Captain Thomas Abel Brimage Spratt[37] published in 1865. He observed the large theatre at the acropolis and the theatre at Kazinedes (that he also identified as amphitheater) in Gortyna (fig. 4), both theatres and the amphitheater at Ierapetra, and the theatre at Lissos. He based his research on the testimony of Belli and he made a lot of comparisons between what he saw and what the Venetian physician drew on his plans, except for the theatre of Lissos because it was not documented by Belli, and Spratt just reported the length of its diameter.

At the end of XIX century, systematic investigations of some of these monuments were initiated.

Large part of the research in Crete has been promoted by the *Scuola Italiana di Archeologia ad Atene* and the activity on the island was so intense that Federico Halbherr, in 1898, established the *Missione archeologica di Creta*[29]. This mission was mainly involved in the site of Gortyna[30], and as a result it discovered the three Roman theatres of the town.

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[29] Cf. VV[38], pp.69-72.

[30] Gortyna is the best preserved Roman town in Crete. It was the capital of the Roman province of Crete and Cyrenaica since 67 BC. These reasons explain the large interest that this town provokes in many scholars.

Figure 4 Plan of the town of Gortyn by T.A.B. Spratt.

Antonio Taramelli, few years after Halbherr, investigated the territory of Gortyna [39]. He made the planimetry of the site, together with plans and sections of the walls he found. He also documented, with plans, sections and descriptions, the theatre placed on the slopes of the acropolis and the one next the temple of Apollo Pythios. He gave his own interpretation of the remains which were still visible at that time and he made several comparisons with the work of Belli and with other ancient theatres. Taramelli dwelled on the difficulties he met to take the measures of the buildings because everything was ramshackle and he underlined that archaeological excavations would be fundamental in order to understand accurately the monuments.

Taramelli also visited the site of the theatre of Lyttos but in this case he managed only to report its construction material because the area was almost completely covered by orange and lemon trees. However, also in these circumstances, it was possible to understand that this theatre had to have remarkable dimensions[40], as affirmed by Belli.

In 1911, Amedeo Maiuri examined the building in Gortyna that was already identified as amphitheatre by Pococke, confirming his same hypothesis, and he compared it with other amphitheaters in Asia, Africa and Croatia[41].

In the same years, Bendinelli studied the architectural fragments belonging to this building[42] and several years later Golvin worked on the sculptures discovered in that site, in particular on the representation of Nemesis that in his opinion could confirm the theory that identifies the monument as an amphitheatre[43].

Lucio Mariani was another archaeologist belonging to the Italian Mission in Crete. He provided only a very brief description of the theatre at Hersonissos[44] and he made a sketch of the town of Lyttos, placing the theatre in the NE area of the town[40].

Thirty years after Taramelli's investigation, Colini started a small excavation in the area of the theatre of the Pythion and he has been able to take measurements of the length of the *scaenae frons* and of the radius of the *media cavea*[45].

During the Second World War, in which Crete was severely damaged, and in the immediate post war, the researches on the island were interrupted to restart in the early '70s.

Albert Leonard, professor at University of Arizona in the department of Classical Archaeology and Studies of the Near Est, has been the director of many archaeological excavations in the Mediterranean area, and he was the first one reporting the Roman theatre on the small island of Koufonissi. He found the cavea but he neither saw any trace of the *scaenae frons*, nor of the *postscaenium*, and he asserted that it was improbable finding other remains because of the proximity of the structure to the modern beach[46].

A few years later, Nikos Papadakis examined the settlement of Koufonissi and he presented the results of the archaeological excavations that were made in the area of the theatre, by the Ephorate of Classical Antiquities of Eastern Crete. In this occasion, 1000 seats were counted in the *cavea*, and the orchestra and the scene building were discovered too[47]. The theatre was pretty well preserved and it was located at 120 meter from the sea[48].

Also Gilles Touchais was interested in the island of Koufonissi but he reported only few information about the theatre there [49], [50].

The works of the *Scuola Italiana di Archeologia ad Atene* have started again in Gortyna in the early ‘80s and Antonino Di Vita was the promoter of the researches about the theatres and the amphitheatre. The latter was clearly identified under the modern village of Agoi Deka and new studies verified the wrong interpretation of Belli and other authors (Pococke, Maiuri and Golvin) that recognized the amphitheatre in the remains that actually have proved to belong to a Roman theatre[51]. This theatre, identified in locality Kazinedes, has been widely studied by Gilberto Montali[52], [53]. He analyzed its architectural and ornamental structure after the discovery of several fragments of columns, sculptures and cornices. He has drawn a hypothetical reconstructive plan and section of the building: when he was unable to acquire the right measures, he used other witnesses and comparisons with other theatres, in order to give a valiant interpretation of the remains. After a detailed analysis of the foundations, he concluded that the seating area had to be divided in *summa*, *media* and *ima* cavea, with a portico at the top. From the radius of the orchestra and the radius of the *cavea*, he deduced the number of rows of seats for each sector and he made an estimate of the capacity of the theatre, which it could host 5000 spectators. He also achieved to reconstruct, for most part, the scene building, the *pulpitum* and the *postscaenium*, and he dated it to the II-III century, attributing it to only one construction phase, according with the analysis of the walls.

Paolo Barresi[54] examined instead the theatre at the acropolis of Gortyna and he elaborated a new interpretation that sees a third order of seats in the upper part of the theatre and he proposed the existence of a high podium around the orchestra. He sustained that it is impossible to have an accurate reconstruction of the scene building because of the total lack of remains.

University of Padua, in collaboration with the *Scuola Italiana di Archeologia ad Atene*, gave a great contribution to the research on the small theatre at Gortyna with the realization of several archaeological excavations, since 2001 till 2010, and resulting reports and publications.

Since the beginning, the results of the excavations have been impressive and they enable the reconstruction of the historical phases of the theatre. The archaeologists studied the ceramic finds collected during the excavations and they carried out topographical surveys through GPS, surveys of the structure of the theatre through laser scanner, low aerial photographic pictures in order to obtain image rectifications and photo mosaic, and geophysical prospection by GPR[55]. They investigated each sector of the theatre: the cavea (included the foundations), the orchestra, the *pulpitum*, the *scaenae frons* and the scene building. They made plans, sections and 3D models of the two phases of the theatre[56], [57].

Recent researches have been focused on the ancient site of Aptera and on its theatre, in order to do some procedures of maintenance, restoration and promotion. The theatre had been already partially investigated by Henrich Drerup in the midst of 1900[58]. He identified the cavea, the orchestra and parts of the seats. He recognized the Roman phase and he described a Doric capital he found *in situ*. Large part of the theatre was dug between the 2008 and the following year. The current state of the building has been documented with plans, sections, photographic shots and topographical survey. In addition to the discovery of the remains dated to the Roman time, two walls of the previous Hellenistic scene have been also identified. The archaeological excavations enabled to propose reconstructions of the theatre in each of its three phases, but particular attention has been given to the last Roman phase which is very well documented[59]. In the middle of the orchestra there are traces of a limekiln used after the theatre fell into disuse, probably in the VI century. Indeed, the building was mostly destroyed in order to obtain construction material as the lime for modern buildings around the area.

Some of the theatres have been examined through geophysical prospection as well, run by the Laboratory of Geophysical-Satellite Remote Sensing & Archaeo-environment of the Foundation for Research and Technology Hellas (F.O.R.T.H.).

In Gortyna, the geophysical survey has been carried out in the area of the theatre of the acropolis. Four methods have been used: magnetometry, magnetic susceptibility, ground penetrating radar (GPR), electrical resistivity tomography. Each one of these techniques was useful to examine the area at various depths and, combining the results reaped from the different instruments, some meaningful data have been obtained to know part of the original aspect of the theatre. Every method gave positive results, but in the area of the orchestra, the GPR and the electric resistivity tomography, were not able to locate the level of the pavement, probably because it is placed in a large depth (at least three meters under the planking level). The results have been clearly showed through the georeference of geophysical maps on topographical plans and on imagines from the satellite Quickbird. An exact overlapping of the plan of Belli has been also attempted with a lot of difficulty as it was not possible to recognize sufficient number of Ground Points (GCPs)[60].

The geophysical prospection at Ierapetra gave interesting results as well. In the area where the small theatre had to be probably placed, magnetic and soil electrical resistance, electrical resistivity tomography, GPR, and seismic methods were employed. Many anomalies have been obtained from each methodology used, revealing some architectural remains. The recognized geophysical anomalies proved the existence of walls located at less than 1 or 1.5 m of depth. Moreover the architectural remains visible on the surface have been mapped through the GPS [61].

At Koufonissi, prospection covered a huge area of 100 x 200 m and the region has been completely investigated through magnetometer and (in some small parts at north-west, at south and in the center) by GPR, reaching up to 2-2.5 m of depth. The GPR clearly located remains of the scene building in the west part from 60-80 cm to 120 cm in depth, and in the eastern part, at superior depths. These anomalies confirm the hypothesis of Papadakis, who mentioned that the scene was around 20-21m long. The location of the *thymele* at the center of the orchestra has been also discovered through GPR. Some anomalies have been identified by both techniques and these anomalies indicate some architectural structures in a good state, probably belonging to the settlement developed north-west of the theatre[62].

Approximately in the same period, also the area of the theatre of Hersonissos has been investigated through different methods: magnetometry, electro resistivity and GPR, covering 2000 m^2. The results were very satisfying: architectural structures have been identified at different depths, above all in the area of the cavea, and the entrance to the theatre have been probably recognized in the interruption of anomalies between the cavea and the wall of the scene building. Unfortunately, the geophysical prospections in the area now occupied by the modern road did not give any noteworthy result, probably because of a pipe along it[63].

The interpretation of geophysical prospections will be one of the instruments useful to reconstruct the original structure of the theatres: they will be integrated with updated satellite images and available plans of the remains in order to verify their accuracy.

All studies aforementioned concern several theatres but taken singularly. There is not an overall integrated study about the Roman theatres in Crete which enable to identify possible similarities, to understand common characteristics and then to verify the presence of a potential regional category.

In 1968, Spanakis collected all the available data about the Roman theatres in Crete[29], elaborating a state of the art, but he did not give any information more or any interpretation (except for few pictures). Indeed he stressed the importance to have a total study about such an interesting and important topic.

The first archaeologist that grouped the Roman theatres in Crete, investigated them and tried to give information about each one of them has been Ian Sanders[16]. When he was a young Ph.D. student at University of Oxford in ‘70s, he made his research about the Roman history in Crete and he examined every known Roman settlement on the island. He realized a gazetteer comprising all the Roman sites and their monuments, therefore also the theatres. Sanders took the measures of these structures, he reported the material used to build them, he provided descriptions and his own interpretation of the remains, and he compared the data he collected with information given by other authors. His work is a direct and systematic witness, full of details, which can give back an image of how these buildings had to look like to an expert eye, at the end of 1900. Ian Sanders was the first scholar to have a scientific approach in the matter of this subject.

Similarly, the archaeologist Valentina Di Napoli is the first one who tried to connect all the Roman theatres in Crete among them in order to find out some common characteristics that can enhance our knowledge of both Greek and Roman culture[15]. However, her research is still based only on the published material, focusing mainly on the sculptural decoration, because as she correctly stressed, the condition of the theatres nowadays does not allow a deeper study of their architecture. She recognizes that, despite these monuments are inspired by the Roman tradition, they still have influences from Minor Asia and Athens. She underlines the will of Crete, and more generally of Greece, to stand out from the central Roman authority. Furthermore, she suggests that it is possible to reconstruct the distribution of the Roman influence within the island of Crete, according to the presence of the theatres, as these monuments (and the other public buildings for performance) are generally located in the main and more influent towns. Di Napoli is the only one who attempts a preliminary study which involves all the Roman theatres in Crete. However, it is important to stress the need to know more about the architecture of these monuments in order to achieve a more valuable conclusion.

Other works which include almost all the Roman theatres in Crete, but inserted in a wider context, are two census lists which aim to collect basic information about nearly every theatre known.

Ciancio Rossetto and Pisani Sartorio made a list which consists of more than one thousand Greek and Roman theatres, based on archaeological discoveries, and literary and epigraphic sources[64]. The authors also included in the catalogue the monuments not visible anymore because they are buried or destroyed. For each case, they gave the following information: position and orientation, time when it was built, current dimensions of the *cavea* and orchestra, material used to build it or to restore it, and references.

In 2006, Frank Sear published a similar work but more specific about the Roman theatres in the Empire[65]. It is focused on the architecture of the theatres and the author analyzed their various characteristics in the different Roman provinces. His list of theatres has similar indications such as the work abovementioned, and in addition, sometimes providing personal interpretation of the available documents.

There are also a few online lists that provide many information about the large part of the Greek and Roman theatres.

The Italian website Engramma[31] made a census of the buildings for performances in the ancient world and it shows them localized on the map, describing their state of preservation and indicating the possible time of building, their general dimensions (large, medium, small) and if they have been identified through archaeological discoveries, other documents or literary sources. Unfortunately, in some cases the website has not correct data or these are not revised with the last discoveries; for example the small theatre in Gortyna appears not to be excavated yet and the theatre in Inatos is not even mentioned.

The ancient theatre archive created by Withman University[32] allows to interact with a map populated by points representing the location of the theatres. It provides information about the typology of the theatres, date of construction plus renovation dates, excavations, dimensions, seating capacity and add plans and images. In addition it has a general bibliography and a glossary.

The website Theatrum realized by Mainz University concerns all the theatres dated back to Greek and Roman times[33]. It is more focused on the information we can obtain from the literature. It gives specific bibliography for each theatre, plus

[31] http://www.engramma.it/eOS/index.php?id_articolo=385

[32] https://www.whitman.edu/theatre/theatretour/home.htm

[33] http://www.theatrum.de/home.html

inscriptions mentioning the theatres or those that have been found in the area of the theatres, and written sources describing the monuments.

All these lists are useful for collecting essential information about many theatres and to facilitate comparisons, but they do not give an interpretation that would help in the understanding of ancient knowledge, cultures and geographical connections of different sites.

4. METHODOLOGY

4.1 3D Visibility analysis

The analysis of visibility in archaeology has found widespread application, above all in landscape's studies, since the '80s[66], [67]. In particular, this kind of analysis has been considered useful to investigate the distribution of sites and relationships among them[68], to understand defensive techniques of ancient populations[69], to study the likely rituals connected to prehistoric monuments[68], [70], and to examine the connection between monuments/sites and astronomical events[71].

Several approaches succeed each other in order to achieve a high degree of reliability and to obtain as much information as possible through visibility analysis. Lake and Woodman[72], in their review of visibility's studies in archaeology, explain in detail the features of the two main groups in this field: non-GIS visibility studies and GIS visibility studies. They observe that actually, the GIS visibility studies reflect the theoretical aspects developed by the non-GIS visibility studies (informal, statistical and humanistic). However, the use of GIS tools incites a more quantitative approach (that gives more accurate results) and opens to numerous kinds of visibility analysis.

The quantitative methodologies used in archaeology are actually borrowed from urbanistic and architectural studies. A brief overview is presented in the following paragraphs in order to show potentialities and weakness of each methodology, and in order to explain the convenient passage from 2D analysis to 3D analysis.

The concept of **isovist** in built environments, has been developed by Benedikt[73] with the purpose to better understand the architectural space and its characteristics[34]. As defined by Benedikt, "an isovist is the set of all points visible from a given vantage point in space and with respect to an environment". The maps produced by the application of this method show a point in the space that it is the observer, lines that represent built structures (walls, for example), and white and grey areas. The white areas are the non-visible ones, the grey areas are the visible ones, which shape

[34] Tandy was the first one to apply this methodology for recording landscapes in 1967.

derives from position and dimension of the elements existing in the space that obstacle the visibility (fig.5).

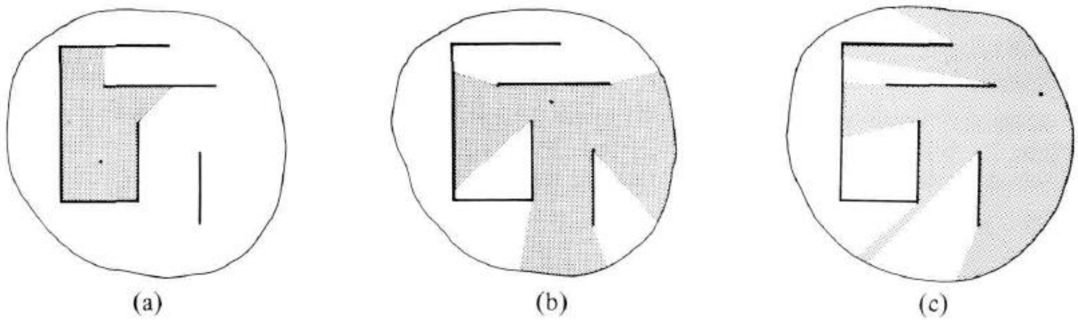


Figure 5 Examples of isovist fields (from Benedikt, 1979).

An example of isovist methodology applied to archaeology is the study of different structures of Byzantine churches in Jordan, by Clark[74]. His aim was to find out which parts of the church are visible from different positions in the area of the assembly, in order to achieve some significant conclusions about the possible categories of Byzantine churches in Jordan, and about the visual impact and visual experience of people participating to religious ceremonies. The study demonstrated that there are churches with a high visibility of the altar area, while in other churches this area is less visible than others; this allowed the author to identify an evolutionary pattern connected with the visibility of the area of the altar. It is important to underline one limitation to this method, stated by the same Clark: it is not possible to add partial obstacles to the vision. This means that in case of complicated and elaborated environments, the isovist methods loses its reliability. Clark also applied an alternative methodology together with the isovist one, the **visibility graph**. Turner *et al.*[75] developed the concept of visibility graph[35] from isovist, in order to investigate configurational relationships in architectural spaces and then to fill the lacks derived from the isovist measure. According to Turner *et al.*[75] the issues derived from Benedikt's methods are two: the mutual visibility among several locations within the same isovist is not known; no suggestions about how to interpret

[35] The term visibility graph was known already since 1994 when De Floriani *et al.* introduce it for landscape analysis, with a different approach respect to the one proposed by Turner *et al.*

the isovist measures have been formulated by the author. Through the creation of a visibility graph is instead possible to know the visual relationships among the users and also between user and architecture. The generation of a grid allows to perceive the interconnections present in a defined space: the colours of each cell indicate the level of reciprocal visibility[36]. This additional analysis enabled Clark [74] to define some areas of the churches investigated as more "integrated" or more "segregated" (that means respectively areas with more inter-visibility and areas with less inter-visibility)(fig.6).

In the field of landscape's studies, the **viewshed analysis** was, and still is, one of the most used methodologies, also because it is a function included in GIS. As well explained by Fisher [78] "the visible area is determined by defining one location as the viewing point and then calculating the line-of-sight to every other point within the area of interest (the target points). If the land surface rises above the line-of-sight, then the target is out-of-sight, and otherwise it is in-sight. The result is based on a Boolean concept of visibility and reported as a binary field". This can be considered as a 2.5 D analysis because it is applied to DEM (digital elevation model). It considers the Z value of the terrain too but it still acts as a 2D because it actually analyses and produces a raster file.

Bishop *et al.*[79] are some of the firsts who criticised this approach: first of all because of the long time needed to generate a viewshed map, second, because it is not a 3D analysis (for example, trees are not considered in the analysis) and consequently, it does not produce any information about the vertical faces of the elements present in the landscape and their function related to the visibility. They stressed the importance of working with a full 3D model in order to know the real visible characteristics of the landscape.

[36] Turner *et al*. have been inspired by space syntax method suggested by Hilier and Hanson[76]to elaborate their visibility graph analysis. The aim of space syntax is to understand the interaction between space and society through movements of people within an environment. For an application of space syntax in archaeology refer to Homann-Vorgin [77].

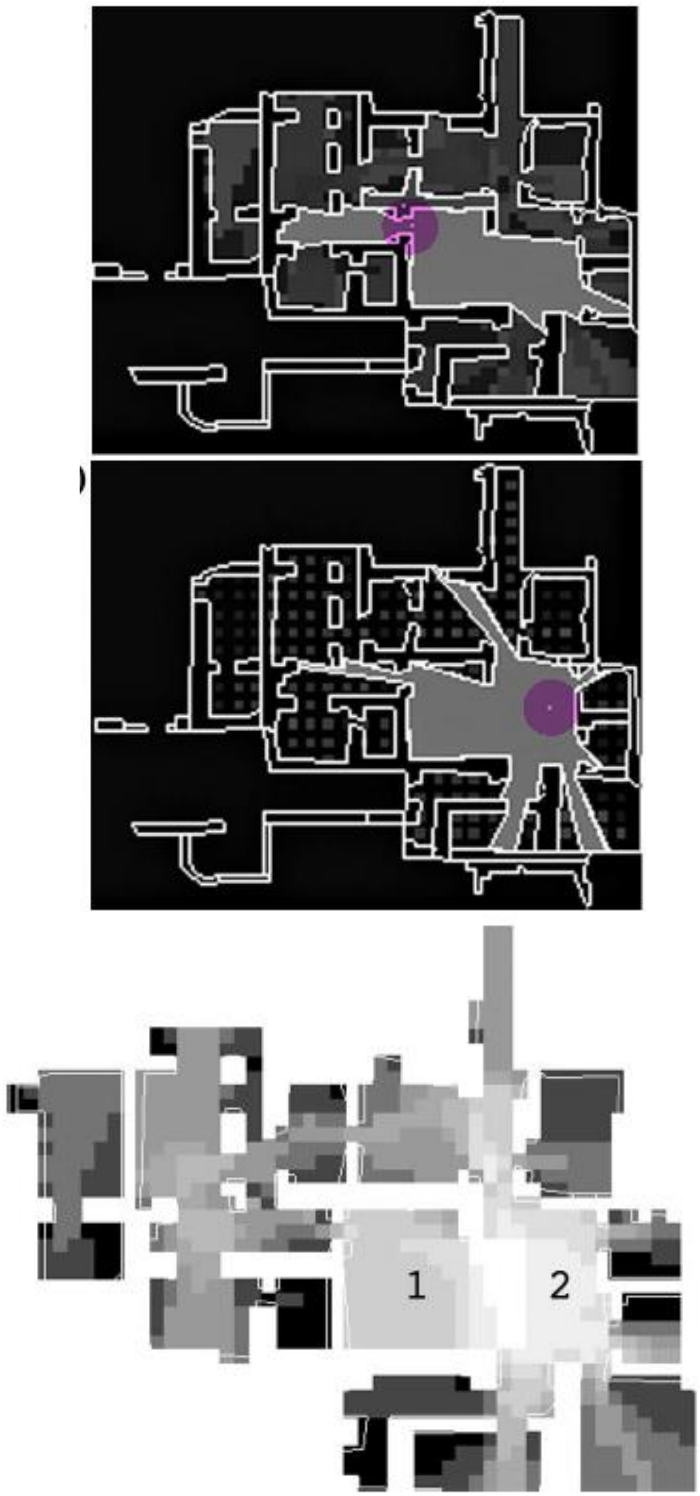


Figure 6 The two images at the top represent the isovist analysis at the church of Aqaba in Jordan, the bottom image represent the visibility graph analysis at the same building (from Clark, 2007).

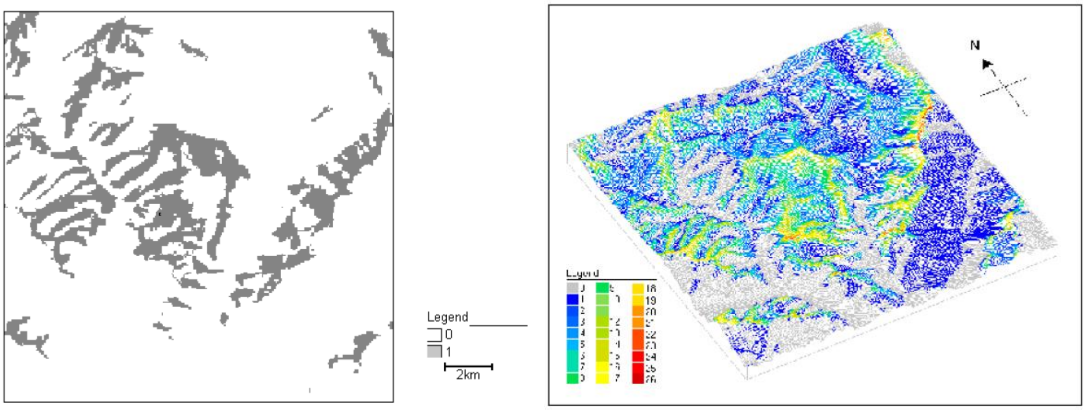


Figure 7 The image on the left represents the map produced by viewshed analysis, the image on the right represents the map obtained by cumulative viewshed analysis (from Wheatley, 1995).

Therefore, they proposed to use a 3D rendering algorithm to obtain images of the 3D model of the landscape, which contain depth information as well, so that you can take into account the shape of the vertical elements and where they are placed respect to each other.

During the last years, the necessity to work in a fully 3D environment for visibility analysis, also in the archaeological field, has become more impelling. The solution adopted to obtain a visibility connected with a 3D environment (above all in an architectural space) is combining the functionalities of 3D modelling software (as 3D Studio Max) and GIS analysis. This methodology is called **texture viewshed** because it actually consists of the creation of a binary file derived from baked textures. A baked texture is a rendered image of a 3D model with all its characteristics, as light effects and material properties. A point of light that emits rays towards all directions will highlight all those areas which view is not impeded by any obstacle, which means it will highlight all those areas that are visible from the position where the point of light is placed. Multiplying the points of light creating a grid of "observers", different areas will be highlighted, depending where the light comes from, that means we will have the level of visibility from several points of view. The enlightenment produced on the faces of the 3D model by each point of view can be baked in order to obtain a white and black raster file: the white areas are the visible one, the black areas are the not visible one. The various baked textures, derived from the enlightenment of each point of light, can be summed up in GIS in order to obtain a cumulative viewshed which black areas will correspond to number 0 (not visible) and white areas will correspond to number 1 (visible). This cumulative viewshed reveals which area is the most visible from a series of observers. This methodology has been applied for the first time in the archaeological domain by Earl[80] to study the visibility, of a roman *domus* at Italica (Spain), in order to comprehend the private Roman space and the interaction of it with people[37]. He distributed the observers (points of light), covering the full area of the peristyle of the 3D model of the house, and he obtained the baked texture for each one of them. Once summed up all the baked textures, he applied the cumulative texture viewshed to the 3D model, showing which areas of the peristyle are the most visible.

Two years after, in 2007, Paliou [81] applied the baked texture methodology to a house at Akrotiri (Greece), dated to late Bronze Age. The aim of her research was to investigate if the fresco representing the “Adorants” placed in one of the room of the house, was visible, not only by the people within the same room, but also by the persons in the adjacent room, which was separated by a pier-and-door partition. First of all, she created the 3D model of the two rooms, a grid of observers has been set in the room adjacent to the fresco, a point of light has been animated to cover all the area of the grid and the scene has been rendered, without material, for each observer point. Through GIS, a map, resulting from the sum of all the rendered images, has been created, and the fresco has been projected on it, so that it is easy to perceive which part of the fresco was more in plain view. This study confirmed the iconographic interpretation: the most visible figure of the three is the central one, and also the gestures of the figures are more evident than the rest of the fresco. One more visibility analysis has been done during the extension of the study to the other frescos in the house of Xeste 3 at Akrotiri, from several positions around the rooms, by Paliou *et al.*[82]. They have created two different maps: “time seen” map, where the

[37] Earl also verifies which area was the most illuminated within the peristyle, baking the texture thorough the day, during four periods of the year.

number of times a cell of the target object is viewed is indicated (fig.8) and a "scalar field" which shows the percentage of visibility of the target through space.

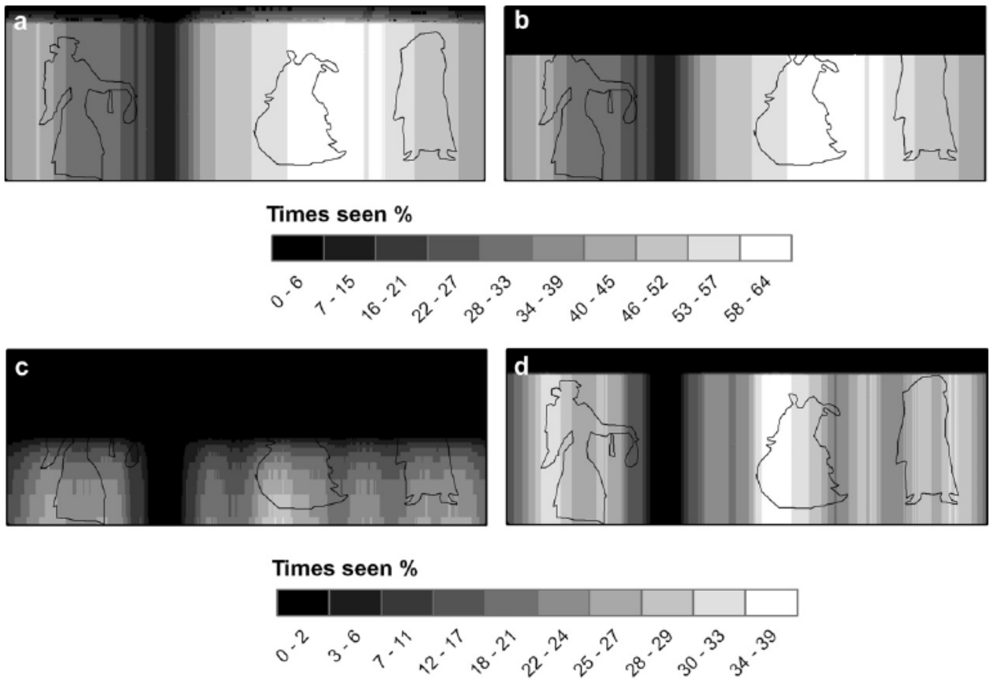


Figure 8 Cumulative texture viewshed of the fresco in Akrotiri's house (from Paliou et al., 2011).

Paliou and Knight[83] used the same approach also to investigate the social interaction of the church of San Vitale in Ravenna (Italy), dated to the VI century. The production of "times seen" map and "scalar field", through cumulative texture viewshed, demonstrated that men, located at the ground floor, had a better visual participation to the liturgy than women, placed in the *matroneum.* In 2014, Papadopoulos and Earl [84] chose texture viewshed analysis to verify the visibility of the North house of the Minoan harbour at Kommos (Greece). They created a grid of 48 observer points and they identified a difference in visible areas in two rooms. The high level of visibility of the central Room N17 made them hypothesize that this was the place reserved to leading activities.

The advantages of the 3D methodology are evident. First of all it is possible to obtain quantitative visibility information about the vertical surfaces. Second, the vertical obstacles are recognized and considered during the measure. Furthermore it allows the visualization of the results in a 3D environment, improving our knowledge of the space and its distribution[38].

In the very last years, one more step ahead has been made: the possibility to calculate lines of sight directly within the 3D model, with the advantage to speed the procedure.

Landeschi *et al.*[86] tried this methodology to compare the visibility of two different targets in the Insula V 1 in Pompeii (Italy), under the Swedish Pompeii Project. They imported the 3D model of the Insula, obtained through laser scanner survey, directly in ArcGIS and they created a grid of observer points from which lines of sight have been generated towards an alphabetical inscription and towards a political announcement, both placed in the house of Caecilius Iucundus. After these measurements, they could easily calculate the percentage of the two groups of lines of sight which did not encounter any obstacle toward the targets and then compare the visibility of the two inscriptions. As expected, the electoral announcement had a much larger visibility than the alphabetical inscription. They also transformed the grid of observers in a raster map that show through different colours (respectively green and red) from which areas the targets are visible and not visible. Landeschi *et al.*[87] expanded the study also to another target within the same house, an erotic fresco, which visibility has been confirmed to be quite high as well. In addition, a vertical map of frequency of visibility has been produced too, which indicates the level of visibility for each area of the fresco, giving the possibility to identify probable more important scenes in the same representation. They also observed as, in a visibility study, distance and enlightenment are important factors to consider as well, before to state some conclusions. Indeed, testing daylight illumination at different times per day, the fresco appears to be always in a dark part of the house, then, its intelligibility is affected by this.

It is interesting to note that till now, visibility analysis in archaeology has been applied in large part in urban contexts where the movements of the observers were

[38] For an exhaustive review of 3D visual analysis see Paliou[85].

considered in order to understand the social space, as humans interact with it, and the symbolical meanings of the structures within this space. In these cases, it is important to know in detail the archaeological sites, in order to make accurate reconstructions useful to achieve reliable results in the socio-symbolical visibility analysis. For example, the exact positions of the frescos, both in the case of Akrotiri and in the case of Pompeii, and the internal structure of the church of San Vitale in Ravenna need to be known or otherwise it is necessary to have enough information to make assumptions about it. On the contrary, in this research, the **3D visibility methodology** is used to obtain information about the architectural structure of a monument, starting from data or assumptions about its function. In this case, the purpose is to achieve a better knowledge of those buildings and monuments that have been destroyed, of which an exhaustive documentation does not exist.

We know the cavea of a theatre was used as a seating area for the public and the stage was used by the actors, during the Roman time. These two information are enough to make conjectures about the possible structure of a theatre because its first function was (and still is) to watch performances, as the original Greek word well explain[39].

Methodology

In this research, 3D visibility analysis is applied to 3D reconstructions of the Roman theatres, in order to validate or to confute the interpretation of part of their architectural structure, and then, in order to achieve more reliable hypothesis about their original aspect. In particular, the visibility of the stage from the spectators' positions in the cavea will be verified. In this case, the advantage to work in a fully 3D environment is the immediate visual perception of the space, and therefore the possibility to understand which obstacles impede the visibility of a determined target and from which position.

In order to carry out the specific analysis, the theatres have been virtually recreated by means of AutoCad and 3D Studio Max software packages. The reconstructions are

[39] The word*θέατρο* comes from the ancient verb *θεάομαι* that means "to see, to watch".

based on ancient and recent plans, travellers' descriptions, reports of archaeological excavations, scholars' interpretations and remains in situ.

Each 3D model has been exported as .3DS files in order to easily import it in ArcScene, the 3D visualization application of ArcGIS, as multipatch shapefile. The preference of ArcScene with respect to ArcMap, is obvious as because the first allows to work directly in a 3D environment. Grids (one for each theatre) representing some of the observers' positions spread out in the cavea have been realized in AutoCAD and then added to ArcScene. Generally, every grid consists of five rows of points, located 75 cm higher than the seats indicating the average eye-level of a seated man/woman. Five rows of observers' points are enough to verify the quality of visibility, considering that from large part of the central area of the theatre, the stage is obviously visible. In particular, it is important to examine the visibility conditions of the spectators seating at the sides of the cavea, where the converging walls of the *analemma*, or the *basilica*, can be an obstacle. In these positions, the points are placed 80 cm far from the converging walls to take into account the space occupied by possible stepladders. However, other rows are placed also in the central area in order to compare the results among different seats, and also to check the visibility from the first rows in case the stage would be too high, impeding the view. A line placed 160 cm higher than the floor of the stage, approximately at its centre, have been edited directly in ArcScene to represent the probable positions of the actor/s playing a performance. The grid represents the observers and the line is the target; sight lines have been constructed between the two through the "visibility" kit of ArcScene 3D Analyst toolbox. Once obtained the sight lines, lines of sight have been built and they show by two different colours which spectators have a full visibility of the actor/s in several positions across the stage (green lines) and which ones have no visibility (red lines).

Another instrument of the 3D Analyst toolkit (still related to the lines of sight) is the identification of the obstruction points, that is the exact localisation of the elements that obstacle the visibility. This option is very useful because it gives the possibility to easily find potential errors in the reconstructions, for example: wrong structure of the *analemmata*, wrong height of the *analemmata*, wrong position of the *basilica*, stage too elevated.

In addition raster maps have been produced as well, in order to visualize the frequency of visibility from the observer points, still through ArcScene. First of all, raster containing Z values of the 3D models have been produced; these have been used together with the grids in order to obtain frequency of visibility maps. Through these maps, along with their colour scale, it is possible to visualize the number of observer points who see the stage, or part of it [88].

Some of the theatres have been modified according to the results of the 3D visibility analysis, in those cases where the reconstructed structures did not enable a good visibility for all the considered spectators. The results obtained from the 3D visibility analysis of the small theatre of Gortyna and of the theatre of Aptera can be used as guideline for the rest of the theatres, because they have been excavated for many years and we have a lot of valuable information about their architecture.

4.2 Virtual acoustics analysis

The statements of Vitruvius in his "*De Architectura*" [89] confirm the idea of the importance of the acoustics in the ancient theatres. In his work about the structure of ancient buildings, in the fifth book, dedicated to the useful recommendations to build a correct theatre, he included a chapter reserved to the acoustics, indicating a "consonant" place as the correct place to understand theatrical performances.

Despite the acoustical aspect of ancient theatres has always intrigued many scholars, both archaeologists and acousticians, there are not many researches that focused on this topic, probably due to the complexity of the subject concerning architectural acoustics in general. It is important to note that performances have been always part of the majority of the societies, since the ancient time, but studies about the behaviour of sound (above all its interaction with space, materials and surfaces) did not progress in the right direction for a long time.

Charles Garnier, architect of the Paris Opera, in 1880 stated: “It is not my fault that acoustics and I can never come to an understanding. I gave myself great pains to master this bizarre science, but after fifteen years’ labour, I found myself hardly in advance of where I stood on the first day. I had read diligently in my books, and conferred industriously with philosophers – nowhere did I find a positive rule of action to guide me; on the contrary nothing but contradictory statements” [90]. The uncertainty about room acoustics is also reflected in the many different shapes of the theatres realized during the centuries. A step ahead towards this direction has been done by Wallace Clement Sabine, at the beginning of 1900, when he discovered that the fundamental reverberation time depends on the volume of the room and the quantity of absorbed sound in that room[91].
From Vitruvius’ words we understand that ancient Greeks and Romans probably knew how to build a good theatre: we have the example of the ancient theatre of Epidaurus, where even now tourists do their little performance at the centre of the orchestra while people sitting at the top receives clearly their words.

The first in depth study about the acoustics of ancient theatres has been carried out by François Canac in 1967 [20]. He made some experiments with models of open-air theatres to understand their acoustics and to identify the acoustic role of architectural elements as niches, *parodoi*, walls, seats, and orchestra’s floor. He verified his results taking into account direct measurements from some ancient theatres in Italy, France, Greece and Asia Minor. He observed that the intensity of the sound is not such a fundamental parameter when there are no external noises and reverberation that interfere with the words of the actors. In addition he demonstrated that the roof creates later reflections that prejudice the clarity of the sound. Furthermore, he listed the conclusions he obtained after the experiments: never weaken the direct sound, reflections have to arrive within 30 milliseconds after the direct sound in order to improve it, take out the surfaces that can produce late reflections, differentiate the theatres in base of their function (for speech or for music). He finally sustained that the valuable acoustics of the ancient theatres is due to rules of geometry and to the excellent ability of the ancients in listening.

Later, only short and sporadic studies have been dedicated to the acoustic of ancient theatres and, in particular, everyone was focused only on one theatre, possibly the best known and preserved one.

A big project on the "Identification, Evaluation and Revival of the Acoustical Heritage of Ancient Theatres and Odea", ERATO, came out only in 2003-2006 and it allowed the discovering of numerous acoustics characteristics of ancient theatres as Aspendos (Turkey), Aphrodisia (Turkey), Jerash (Jordan) and Syracuse (Italy). In addition to in situ measurements, simulated measurements have been calculated as well through the software Odeon Room Acoustics. Virtual acoustics analysis uses 3D models along with ray-tracing plus image source methods in order to measure the impulse response length and recognize the values of several acoustics parameters[40]. Thanks to this technique, during the ERATO project it has been possible, not only to verify the actual acoustic conditions of some ancient theatres, but also to analyse the ancient acoustics of the buildings simply reconstructing their original aspect in 3D. The main concern of ERATO project was to obtain information about reverberation time, sound strength, clarity, and speech transmission index, in order to appreciate the acoustic conditions of ancient theatres in the current state of preservation, and the acoustic characteristics that those theatres probably had when they have been built. This study has been useful to understand the correct way to valorise those monuments today by the representation of performances, and to know the way they were used in the past (for example if for plays or concerts). In particular, the scholars participating to ERATO project stressed the various acoustic characteristics between open-air theatres and odea, which testify their different functions.

[40] The company Odeon A/S in Denmark is the producer of the software Odeon Room Acoustics that is one of the most used for digital acoustics simulations, also for ancient theatres (theoretical aspects of this software are described after).

In 2011, at Patras (Greece), the Acoustics of Ancient Theatres Conference demonstrated once again the interest towards this topic and it contributed with many researches to the development of new methodologies in order to virtually analyse the acoustics of Greek and Roman theatres. In particular, the contributions of Professor Gino Iannace from the II University of Naples are very interesting as he has been working for more than 10 years to find out how acoustics analysis can help to improve our understanding of architecture and history of ancient theatres. In addition he studied, together with several colleagues, some variable aspects to have more accurate results, as the effects produced by the *velaria* (awnings)[92] and by the presence of the audience[93]. He took measurements and made experiments directly on some ancient theatres but he also used virtual acoustics analysis to compare the measured and simulated results, and to study the original structure of ancient theatres (Taormina, Benevento, and Pompeii)[94]–[96].

<u>Theoretical concepts</u>

A sound perceived by a listener in a given space is characterized by three components: **direct sound, early reflections and late reflections**.

1. The direct sound is that part that directly reaches the ears of a listener, travelling in a straight line from the source, and it arrives first than the other components.
2. Early reflections come from the sound hitting obstacles (such as walls, ceiling, floor, large objects) that reflect the received acoustic impulse; these are the first reflections that arrive after the direct sound. They cannot be distinguished by the ears but if they arrive within 20 milliseconds after the direct sound, they improve the subjective intensity of the sound.
3. Reflections that arrive after the early reflections, are defined late reflections: they contribute having the pleasant perception of the vastness of a room and enjoying a full experience of the sound but, when reflections keep arriving for a long time, we have a reverberant sound that invalidate the comprehension of the sound. This happens because a long/repeated time of reflections makes a

sound longer than it should be and when a second sound (that can be the second syllable of a word, for example) is emitted, the first sound is still audible, so that the two sounds are not identifiable and distinguishable, therefore they are not comprehensible.

The duration of reflections is indicated by the reverberation time (RT) which Sabine, at the beginning of 1900, discovered to be a function of the volume of the room (V) and the total acoustics absorption (A, that is the sum of all the surfaces absorbing sound) and he formulate the equation: RT (in seconds) = 0.16V/A[91]. Each material has different characteristics that implicate a different level of absorption of the energy belonging to the sound, which is indicated by the absorption coefficient. A sound finishes when all its energy is absorbed by the surrounding materials; for each reflection of sound, part of the energy is absorbed.

More precisely, the reverberation time is the time a sound takes to decreases by 60 dB (T60) after it stops. Since it is not possible to record a decay of 60 dB and because, for the quality of the acoustics for the human ear, the first 20-30 dB of decay are the most important, the value of the reverberation time of the linear portion between -5 to -35 dB of the decay's curve is extrapolated (T30). The first 5 dB of decay are excluded from the measurement in order to avoid the strong early reflections (fig. 9). For the speech, the ideal time of reverberation is around 1 second, for music is around 2 seconds.

Also the first 10 dB of decay (early decay time, EDT) are important for the acoustics quality because it represents the subjective perception of the reverberation (while T30 is the real reverberation) which is actually related to the feeling of how much these reflections annoy the listener. The EDT indicates the diffusion of the sound: in an ideal environment, it should be the same as T30, but it is usually a little lower and the level of disparity between them is a signal of good or bad diffusion of the sound. Previous researches about well-known and well preserved theatres (Aspendos, Epidaurus, Jerash) demonstrated that usually, in open-air theatres, the difference between T30 and EDT is between 0.2 seconds and 0.4 seconds [97].

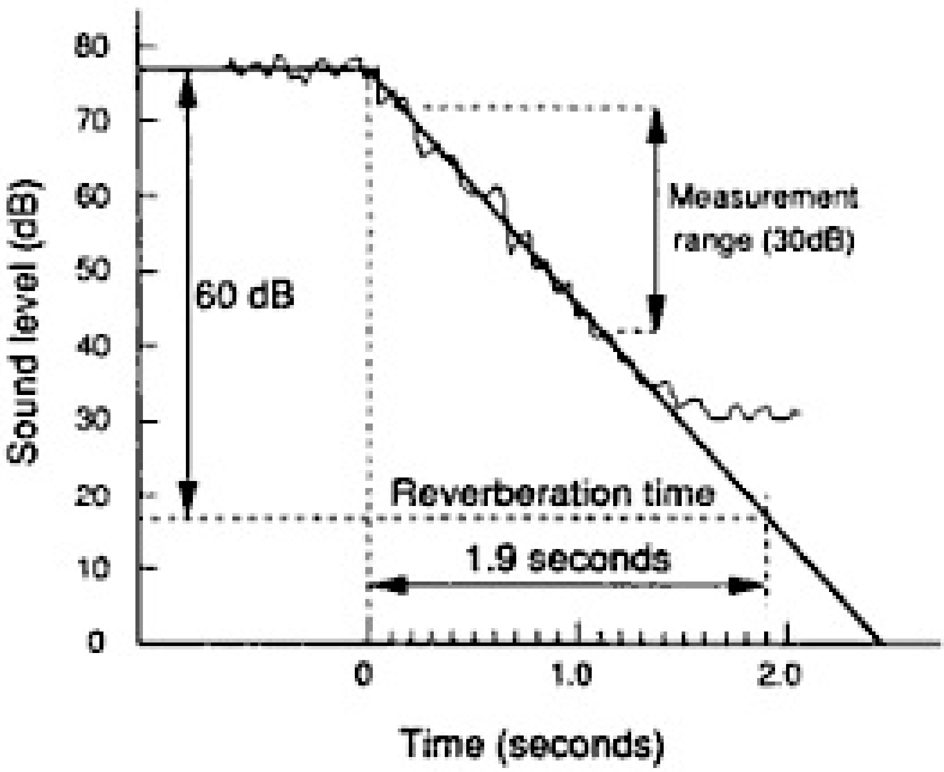


Figure 9 Illustration of the measurement of reverberation time (from Barron, 2010).

T30 and EDT are two important acoustic parameters connected to the reverberation of the sound, but there are other three parameters that also help understanding the quality of the acoustics in a given environment: two are connected to energetic criteria, clarity and definition, and another one is connected to spoken intelligibility, namely speech transmission index.

Clarity (C80) has been introduced by Reichart and Leumann in 1974 and it represents the comprehension of single sounds within a complex signal. It consists of the ratio between the energy (of the sound) that arrives within 80 ms, that is direct energy plus energy of early reflections, to the energy that arrives later (fig.10). If the energy of the late reflections is higher than the energy of direct sound and early reflections, clarity, that is comprehension, is not very good. We may have a more appropriate acoustics for speech when the value of C80 is equal or greater than 3dB, while for a good listening of the music we should need values under 3dB [98].

$$C_{80} = 10\log\left(\frac{\int_{0}^{0.08} p^2(t)dt}{\int_{0.08}^{\infty} p^2(t)dt}\right) \qquad [\text{dB}]$$

Figure 10 Ratio of C80 (from Spagnolo, 2014).

Definition (D50) has been introduced by Thiele and Mayer in 1953 and it indicates the level of clarity of the speech, the ease for the listener to understand the message of the speaker. The index of D50 is the ratio between the energy that arrives within the first 50 ms, direct sound plus early reflections, and the remaining energy of the signal (fig. 11). Also in this case, the first energy has to be superior to the late energy in order to have an acceptable quality of the acoustics for the speech. The desirable value of D50 for a speech should be higher than 0.50, for the music should be lower than 0.50 (by definition it is included within 0 and 1)[98].

$$D = \frac{\int_{0}^{0.05} p^2(t)dt}{\int_{0}^{\infty} p^2(t)dt}$$

Figure 11 Ratio of D50 (from Spagnolo, 2014).

Speech Transmission Index (STI) has been developed by Houtgast, Steeneken and Plomp in 1973. It establishes objectively the quality of level of spoken, calculating the combined effect of background noise and reverberation on the intelligibility of the speech. When there are no interferences on the characteristics of modulation of the signal, there are suitable conditions of intelligibility. Values of STI between 0.60 and 0.75 are good; greater than 0.75 are excellent[98].

Methodology

Basically, the software Odeon Room Acoustics uses two geometric methods in order to calculate and study the impulse response in a room: ray tracing method and image source method.

"Ray tracing methods find propagation paths between a source and receiver by generating rays emanating from the source position and following them through the environment until a set of rays has been found that reach the receiver" [99]. These methods are very simple because based only on the intersections of rays with surfaces and furthermore they are able to identify every type of reflections generated by the contact of the acoustic impulse with surfaces: specular, diffuse, diffraction and refraction. One of the problems with these methods is that the same paths may be counted several times; some reflections may not be found and some false reflections may be considered as real ones.

The image source method discovers all the possible sound reflection paths. It consists in the identification of virtual sources generated by the trajectories of the reflections created by each wall of the room. It is useful above all for the early reflections, whose arrival time and direction to the receivers can be easily conceived. Unfortunately, in the case of a room with an elaborated geometry, the calculation times become very long, because increasing the reflection order, the image sources will increase and then the times for calculating the impulse response will increase as well.

In order to remedy the disadvantages of both methods, Odeon uses a hybrid model that combines ray tracing method and image source method: its concept is to recognize image sources, tracing rays leaving from the sources and identifying the surfaces they hit.

Odeon doesn't only calculate the impulse response in order to obtain values of acoustics parameters, but it also produces the auralisation of the impulse response. Through the convolution of an anechoic sound and the impulse response, we obtain a file that reproduces the sound how it would be in that specific room or environment, giving the feeling to the listeners that they are virtually transported in that place.

Odeon gives the possibility to model the room we want to analyse through the "Odeon Editor", or 3D models can be imported in Odeon after having being created by other 3D modelling software.

Before starting any calculation, it is important to set the parameters in "room setup":

1. Impulse response length: it has to be at least 2/3 of the reverberation time, otherwise T30 won't be calculated. To have an estimation of the reverberation time, we have to use the Quick Estimate tool before of any other calculation. The value we are going to put corresponds to the milliseconds of the decay curve that is going to be calculated.
2. Number of late rays: "determines density of reflections in the late part of the decay" [100]. In this study, in order to simulate the open-air theatres, the number of late rays has been set to 500000 [101].
3. Max reflections order: establishes how many times a ray can be reflected. It should be as large as possible in order to follow the natural behaviour of the impulse response. This parameter is useful to stop, for example, rays that are "trapped between two very narrow surfaces"[100].
4. Impulse response resolution: "is the width of the time steps in the impulse response histogram in which the energy of the reflections are collected during a point response calculation" [100].
5. Transition order: allows to choose which method we want to use for calculations, or, if we want to use both, at which order of reflections the software switches between image source and late rays. In this study, it has been set at 2 because previous researches, demonstrates that it is the most suitable for open-air theatres [102].

The following and very important step is to assign the materials to each surface. The absorption coefficients of the materials in the room influence much of the energy of the sound that propagates in the area and in this way they influence the quality of the acoustics. For an accurate analysis we need to set also the scattering coefficient of each surfaces as it also characterizes the behaviour of the sound. The scattering coefficient indicates the decrease of intensity of a signal, due to the discontinuities the signal encounters when it reaches the surfaces and their material. It is preferable not to model in detail but to put a higher scattering coefficient to take into account decorations, for example. In this study a scattering coefficient of 0.5 and 0.7 has been used, depending on the surface.

It is important also to establish the auralisation settings; in this case the "create binaural impulse response file" has been selected in order to obtain convolved files that have to be listened through headphones.

Once the main parameters are set, sources and receivers can be placed typing their location on the x, y and z axis. An overall gain of 60 dB is assigned to the source because it corresponds to the decibels reached by the human voice, and it has been chosen an omnidirectional source, that means the sound is emitted toward all directions (360°).

It is important to check the correctness of the 3D model before to launch any calculation; Odeon makes available a series of tools to verify that there are no problems in the 3D model that could invalidate the process or the results.

First of all, there should be no holes in the 3D models in order to avoid the dispersion of the sound and this can be checked with the "3DOpenGL" tool that shows the 3D model from the inside, with colours corresponding to the materials assigned to it, and it easily allows to observe the model and notice any hole. Not only evident holes are problematic, but we have to ensure that 3D models are completely closed, referring to "water tightness": the "3D Investigate Rays" tool and "3D billiard" tool emit, respectively, a number of rays and spheres towards all directions leaving from the source; even if only one ray or one sphere will pass through the surfaces of the model, it means that it is not water tight and in this case we have a dispersion of sound and reflections. Often, warped surfaces constitute the cause of not "water tightness" models; in order to verify that there are no warped surfaces it is enough to use "3D geometry debugger" which exactly indicates which surfaces present this problem and then they can be easily modified through the 3D editor.

“3D billiard” tool can be used also to see the quantity and the order of reflections we have in the model and to observe the propagation of the sound in the room.

The last step is the creation of the job list: every receiver is linked to a specific source creating at least as many jobs as the total number of the receivers; the impulse response that reaches every receiver can be calculated in the different jobs. From the job list, it is possible to select also the grid calculation, in order to have a map that shows the quality of the distribution of each parameter. The grid has to be defined choosing the surfaces where the receivers need to be located, the distance between the receivers and the height of the receivers with respect to the surface. In this study, a distance of 2 or 3 m (depending on the size of the theatre) has been set to avoid long time calculations, together with a height of the receivers of 0.75 m above the surfaces.

3D models of the most well-known Roman theatres in Crete have been imported as .3DS file in Odeon, paying attention to insert the correct unit of input file (that is centimeter in this case) and the most convenient coordinate system. The option “glue surface” has been selected in order to obtain an inferior number of surfaces because the software is able to put together many sub elements, forming larger surfaces.

In order to make calculations, Odeon needs an enclosed room. In case of open-air theatres, this issue has been solved creating a “bounding box” around the 3D model of the theatres, as suggested by the manual of the software and by previous researches [93], [96], [103]. The box needs to have almost the same dimension as the theatre, in order not to modify the volume of the 3D model that would influence the reverberation time. To all surfaces of the bounding box, a material with absorption coefficient equal to 1 (that means totally absorbent) has been applied, so that the sound is not going to be reflected by those surfaces but it will disperse as it is in an open-air area.

As already said, the selection of the materials is very important because the absorption coefficient of the material is one of the main characteristics from which the acoustics quality depends. Luckily, the materials used for each theatre are known from the descriptions of the previous scholars and archaeologists. For materials like marble, wood, bricks, limestone, the absorption coefficients is noted in literature.In addition, to the seating area has been assigned a material with an absorption coefficient that corresponds to the presence of an audience with a density of 2 persons for m^2. It is possible also to use the transparent material that is useful when some objects (like porticos, or roof, columns, etc.) in the 3D model do not want to be considered in the first calculations, but in the following, in order to verify the influence of those elements in the quality of the acoustics.

Because the cavea is a semicircle (or in some cases almost a semicircle) its two half are symmetrical between them, so the receivers (representing the spectators) have been placed only in one half of the seating area, distributed in three radial rows: one 0.80 m far from the converging *analemma*, another one in the middle of the cavea and a third one between these two, at 45° respect to the axis of the end of the semicircle. One receiver every three/four steps is enough to have detailed information of the acoustics in the whole seating area. It is not convenient putting receivers at every step or seat because the calculation of the impulse response length for every receivers is time consuming. Receivers are placed 0.75 m above the seats, where the ears of a spectator might be. Also the receivers of the grid have been set at the same height and the distance among them at 2 or 3 m, depending on the dimensions of the theatre; in this case too, increasing the density of the receivers, calculation time will increase as well.

One source, representing the actor, is placed at the centre of the stage, 1.60 m above the floor, where the mouth of a person might be.

The range between 125 Hz and 2000 Hz has been considered in order to judge the obtained values of the acoustics parameters, because these are the frequencies well perceived by the human ear in order to comprehend a talk.

The sound file used for the convolution with the impulse responses in order to obtain the auralisation has been recorded at the Laboratory of Acoustics and Sensors Orso Mario Corbino of the CNR of Tor Vergata in Rome (Italy), directed by Dr. Paola Calicchia and performed by a student from University Tor Vergata, Martina Giovanetti, with the collaboration of Dr. Cristina Pace from University of Rome Tor

Vergata for the literary aspect. The monolog in ancient Greek, performed by Martina, is taken from the work of Euripides “The Trojan women”, lines 634-684. The file is 4.46 minutes and Dr. Calicchia took care of the quality of the files, removing the background noise.

5. THE CASE STUDIES

The case studies presented in this chapter consist of seven of the twelve Roman theatres built in Crete during the Roman times. Only seven have been chosen because of the remaining five we lack fundamental information:

1. Theatre of Chania: it has been destroyed and the only plan that documented it, realized it at the end of XVI century by Onorio Belli, has been lost.
2. The theatre of Kissamos is under the modern village.
3. The theatre of Lyttos is known only from Belli's plan (fig. 12) dated to the XVI century, and its approximate location is indicated in a sketch by Lucio Mariani [44]. Taramelli also visited the site of the theatre at the end of XIX century, but he described it as a field of lemons and oranges. The only thing that he could notice is that it was dug into the rock [40].
4. The large theatre of Ierapetra is under the modern town[61][41]. The only representation we have is Belli's plan (fig. 13). Captain Spratt described it as a "mere semicircle of rubble masonry"[37]; indeed, this is how it looks like in the picture took by Spanakis[29].
5. Also the structure of the small theatre of Ierapetra is known only from Belli's plan (fig. 14). Spratt identified it in a "mass of masonry"[37] in the west side of the town, and again Spanakis confirmed that nothing has been left of this theatre [29]. Finally, in 2013, after the investigation of the area through geophysical prospections in 2010, which indicated the position and the depth of some architectural parts of the theatre[61], the archaeological excavations have been initiated and they revealed six rows of seats[42].

[41] Sanders confused the two theatres of Ierapetra in his representation of the area corresponding to the ancient town: the large theatre is located in the central area, the small theatre is on the west side of the town, and not the opposite as he showed[16].

[42] No scientific publications have been made yet about the new discoveries. Concise results have been presented during the conference Έργο Κρήτης, in November 2016, in Rethymno (Greece), by the archaeologist Chrissa Sofianou.

All the Roman theatres in Crete are distributed all around the island, except for the area of Rethymno. Some of them are located close to the sea (Hersonissos, Koufonissi and Lissos). Generally, there was one theatre for each ancient town, except for Ierapetra, where there were two, and Gortyna, where exceptionally there were three.

A couple of theatres have more than one construction phase: the theatre of Aptera had a Hellenistic one, a first Roman one and a second Roman one; the theatre at acropolis of Gortyna was probably originally built in the Greek times and then partially rebuilt by the Romans; the theatre of the Pythion in Gortyna had two Roman phases.
This few general information already show a varied and interesting panorama which needs to be investigated in more depth.

A short introduction about the evolution of the ancient theatre and its several characteristics is presented in the following pages in order to facilitate the comprehension of the features of the Roman theatres in Crete.

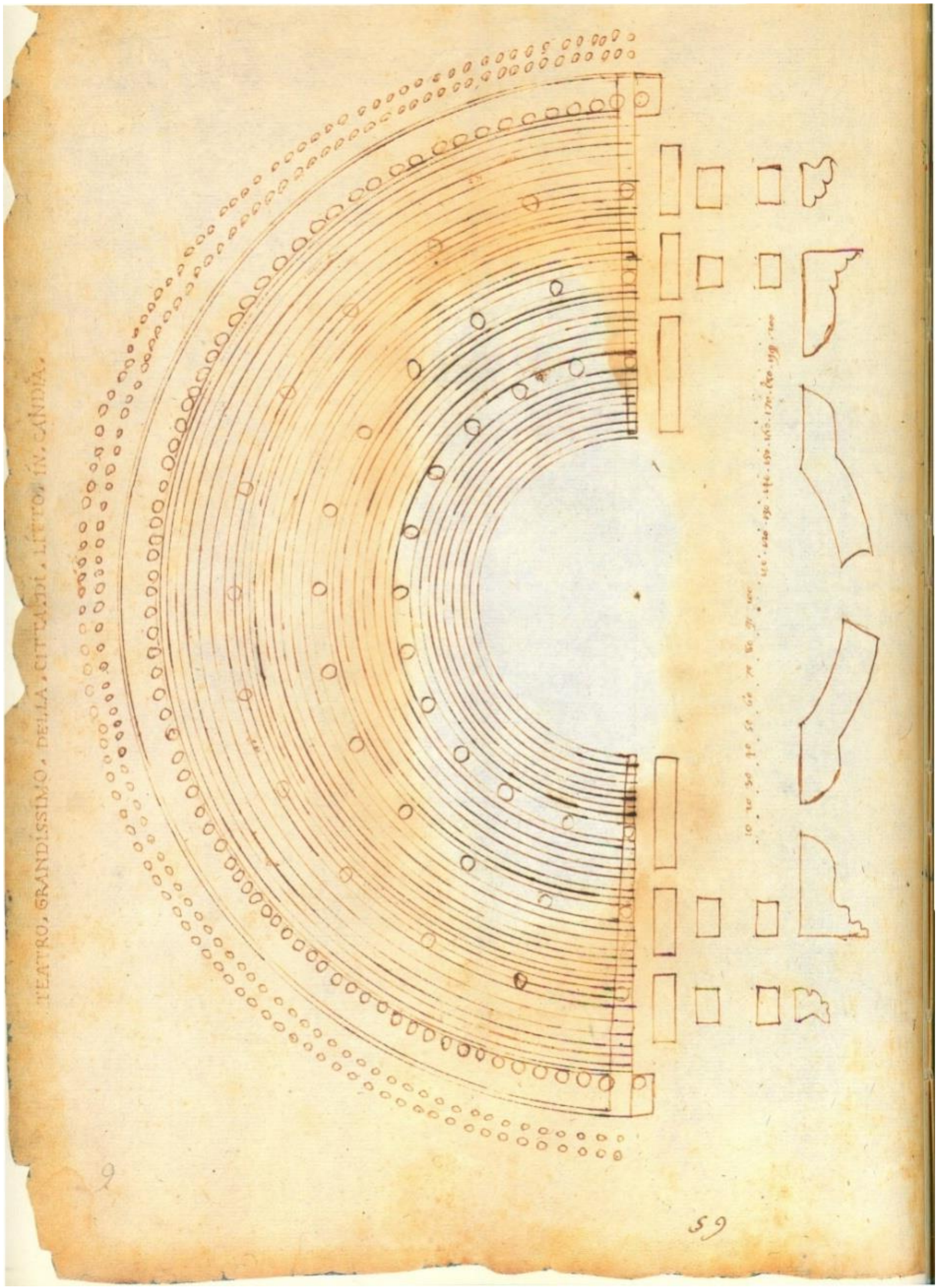


Figure 12 Ancient plan of the theatre of Littos (from Beschi, 1999).

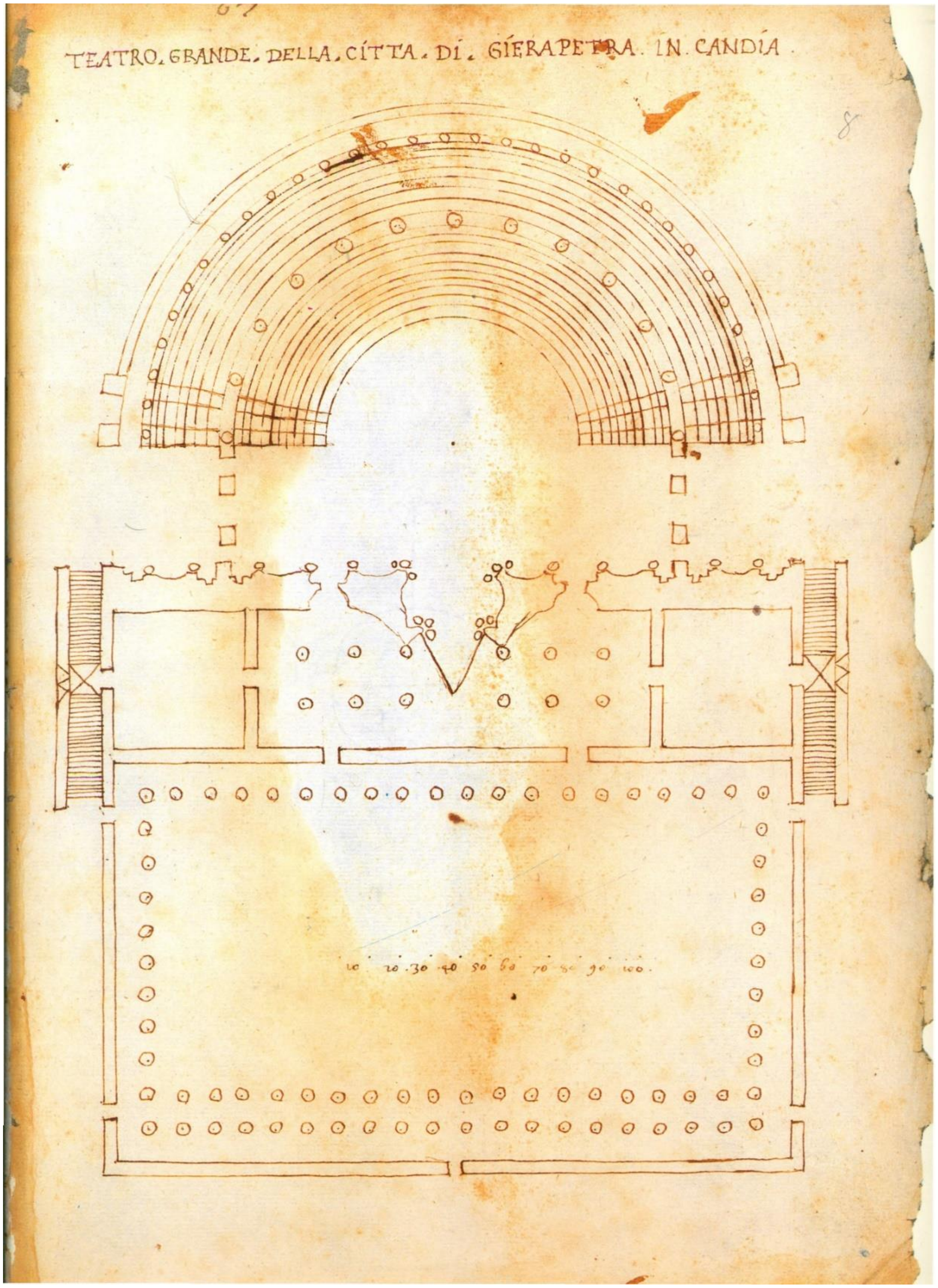


Figure 13 Ancient plan of the large theatre of Ierapetra (from Beschi, 1999).

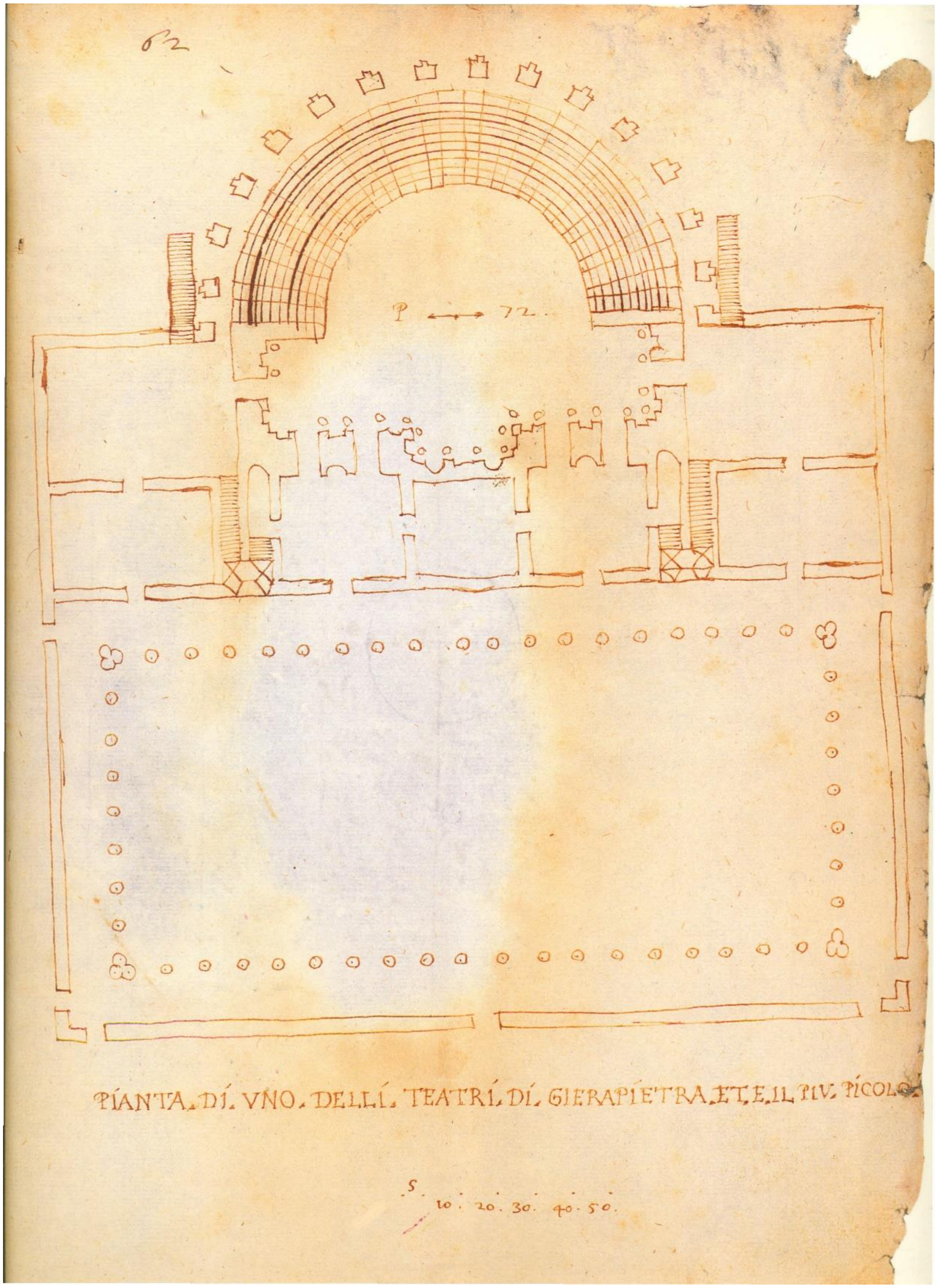


Figure 14 Ancient plan of the small theatre of Ierapetra (from Beschi, 1999).

5.1 The ancient theatre

The theatre is one of the greatest legacy we have inherited from the past. Nowadays, we conceive the theatre as something elaborated, with a cultural connotation, which sees the involvement of a specific architectural structure, a plot, actors, stage costumes, scenography, and much more. Actually, the theatre has been developed from a very simple concept as indicated by the word theatre itself. It comes from the ancient Greek verb *theaomai* which means "to look, to see" and indeed, the shape of the seating area probably wanted to reflect the natural distribution that people uses when observing an event [19]. Also the circular shape of the Greek orchestra (the best example is the theatre of Epidaurus), which was the place where the chorus performed, reminds the disposition of people around a performance or any other activity (as a political speech). Before the birth of a typical architectural structure in the midst of the VI century BC, some events took place in a simple empty area, where the spectators found space all around, and probably climbing slopes in order to have a better visibility. Later, some temporary benches were placed on the slopes of the hills for the comfort of the spectators, as testified also by a depicted vase dated to the VII century BC (fig. 15). However, the wooden stands were easily subject to collapse and this is why the ancient Greeks started excavating the slope of the hills and using stones to make the seats.

The very first theatres, probably dated to the VI century, had a cavea with a rectangular or trapezoidal shape, as the one of Thorikos (fig. 16) and Trachones in Attica (Greece). These first theatres were probably inspired also by the rectilinear terraces of the Minoan palaces (like the one in Festos), where the spectators used to watch the *tauromachia*[17]. Later, the Greek theatre started evolving towards its traditional well known shape: a circular orchestra, a horseshoe cavea, and a scene. Probably the scene, in the VI century, was a simple wooden background, but with the evolution of both tragedy and comedy (the increasing number of characters and the more elaborated surroundings in the story) the actors needed a building with rooms in order to change their costume and the scene needed some more particular structures mentioned in the work (as an house or a temple)[43].

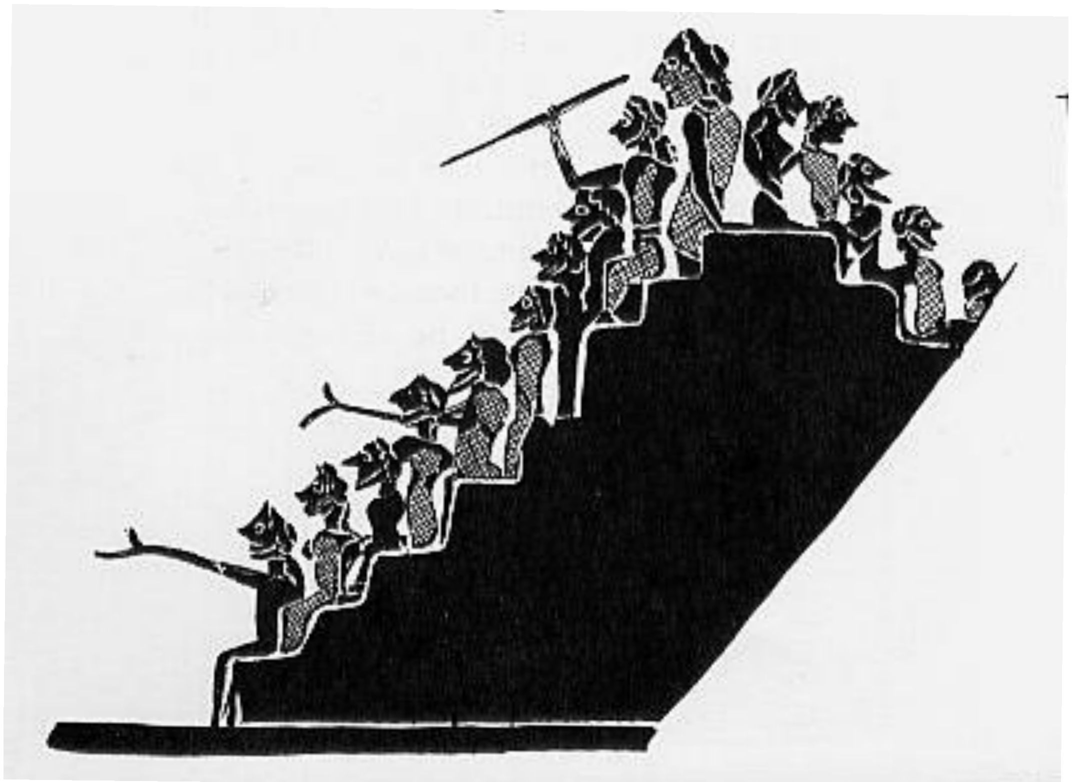


Figure 15 Vase of Sophilos (VII Century BC).

Several archaeologists focused their attention on the theatre of Dionysus in Athens, since the end of the XIX century. Numerous hypotheses have been formulated about its evolution during the centuries. Unfortunately, no remains of the scene dated to the VI-V century have been found, so Fiechter[104] proposed different possible reconstructions of the background buildings, and more hypothetical representations have been suggested by some other scholars as well[19]. In general, the scene was a simple one storey building that could be furnished with one to three doors, some columns on the front, and two side rooms (*paraskenia*), but this last characteristic was probably more typical in the Hellenistic theatre.

[43] It is important to underline that the reconstructive hypotheses about the architectural structure of the theatres are mainly based on: archaeological evidences, the descriptions given by Vitruvius and Pollux, the paintings on vases or the frescos on walls of rich houses, and the works written to be performed in the theatre.

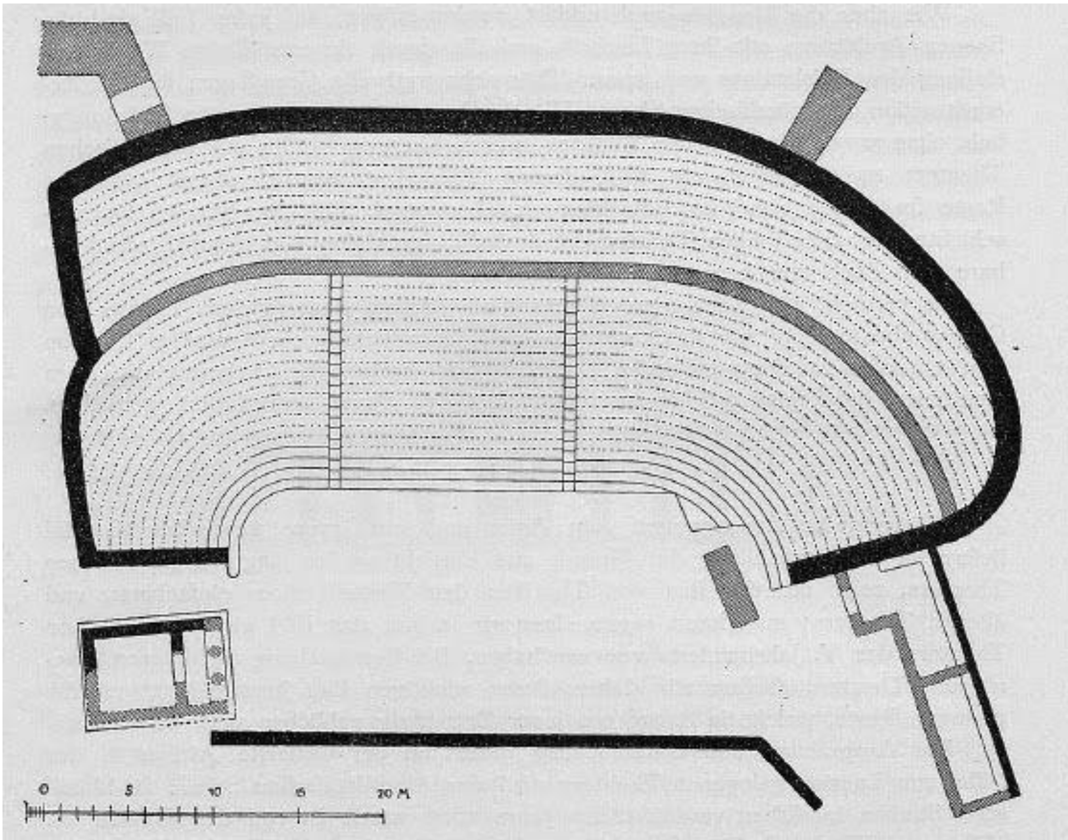


Figure 16 Plan of the theatre of Thorikos (from Dörpfeld, p. 110)

In the Hellenistic times, the theatrical plot changes: the single characters become fundamental, they have a marked personality, they are specific individuals who deserve the right attention, while the chorus starts losing its importance. This evolution in the theatrical work provokes a changing in the structure of the theatre: the space of the orchestra, reserved to the chorus, is reduced by the scene that is moved forward. Furthermore, another element is added in front of the scene, the *proskenion,* which is the high stage where the actors played. As an example we can take the most probable reconstruction of the theatre of Dionysus in Athens dated to the Hellenistic time, that is the one proposed by Dörpfeld[105] (figs. 17 and 18).

Another characteristic of the Greek theatre are the open *parodoi*, namely the entrances to the orchestra, which separated the cavea from the scene, as it is also evident in fig. 18.

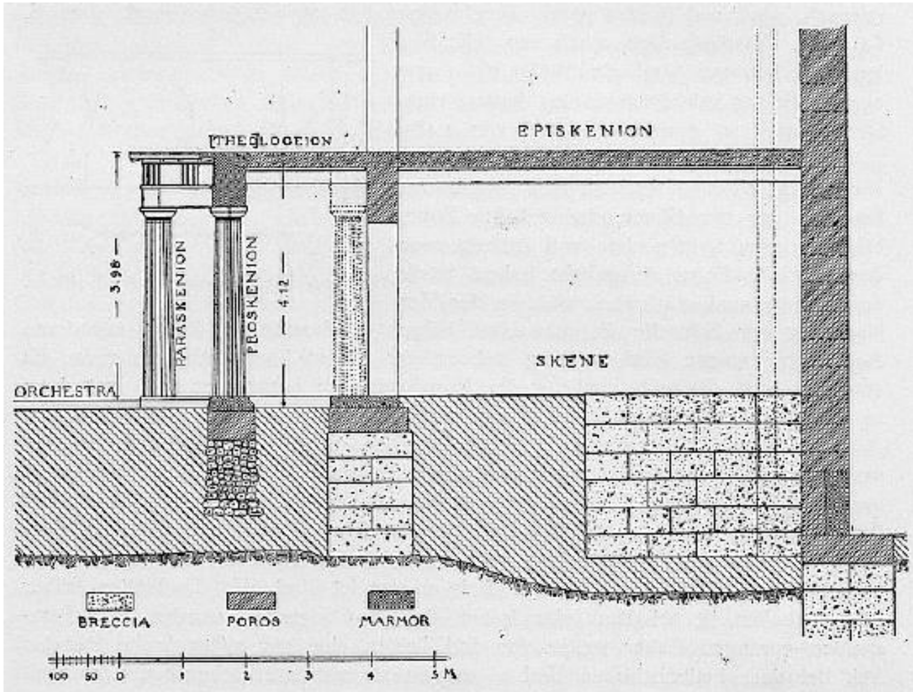


Figure 17 Reconstruction of the scene of the Hellenistic theatre of Dionysus in Athens (from Dörpfeld, 1896).

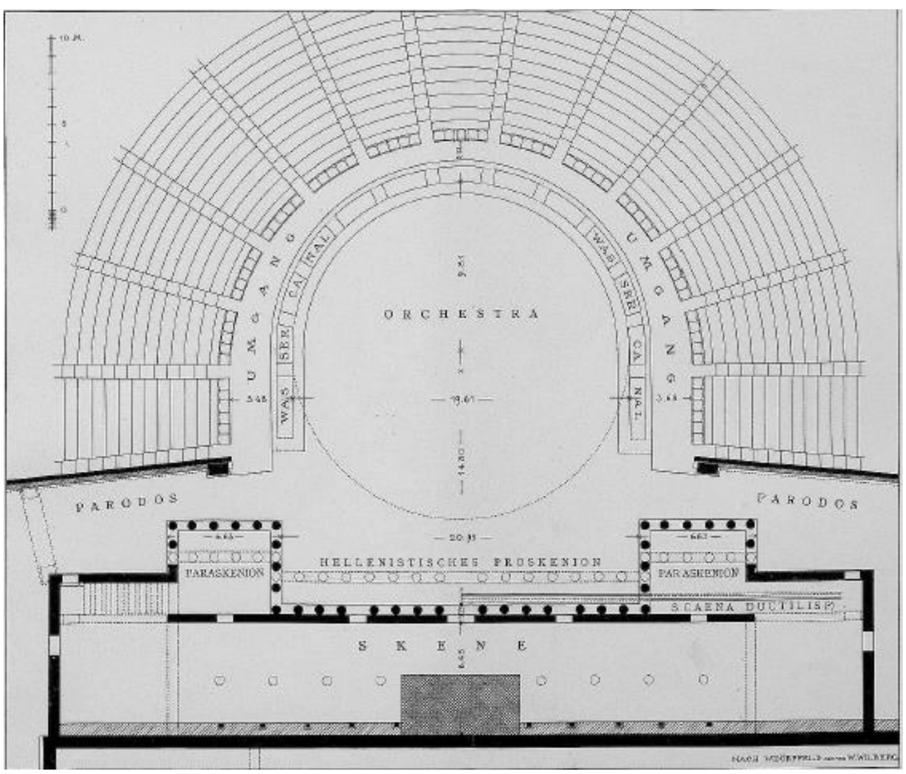


Figure 18 Plan of the reconstruction of the Hellenistic theatre of Dionysus in Athens (from Dörpfeld, 1896).

All the areas under the Greek influence, as *Megali Hellas* (Sicily, Calabria and Puglia) and Asia Minor (Turkey), developed the same typology of theatre as in the motherland, although with some local differences (see the theatres of Syracuse, Segesta, Pergamon, Ephesus, Priene and many others). They differ in size, orientation, materials but we can recognize at least four similar and common features: the cavea was dug in the hill, the orchestra was circular, the stage was very high, the scene simply decorated, and the scene and the cavea were separated by the *parodoi*.

In Rome, a stone theatre was born quite late: till the midst of I century BC, only wooden structures were used and these were immediately destroyed after the performances. One of the concerns of the Roman politicians was the possibility that the theatres could be used by the citizens to gather and talk about the political situation, and then organize rebellions.

Finally, in 55 BC Pompey built the first stone theatre in Rome, with the excuse that the cavea was a monumental stair to access the temple of Venus placed at its top. Already this first theatre differed from the Greek-Hellenistic one, and the successive Roman theatres were built following the style of the theatre of Pompey (fig. 19). In Rome, two more theatres arose: one built by Balbus in the 13 BC, and another one begun from Cesar and completed by Augustus in 11 BC, and dedicated to his nephew Marcello. These three theatres were very similar: they were built in a flat area on high substructions (not against the hill as the Greek theatres), the cavea and the scene were forming a unique block (there were no open *parodoi* as in the Greek theatres), the stages were low and deep, the *scaenae frontes* were very richly decorated (during the Empire the ornaments in the theatres were even richer), there were some corridors used by the spectators to directly reach the different sectors of the cavea (*vomitoria*), and they probably had a portico in *summa* cavea. Their common characteristics are the same that connote large part of the theatres built by the Romans all around the Empire (figs. 20 and 21), but in some cases there are some local differences.

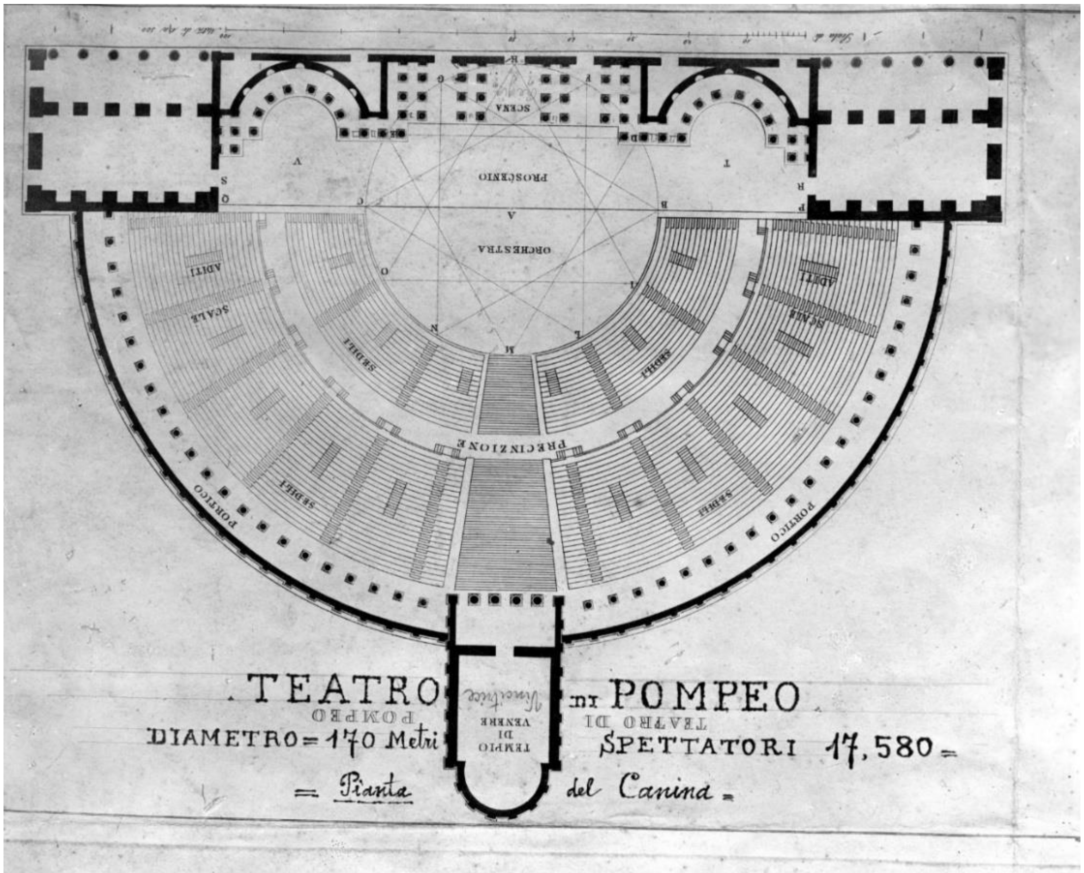


Figure 19 Plan of the theatre of Pompey in Rome made by Canina (from the online photo archive of the American Academy in Rome).

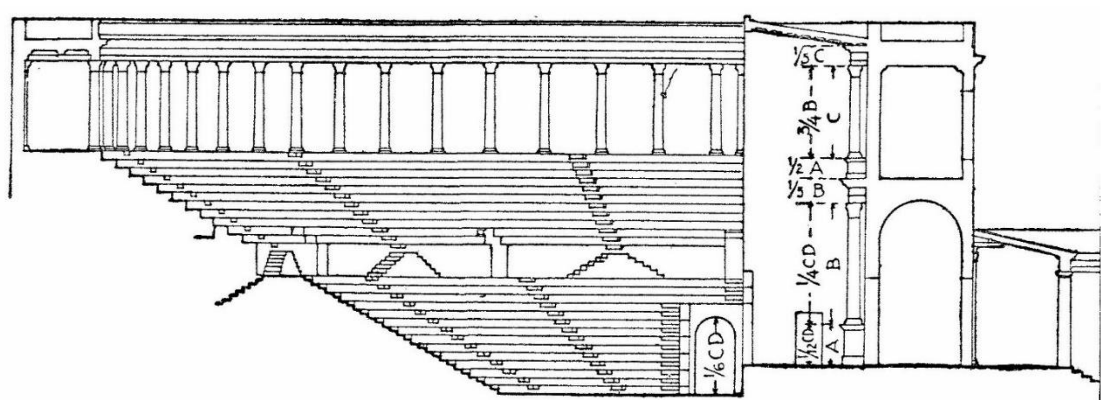


Figure 20 Section of the Roman theatre according the Vitruvius.

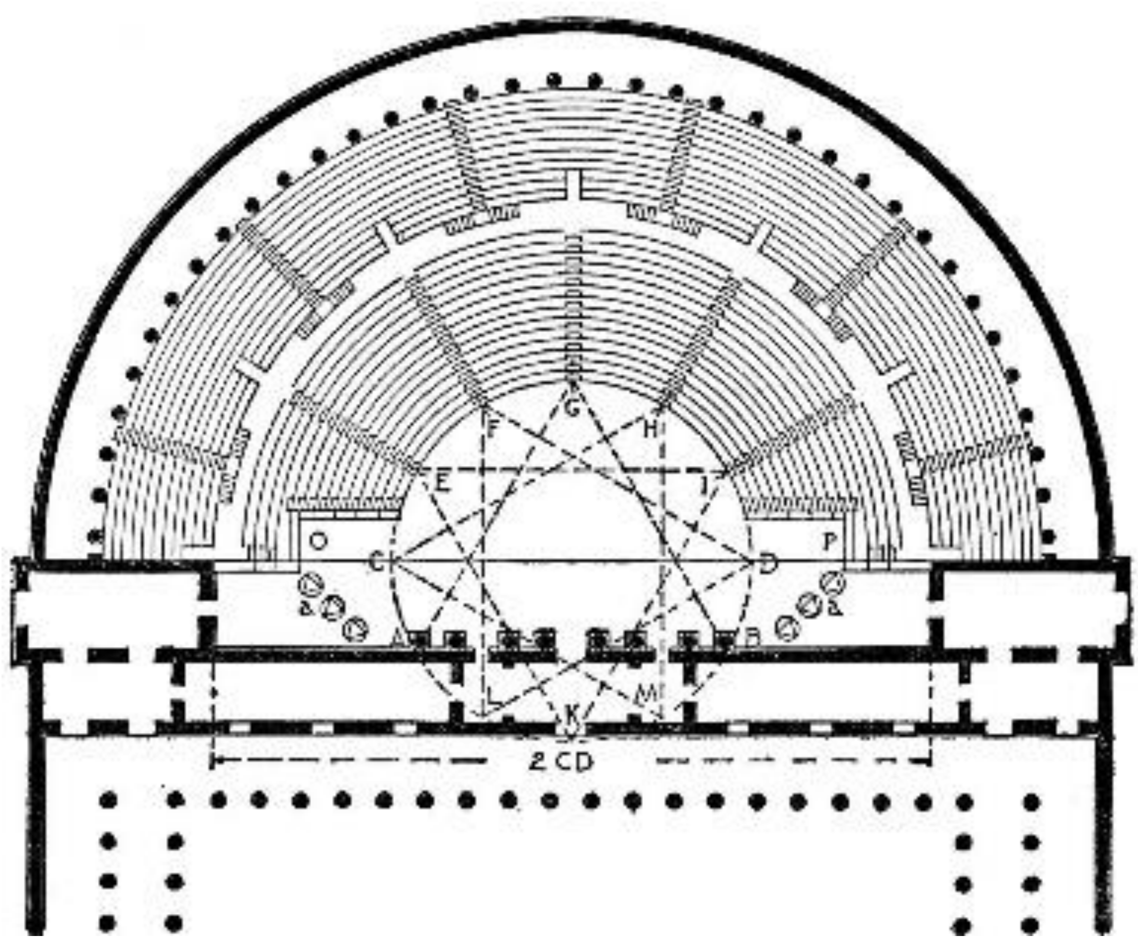


Figure 21 Plan of the Roman theatre according to Vitruvius.

The Romans built new magnificent and functional theatres in Italy (Pompeii, Ostia, Volterra, Verona, etc.), Spain (Mérida, Malaga, Italica, Augusta Emerita, etc.), France[44](Orange, Arles, Lyon), North Africa (Sabratha, Leptis Magna, Thugga, etc.), and in the eastern part of the Empire (Palmyra, Petra, etc.) [65].

Instead, in Greece, Southern Italy and Asia Minor, the Romans built only few new theatres (Corinth, Athens, Aspendos, etc.) and they modified numerous prior Greek theatres. The more frequent modifications consisted in the embellishment of the *scaenae frons*, the substitution of the *logeion* with a lower and deeper stage, and the covering of the *parodoi* in order to unify the cavea and the scene. Dörpfeld clearly shows in a plan the comparison of the theatre of Dionysus in Greek time and in

[44] In France a new type of theatre was diffuse: the Gallo-Roman theatre.

Roman time (fig. 22): the orchestra became smaller, the cavea is transformed into a perfect semicircle, the stage partially occupied the orchestra, and the *parodoi* became parallel to the cavea and the scene[105]. However, in this case as in some other Greek theatres, the *parodoi* remained open, so the cavea and the scene were separated also during the Roman times.

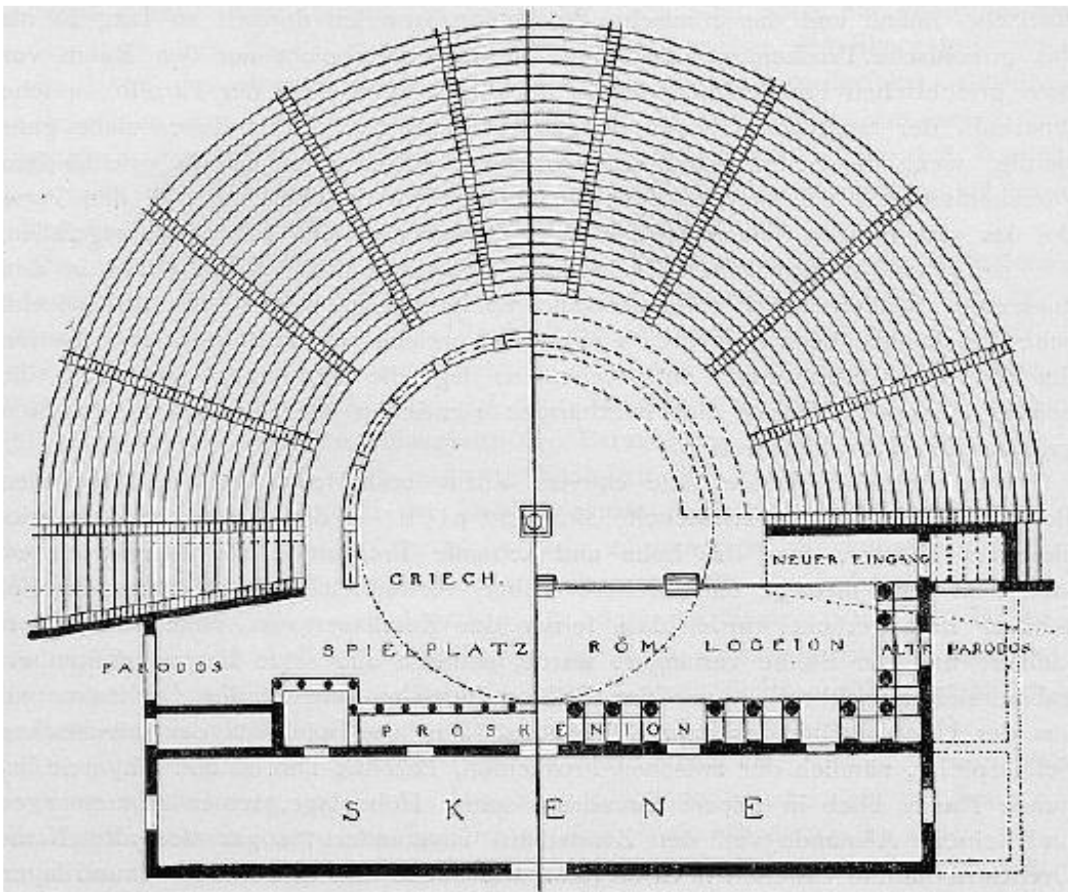


Figure 22 Plan of the theatre of Dionysus in Athens, comparing the Greek and Roman structures (from Dörpfeld, 1896).

Concluding, it is possible to affirm that the Greek and the Roman theatres of the ancient world have different features and they are easy to distinguish. The Romans developed their own type of theatre, borrowing from the Greeks the three fundamental elements constituting this building (cavea, orchestra and scene) and evolving them in a more practical and representative way. However, often some typical Greek characteristics were kept in older theatres that were only subjected to minor modifications by the Romans, with the ultimate aim to make them more marvelous[45].

[45] Few theatres in the Greek world were also modified with the scope to use them for gladiatorial games (for example in Athens), but these brutal shows were never really accepted by the Greek society of the time so they were not happening very frequently.

5.2 Theatre of Aptera

The theatre of Aptera, as several other theatres in Crete, has been first discovered by one of the several British travelers that undertook their trip in Greece in the XVIII-XIX century. Robert Pashley stated that he could easily recognized the remains of the theatre despite its not optimal conditions of preservation[36]. After him, few other scholars visited the site and gave a brief description of the monument.

In 1901, the archaeologists Savignoni and De Sanctis identified part of the *proscaenium* in few squared blocks that were still in their original position[106].

Fifty years later, the classicist Dilke included the theatre of Aptera in his study about Greek theatres. His report is slightly more detailed than the previous ones. He discerned two phases: a Hellenistic one that he dates to the III century BC, and a Roman one. He took the measurements of the survived seats (0.34 x 0.61 m) and hypothesized a maximum of 35 rows of seats observing the area where the cavea lied[107].

Drerup was a German archaeologist that widely investigated the area of Paleokastro and Aptera. He also recognized a couple of different phases (one of them is Hellenistic) in the theatre of Aptera and he reported its dimensions: diameter of the cavea 55 m, diameter of the orchestra 18 m, length and width of the scene building respectively 25 and 6 m[108].

The archaeologist Ian Sanders, in his research about Crete during the Roman time[109], and the architect Frank Sear, in his catalogue of the Roman theatres[65], mentioned this monument but they did not add any information more.

Therefore, the scarcity of the data about this theatre, till very recent times, is evident. Only occasional and summary inspections were made in the site of the theatre before systematic archaeological excavations started twenty years after the last investigation. Finally, in 2000 the Ephoria of Prehistoric and Classical Antiquities of Chania started working at the theatre of Aptera in order to discover it, understand it and restore it. The archaeological excavations are still ongoing but the results obtained till now allowed to reconstruct the architectural structure of the theatre.

Vanna Niniou-Kindeli and Nikos Chatzidakis already presented the first results of their research in 2010[110], and later they gave a more detailed report including new discoveries of more recent times as well[111]. The theatre they describe is the one which corresponds to the second Roman phase, but they identified other two phases: a Hellenistic one and a first Roman one. The description, the plan (fig.24) and the section (fig. 23) of the monument clearly explain its original aspect since the III century BC till probably the 365 AD, when a strong earthquake destroyed it. They added much information about building materials and building techniques, single architectural elements, finds such as coins and pottery fragments. The data about the diameter of the cavea coincide with the ones already obtained by Drerup, whereas, the dimension of the orchestra revealed by the archaeological excavations is different, not 18 m as previously stated but 10.9 m. The rows of seats are 40, and not maximum 35 as hypothesized by Dilke, and the dimensions of the seats are slightly superior than the one proposed by the latter (0.38 x 0.80 m).

The structure of the cavea is particular for a Roman theatre because the upper part extends toward north, so that the seating area acquires an elliptical shape, that it is indeed dated to the Hellenistic phase. There was an *ambulacrum* that divided the cavea in two sectors, forming an *ima* cavea and a *summa* cavea. The whole cavea is divided into four *cunei*. Part of the structure lies on a natural hollow and part is sustained by the *analemma* that runs all around the cavea. The converging walls of the *analemma* are not perpendicular respect to the central axe of the theatre, but they are slightly tilted toward the center of the orchestra. The orchestra is small and divided from the cavea by a covered conduit. There are vaulted *parodoi* which remind more a Greek theatre than a Roman one. There are two *basilicae* that flank the *proscaenium*. The actors reached the stage from the *postscaenium* through three openings in the scene building. There are no data about the possible height of the façade of the scene or about the dimensions of the columns, which pedestals have been found.

The full building was made out of local stone, some big squared blocks are still in situ; the stage's floor was made out of wood, and the *scaenae frons* was covered with bricks.

In order to reconstruct the 3D model of the theatre, the plan and the section realized by Niniou-Kindeli and Chatzidakis have been taken into account, while for the height of the *scaenae frons*, Vitruvius's indications has been used as well.

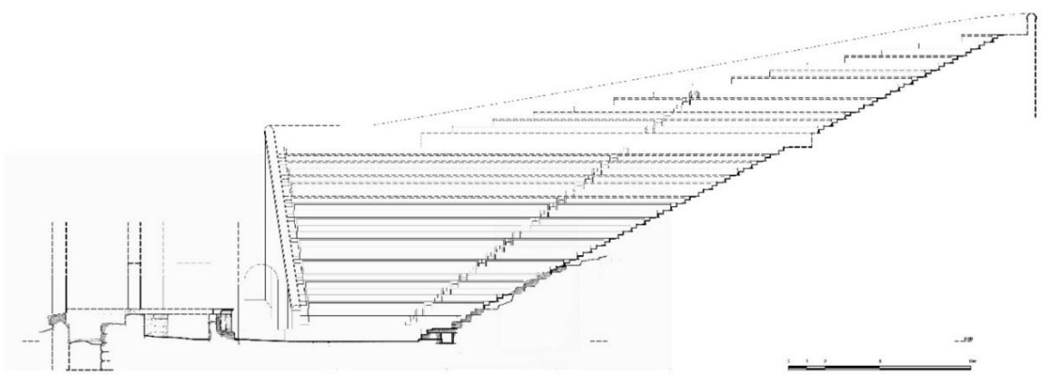


Figure 23 Section of the theatre of Aptera in its 2nd Roman phase (by Niniou-Kindeli and Chatzidakis, 2016).

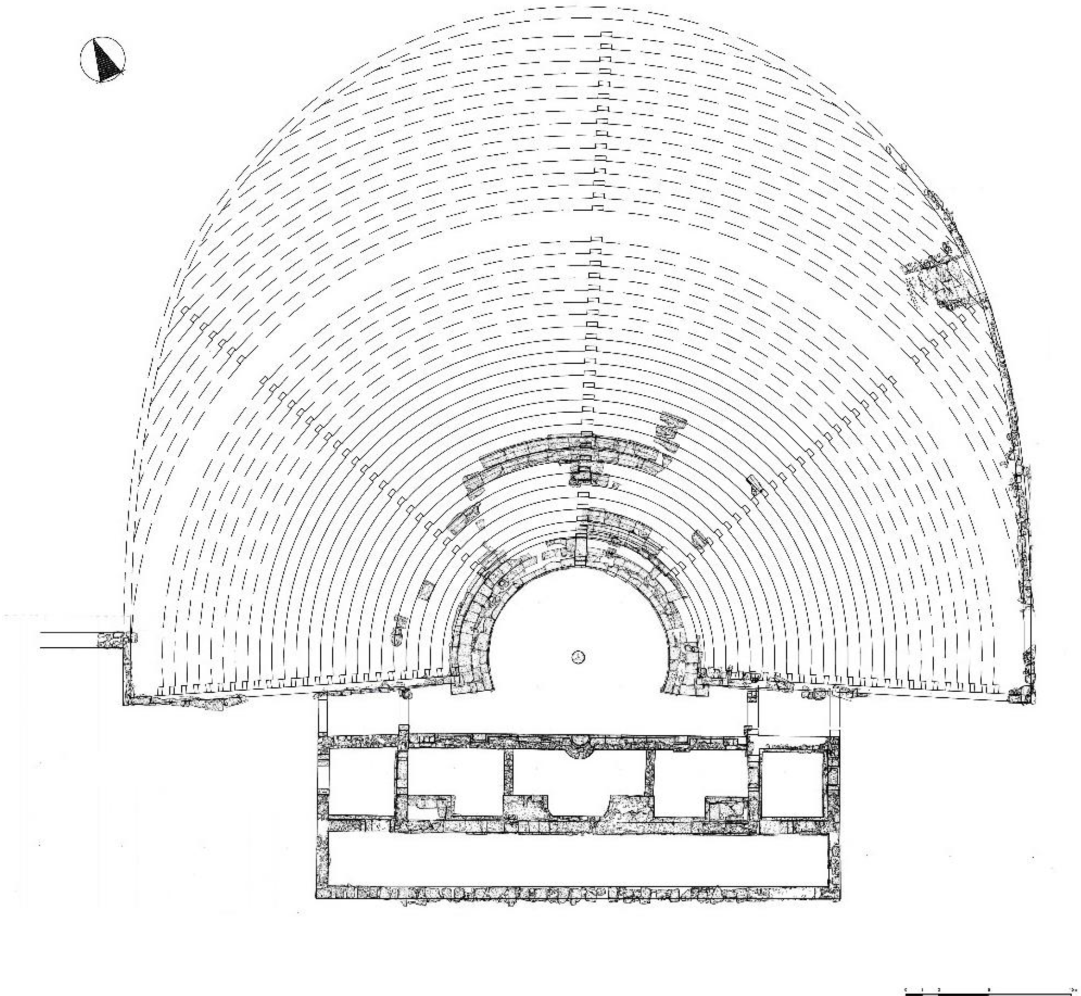


Figure 24 Plan of the theatre of Aptera in its 2nd Roman phase (by Niniou-Kindeli and Chatzidakis, 2016*).*

The plan and section have been scaled in AutoCad and then imported in 3D Studio Max. The plan has been traced and then the cavea extruded, according to the elevation shown in the section and to the description provided in the text, in order to create the 3D model. The height of the scene building and of the columns have been reconstructed according to what the Roman architect Vitruvius wrote in his book "*De Architectura*"[89]. The height of the columns of the first storey correspond to 1/4 of the diameter of the orchestra (2.725 m), the pedestals are 1/12 of the diameter of the orchestra (0.908 m), and trabeation is 1/5 of the height of the column (0.545 m). About the columns on the second storey: they are 3/4 the height of the columns of the first storey (2 m), their bases are half the height of the bases of the lower level (0.45

m), the trabeation is 1/5 the height of the correspondent columns (0.40m) (figs. 25-27).

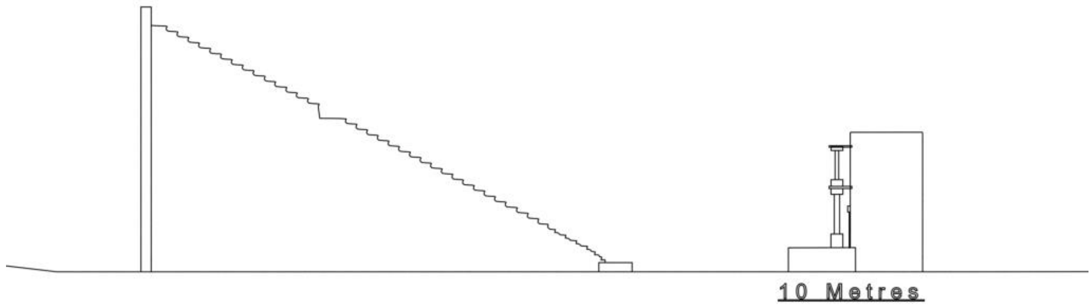


Figure 25 Hypothetical reconstructive section of the cavea and the scene building of the theatre of Aptera.

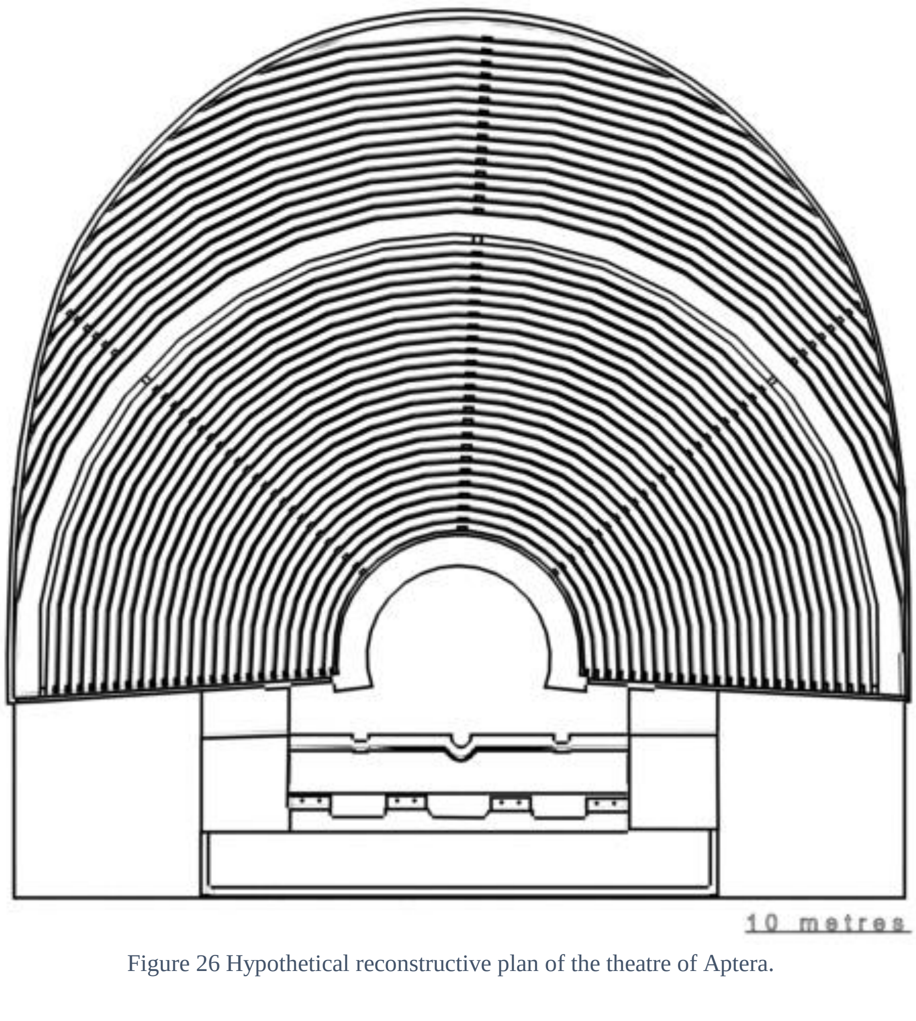


Figure 26 Hypothetical reconstructive plan of the theatre of Aptera.

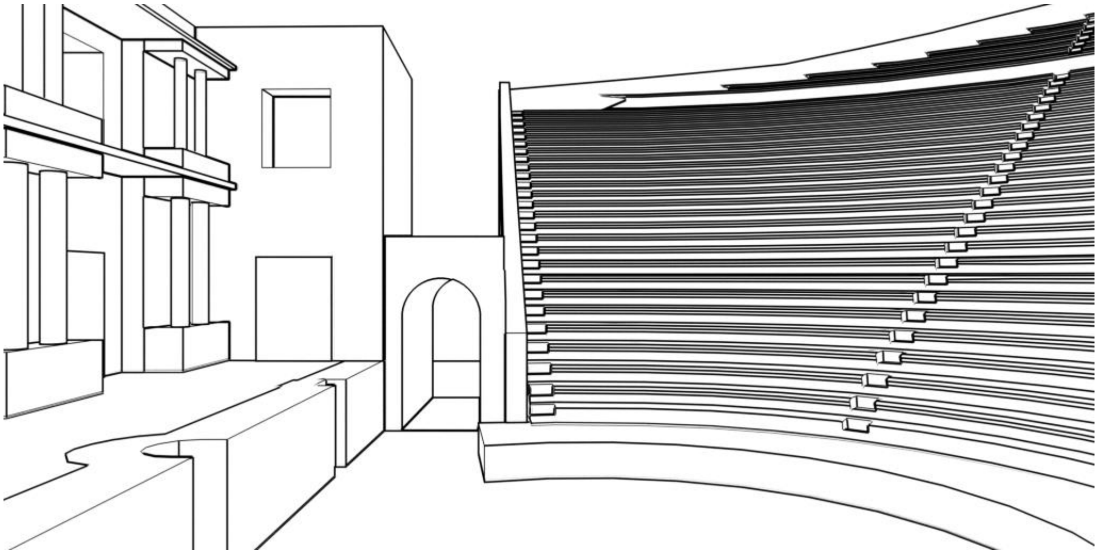


Figure 27 Hypothetical reconstructive drawing of the theatre of Aptera.

5.2.1 3D visibility analysis

The model analysed through 3D visibility analysis is only one, because the theatre is well documented and its original shape is almost completely known from the archaeological excavations. In this case, the analysis is more useful to obtain new information than to verify its reliability and accuracy. Furthermore, the results obtained from this theatre can be used as a reference for the other theatres which are less known.

The grid in the cavea is composed by 163 observer points, distributed in four rows and placed 0.75 m above the correspondent seat (for detail explanation refer to the methodology chapter, p. 56)(fig. 28).

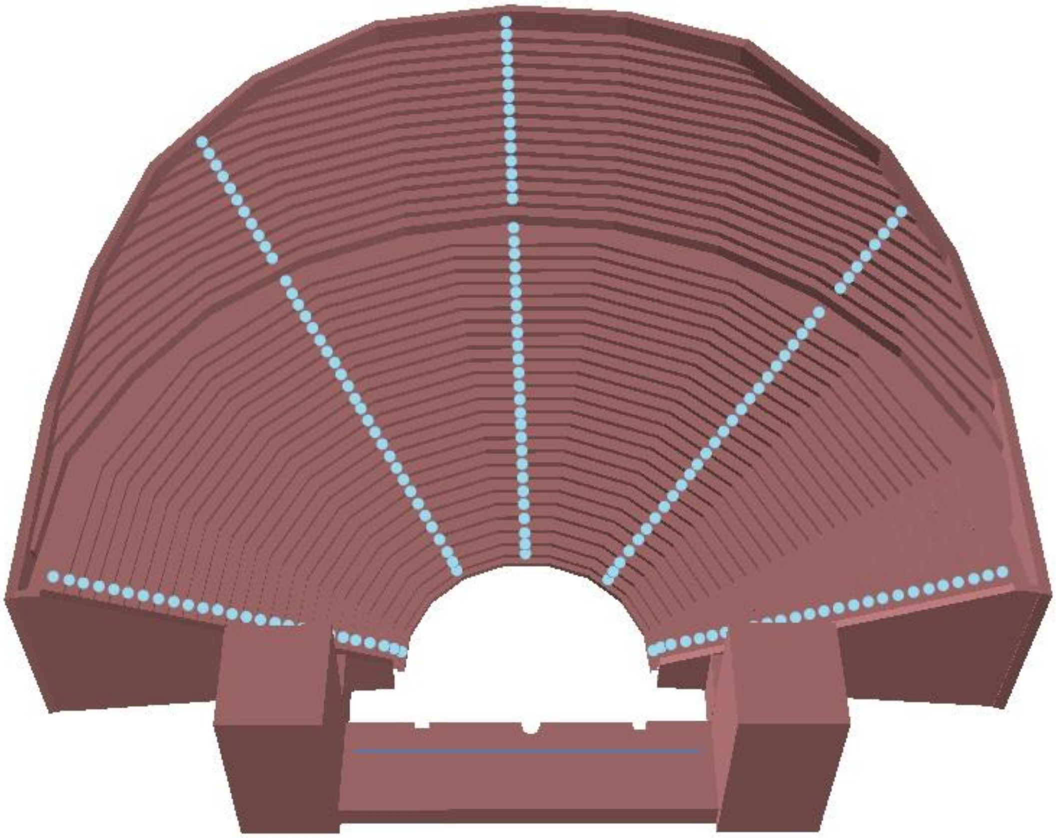


Figure 28 3D model of the reconstructive hypothesis of the theatre of Aptera together with the grid of observer points in the seating area and the target line on the stage.

The calculation of lines of sight gives as result that the 92% of the lines between observer points (selected seats in the cavea) and target line (positions of the actor/s) are visible trajectories. It is a quite high percentage that confirms the assumption that everyone (or almost everyone) could see the actors during the performance. Note that the target line covers almost the full length of the stage, and from the visualization of the lines of sight, it is evident that the major issues of visibility are on the sides of the stage, while the large part of the performance was most probably played in the central area[46]. The results obtained from the calculation of the lines of sight, are confirmed also from the frequency of visibility map. The total visibility of the central part of the stage is shown in figure 29 and in the correspondent graph (fig. 30).

[46] The sides of the stage, in the Roman theatres, were generally occupied by the chorus.

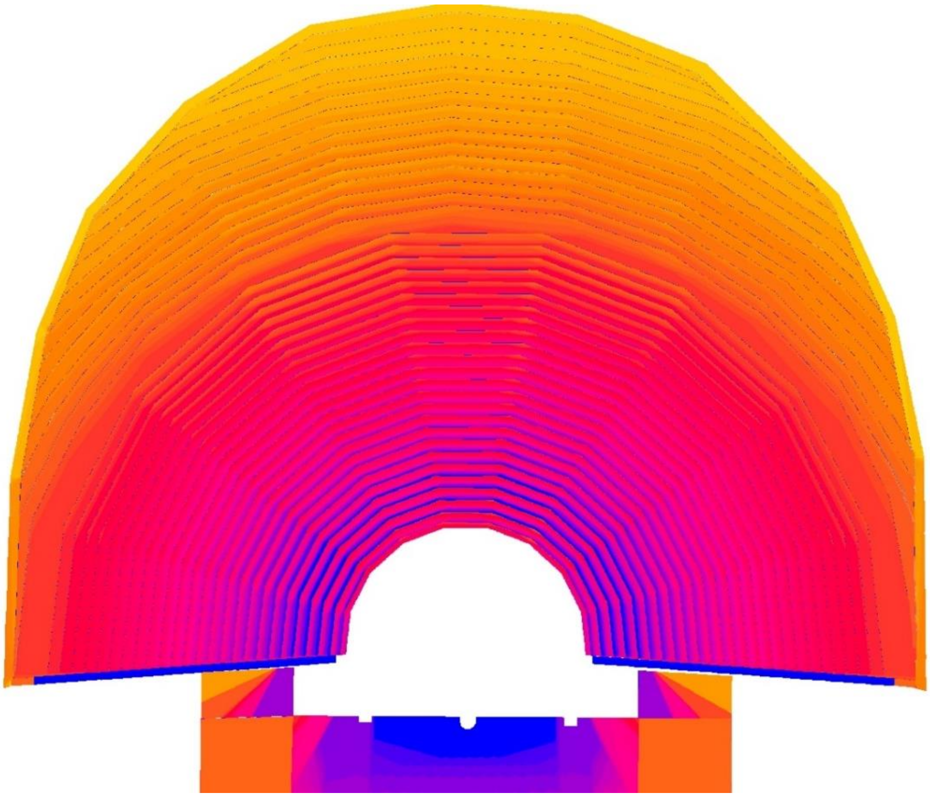


Figure 29 Map of frequency of visibility of the theatre of Aptera. The colors show the different level of visibility for the observer points, as it is explained in its correspondent graph (fig. 29).

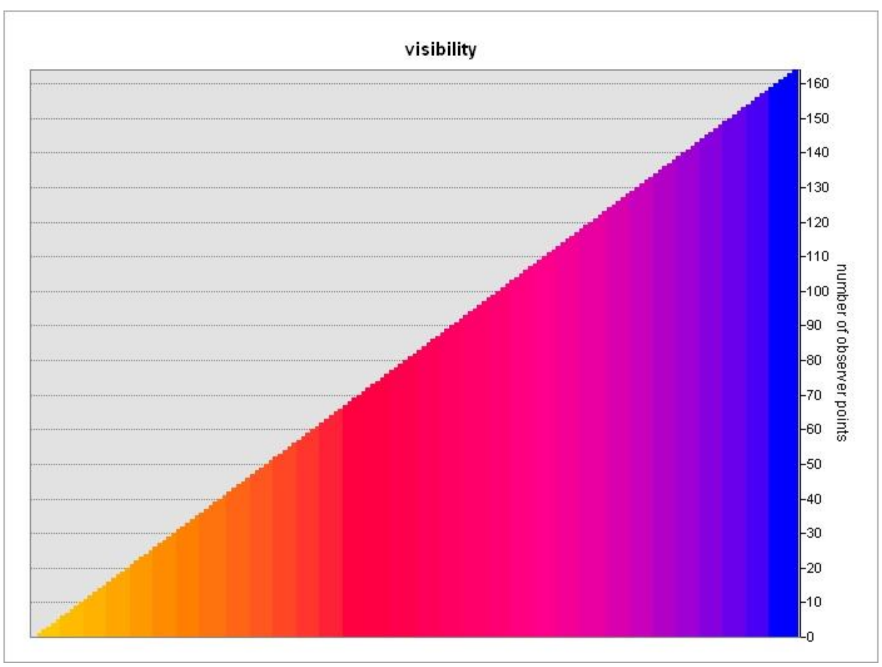


Figure 30 Graph of visibility analysis. The color scale is from yellow to blue. The yellow color means that those areas are visible to none of the observer points; the blue color indicates the part of the theatre visible from all 164 observer points.

5.2.2 Virtual acoustics analysis

For the virtual acoustics analysis, the same reconstruction has been tested in order to obtain information about its acoustic properties. By the way, the same reconstruction has been tested with a variation too: one model with roof above the stage (N. 1) and one model without (N. 2), in order to verify the possible presence of this element.

The materials applied to the surfaces of the 3D models are the following, as suggested by Niniou-Kindeli and Chatzidakis[111], and also confirmed by previous scholars as Sanders[109] and Sear[65]:

1. Stone: *postscaenium*, *analemmata*, *diazoma*, columns.
2. Bricks: *versurae*, *scaenae frons*.
3. Limestone: *proscaenium.*
4. Wood: stage's floor.
5. Compact earth: orchestra's and *parodoi*'s floor.
6. Audience: seating area.

Totally, 32 receivers have been placed only in one half of the cavea: one every three seats, forming three lines respectively of 8, 10 and 12 receivers (figs. 31 and 32) (for detail explanation refer to the methodology chapter, p. 65). The source is at the center of the stage, little closer to the orchestra than to the scene building in order to allow the direct sound to reach all the receivers.

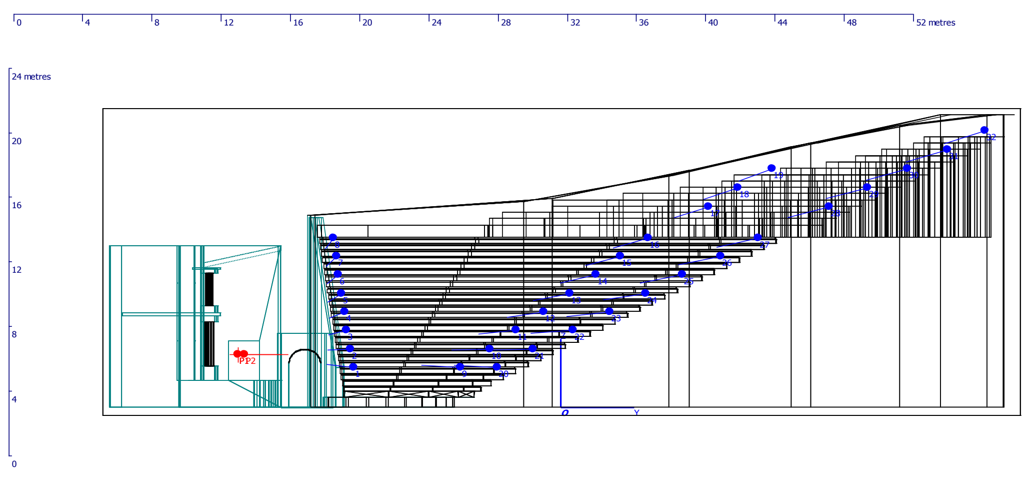


Figure 31 Section of the 3D model of Aptera's theatre plus receivers and source.

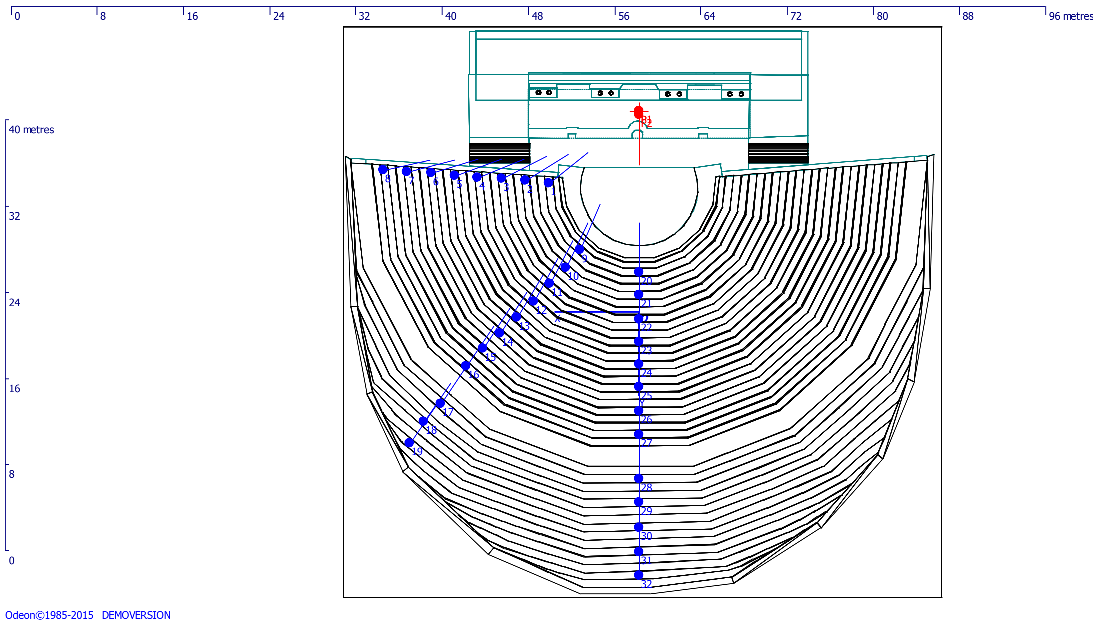
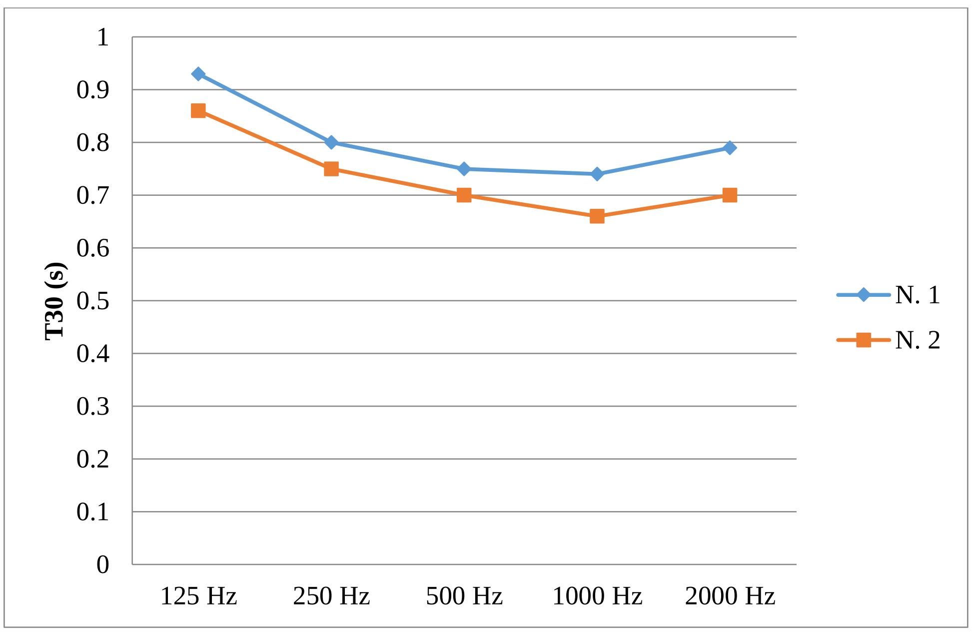
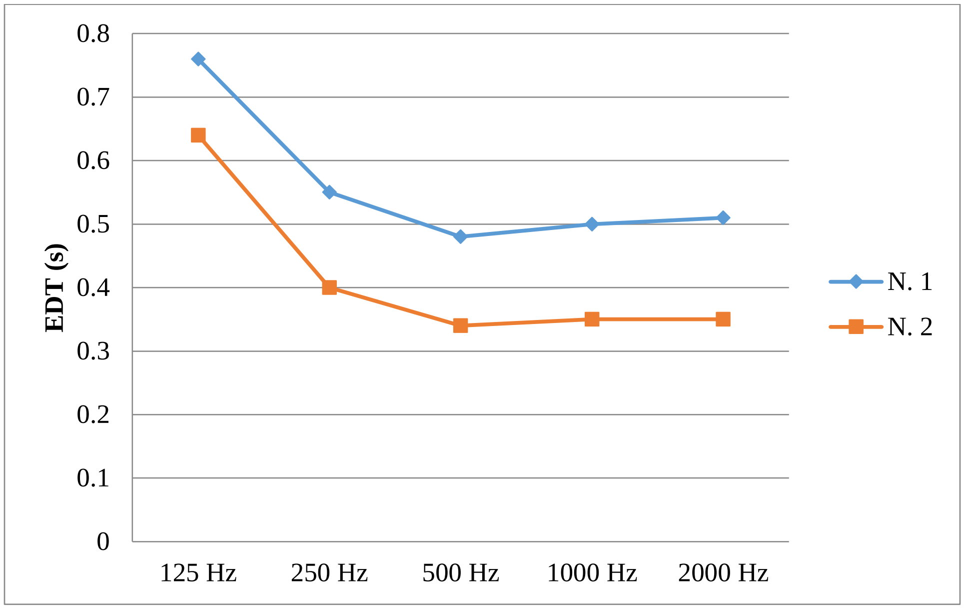


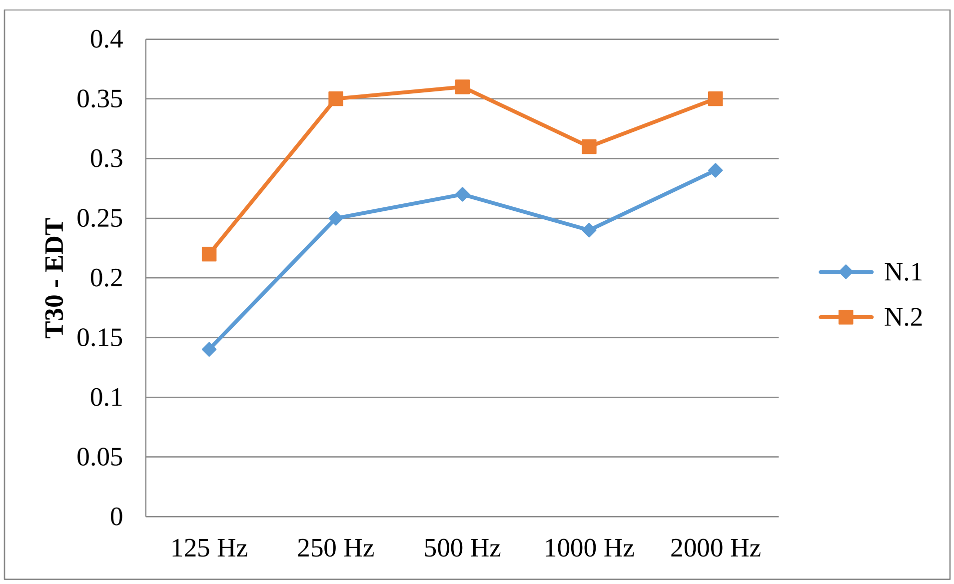
Figure 32 Plan of the 3D model of Aptera's theatre plus receivers and source.



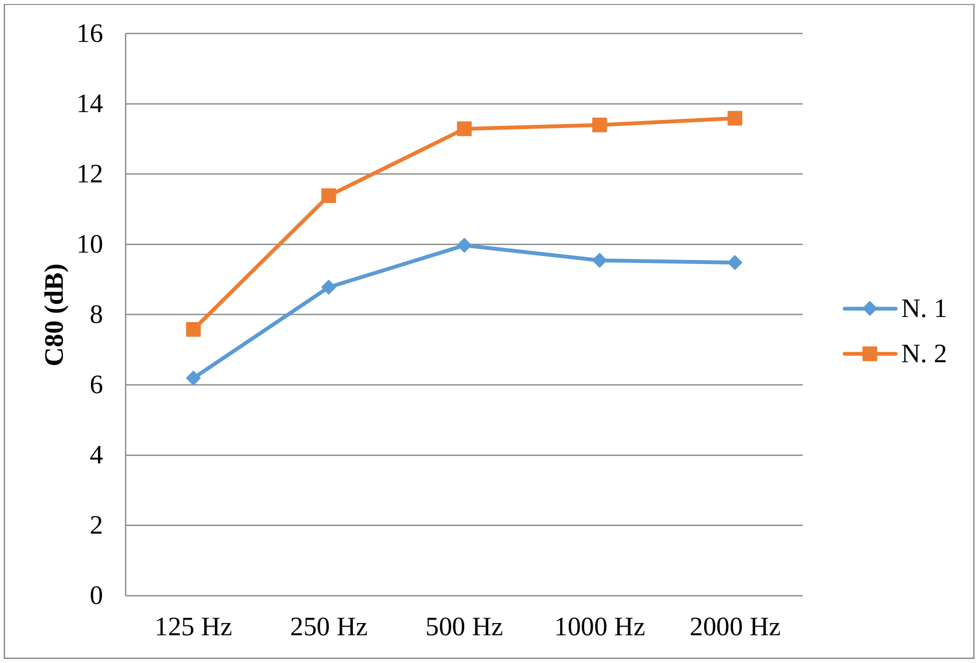
Graph 1 Average values of T30 of the models N.1 and N.2.



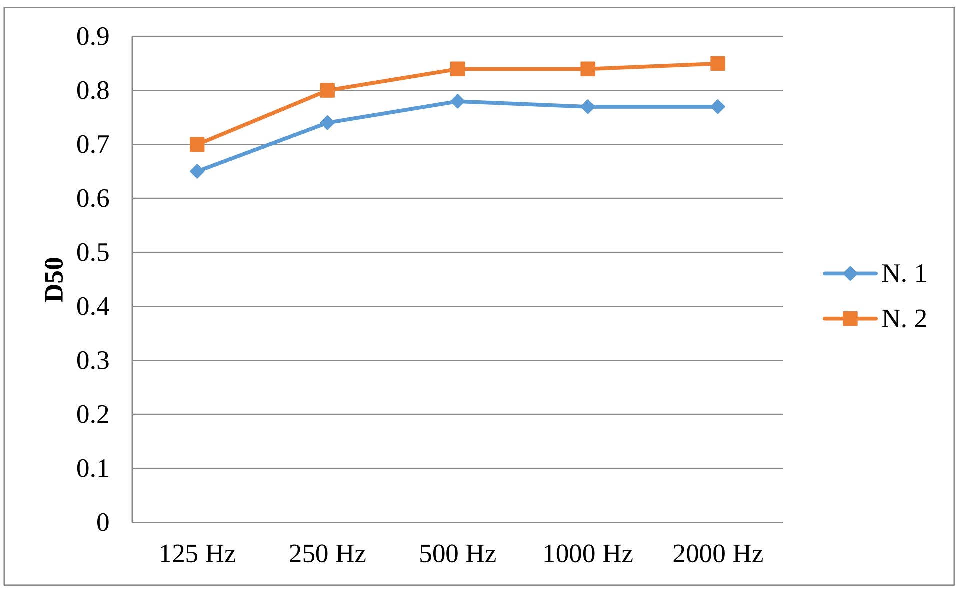
Graph 2 Average values of EDT of the models N.1 and N.2.



Graph 3 Average differences between T30 and EDT of the models N.1 and N.2.



Graph 4 Average values of C80 of the models n.1 and n.2.



Graph 5 Average values of D50 of the models n.1 and n.2.

The average STI value of the receivers for the model without roof is 0.79 (fig. 33) and for the model with roof is 0.74 (fig. 34).

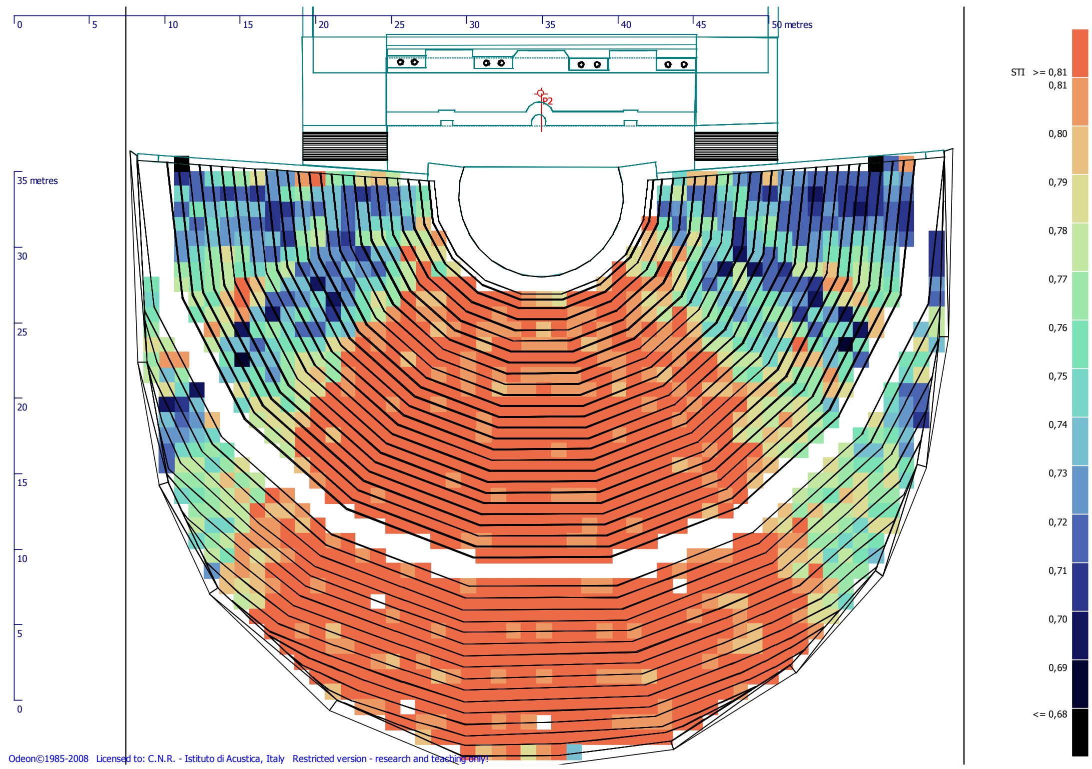


Figure 33 Grid of receivers in Aptera's theatre representing the STI values of the model N.1.

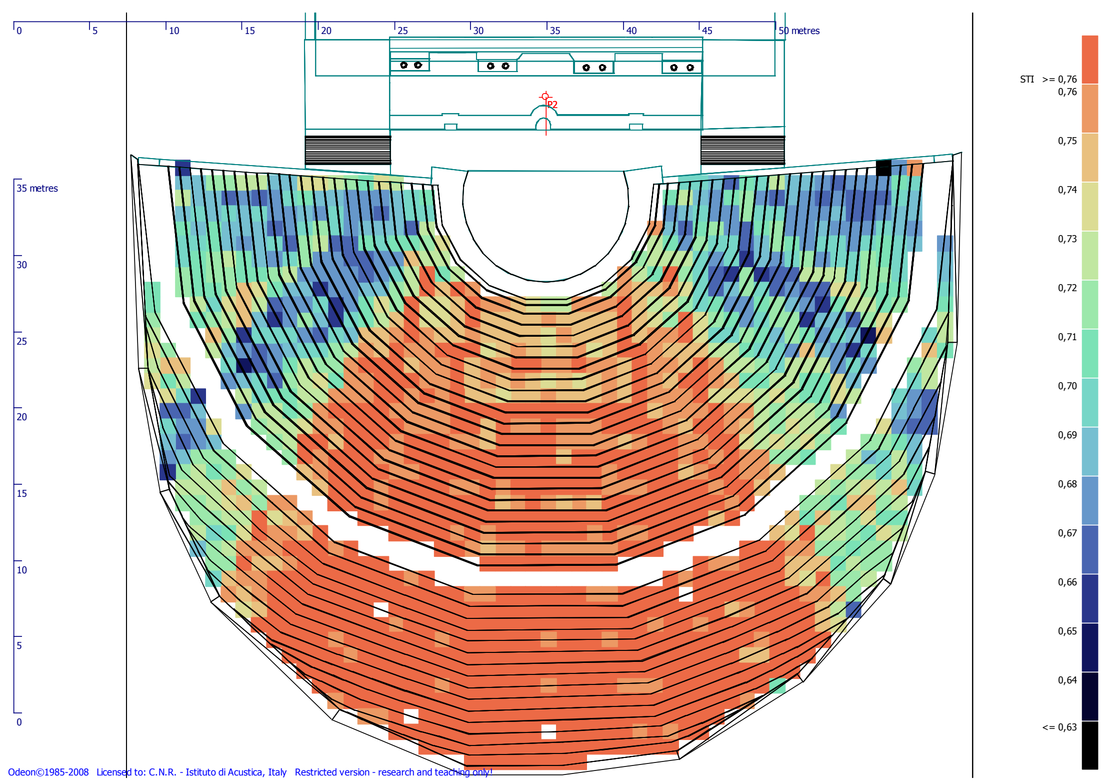


Figure 34 Grid of receivers in Aptera's theatre representing the STI values of the model N.2.

Both reconstructions give acceptable results for the specific parameters of the acoustics analysis as indicated in the graphs N. 1-5. Consequently, the presence of the roof above the stage in the theatre of Aptera was probably not necessary, because the acoustics was already good enough and actually in the model without roof we definitely have a better comprehension as it is shown by the higher values of C80, D50 and STI.

Furthermore, the virtual acoustics analysis testify that this theatre was probably used for spoken performances and not for music as Niniou-Kindeli and Chatzidakis[111] proposed.

5.2.3 Results and comments

The good level of visibility and the good quality of acoustics confirm the 3D reconstruction of the theatre of Aptera, based for large part on the documents produced by Niniou-Kindeli and Chatzidakis thanks to the archaeological excavations, and on the classical rules given by Vitruvius with regard to the height of the scene building.

The Roman theatre of Aptera has a particular shape, probably due to the previous Hellenistic phase. The Romans did not completely rebuilt the theatre but they took advantage of the preceding Greek structure, modifying only what needed, adding a more monumental scene building on two storeys and a conduit around the orchestra in order to collect water (figs. 35 and 36).

Niniou-Kindeli and Chatzidakis propose, as comparisons for the cavea, the theatre of Delos (fig. 37) and the one of Thebe (fig. 38)[111], but actually the contour of the cavea of the latter is irregular more than elliptical, and also the seating area of the one in Delos presents some differences.

I notice more similarities with the theatre of Metapontum[47], in Italy, that has been built in the IV-III century BC[65]: the shape of the seating area, the structure above the *parodoi* which connects *analemmata* and scene building, the probable conduit

[47] Metapontum was a Greek colony of South of Italy, established since the VII century BC.

around the orchestra (fig.39), and they were both built on a flat area, despite they were originally Greek-Hellenistic theatres.

In conclusion, the theatre of Aptera does not have a typical Roman structure. Instead, it keeps its Greek peculiarity, integrated with Roman characteristics as the deep and not too high stage, and the monumentality of the *scaenae frons.*

Figure 35 Rendering of the 3D model of the theatre of Aptera.

Figure 36 Rendering of the 3D model of the theatre of Aptera.

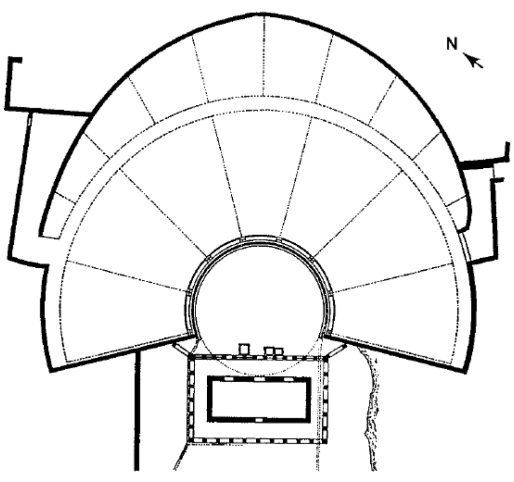


Figure 37 Plan of the theatre of Delos in Greece (from Sear, 2006).

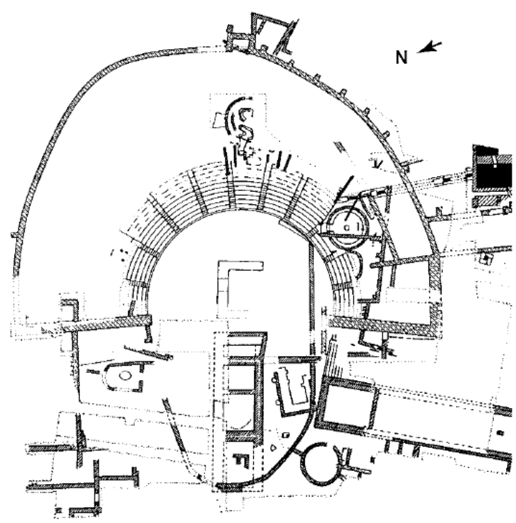


Figure 38 Plan of the theatre of Thebe in Greece (from Sear, 2006)

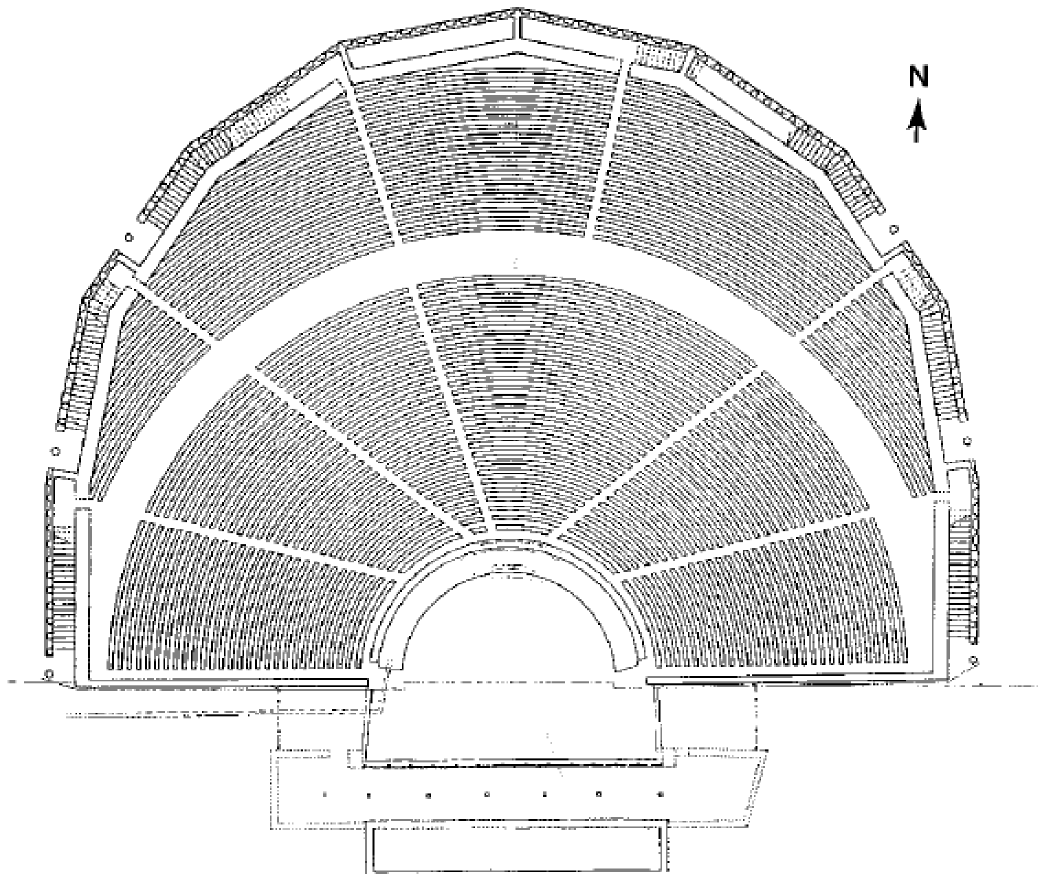


Figure 39 Plan of the theatre of Metapontum in Italy (from Sear, 2006).

5.3 Theatre of Hersonissos

The theatre of Hersonissos is localized within the modern town, on the street called Dimokratias. It is oriented toward west and the archaeological excavations, which started in 1995, brought to light part of the cavea and some of the pillars of the outer wall.

Large part of the information we have about this monument are partial and incoherent because the excavations have not finished yet and it seems not possible to reveal the scene building, being located under the modern road.

Onorio Belli, at the end of XVI century, was the first one to mention this theatre: he made a drawing representing its plan[26]. His drawing shows (fig. 40) a cavea consisting of 11 rows of seats, 16 pillars of the outer wall of the cavea, a *scaenae frons* consisting of niches and semi columns with only one entrance for the actors, a deep *postscaenium* joined together with an ellipsoidal portico placed at its back, two large entrances on both sides of the orchestra give the access to the theatre from the outside. He did not add any comment about the state of preservation at the period he made the plan, and he only commended that it was a theatre of not considerable dimensions.

This plan presents two peculiar characteristics: the long distance between cavea and scene building (around 16 meters), and the ellipsoidal porticos at the back of the *postscaenium*. It might be possible that the building, interpreted by Belli as a portico annexed to the theatre, was another monument very close by, for example a stadium[48]. Isler[64] described Belli's drawing as a plan with "fanciful details", above all because of the two elements aforementioned.

No other travelers of the past centuries wrote about this theatre. The theatre of Hersonissos has been mentioned again only in the midst of the XIX century, by Edward Falkener[32] in his study of the plans left by Belli. The theatre of Hersonissos represented by Falkener (fig. 41) has 16 rows of seats, there are 44

[48] In the plan of the small theatre of Gortyna, Belli probably represents the temple of Apollo Pythion as a portico at the back of the *postscaenium* of the theatre.

columns in the porticos instead of 46 as indicated by Belli and it presents some other differences in measurements with the one of Belli.

At the very beginning of the XX century, the archaeologist Lucio Mariani[44] reported what he saw at his time: the theatre is looking at SW, the internal diameter is 27 meters, its shape seems Greek but it has been built with stones, bricks and Roman mortar, and the orchestra looks dug into the ground.

About thirty years ago, the site of the theatre has been visited by the archaeologist Ian Sanders[16]. He provided a detailed description of the remains, adding measurements as well. Part of Belli's plan is confirmed by the illustration made by Sanders, he also saw the pillars of the 14 arches on the retaining wall of the cavea and the pillars subdividing the *parodoi* into three passages. In the 80's of last century, the area of the scene building was already completely destroyed, or anyway not visible on the surface.

Through a small archaeological excavation carried out in 1995 by the 23rd Ephorate of Prehistoric and Classical Antiquities, the archaeologists identified: part of the *analemma* and some of its pillars, part of a staircase in the *analemma*, a portion of the central seating area, the west side of the stage and part of probable *basilicae*, and part of the floor of the orchestra [112].

In order to better understand the dislocation of possible remains underneath the ground, in 2009 a geophysical prospection survey was carried out by the Laboratory of Geophysical-Satellite Remote Sensing and Archaeo-environment of F.O.R.T.H. The methodologies used have been GPR (Ground Penetrating Radar), electric tomography and magnetometry, on a surface of 2000 m^2. The identified anomalies (fig. 42) have been interpreted as rows of seats till 9 m from the *analemma* without presence of an *ambulacrum*, gaps indicating the *parodoi*, and a long wall NW/SE[49]. The geophysical prospection could not identify traces of the scene building[63].

[49] This wall may be interpreted as the *proscaenium* and one of the sides of the *basilica*.

Following archaeological excavations enabled the company “d-code” to draw a plan of the archaeological remains and to design a partial reconstruction of the monument in order to use it for theatrical performances[50](figs. 43 and 44).

Summarizing, the information we have are quite exhaustive about the cavea, but we do not have any data about the scene building, except for Belli’s plan. The recent archaeological excavations and the geophysical prospection partially confirmed the plan of Belli: presence of pillars and arches in the outer wall of the cavea, presence of *parodoi*, and seating area without any separation. At the same time, they also highlight what is wrong in Belli’s plan: the distance between cavea and scene building plus other dimensions as diameter of the cavea and orchestra.

The plan realized by the company “d-code” has been the basis from where to start to create the 3D model of the theatre, having been elaborated after the first archaeological excavations.

It has been imported and scaled in AutoCad. The width of the seats is known (60 cm), and also the external and internal boundaries of the cavea, delimited respectively by the *analemma* and by the orchestra, then it has been possible to obtain the number of rows of seats (15), calculating the distance between cavea and orchestra. According to the picture of the face of one row of seats, their height should be approximately 50 cm (fig. 45), and thus we can deduct we have a total height of the cavea of about 7.50 m.

We have traces of the front of the *proscaenium* as well and this has been reconstructed composed by several semicircular niches because one of them has been found (fig. 46).

Traces of the wall of the *scaenae front* have been identified as well and it seems like there should be three openings to enable the entrance of the actors on the stage, and

[50] Website of the company with the project of restoration and valorization of the theatre of Hersonissos. http://www.d-code.gr/%CE%B1%CF%81%CF%87%CE%B1%CE%B9%CE%BF-%CE%B8%CE%B5%CE%B1%CF%84%CF%81%CE%BF-%CF%87%CE%B5%CF%81%CF%83%CE%BF%CE%BD%CE%B7%CF%83%CE%BF%CF%85/

not one as it is represented in Belli's plan. Connected to the south side of the stage, another wall NW/SE has been identified and it might be part of the east wall of the *basilica* on the south side.

The height of the whole scene building has been reconstructed the same as the cavea's height, as it is typical in the Roman theatres, and following Vitruvius' instructions. Couples of columns have been represented flanking the three doors of the *scaenae frons*, also if they have not been testified by any source, because one of the main characteristics of the Roman theatres is the rich decoration of the *scaenae frons*. It is important to stress that also if it is highly probable that there were columns decorating the scene building, none of them has been found, maybe due to the fact that the area of the scene has not been excavated, being located where the modern road is. The columns (with a diameter of 0.44 m and a height of 3.53 m) have been reconstructed according to the Vitruvian rules, which proportions are indicated in the figures 20 and 21.

It has been decided not to represent the *postscaenium* and the potential portico at its back because we do not have any data about them, except for Belli's plan that does not seems so accurate.

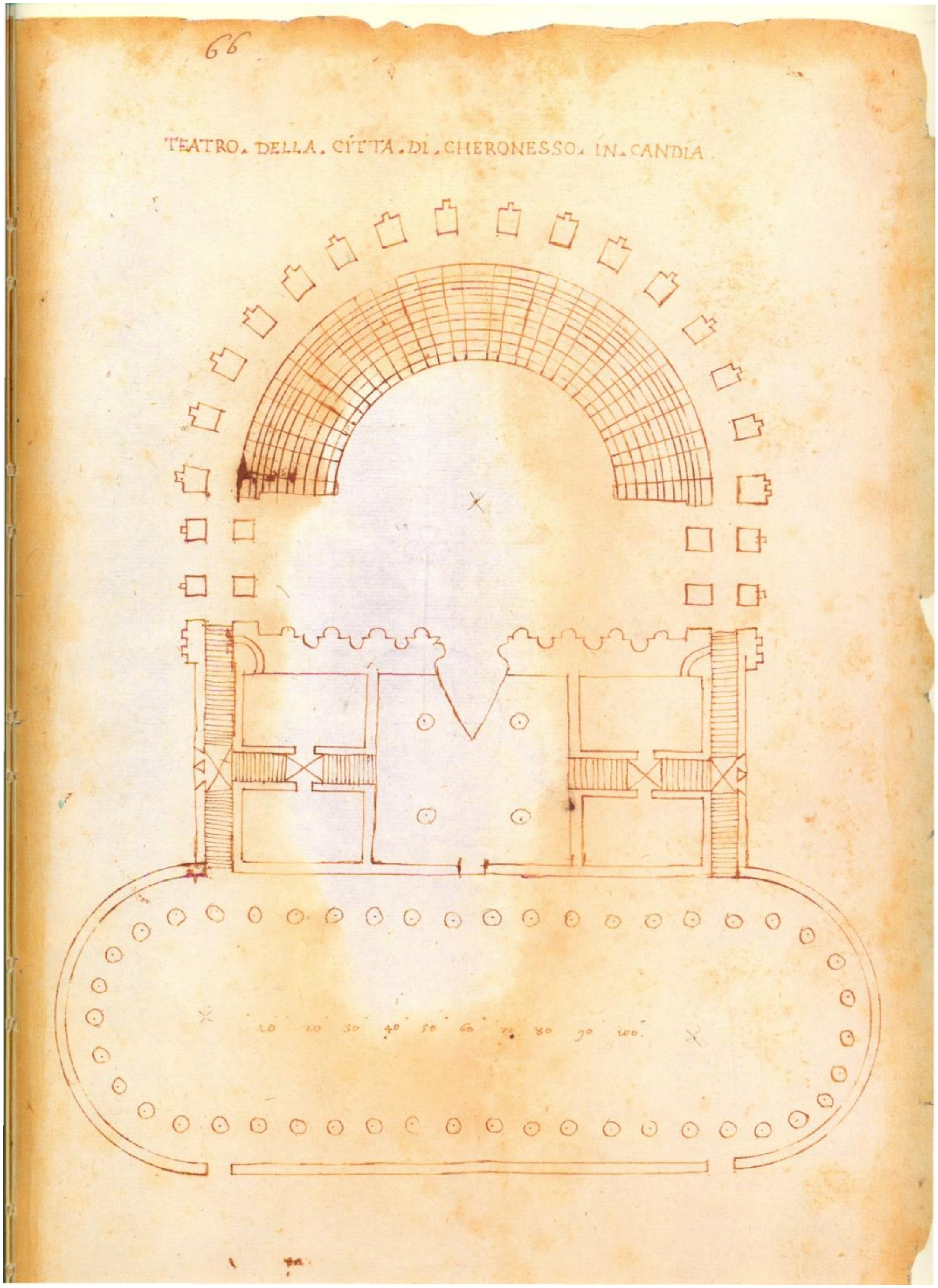


Figure 40 Plan of the theatre of Hersonissos made by Belli (from Beschi, 1999).

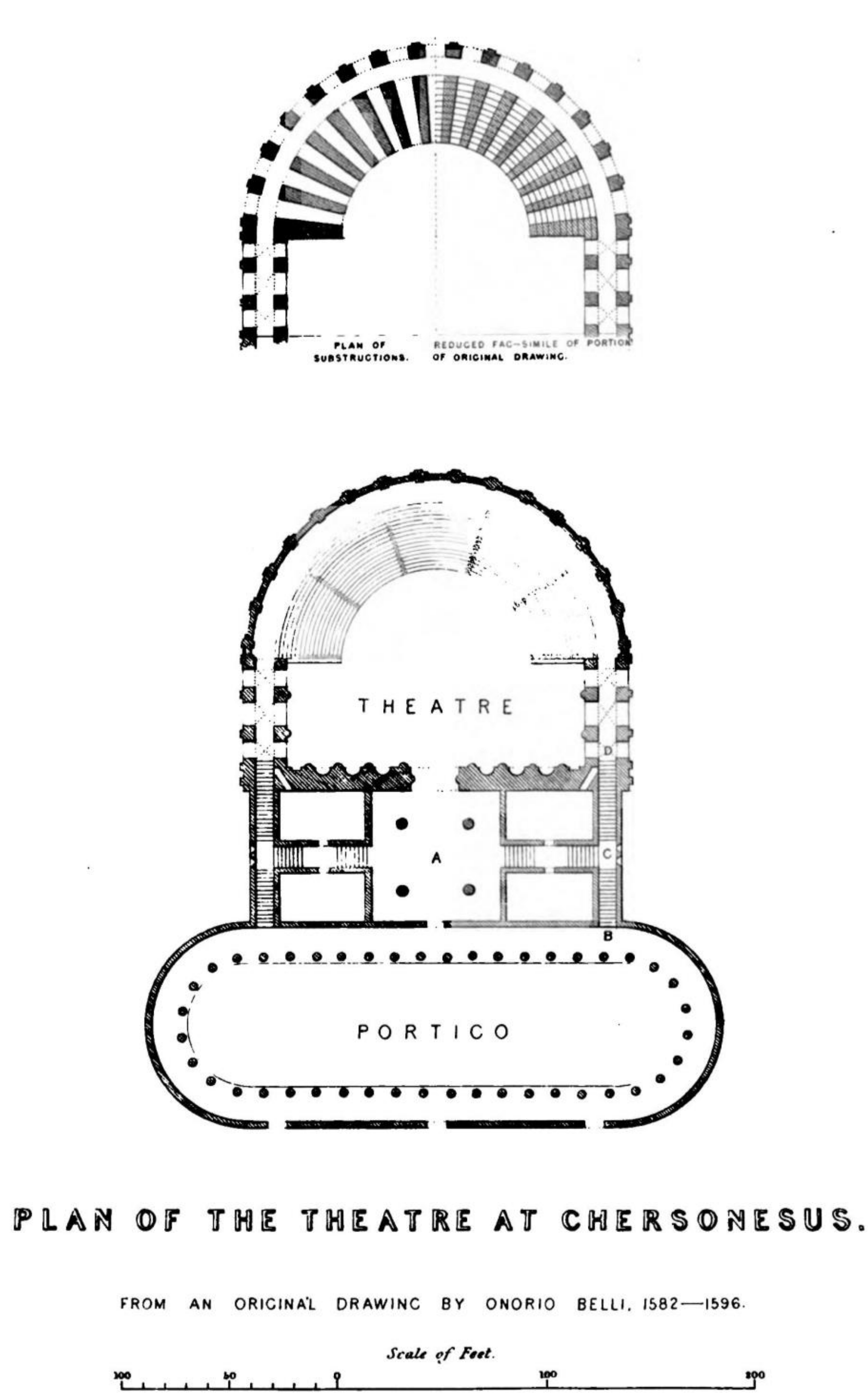


Figure 41 Plan of the theatre of Hersonissos by Falkener (1854).

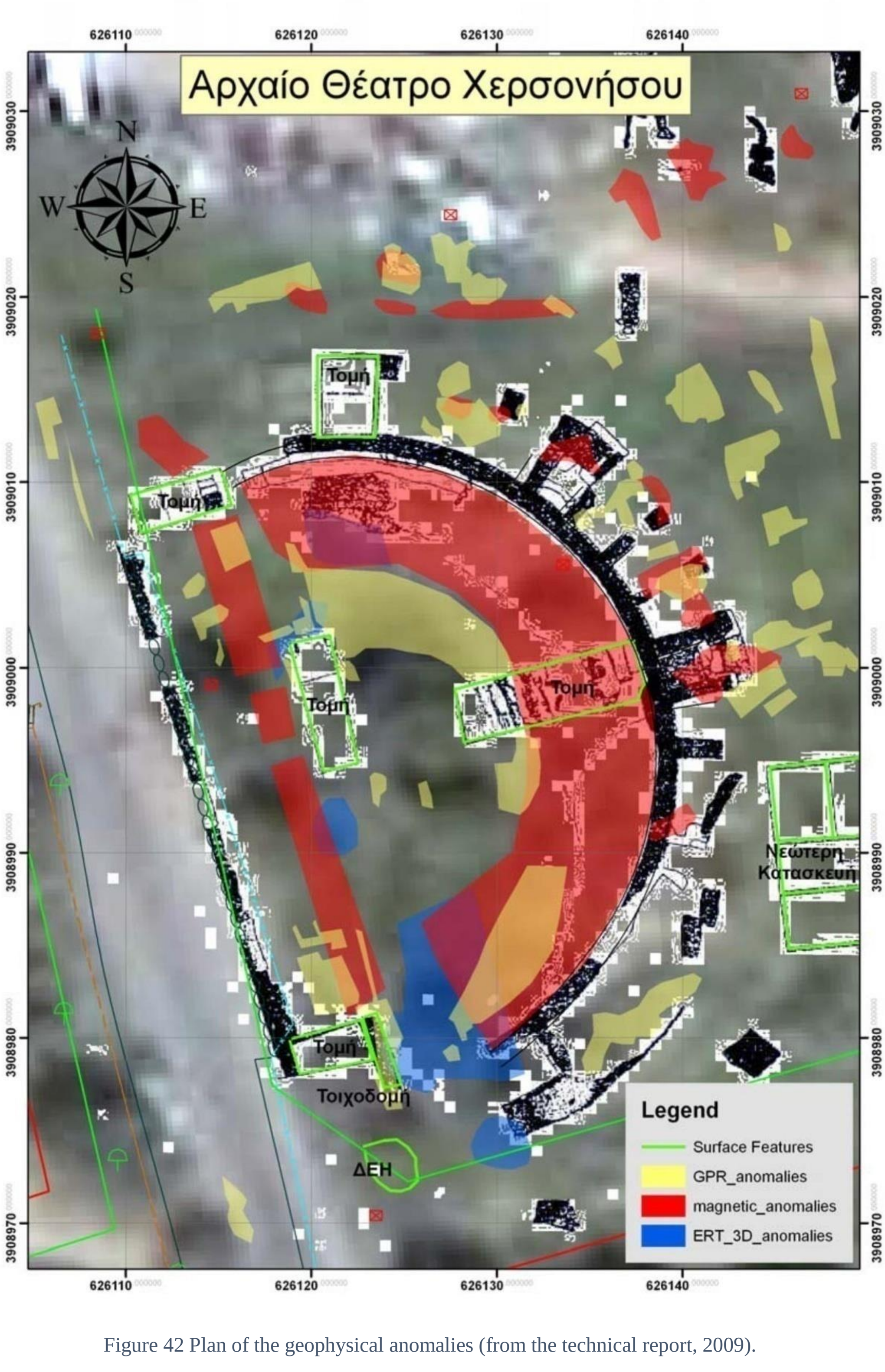


Figure 42 Plan of the geophysical anomalies (from the technical report, 2009).

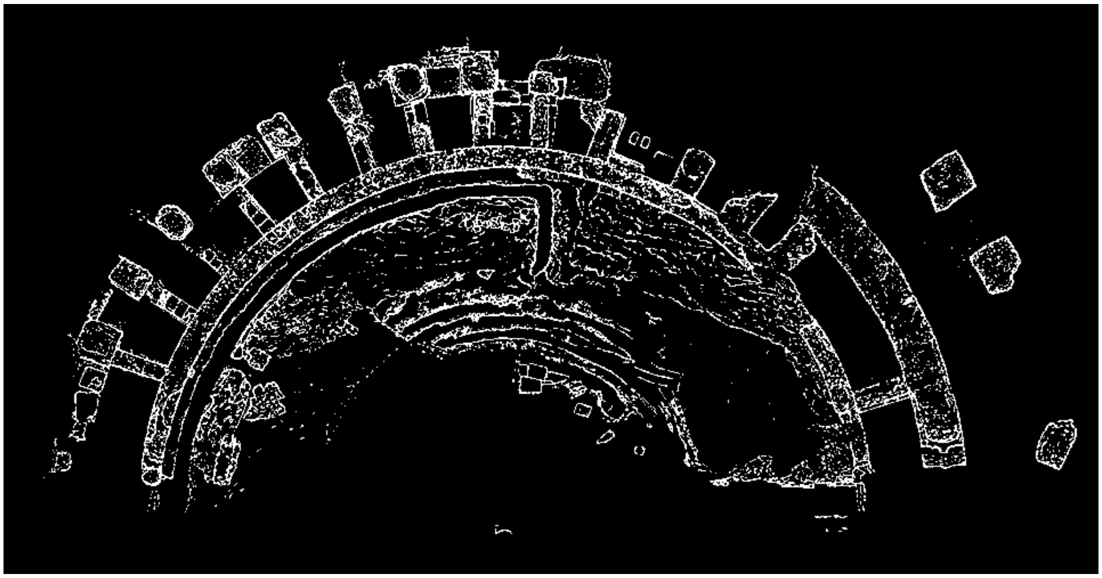


Figure 43 Plan of the remains of the theatre at Hersonissos (from d-code website).

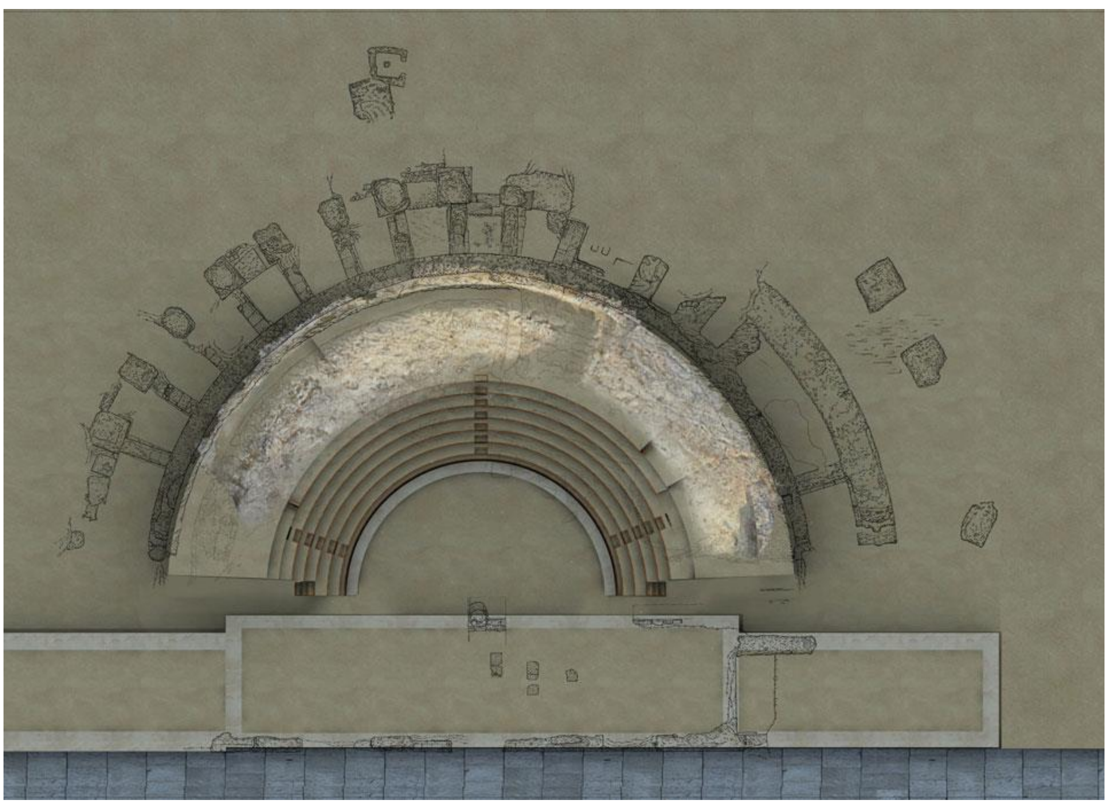


Figure 44 Survey of the remains of the theatre of Hersonissos (from d-code website).

Figure 45 Picture of the face of some of the seats of the theatre of Hersonissos, with metric reference (from http://anaskafi.blogspot.it/2013/12/2013.html#ixzz44J8P8WiO).

Figure 46 Semicircular niche of the proscaenium of the theatre of Hersonissos (from http://anaskafi.blogspot.it/2013/12/2013.html#ixzz44J8P8WiO).

5.3.1 3D visibility analysis

The 3D visibility analysis in this case was useful to check if the walls of the *basilicae*, at that distance from the cavea, impede the visibility of the stage from the spectators' positions.

A grid composed of 58 observer points has been created in order to represent some spectators' positions, each point is placed 75 cm higher than the seat, divided into 4 rows (for a detailed explanation refer to the methodology chapter, p. 56) (fig. 47).

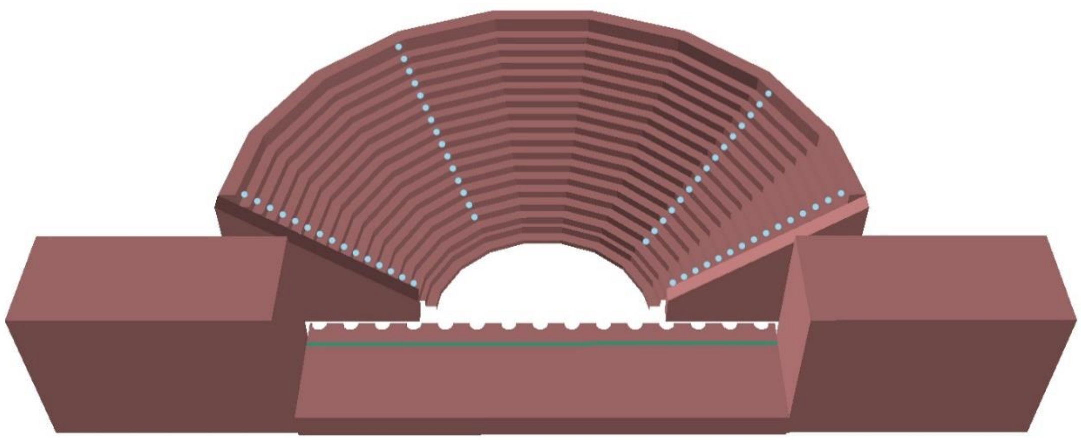


Figure 47 3D model of the theatre of Hersonissos with the grid points representing the observers in the seating area.

The calculation of lines of sight showed that the *analemmata* partially cover the visibility towards the stage of the spectators seating at the sides of the cavea, but it is an issue limited to the very external sides of the stage. The percentage of not visible trajectories between spectators and actors' positions is only the 9%, and consequently the 91% of the lines represent visible trajectories.

The map of frequency of visibility confirms that the central area of the stage (where probably large part of the performance took place) is visible by all the spectators: the blue colour represents the area visible by every observer points (figs. 48 and 49).

The 3D visibility analysis confirms the hypothetical reconstruction of the theatre of Hersonissos, showing an ample visibility of the stage from the cavea.

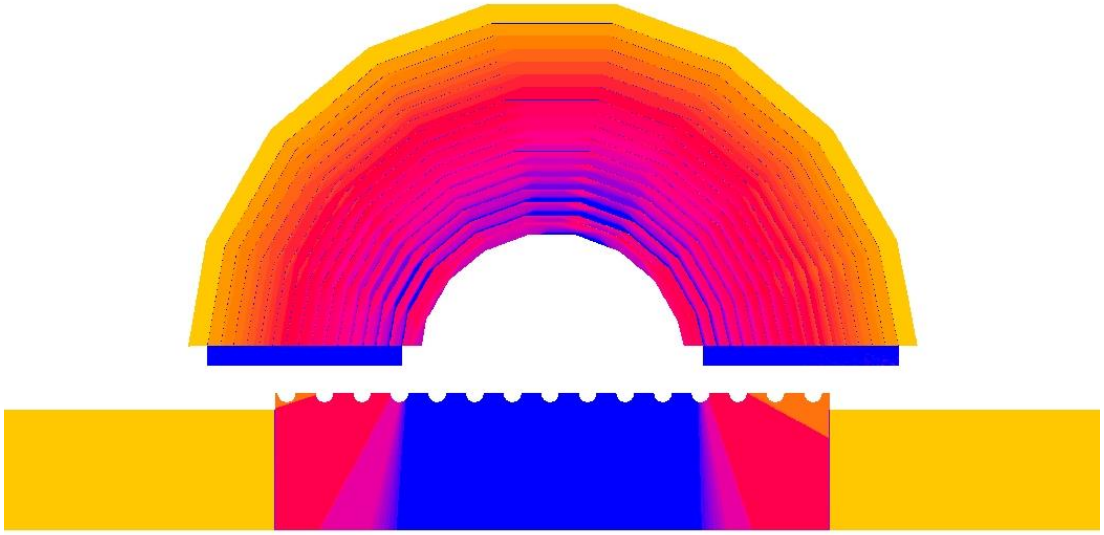


Figure 48 Map of frequency of visibility of the theatre of Hersonissos. The colors show the different level of visibility for the observer points, as it is explained in the correspondent graph (fig. 48).

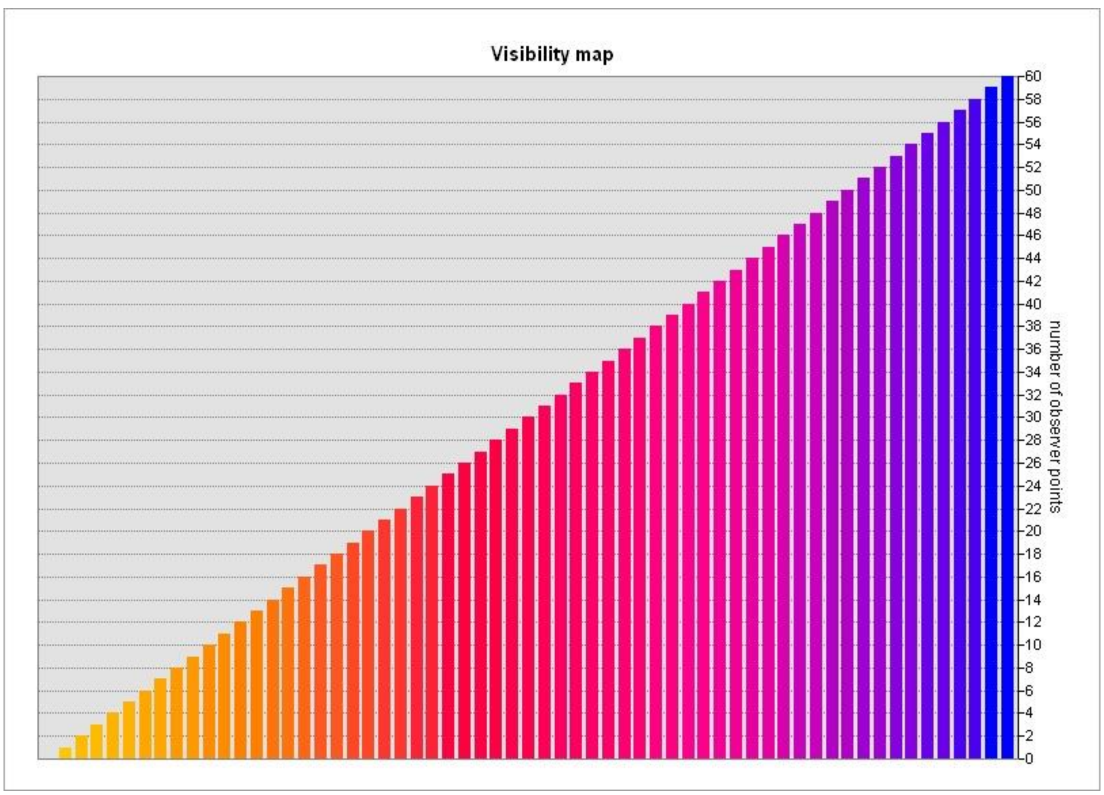


Figure 49 Graph of visibility analysis. The color scale is from yellow to blue. The yellow color means that those areas are visible by none of the observer points; the blue area indicates the part of the theatre visible from all 60 observer points.

5.3.2 Virtual acoustics analysis

In this case the virtual acoustics analysis can be useful above all to confirm the formulated hypothesis by archaeologists and architects, and already verified by the 3D visibility analysis. Despite this, more than one reconstruction has been tested to compare the results and formulate a more accurate hypothesis. One 3D model represents graphically the results of recent studies after the archaeological excavations (N.1); in the second 3D model, a roof has been added above the stage (N.2); the third 3D model consists of the model N.1 plus a portico in *summa* cavea (N.3); the forth 3D model is the combination of the second and the third (roof plus portico) (N.4).

The materials applied are the following, according to the descriptions of Belli and Sanders, and to the visible remains:

1. Stone: cavea, *proscaenium*, orchestra, scene building.
2. Bricks: *analemmata*.
3. Audience: seating area.

Fifteen receivers have been placed distributed in three radial lines, one receiver every three steps (figs. 50 and 51) (for a detail explanation refer to the methodology chapter, p. 65).

The results obtained from the virtual acoustics analysis are shown in the graphs 6-11. The difference between T30 and EDT is between 0 and 0.4, it means that in some cases the early decay time and the reverberation time is the same. The model N.1 presents quite low values for T30 and EDT even for speech, but a spoken performance is still understandable as it is demonstrated by the auralised file. Indeed, the model N.1 has a high value for STI indicating a probable excellent intelligibility of the speech. Few receivers in the models N.3 and N.4 show that C80 is under 3 dB and D50 is under 0.5, which might denotes a not perfect acoustics nor for spoken performances either for music.

Concluding, we can affirm that the virtual acoustics analysis confirms the interpretation of archaeologists and architects, and the reconstruction proposed in this research, based on the archaeological excavations and the Vituvian rules. The presence of a portico in *summa* cavea would have worsen the acoustics quality of the theatre, but it might be possible that the stage was covered by a roof. According to the virtual acoustics analysis the theatre could be used for spoken performances.

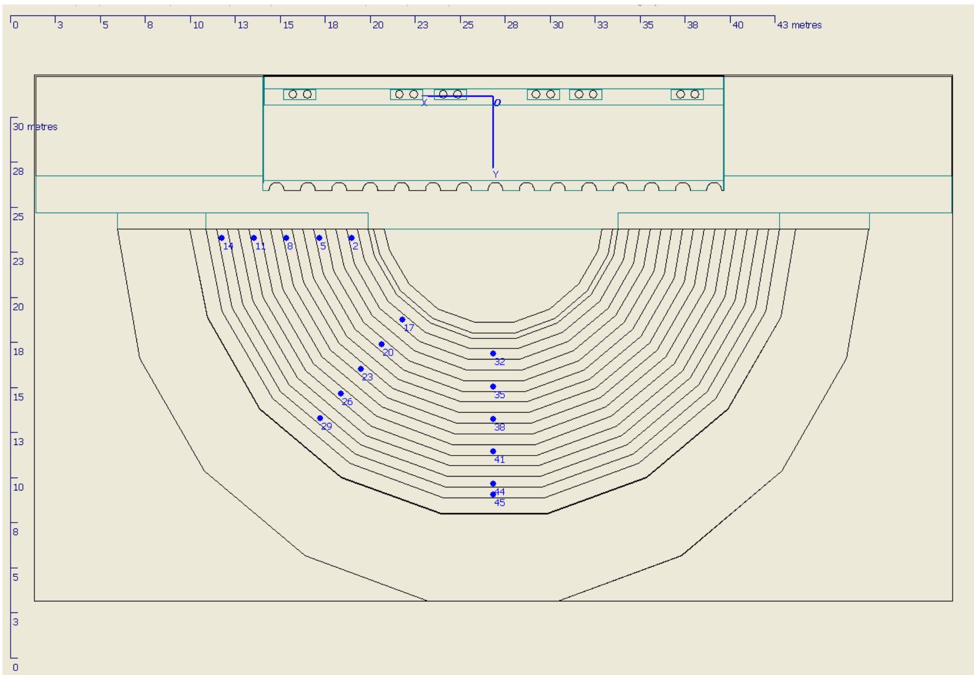


Figure 50 Plan of the model N.2 of the theatre of Hersonissos plus receivers and source.

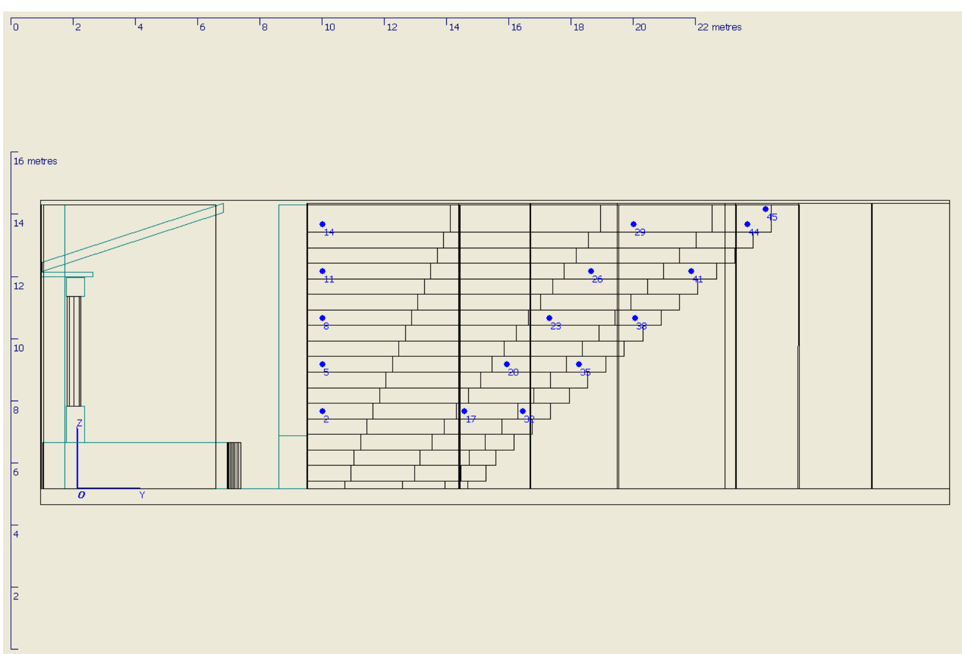
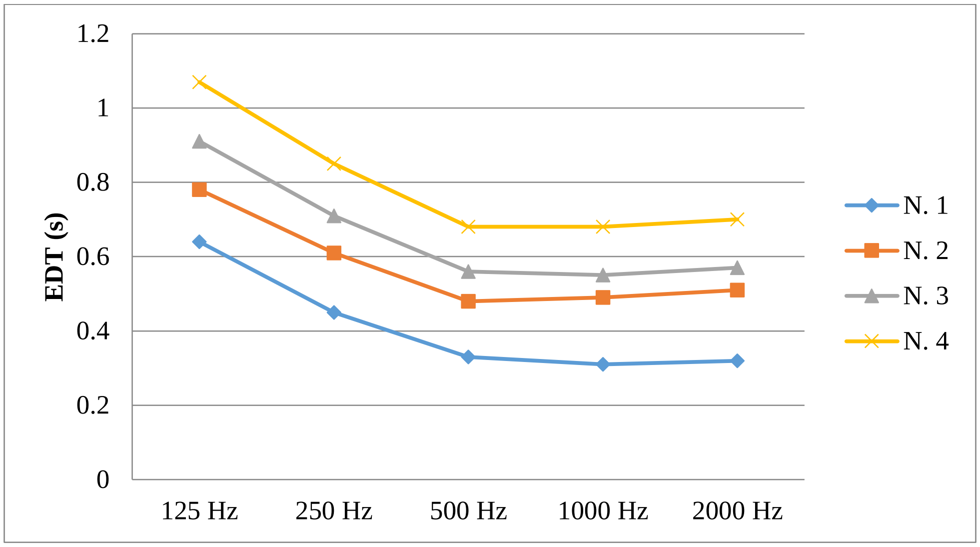
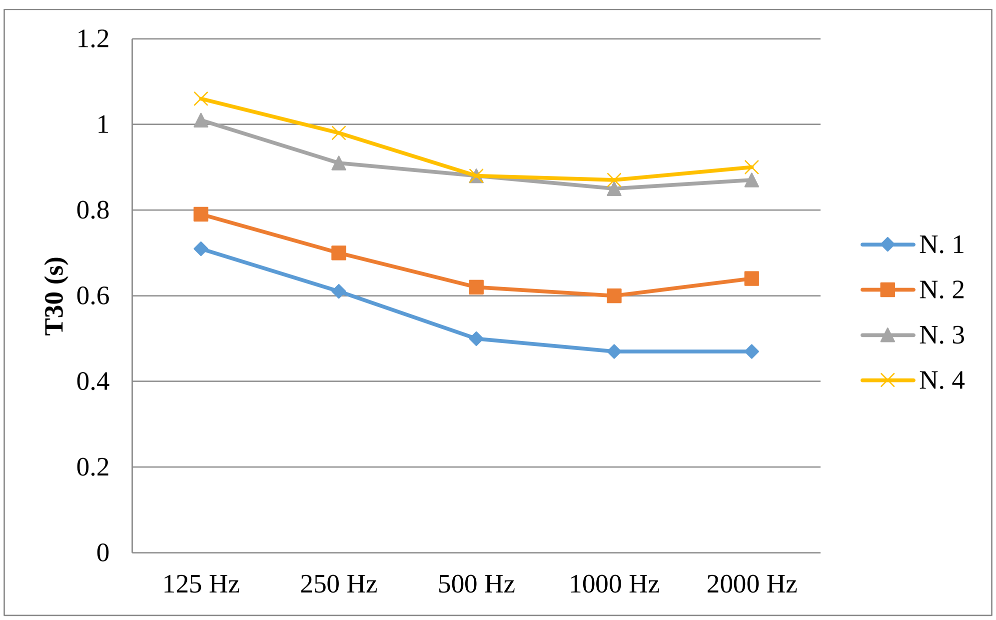


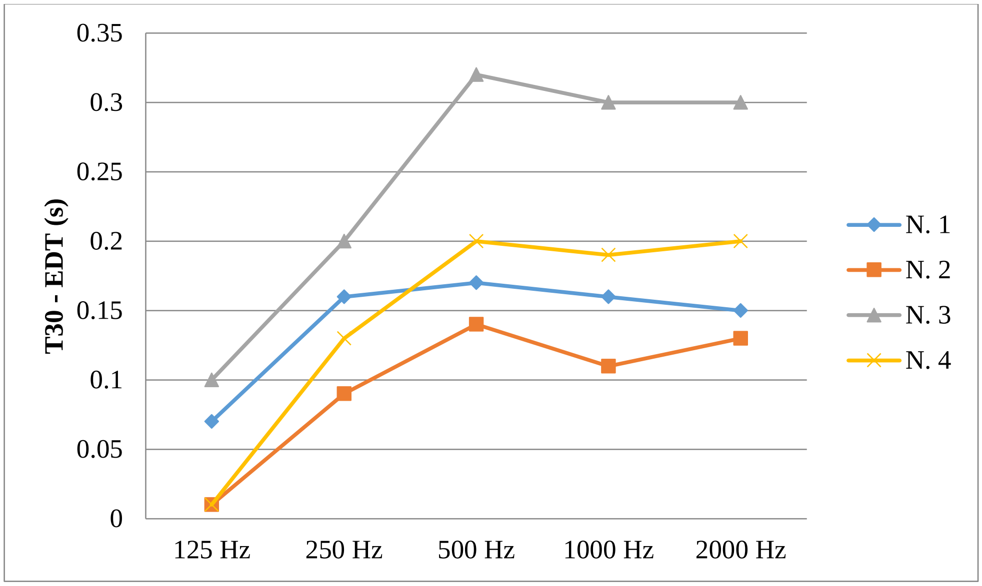
Figure 51 Section of the model N.2 of the theatre of Hersonissos plus receivers and source.



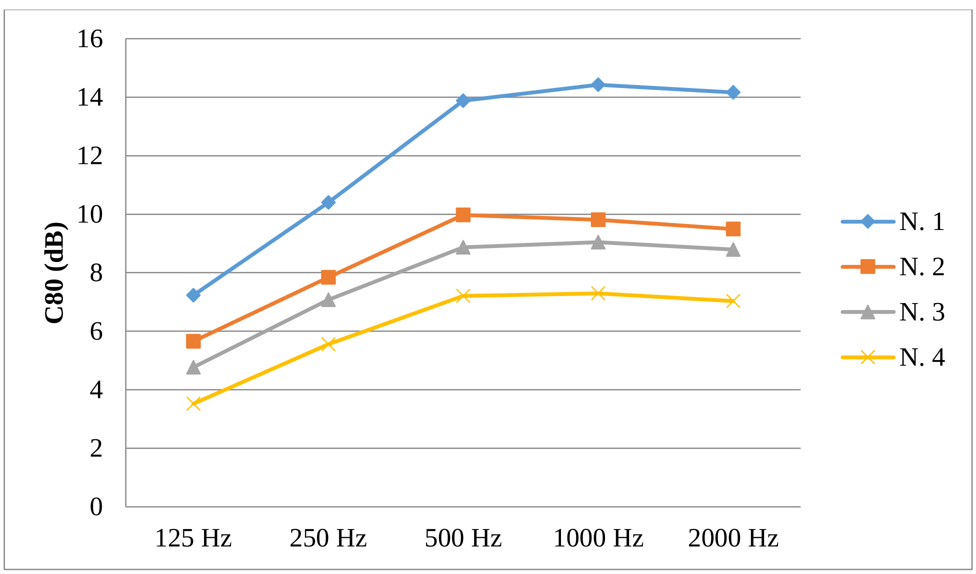
Graph 6 Average values of EDT for each model, at each frequency.



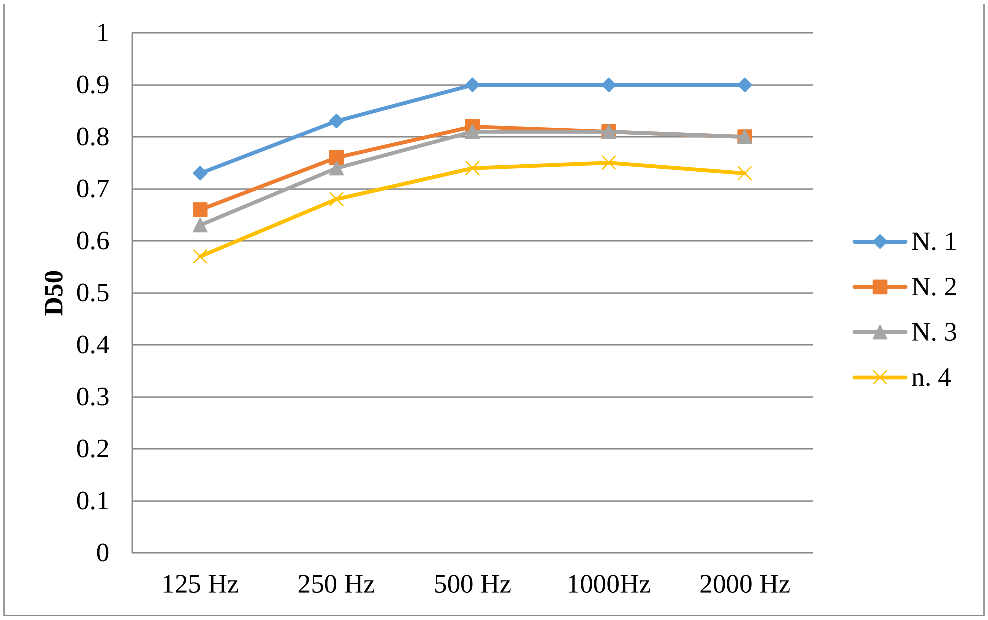
Graph 7 Average values of T30 for each model, at each frequency.



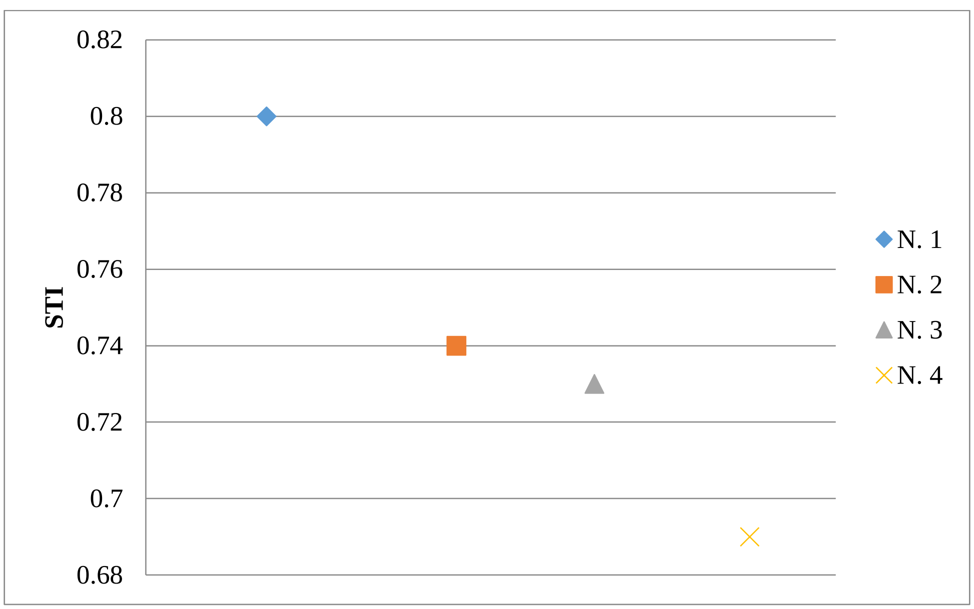
Graph 8 Average values of the differences between T30 and EDT for each model, at each frequency.



Graph 9 Average values of C80 for each model, at each frequency.



Graph 10 Average values of D50 for each model, at each frequency.



Graph 11 STI values for each model.

5.3.3 Results and comments

The archaeological data, the 3D visibility analysis and the virtual acoustics analysis have allowed a pretty reliable reconstruction of the original aspect of the theatre of Hersonissos (figs. 52-56). The cavea was semicircular with a diameter of about 42 m, and composed of 15 rows of seats made out of local stone, surrounded by the *analemma* covered with bricks. The *parodoi* provided access to the orchestra, separating the scene building from the cavea. The front of the stage is decorated with several semicircular niches. The *scaenae frons* have three entrances for the actors and at the sides of the stage there are two *basilicae* which are not attached to the *analemmata.* The scene building was probably composed of only one storey. We do not have information about the *postscaenium* of the theatre.

It is clear that Belli drew a plan that is different from what the archaeological data show, but it is also true that if he has been inaccurate about measurements and numbers, the structure that he represents is not so wrong. It is confirmed that the cavea was not divided by any *ambulacrum* and the presence of *parodoi* separating the cavea from the scene building allowing the entrance to the theatre. It might be possible that the *parodoi* were covered by a vault, as it has been reconstructed by the archaeologists for the theatre of Aptera, and how it was more common for the Roman theatres.

The theatre of Hersonissos does not present such a particular structure, but even the most similar theatres have some different characteristics. One of the theatre that resembles the one in Hersonissos is the Roman theatre (not a more exact date is available) of Issa[51] in Croatia. It had open *aditus* which separated the cavea from the scene building, a rectilinear *scaenae frons* with three openings and two basilicas. Furthermore the cavea does not look divided by any corridor and it is composed of about 20 rows of seats (fig. 57)[65]. A larger and more elaborated version of a similar

[51] Issa was a Syracusan colony.

theatre is represented by the Roman theatre (I century AD) of Regina in Spain (fig. 58).

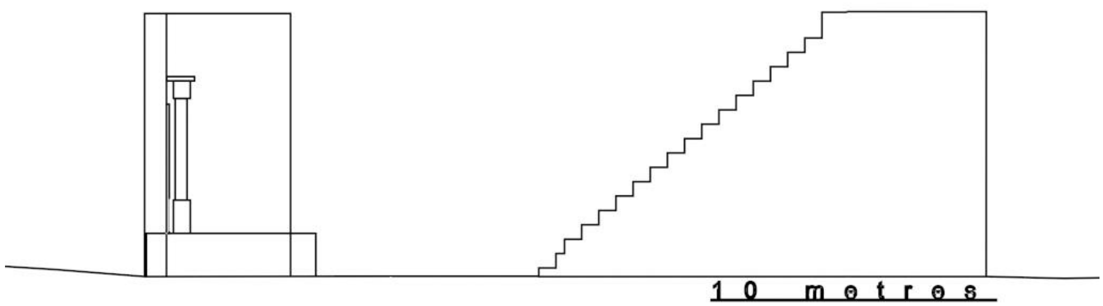


Figure 52 Reconstructive section of the cavea and the scene building of the theatre of Hersonissos.

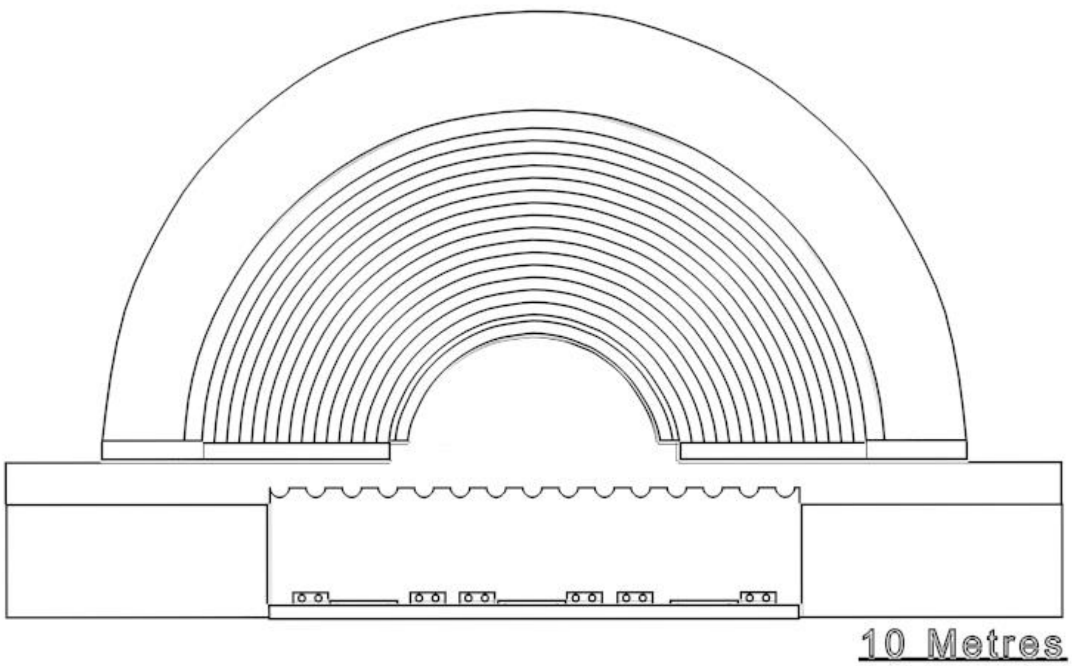


Figure 53 Reconstructive plan of the theatre of Hersonissos.

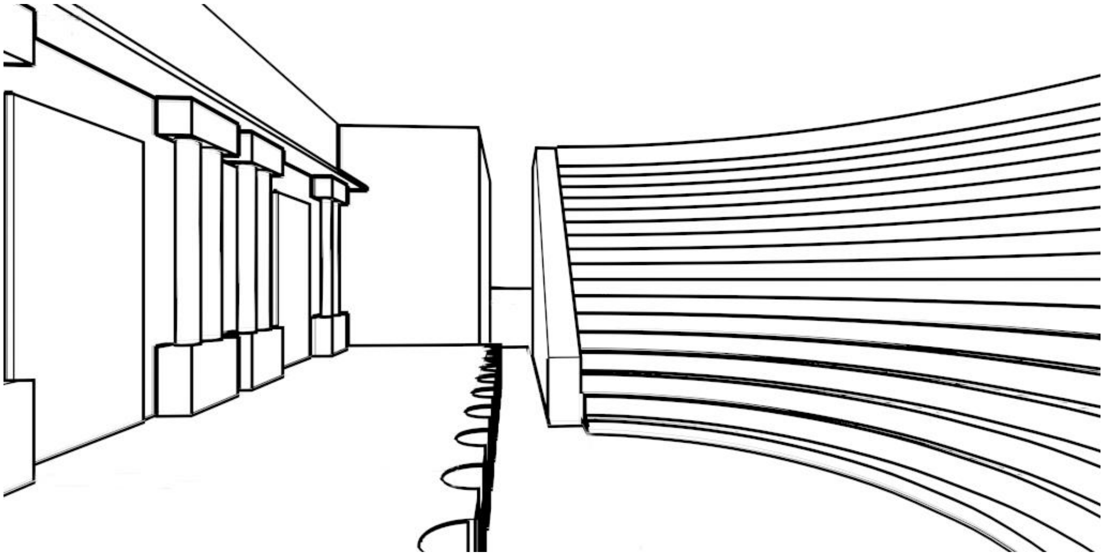


Figure 54 Reconstructive drawings of the theatre of Hersonissos.

Figure 55 Rendering of the 3D model of the theatre of Hersonissos. Particular of the *parodos* and the *proscaenium*.

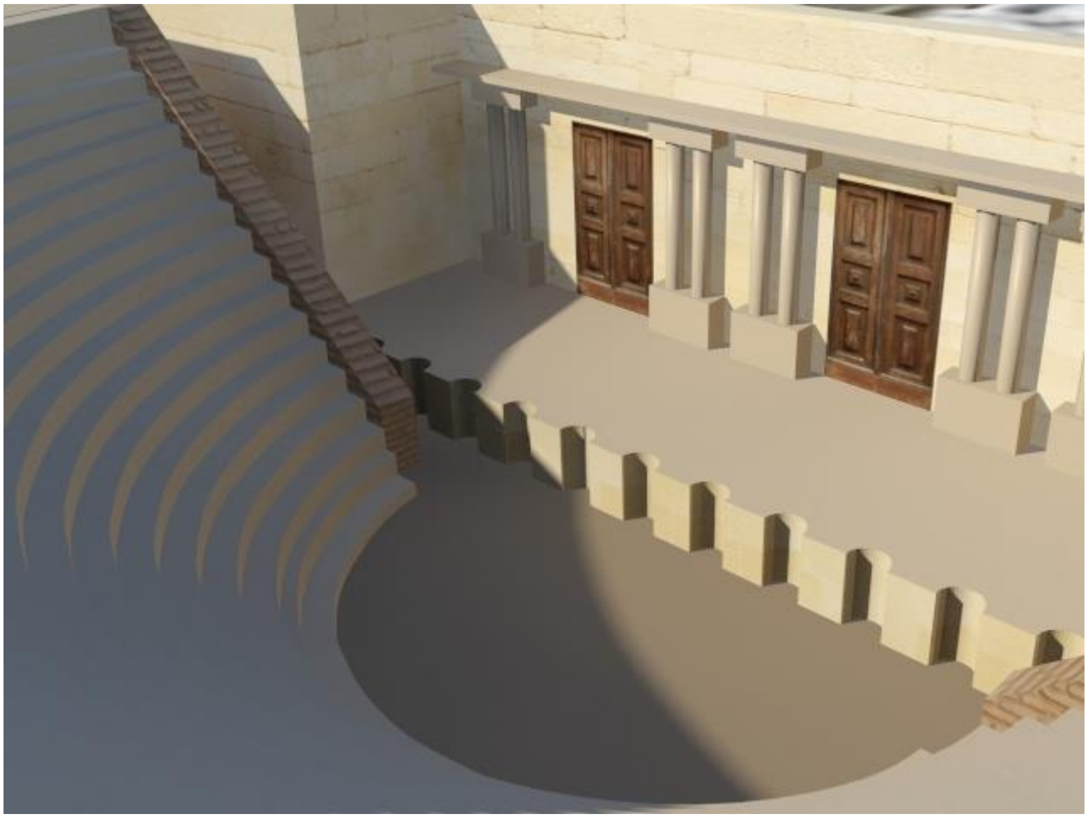


Figure 56 Rendering of the 3D model of the theatre of Hersonissos.

We cannot state anything about the presence of a *postscaenium* and/or a portico *postscaenam* because the area has not been investigated, but it is possible to affirm that there are not theatres with a portico *postscaenam* as represented by Belli. The only possible comparison is with the Roman theatre of Hippo Regius in Algeria, which had at the back of the *scaenae frons* a long elliptical structure (fig. 59), which it might be a *postscaenium* more than a portico. It was built in the I century AD, as the theatre of Hersonissos.

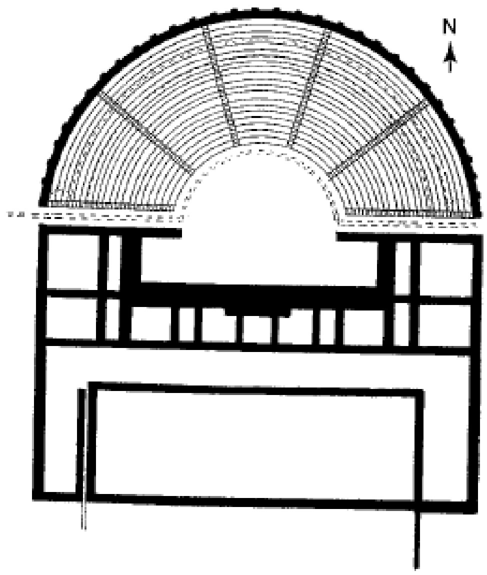


Figure 57 Plan of the theatre of Issa in Croatia (from Sear, 2006).

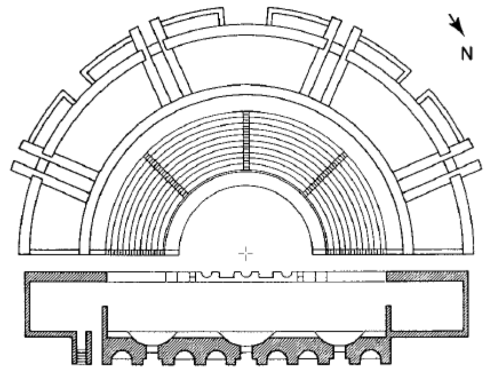


Figure 58 Plan of the theatre of Regina in Spain (from Sear, 2006).

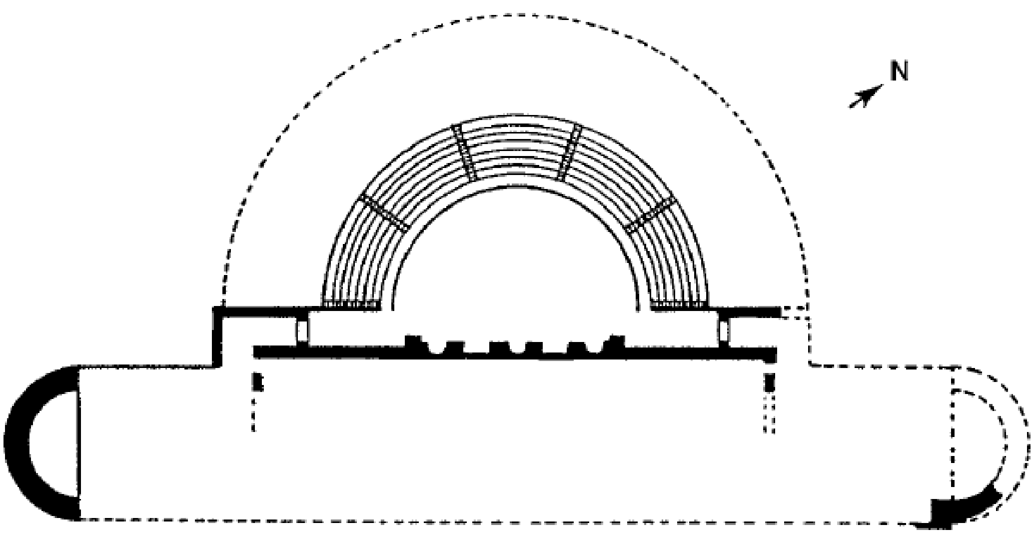


Figure 59 Plan of the theatre of Hippo Regius in Algeria (from Sear, 2006).

5.4 The theatre at acropolis of Gortyna

The most ancient theatre of Gortyna is placed on the south-east slopes of the acropolis of the ancient town. It is known as a Roman theatre but it is originally a Greek one that was modified by the Romans only at a later time. This probably explains the structure of the theatre, which is half dug in the ground and half built, as it was typical in the Greek times.

The theatre is currently under investigation by the Ephorate of Prehistoric and Classical Antiquities of Heraklion; archaeological excavations started only recently, in 2011.

The first one to mention this theatre was Onorio Belli[26] at the end of the XVI century, during its exploration of the island of Crete. He described its *scaenae frons* as very richly decorated, with white marble and ionic columns; in addition he left a plan of the monument (fig. 60). In the plan he drew also a portico in *summa* cavea and a peculiar long distance between the cavea and the scene building (around 18 meters). Belli explains through a note in the plan that the circles in the *ambulacrum* are cells where bronze vases might be preserved in order to reinforce the voice of the actors as suggested by Vitruvius[89]. I wonder if Belli did not get confused with possible openings of the *vomitoria* which leaded the spectators to the central corridor, as suggested by Barresi[54], or most probably with niches used to host some statues or sculptures[52].

Edward Falkener[32], more than a couple of centuries after, re-elaborated Belli's plan according to his knowledge about architecture (fig. 61). He drew more columns in the portico in *summa* cavea (44 instead of 36 as indicated by Belli) and he added pillars all around the cavea and not only at its two endings as in Belli's plan. It does not look plausible that there were pillars all around because the back side of the cavea is lying

[52] The real existence of such bronze vessels is discussed because there is not archaeological evidence of them. In addition, only few examples of cavities in the cavea exist (Beth Shean, Gerasa, Schytopolis), but we do not know if they were used to host these kind of vases[113].

against the hill. The dimensions of the two plans are little different as well (Falkener drew a longer diameter for the cavea and for the orchestra[53]).

In the second half of the XIX century, the theatre is documented also by one of the British travelers, Captain Thomas Spratt[37], during his journey in Crete. In his drawing he represents the ruins of the cavea lying on the hill, at the back of the church of Saint Titus (fig. 62). He measured a cavea 280 feet long, but he admitted that it was very scarcely preserved and that the measure might be slightly more as Belli indicated. He did not manage to collect any other archaeological evidence because of the bad state of the remains, he only noticed some blocks of limestone in the cavea and some fragments of a grey marble column with a capital of Parian marble in the area of the scene.

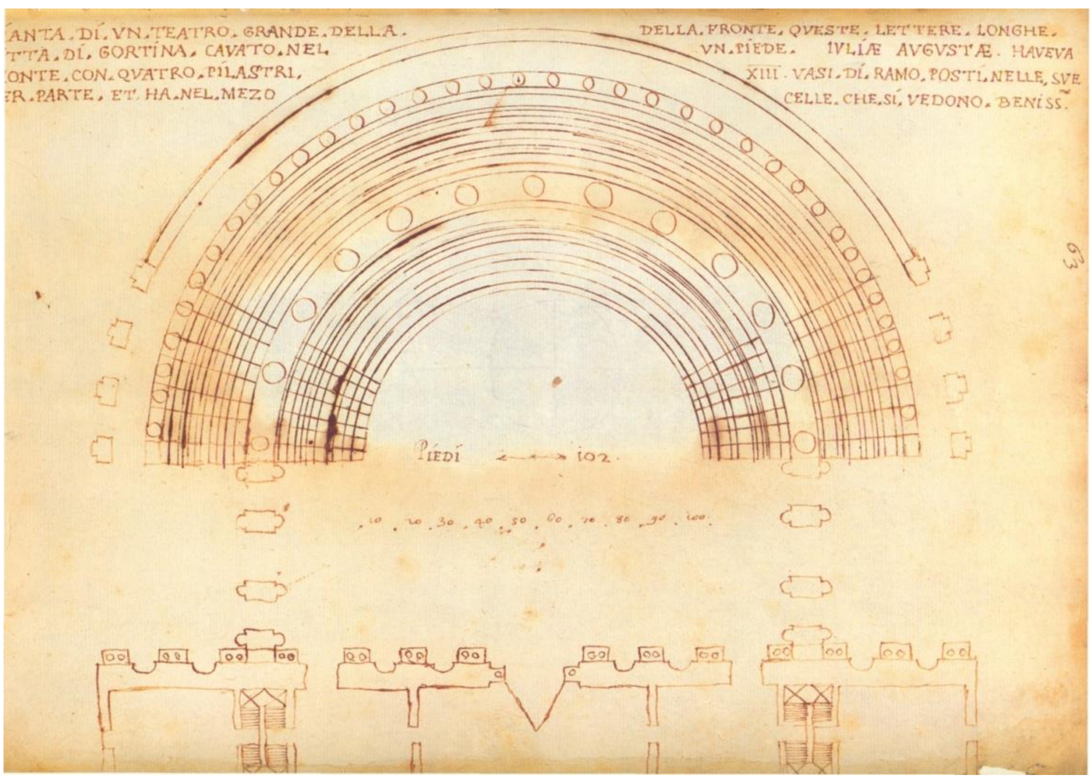


Figure 60 Plan of the theatre at acropolis of Gortyna made by Belli (from Beschi, 1999).

53 The diameter of the cavea indicated by Falkener is around 98 meters, the one indicated by Belli around 84 meters. The diameter of the orchestra indicated by Falkener is around 39 meters, the one indicated by Belli is 37 meters.

The first archaeological investigation have been carried out by Antonio Taramelli[39] at the very beginning of the XX century. Despite he thought the conditions of the theatre were the same as at Spratt's time, he managed to take more measurements and also to compare his observations with Belli's plan. Unfortunately, as for the theatre of the Pythion, he only identified some remains of the cavea, but nothing about the scene building. All the details about the structure of the cavea and about its dimensions can be read in the plan and in the section he drew (figs. 63 and 64). As Belli, he divides the cavea into two sectors by an *ambulacrum.*

More recently, Ian Sanders[16] visited and reported the site of the theatre at acropolis, but he only summarized what Belli represented in his plan, without adding any information more, claiming that the theatre was badly preserved.

At the beginning of XXI century, the archaeologist Paolo Barresi carried out a more accurate investigation that let him produce a different interpretation of the remains[54]. He recognized a third sector of the cavea in the upper part, of not more than 5 rows of seats, and then he calculated a diameter of the cavea of 94 meters and a capacity of 5000 spectators. He identified a large wall around the orchestra that he interprets as a high podium, typical of the Roman theatre in the Orient. He dates the structure between the II and the III century, according to the type of bricks and the typology of vaults.

In 2009 a geophysical survey in the site of the theatre was carried out by the Laboratory of Geophysical - Satellite Remote Sensing & Archaeo-environment of Foundation for Research & Technology, Hellas (F.O.R.T.H.)[60]. Several techniques were used in order to discover different kind of anomalies that could suggest the traces of architectural structures: magnetometry, electromagnetometry, georadar and electric tomography. Every method used gave positive results, but in the area of the orchestra, the GPR and the electric resistivity tomography, were not useful to locate the pavement, probably because it is located deep into the ground (at least three meters under the planking level).

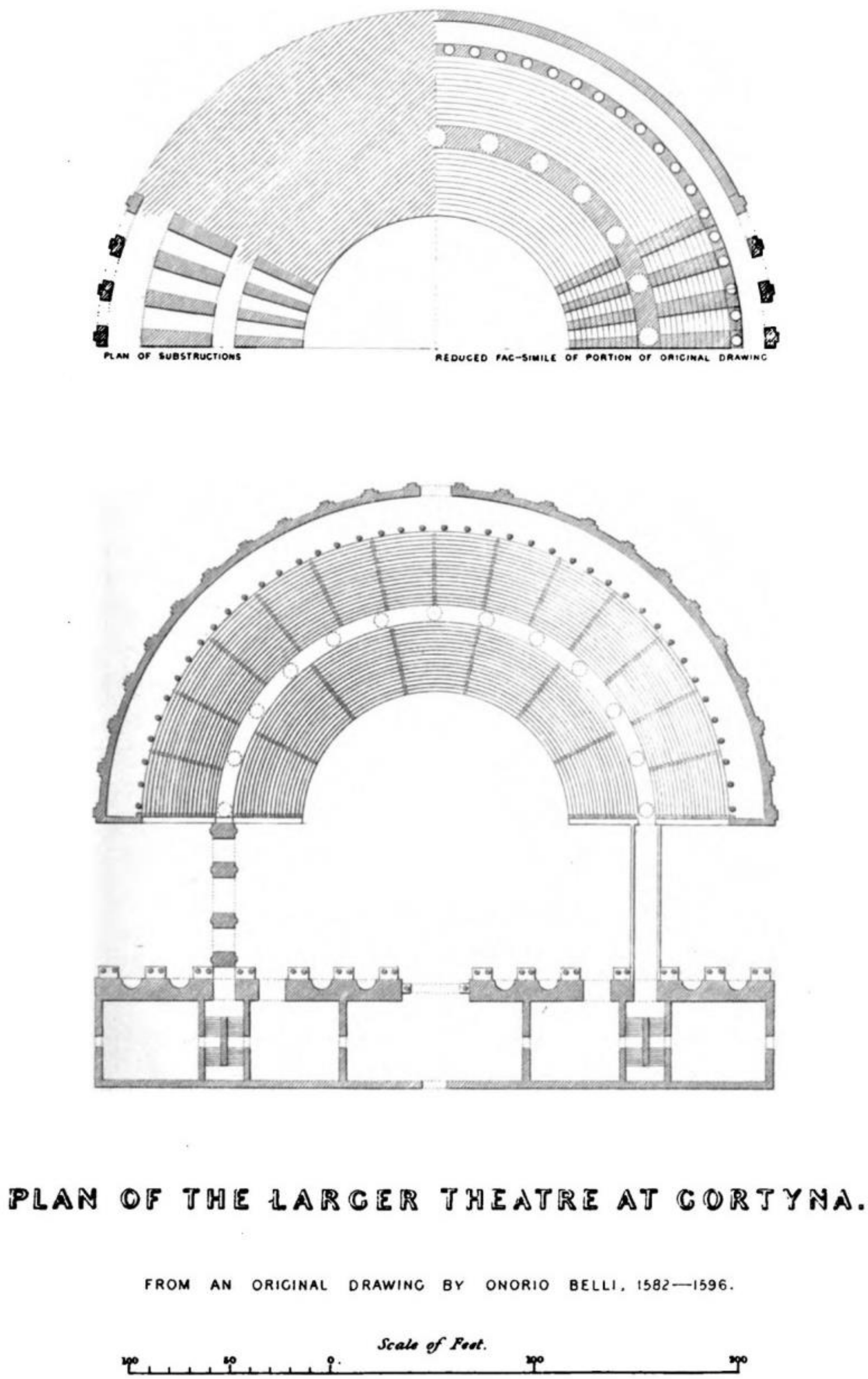


Figure 61 Plan of the theatre at acropolis of Gortyna made by Falkener (1854).

Figure 62 Drawings of the ruins of the theatre at acropolis of Gortyna made by Spratt (1865).

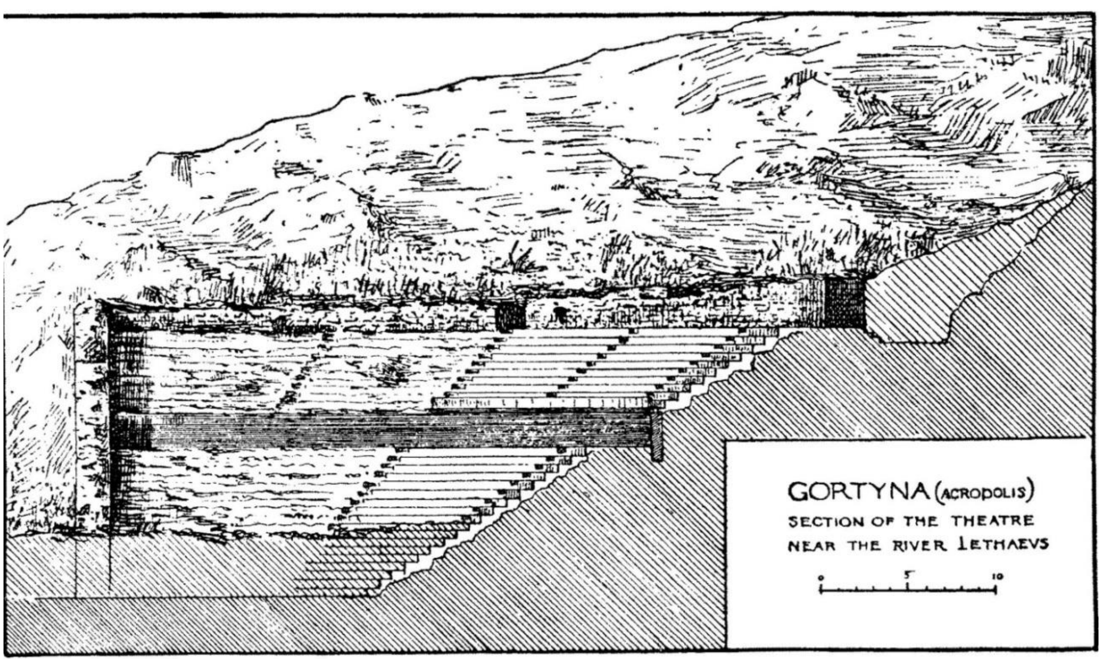


Figure 63 Section of the theatre at the acropolis in Gortyna made by Taramelli (1902).

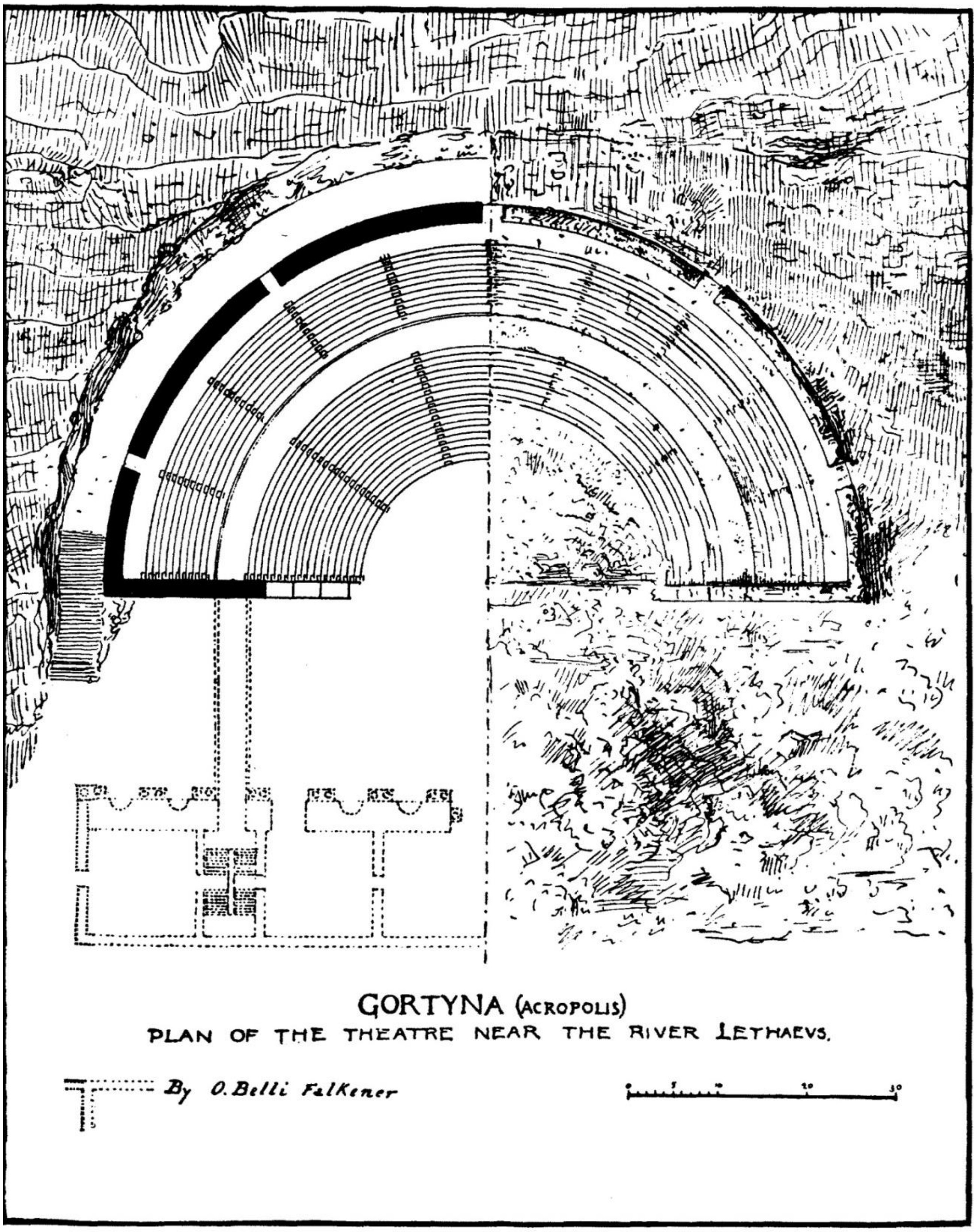


Figure 64 Plan of the theatre at the acropolis of Gortyna made by Taramelli (1902).

The prospection confirmed the intuition of Barresi about the presence of two *ambulacra*, and the partition of the cavea into three sectors, and not two as was suggested by Belli and Taramelli. Some of the rows have been identified till ten meters from the upper *ambulacrum* (towards the external side of the theatre), which is better preserved than the lower one whose surface is visible only on the north side. At north side, the wall supporting the cavea is better conserved. Furthermore, it was possible to recognize traces of few stepladders connecting the two corridors, the internal edge of the cavea, some traces of pillars supporting the cavea, part of the scene building in the west area, and part of a street N-S oriented, about 8 m wide (fig. 65).

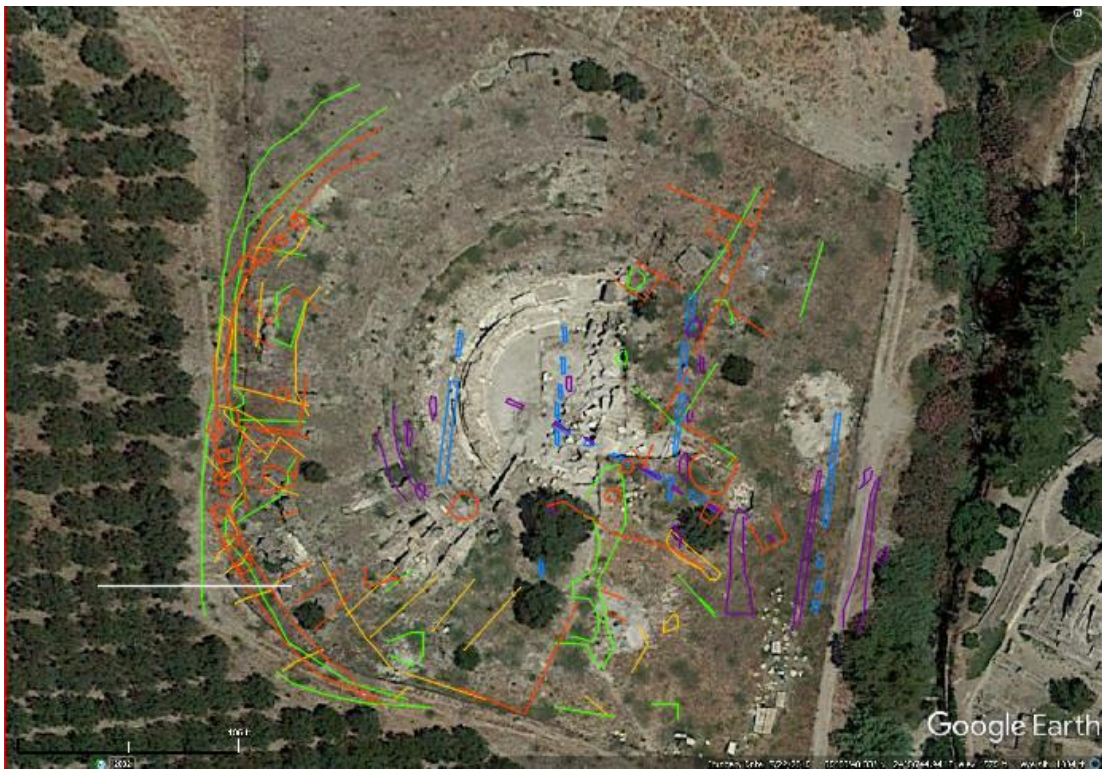


Figure 65 Geophysical anomalies identified in the site of the theatre at the acropolis of Gortyna.

Finally, in 2011 the archaeological excavations have started, carried out by the 23rd Ephorate of Prehistoric and Classical Antiquities in Heraklion, Crete. The first excavations revealed that actually the theatre is composed by an *ima*, *media* and *summa* cavea, divided by two corridors; the archaeologists also identified the boundaries of the orchestra, with part of its floor made by several marble tiles, and part of the façade of the *proscaenium*. Furthermore they found many fragments of pottery and marble decorations probably coming from the *scaenae frons*[114]. The archaeological excavations of the site are still in progress and the very last discoveries were presented to the conference Έργο Κρήτης, which took place in Rethymno, Crete, in November 2016.

The figure 66 shows the recent situation of the remains of the theatre. The *ima* and *media* cavea, the lower corridor, some of the stepladders, the front of the *proscaenium* and few architectural ornaments, such as fragments of columns, are clearly visible.

Figure 66 Remains of the theatre at acropolis in Gortyna.

Despite the theatre has been investigated by several scholars, its reconstruction is complicated and uncertain, because of the contradiction among the data and because no recent plans or section of the remains have been published yet.

After the analysis of the available documents, the plan of the cavea was drawn in AutoCad, according to the visible remains from a satellite pictures, namely from Google Earth, combined with the geophysical anomalies (fig. 67). The boundary of the orchestra is easy recognizable, as also the first *ambulacrum* of the cavea, the front of the *proscaenium* decorated with semicircular niches and few stepladders in the *ima* cavea. The last research testifies that the *ima* cavea is composed by four rows of seats, then the area between the edge of the orchestra and the first *ambulacrum* has been divided into four regular rows about 0.85 m large (which it makes sense for a row of seats). A mark in the ground more accentuate, highlighted also by the geophysical map, was interpreted as the area of the wall of the upper corridor that it has been created with the same width as the lower one and so a *media* cavea of 8 rows of seats have been formed. The *summa* cavea has been made of 20 rows of seats because some large blocks of stone in the upper part of the area were chosen as external boundary, interpreted as part of the retaining wall. Following this procedure, the diameter of the cavea results to be as long as in Belli's plan, that is about 84 m. The *analemmata* on the sides of the cavea probably formed a corner inferior than 90°, as also Barresi underlined saying that the cavea is not a perfect semicircle but it is a little bit smaller.

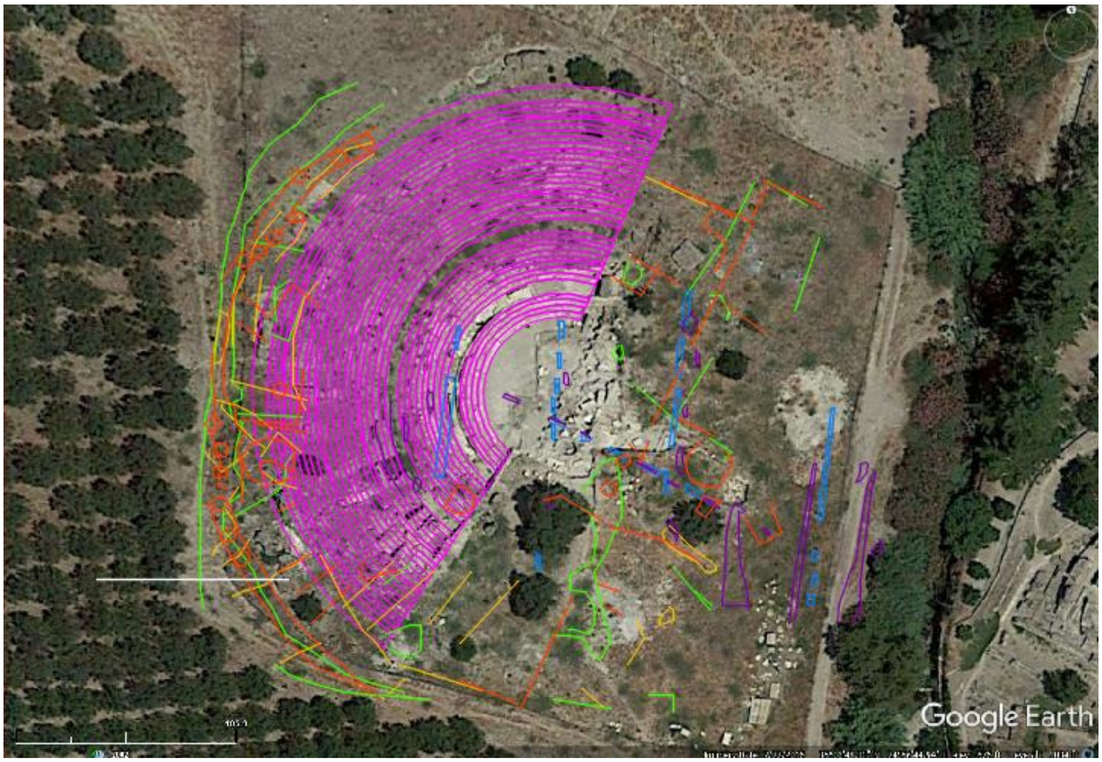


Figure 67 Satellite picture of the area occupied by the theatre at the acropolis of Gortyna, integrated with geophysical anomalies and reconstruction of the cavea.

The back wall of the scene building was identified with the long red anomaly shown in fig. 65 that runs, with some interruptions, parallel to the cavea. The arrangement of the *scaenae frons* has been partially based on Belli's description, having no other data available. Three openings have been placed on the *scaenae frons* reserved to the actors, the central one larger than the lateral ones, and it has been decorated with columns on two storeys. Belli said the storeys of the *scaenae frons* were five but no theatres are known with more than three storeys; here only two have been represented because their total height (following Vitruvius' proportions) corresponds to the height of the cavea (more than 17 m), as it is usual in Roman theatres. The columns have been made with the diameter indicated by Belli (0.5 m) and the height (5.70 m) obtained by the ratio suggested by Vitruvius (figs. 20-21)[89]. The *analemma* on the south side is pretty evident from the satellite picture and it had been recognized also by Barresi who claims that the *aditus* was probably covered by a vault, because of the fragments found on the floor. No marks of a connection wall between the cavea and the scene building are visible, and Barresi only mentions fragments of vault that fell on the floor of the *aditus* and not blocks forming the seats, so probably none row of seats was at the top of the *aditus* and the theatre did not have the classic closed structure of the Roman theatres.

5.4.1 3D visibility analysis

In order to verify the visibility from the cavea to the stage, 120 observer points were placed in the seating area and a line as a target, in the center of the stage (for a detail explanation refer to the methodology chapter, p. 56). Two different 3D models were tested: one with *aditus* allowing the entrance to the theatre from the external area (N. 1) (fig. 68), another one with the *basilicae* connected to the cavea creating a closed structure (N. 2) (fig. 69).

Analyzing the resulting lines of sight calculated for both models, we have as results that the differences are not too considerable: the model N.1 presents the 17% of not visible trajectories, the model N.2 the 18% of not visible trajectories. On the other hand, differences are noticeable if we investigate the maps of frequency of visibility of both models. The frequency of visibility map of the model N.1 presents a wide central area completely visible by all the observer points (figs. 70 and 71). Instead, the map of the model N.2 shows that only the frontal part of the central area is visible by everyone; the back is still visible from a high number of "spectators" but not by all of them (figs. 72 and 73).

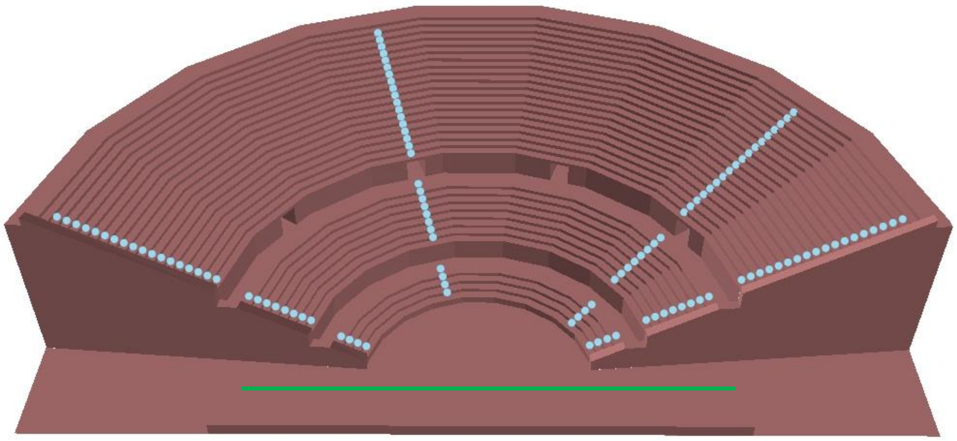


Figure 68 3D model of the theatre at the acropolis of Gortyna, with open passages on the sides, plus grid of observer points in the cavea (N.1).

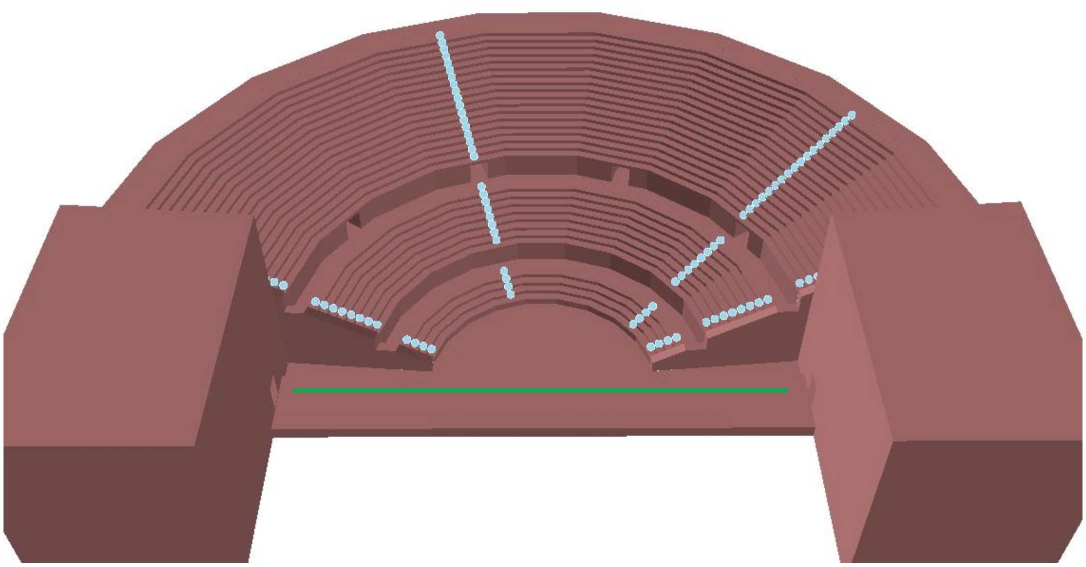


Figure 69 3D model of the theatre at the acropolis of Gortyna, with *basilicae* on the sides, plus grid of observer points in the cavea (N.2).

Comparing the results obtained from the lines of sight and from the frequency of visibility map, it is deducible that the main issues for the visibility, above all in the model N.1, are on the sides of the stage. This explains also the high visibility shown on the visibility map but with a quite high number of not visible trajectories: large part of the 17% and 18% of the two groups of not visible trajectories is attributable to the side of the stage, which is indeed very long.

Concluding, it is possible to affirm that the visibility of the two 3D reconstructions is not that different between them, but the model N.1 is definitely more suitable for a performance who used the full central space of the stage.

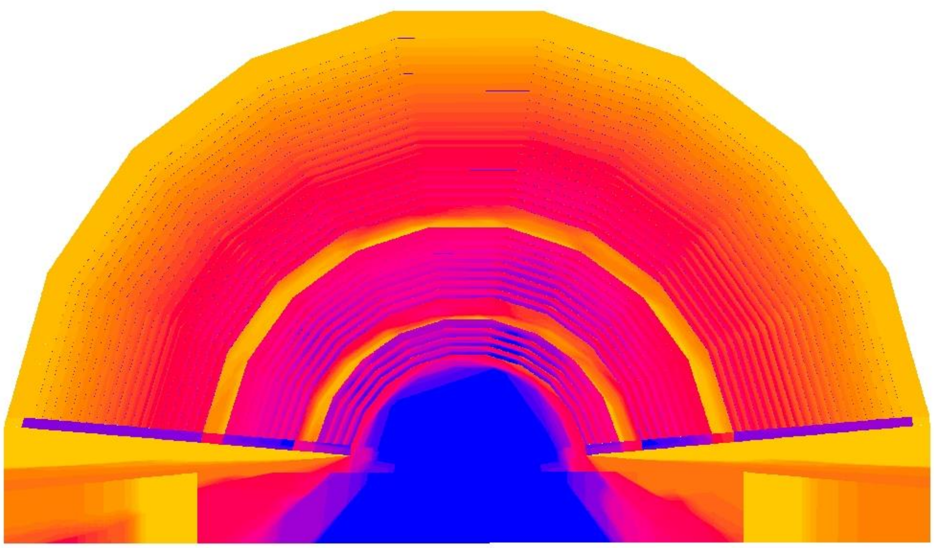


Figure 70 Map of frequency of visibility of the theatre at the acropolis of Gortyna (model N.1).The colors show the different level of visibility for the observer points, as it is explained in the correspondent graph (fig. 70).

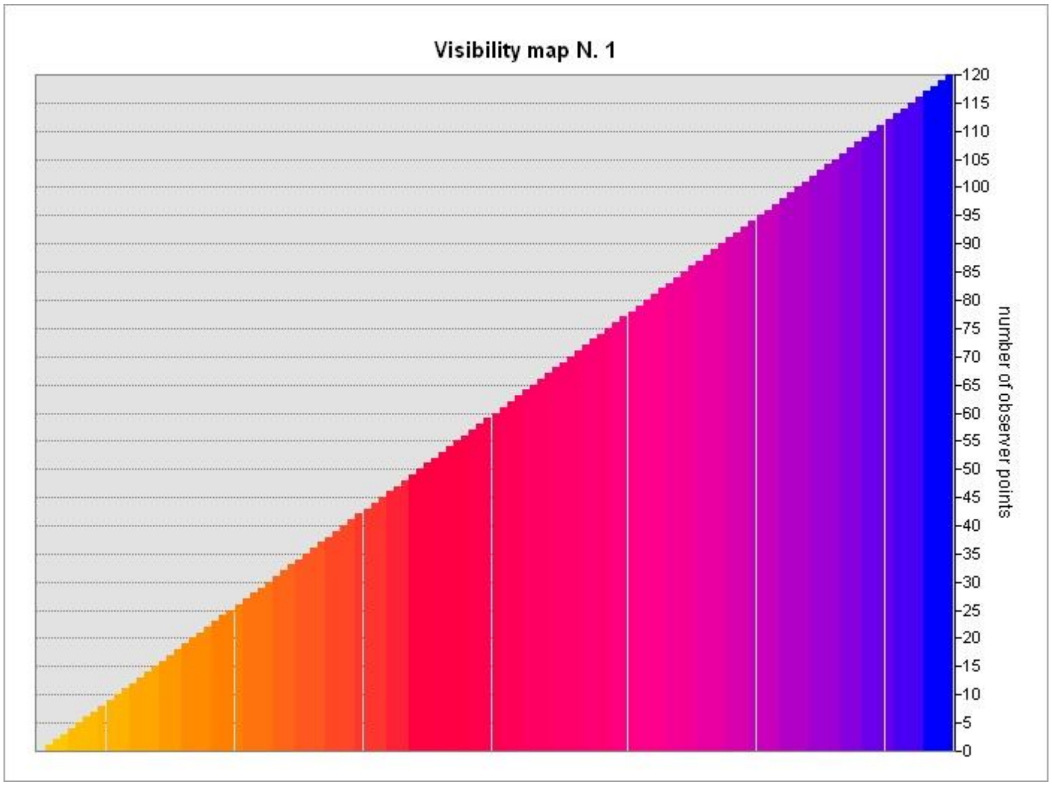


Figure 71 Graph of visibility analysis (model N.1). The color scale is from yellow to blue. The yellow color means that those areas are visible by noneof the observer points; the blue colour indicates the area visible by all 120 observer points.

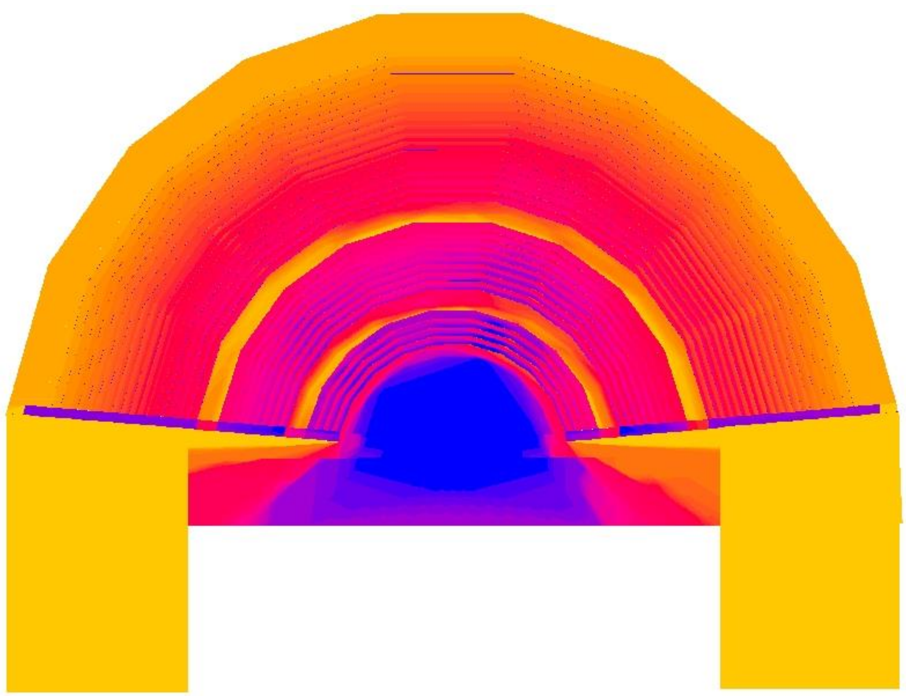


Figure 72 Map of frequency of visibility of the theatre at the acropolis of Gortyna (model N.2). The colors show the different level of visibility for the observer points, as it is explained in the correspondent graph (fig. 72)

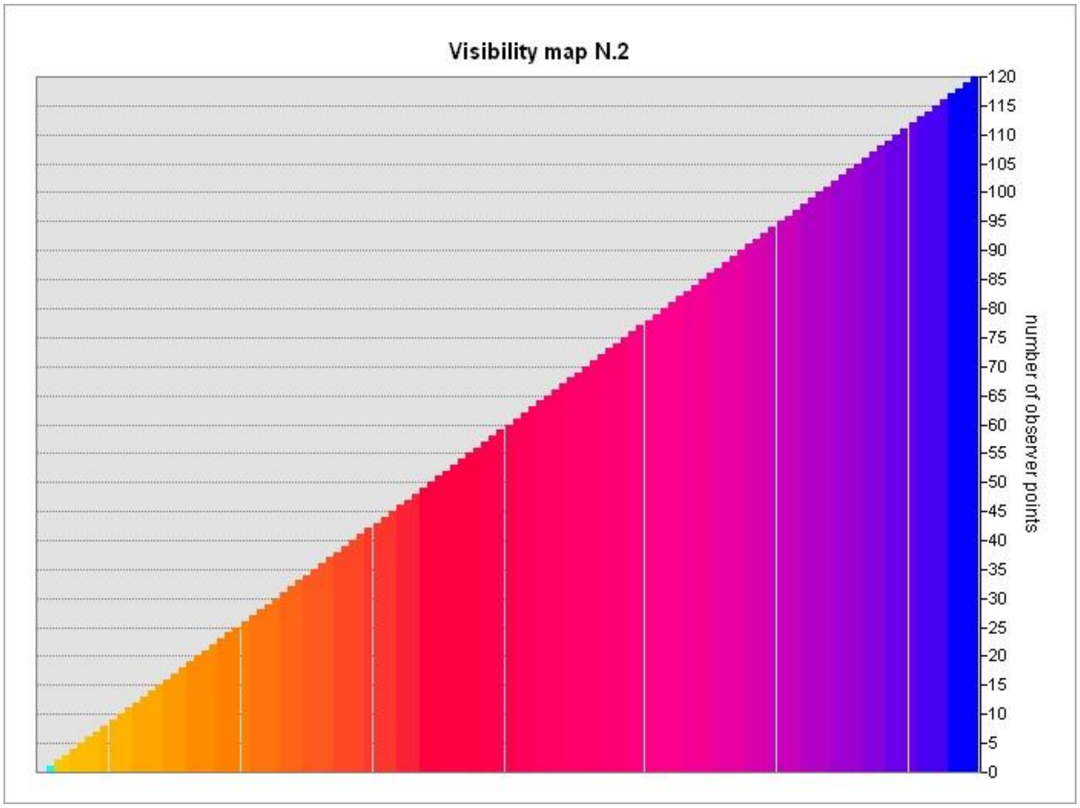


Figure 73 Graph of visibility analysis (model N.2). The yellow color means that those areas are visible by noneof the observer points; the blue colour indicates the area visible by all 120 observer points.

5.4.2 Virtual acoustics analysis

Because of the uncertainty of the data available and consequently the doubts about the original structure of the theatre at the acropolis of Gortyna, three reconstructions have been elaborated in order to verify which one may be the most reliable one, according to the quality of the acoustics.

Thirty receivers have been placed on the cavea, one every two or three rows of seats, and one source more or less at the center of the stage (for a detailed explanation refer to the methodology chapter, p. 65) (figs. 74 and 75).

The materials applied to the models, as suggested by Barresi[54], Kanta *et al.*[114], Taramelli[39] and Belli[26], are:

1. Bricks: *analemmata*, *diazoma*'s wall, *postscaenium*

2. Marble: *scaenae frons*, portico, orchestra
3. Porous stone: cavea, portico's floor, *diazoma's* floor, stage.
4. Wood: *scaenae frons'* doors.
5. Audience: seating area

The model N.1 consists of the reconstruction that has been described above: cavea divided into three sectors, little less than a semicircle, with *scaenae frons* on two storeys. The model N.2 is the same as the N.1 but with the addition of the portico in *summa* cavea. The model N.3 represents the theatre closed, with two *basilicae* at the sides of the stage that are connected to the *analemmata*, plus portico in *summa* cavea. The latter is based on the reconstruction proposed by the archaeologists at the presentation Έργο Κρήτης, in November 2016 in Rethymno, Crete.

The results are shown in the graphs 12-17. All five parameters (reverberation time, early decay time, clarity, definition and speech transmission index) demonstrate that the model N.1 is the one having the best acoustics for speech performance: reverberation time around 1 second, difference between early decay time and reverberation time within a range of 0.2-0.4 seconds, clarity above 3 dB, definition above 0.50 and speech transmission index over 0.60. To note, instead, that the other two reconstructions not only have a worse acoustics than the N.1, but some values are not even within the range of acceptable values for the comprehension of a speech (see C80 for model N.2 and model N.3, and D50 for model N.3) nor of a music performance. To be exact, the percentage of not acceptable values for a good acoustics, calculated for each receivers, are the followings:

Model N.2: C80 23%, D50 25%

Model N.3: C80 37%, D50 31%, and the 43% of the results for the STI are under 0.60 (included between 0.47 and 0.59).

Therefore, it is possible to affirm that the model N.1 may be the only one that allows a complete understanding of speech performance from all the seats, while the model N.2 and the model N.3 might not be suitable neither for spoken nor for music performances.

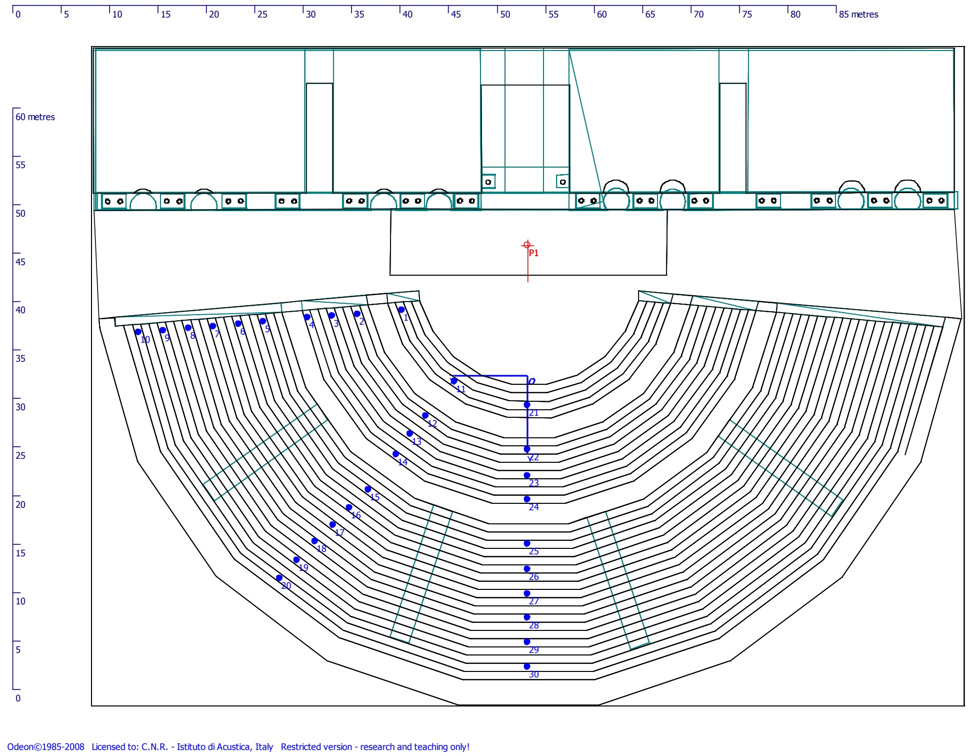


Figure 74 Plan of the model N.1 of the theatre at acropolis of Gortyna, plus receivers and source.

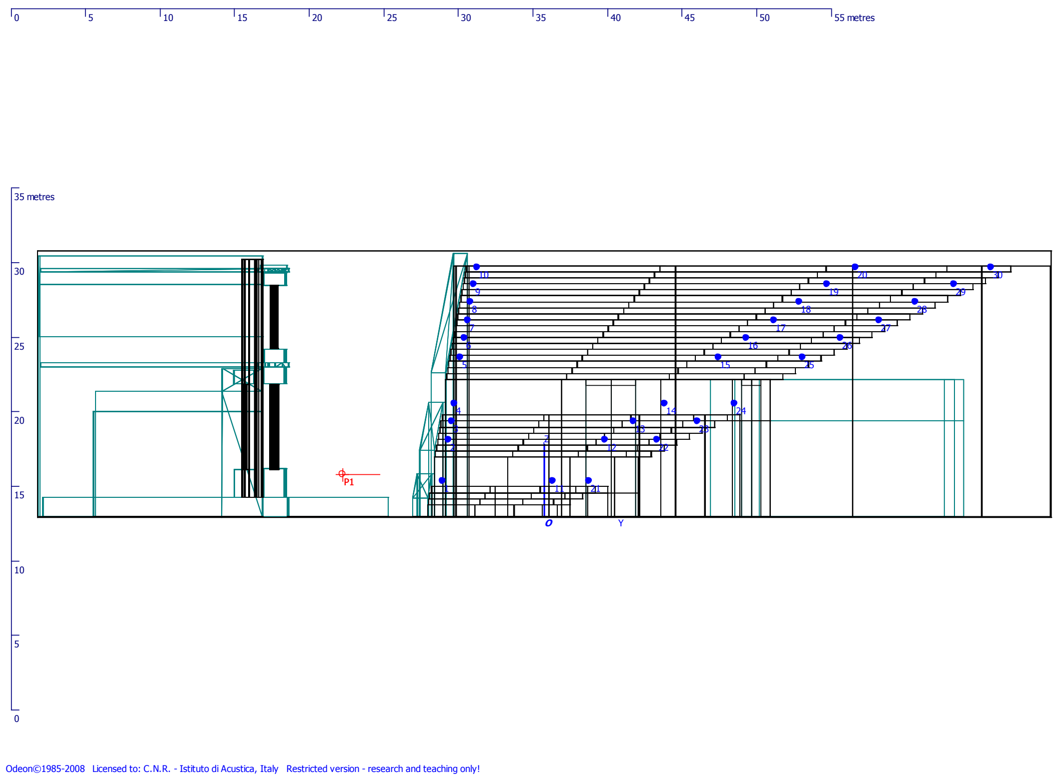
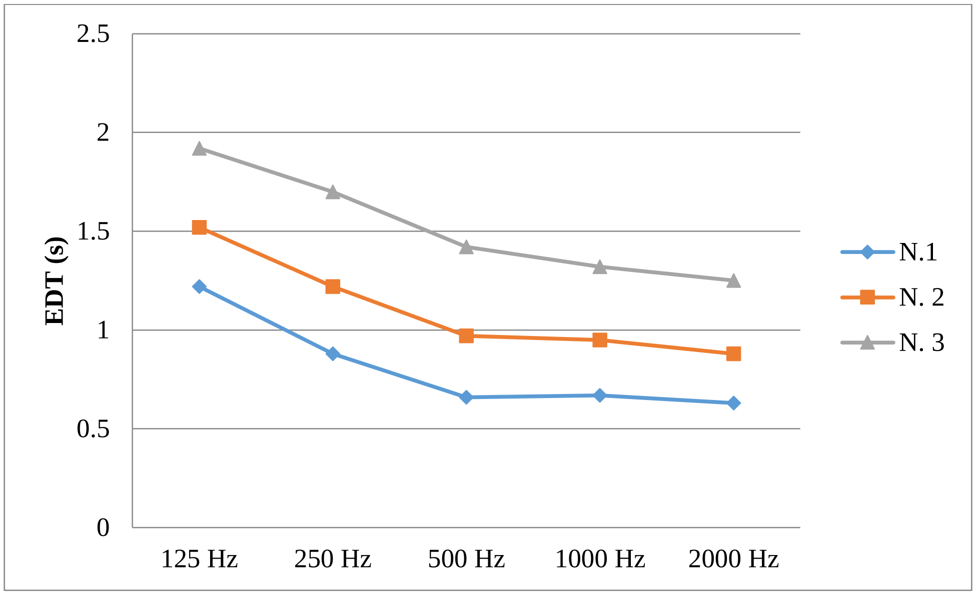
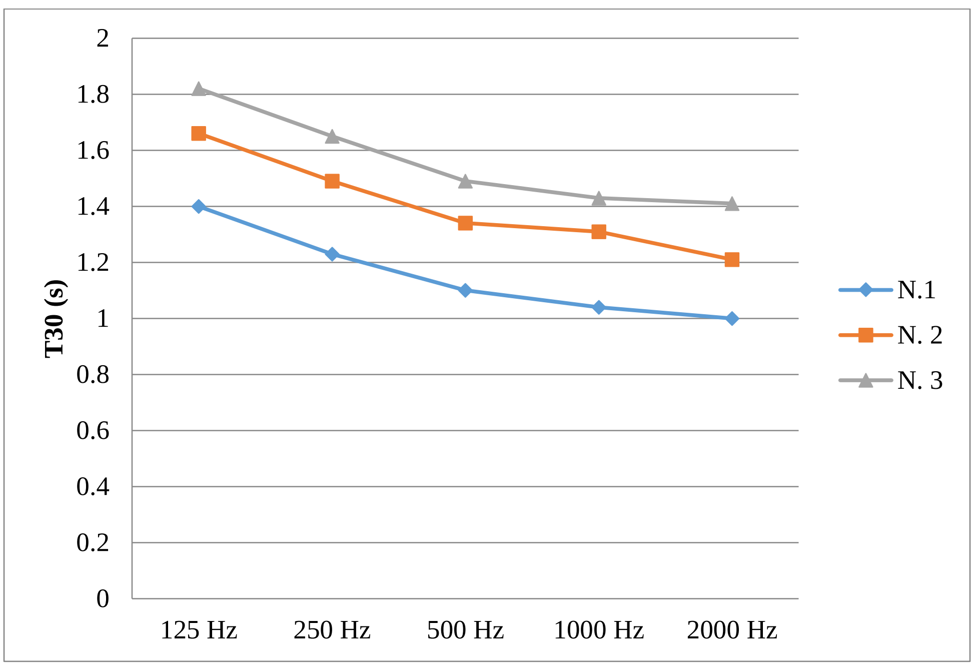


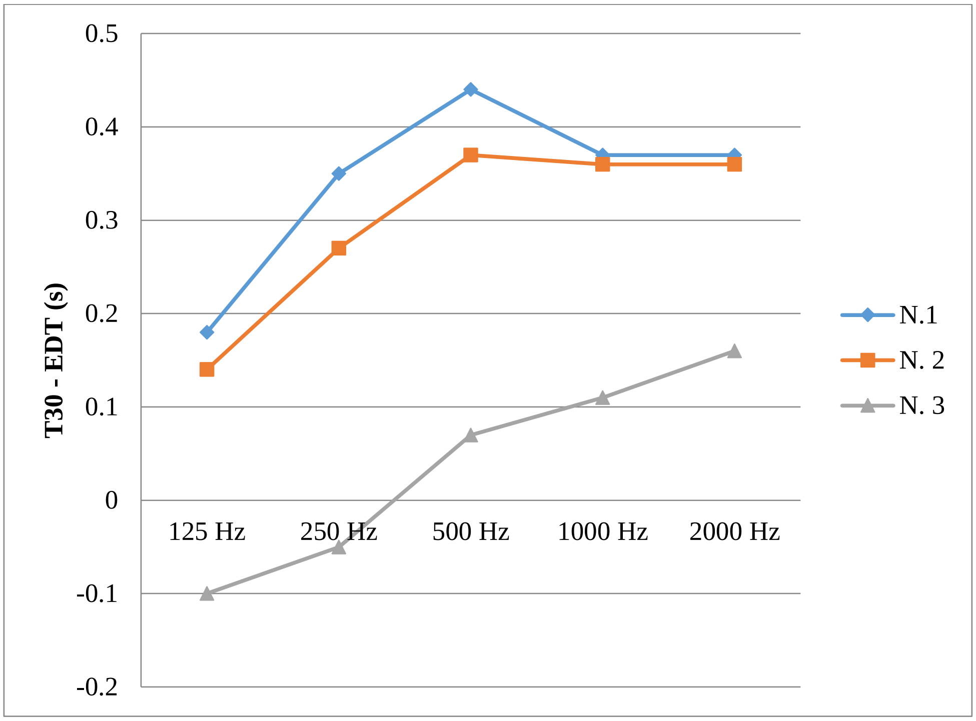
Figure 75 Section of the model N.1 of the theatre at acropolis of Gortyna plus receivers and source.



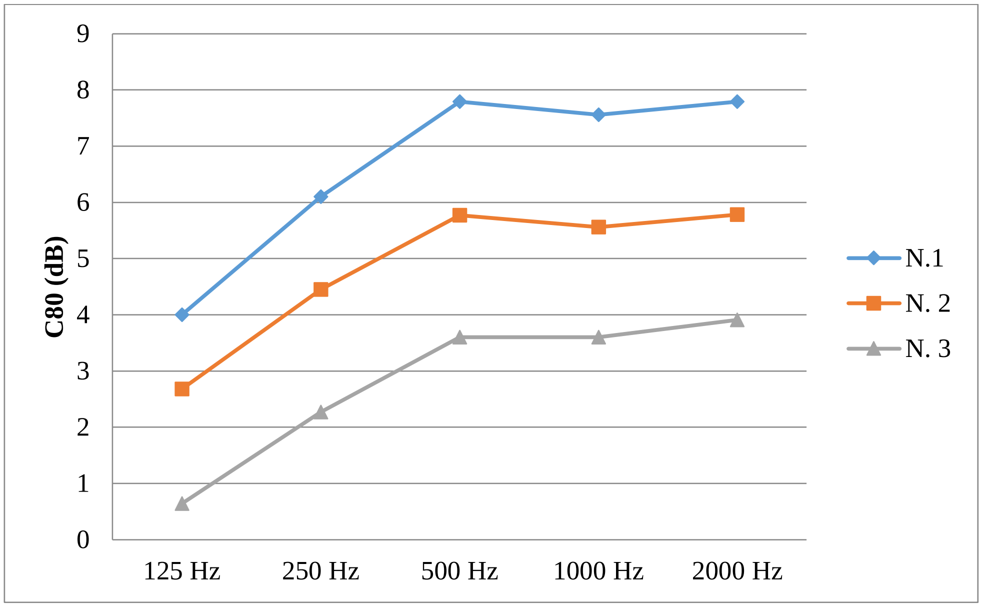
Graph 12 Average values of early decay time for all the receivers, at each frequency.



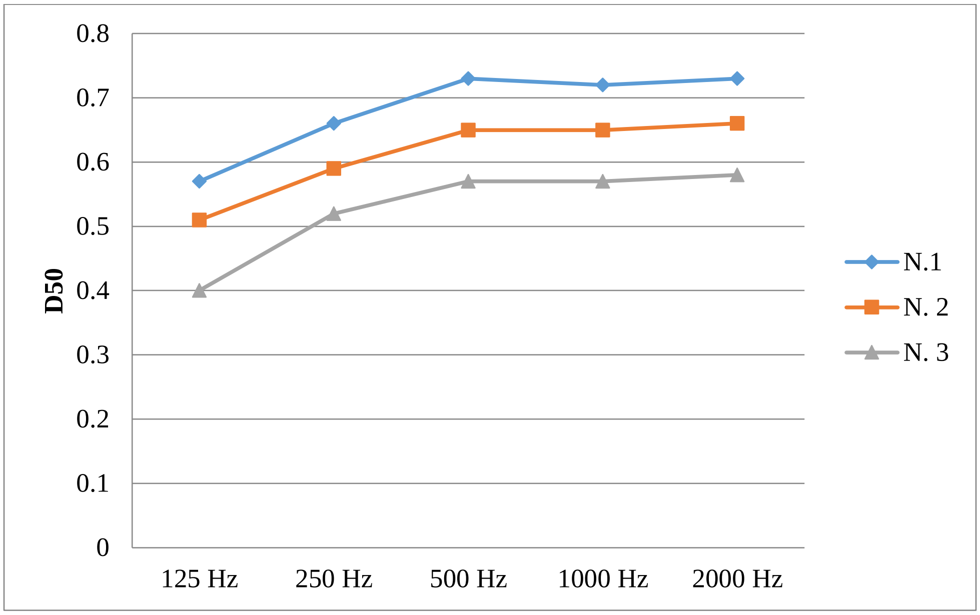
Graph 13 Average values of reverberation time for all the receivers, at each frequency.



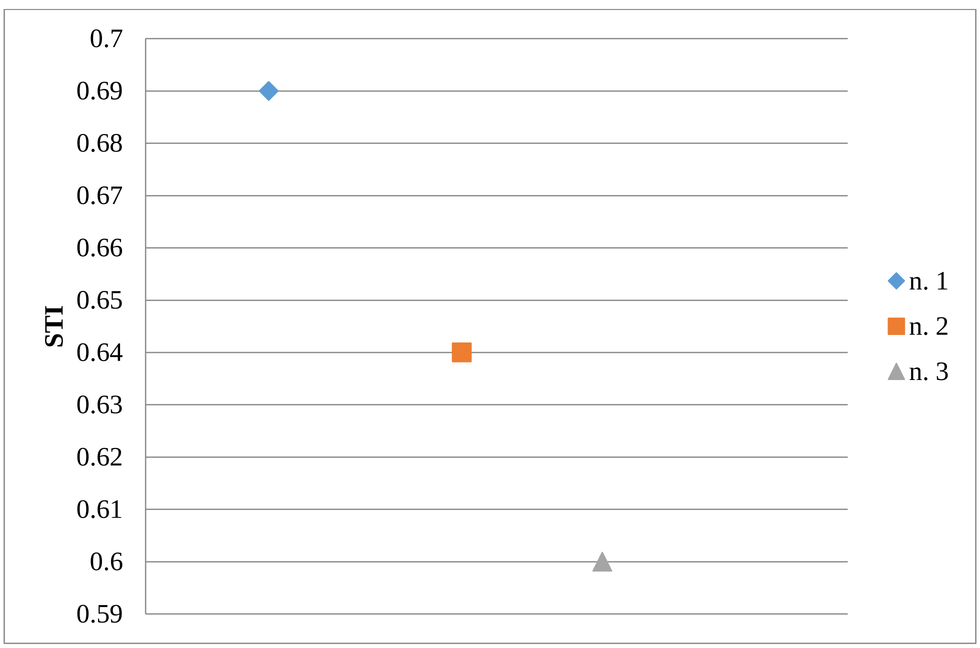
Graph 14 Average values of the difference between T30 and EDT, at each frequency.



Graph 15 Average values of clarity for all the receivers, at each frequency.



Graph 16 Average values of definition for all the receivers, at each frequency.



Graph 17 Values of speech transmission index for all the receivers.

5.4.3 Results and comments

3D visibility analysis suggests that the most reliable reconstruction should be the one without *basilicae* attached to the cavea. Virtual acoustics analysis confirmed this hypothesis and also indicates that there should not be a portico in *summa* cavea.
The cavea of the theatre at the acropolis of Gortyna, which diameter measures about 89 m, results to be divided into three sectors by two *ambulacra*, and having a shape little inferior than a semicircle, according to aerial pictures and recent archaeological excavations). The *scaenae frons* had probably two storeys (according to the Vitruvian rules) decorated with columns and three openings for the actors, plus a *postscaenium* (fig. 76-79).

The *scaenae frons* and the *analemmata* look to be too distant between them (about 10 m) to be connected by a vault covering the *parodoi* as proposed by Barresi. Furthermore, according to the geophysical anomalies, the *summa* cavea seems to be composed of 20 rows of seats and not five as supposed by Barresi.

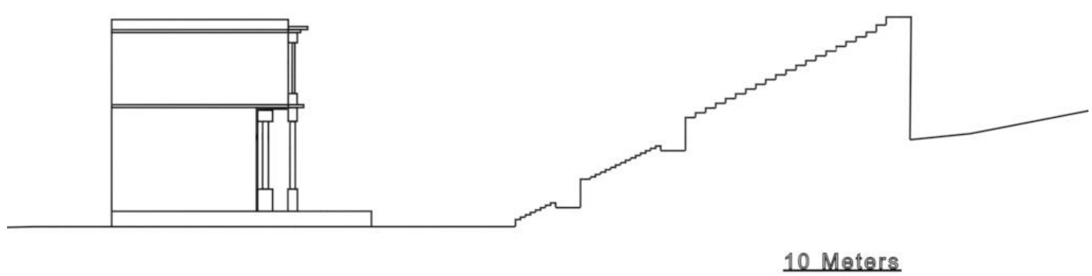


Figure 76 Hypothetical reconstructive section of the theatre at acropolis of Gortyna.

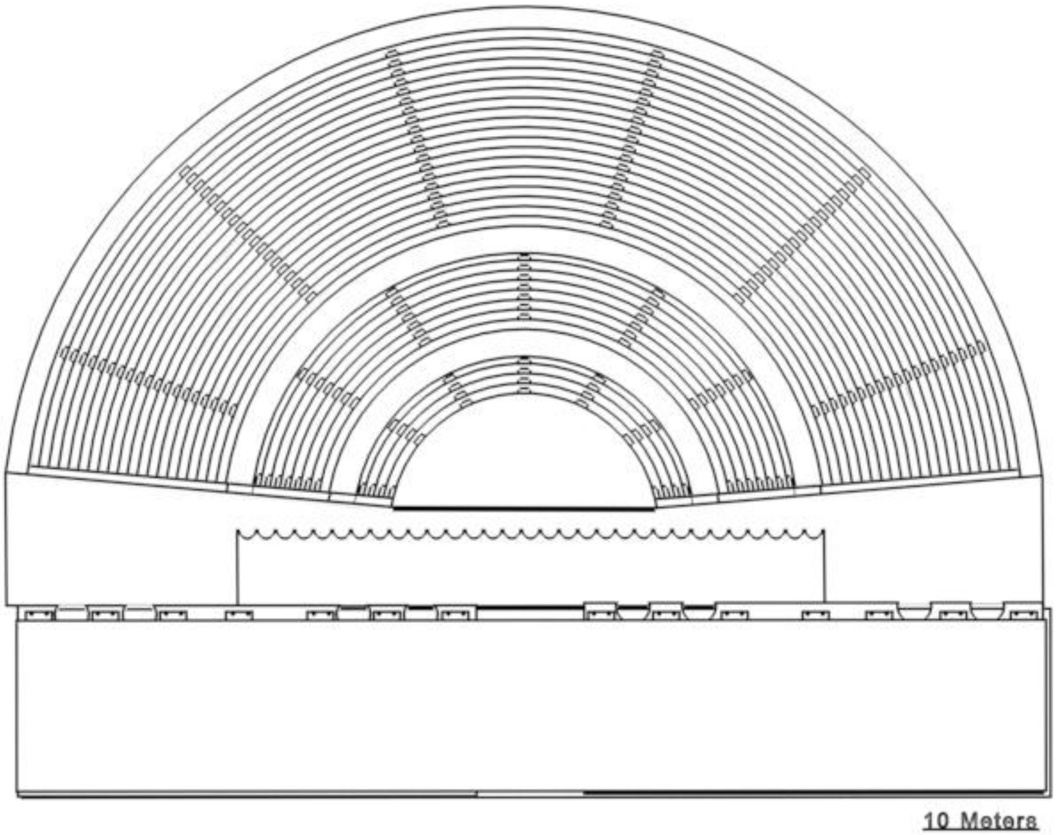


Figure 77 Hypothetical reconstructive plan of the theatre at Acropolis of Gortyna.

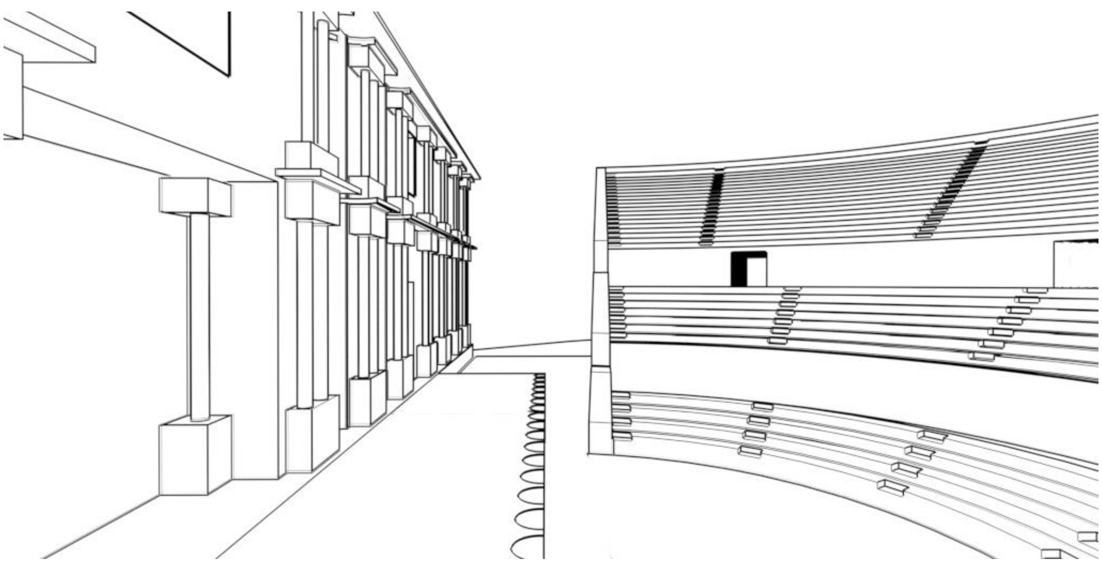


Figure 78 Hypothetical reconstructive drawing of the theatre at acropolis of Gortyna.

Figure 79 Rendering of the 3D model of the theatre of the acropolis at Gortyna

There are not numerous theatres with oblique *aditus* leading to the orchestra, as it looks to be in the theatre at the acropolis of Gortyna, but there are a couple of interesting comparisons.

The theatre of Verona in Italy has taper *aditus* as they approach the orchestra. The *analemmata* are connected to the *scaenae frons* through an arch for each side, and Giovanna Tosi [115] sustained that they were covered with barrel vaults, sustaining the external seats and the *tribunalia* (fig. 80). This theatre, as the theatre at the acropolis of Gortyna, has part of the back side of the cavea lying against the hill and the rest is sustained by the *analemma* and radial walls. Also the location of the two theatres is similar, because both had a river running at the back of the scene building: in Gortyna there was the river Leteus, in Verona there is the river Adige. The theatre of Verona is dated to the first half of the I century AD.

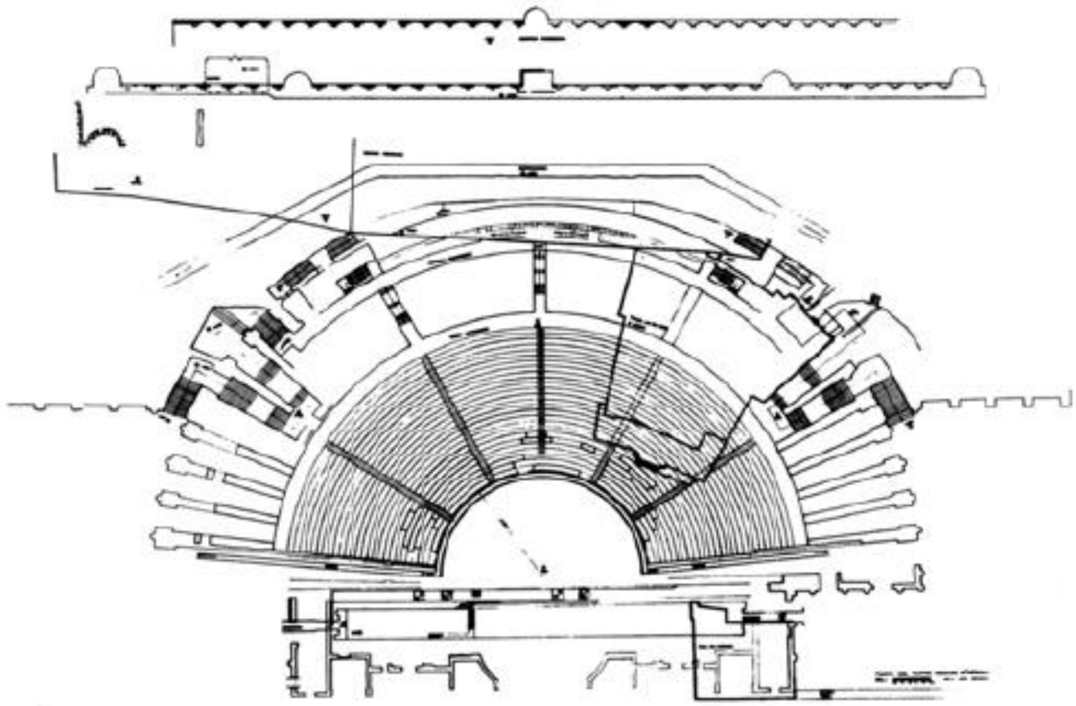


Figure 80 Plan of the Roman theatre at Verona (from Bolla, 2010).

The theatre of Tipasa in Algeria has a similar structure as the one of Verona: oblique *aditus* and taper towards the orchestra covered with barrel vaults, and basilicas at the sides of the scene building (fig. 81). There are no traces of *tribunalia* over the barrel vault of the *aditus*, but Edmond Frézouls[116] stated that there must be some platforms there. The theatre of Tipasa is dated around 200 AD.

A second theatre in Italy that might be compared with the one at the acropolis of Gortyna, is the theatre of Aquinum, dated to the midst of the I century BC[14]. Unfortunately we have some data only about the cavea, then the oblique *analemmata* are evident but we do not know about the presence of *aditus* and their possible structure (fig. 82).

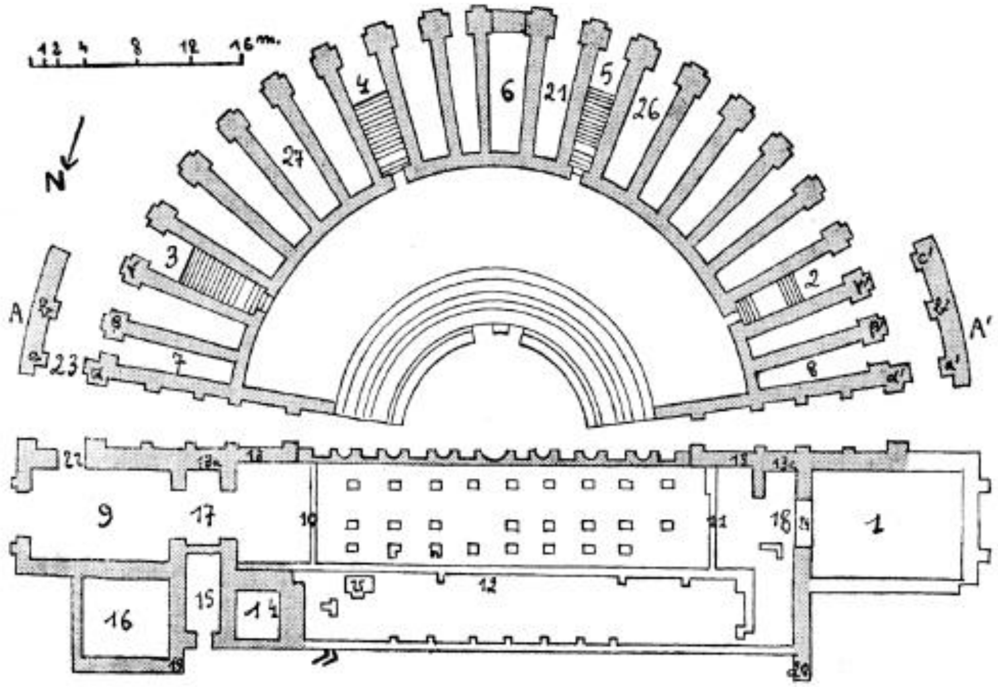


Figure 81 Plan of the theatre of Tipasa in Algeria (from Frézouls, 1952).

Figure 82 Plan of the cavea of the theatre of Aquinum in Italy (from Ciancio Rossetti-Pisani Sartorio, 1994).

5.5 Theatre of the Pythion at Gortyna

The "small" Roman theatre of Gortyna, as defined by Belli, is located at south-west side of the temple of Apollo Pythios.

It has been documented by several scholars during the centuries and it has been widely investigated through archaeological excavations by the Italian School of Archaeology in Athens and University of Padua (Italy) since 2001, for about ten years.

Onorio Belli[26] was the first one to provide a plan (fig. 83) and a very brief description of this monument. He saw a theatre of only one *maeniana*, Doric columns of black and white marble decorating the *scaenae frons*, and a large rectangular portico at the back of the *postscaenium.* In the plan of this theatre too, Belli represents the unique characteristics of a very long distance between the cavea and the scene (around 13 meters).

In his manuscript about the Roman theatres in Crete, inspired on Belli's documentation, Edward Falkener[32] reproduces a plan of the "small" theatre very similar to Belli's plan (fig. 84). Only some measurements are different and Falkener also added a few rows of seats to the cavea.

This theatre, as the others in Gortyna, was part of the project of investigation of the *Missione Italiana di Archeologia a Creta*, since the end of XIX century.

The archaeologist Antonio Taramelli[39] made a careful analysis of the site at the very end of the XIX century, reporting a detailed description of the remains, adding a plan and a section of the cavea[54](figs. 85 and 86). Taramelli identified the most used materials for the construction of the theatre: local porous stone (largely pillaged by the inhabitants, still at Taramelli's time, in order to obtain building material) and bricks. He saw the arches opened in the outer wall of the cavea, connected to the internal corridors which gave access to the orchestra, together with buttresses at their sides, in order to reinforce the wall. Taramelli was the first one to recognize that the

[54] Taramelli said the area of the scene and of the building behind the scene were covered by a cornfield, so it was not possible for him to take any measurement.

cavea was divided by an *ambulacrum* into two sections and to affirm that Belli's plan was incorrect in some parts[55].

In 1936 another inspection and a little archaeological excavation was carried out by Antonio Maria Colini[45]. In this case, he was able to identify the *scaenae frons* for a length of 23.80 m, and up to 5 m of its height. He assimilated the structure of the theatre of the Pythion with the *odeum* of the agora, recognizing a dependence from the local constructive tradition.

In 1982, Ian Sanders[16] described it as the best preserved Roman theatre in Crete. In his report, he confirmed what Taramelli said about the area of the cavea. Furthermore, he added some information about the scene building: he measured a *scaenae frons* 50 meters long, decorated with four exedras and free standing columns at the sides of the central door. He also confirmed part of Belli's plan because he stated that in the central hall of the *postscaenium* there were four columns made out of granite[56].

Finally, at the beginning of the XXI century, extensive archaeological excavations of the area, together with geophysical prospection and aerial pictures[55], have been carried out by the Italian School of Archaeology in Athens and University of Padua, since 2001 till 2013. They have been able to reconstruct the history of the theatre and also to discern two different constructive phases: a first one dated to the II century and a second one dated to the end of the II century-beginning of the III century [57].

[55] He suggested to undertake archaeological excavations above all in the area of the scene building and of the portico, in order to verify Belli's plan.

[56] It is not clear if Sanders made this affirmation on the base of Belli's plan or if he really saw the columns of the *postscaenium*.

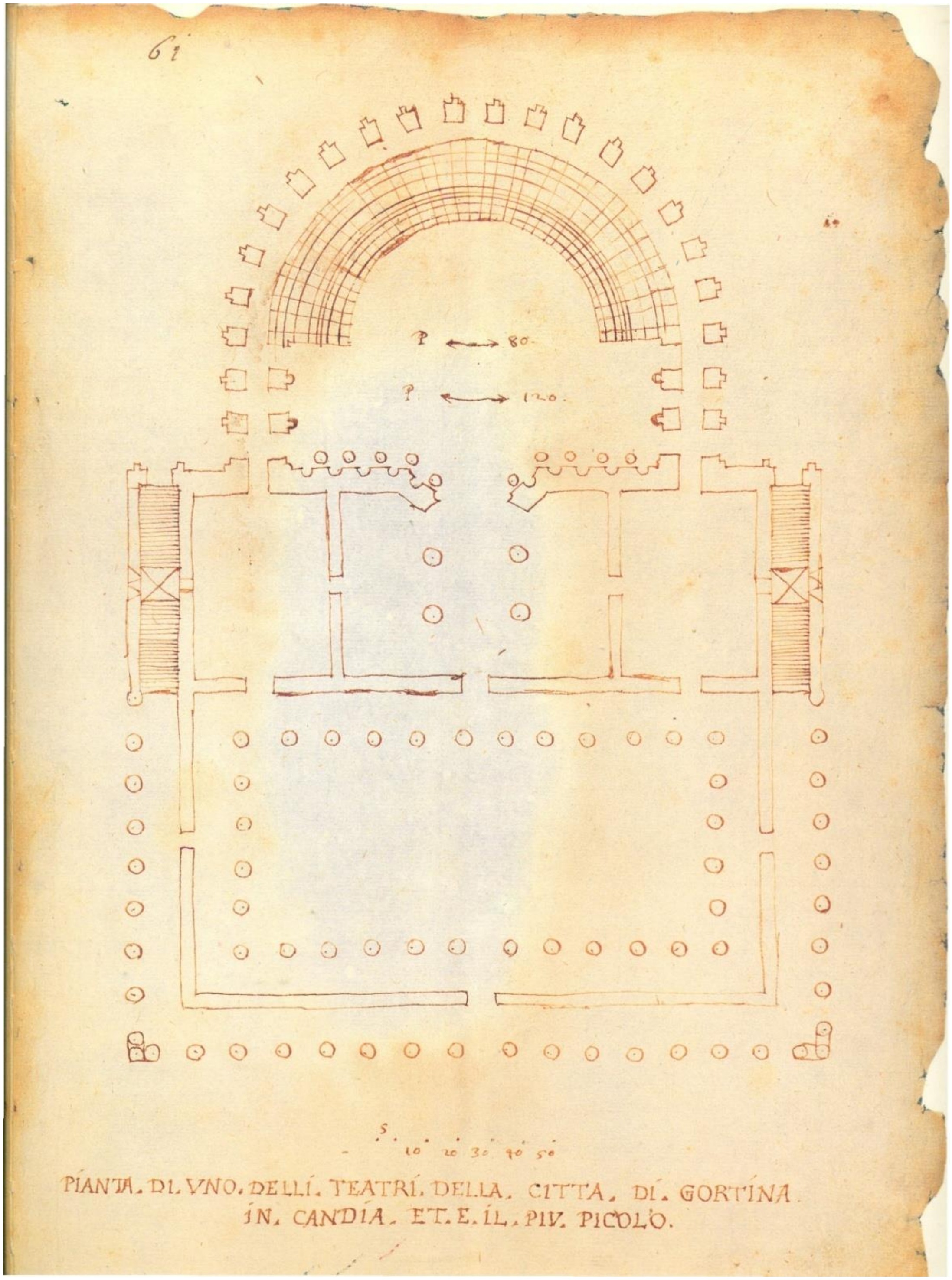


Figure 83 Plan of the theatre of the Pythion at Gortyna made by Belli (Beschi, 1999).

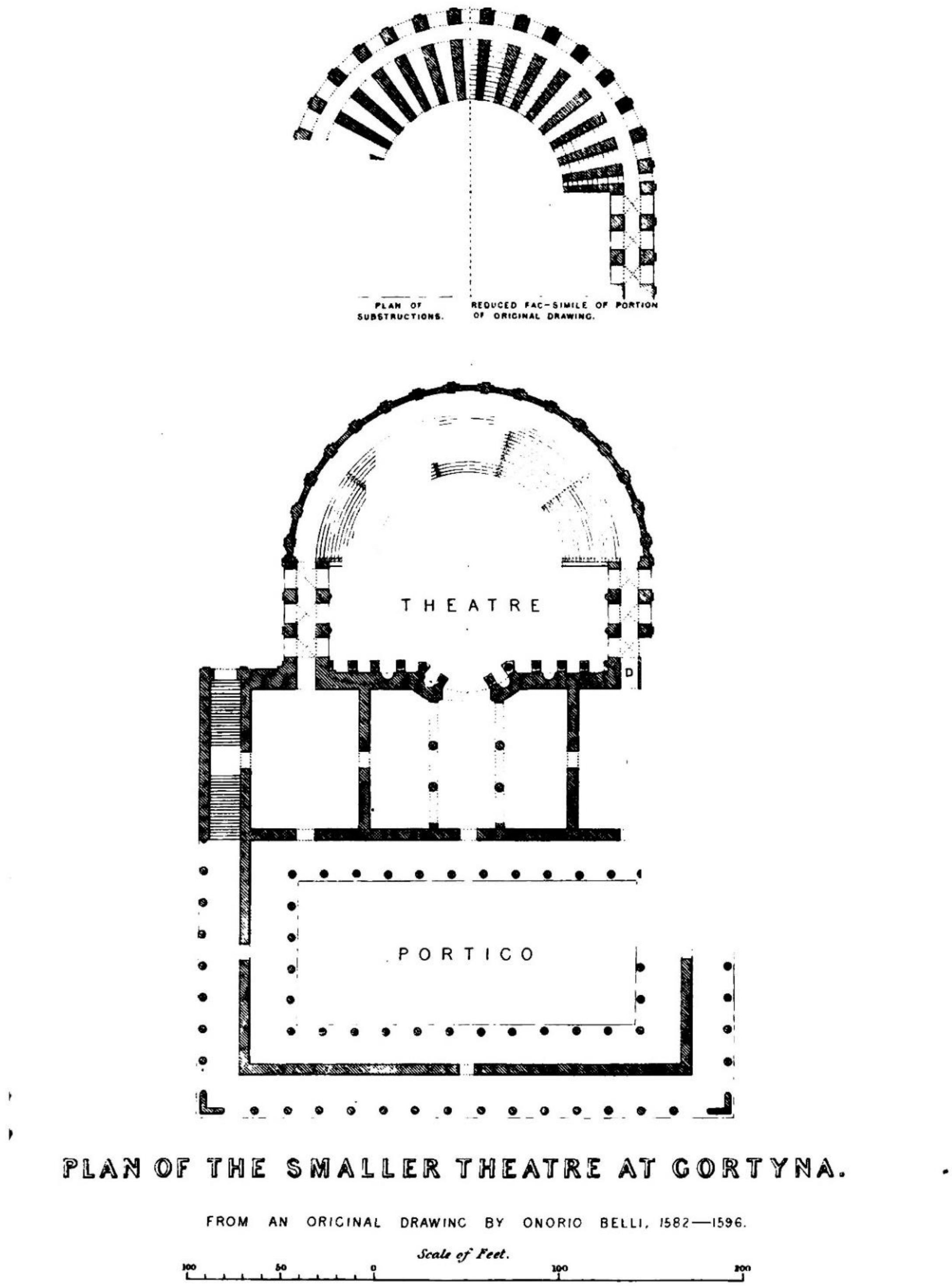


Figure 84 Plan of the theatre of the Pythion at Gortyna made by Falkener (1854).

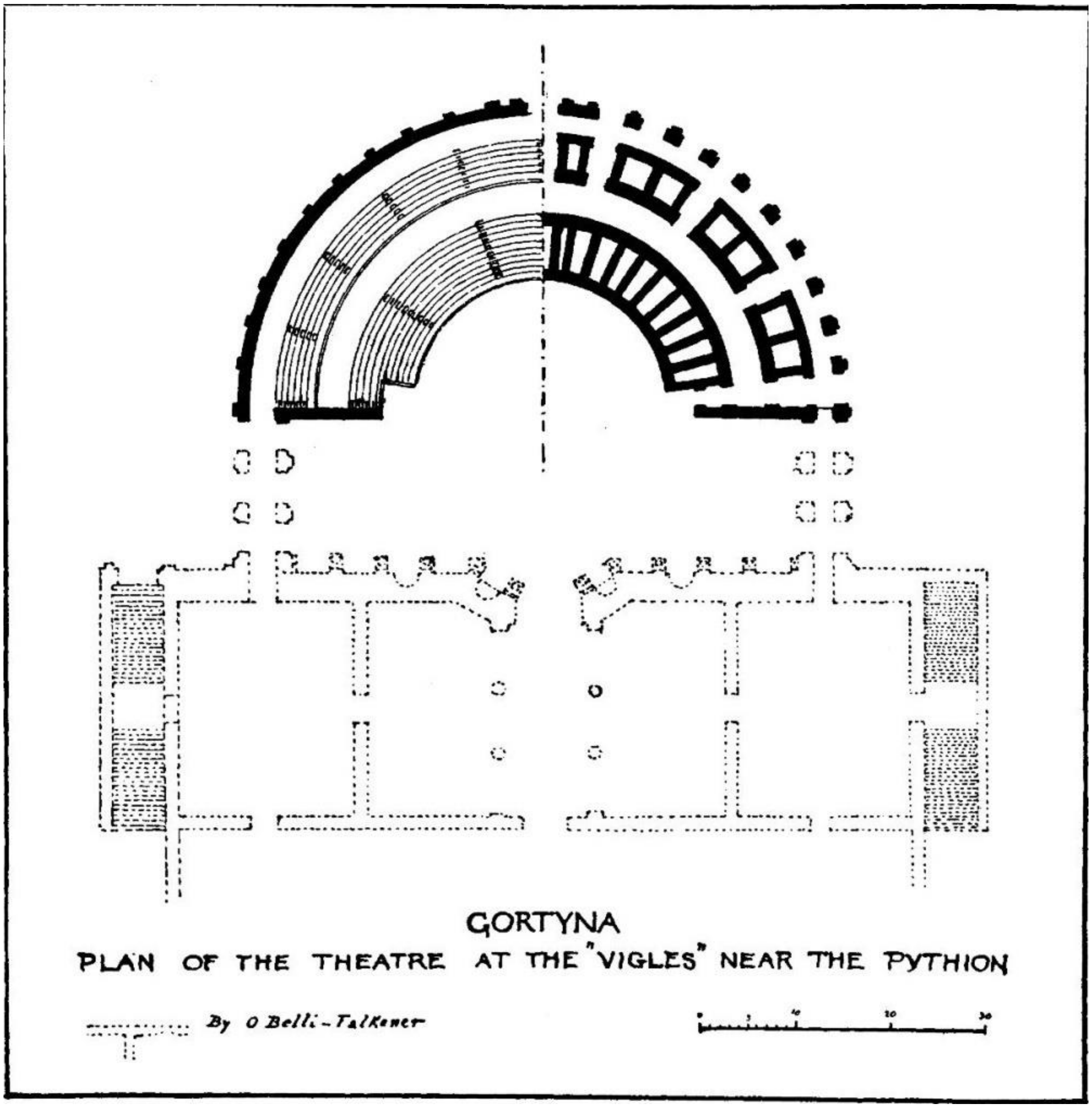


Figure 85 Plan of the theatre of the Pythion at Gortyna made by Taramelli (1902).

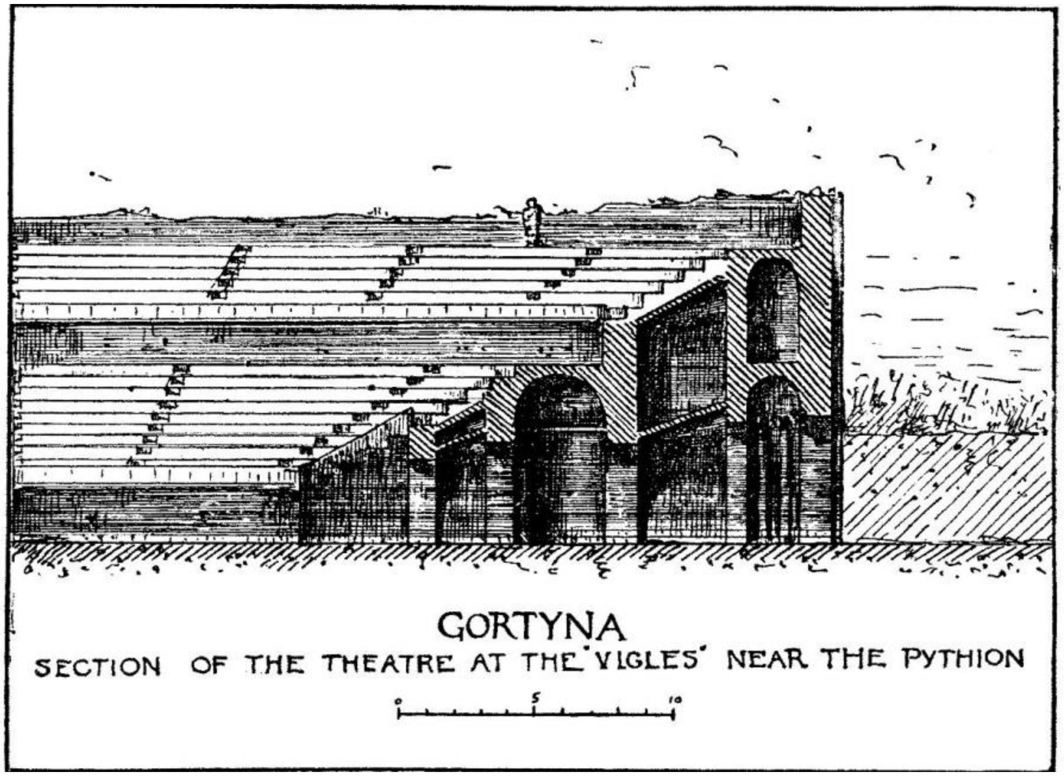


Figure 86 Section of the cavea of the theatre of Pythion at Gortyna made by Taramelli (1902).

The first campaigns of archaeological excavations (2003-2004) were focused in several areas in the site of the theatre. In the area occupied by the scene building the archaeological excavations enabled the identification of the oriental corridor of access to the theatre (which was connected also with the vaulted passage under the *ima* cavea), the external wall of the *scaenae frons*, and at least three doors: two of them connecting the scene building with the stage and with the external area, and the third one giving access to the corridor and the internal area of the theatre. The floor of the stage, composed by slabs of limestone, has been identified as well. In the area of the cavea, the archaeologists excavated a very large area and removed several layers of fillings produced by anthropogenic activities after the abandonment of the monument, and they have discovered some of the sustaining walls under the seating area, the central *ambulacrum* of the cavea and nine rows of seats, made out of the local white limestone, belonging to the *ima* cavea[55].

During the excavations in 2005, one more row of seat has been found, together with a small part of the orchestra paved with tiles of marble, and more rooms under the cavea (fig. 87)[117]. The new discoveries enabled the archaeologists to partially reconstruct the theatre and to hypothesize its full structure (figs. 88-89).

Figure 87 Part of the cavea and of one of the *vomitoria* (from the report of the archaeological mission 2005).

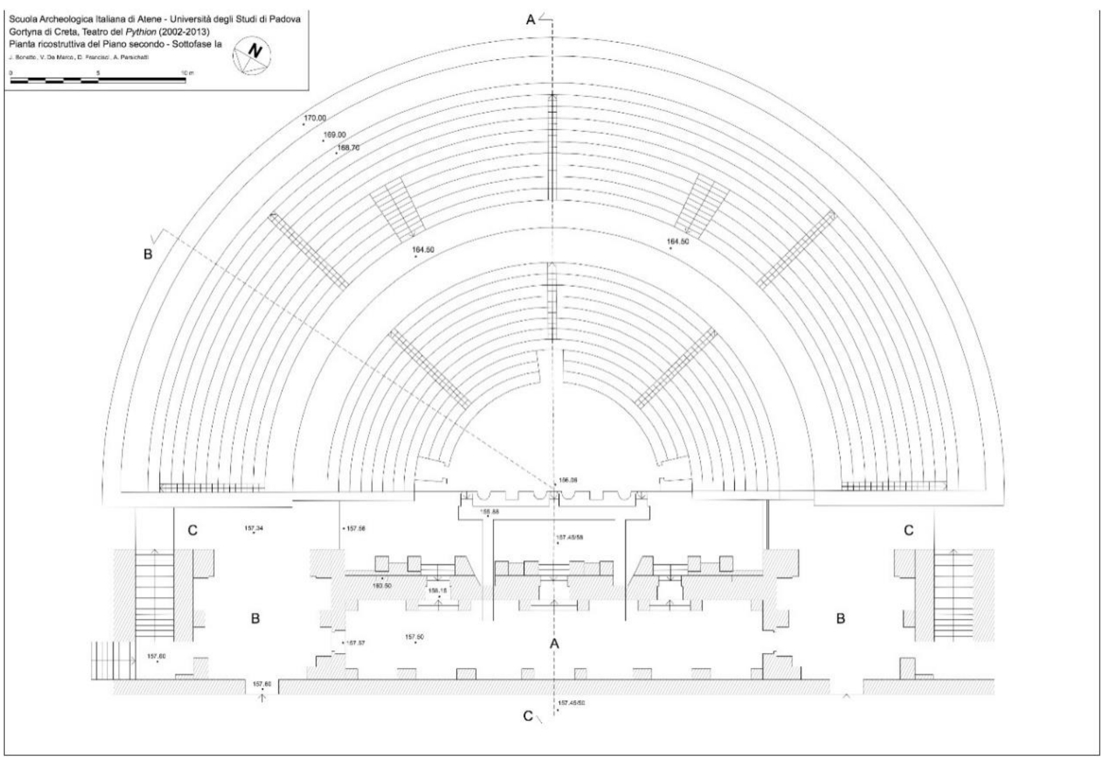


Figure 88 Plan of the theatre of the Pythion at Gortyna (from Bonetto et al., in press).

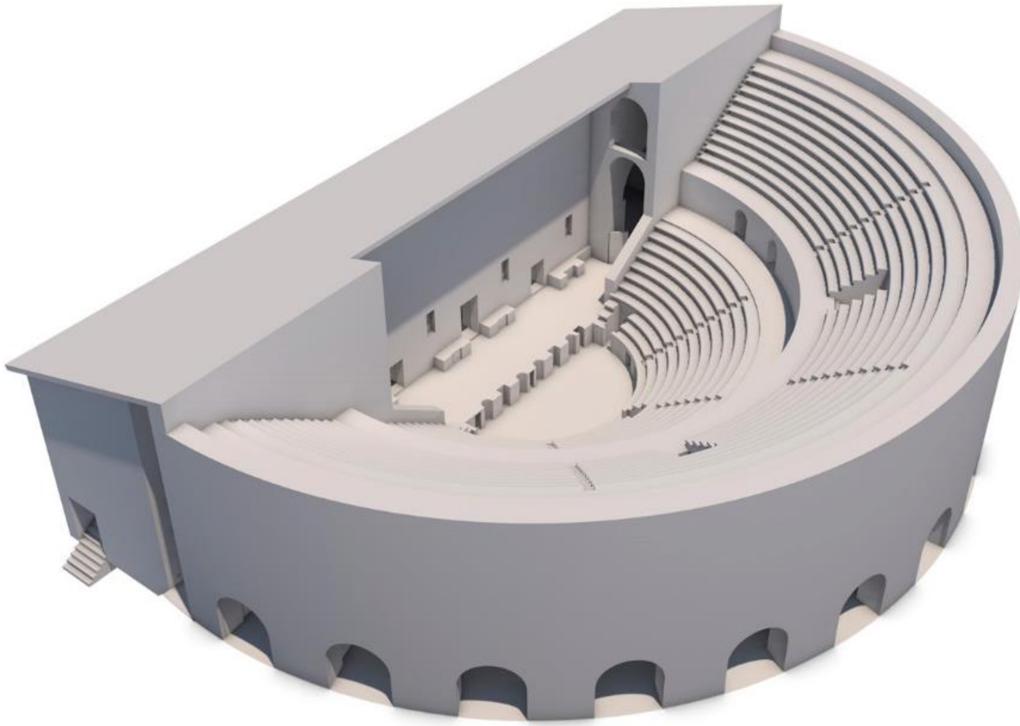


Figure 89 3D reconstruction of the theatre of the Pythion at Gortyna by A. Ciancio Rossetto (Bonetto et al., in press).

In the following campaigns, till 2013, the archaeologists collected more data about the architecture of the theatre, and about its history, when it was destroyed and how the area was reused after. In particular in 2010, they found out that the scene building had two floors covered with vaults and paved with lime mortar with crushed pottery[56]. Obviously, during these years, fragments of architectural decorations and fragments of pottery have been found as well and pottery in particular was useful to date several events connected to the theatre. In addition, more recent archaeological excavations enable the archaeologists to reformulate their hypothesis about the structure of the theatre and they identified two different phases. The main differences between the two is the presence of niches in the wall at the base of the *ima* cavea and the different material of this part and of the orchestra[57].

Summarizing, the University of Padua together with the Italian School of Archaeology in Athens reconstructed a theatre with a cavea divided into two sectors by a corridor, both *ima* and *summa* cavea have 12 rows of seats, there are three *vomitoria* for the access to the cavea and others for the access to the *ambulacrum*, the *scaenae frons* is rectilinear with three openings reserved to the actors, at the sides of the stage there are the *aditus* that through a door lead outside the theatre and to the rooms under the cavea[118].

<u>5.5.1 3D visibility analysis</u>

In order to verify the visibility of the theatre of the Pythion in Gortyna, a grid of 88 observer points, distributed on four lines, was placed in the cavea of the 3D model designed by the University of Padua (fig. 90) (for detailed explanation refers to the methodological chapter, p. 56).
The resulting lines of sight between the grid and the target line on the stage (representing the position of the actors), demonstrate that 81% of the trajectories between "spectators" and "actors" are visible, while 19 % are not visible. Certainly, the main issues are for those spectators seating at the sides of the cavea, because the high *analemmata* obstacle the visibility, as demonstrated by the obstruction points (fig. 91).

From the frequency of visibility map it is also clear that only the very frontal part of the stage is visible by all the spectators (figs. 92 and 93). The central part of the stage looks visible only to a range of 74-77 observer points that is at least 11 spectators do not even see the central part of the stage, being completely excluded by the possibility to watch the performance.
Also if the percentage of not visible trajectories and areas is not that high, we have to notice that it is significant. Being sure about the location and the dimension of the stage, I may have some doubts about the position and the height of the side walls of the cavea that obstacle the visibility of some of the spectators. Certainly it is also to be considered that it might be possible that not all the seats were suitable to watch the performance and that people might sit even farer than a meter from the retaining walls. However a second model has been created with obliquus *analemmata* that follow the orientation of the terminal part of the terraces: the height of the wall respect the beginning of the first seat is 0.45 m and the height respect the end of the

last seat is 0.85 m, so that the spectators are protected by a wall with an average height of 0.65 m.

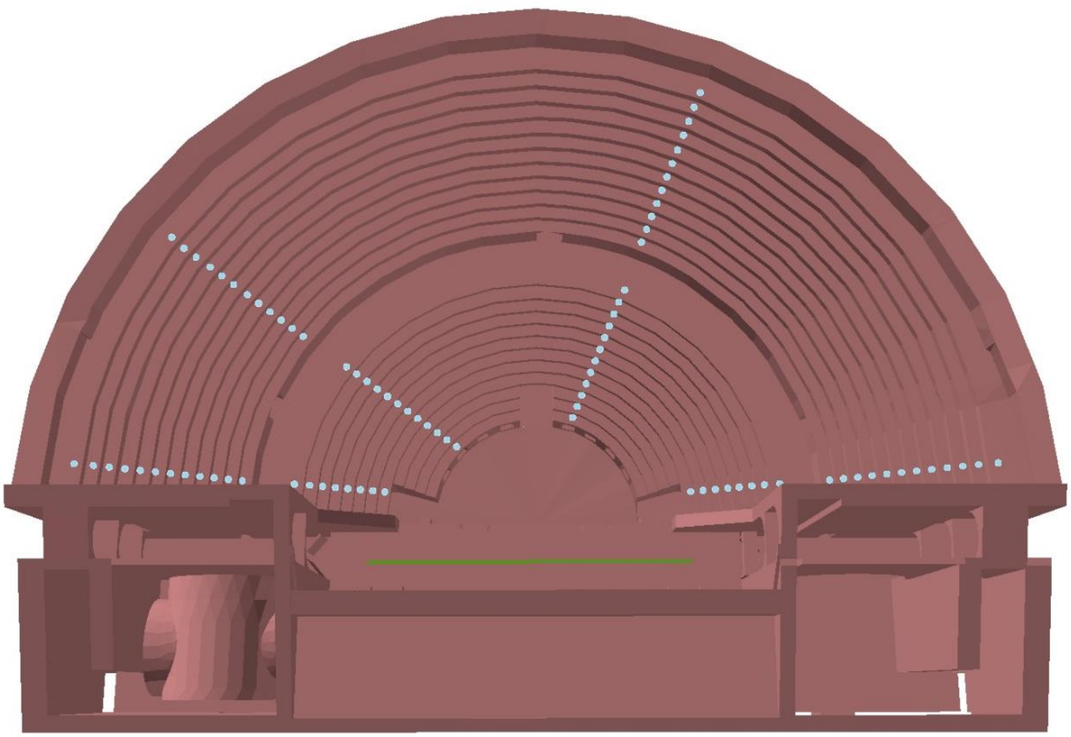


Figure 90 3D model with grid of observer points plus line of actors' position.

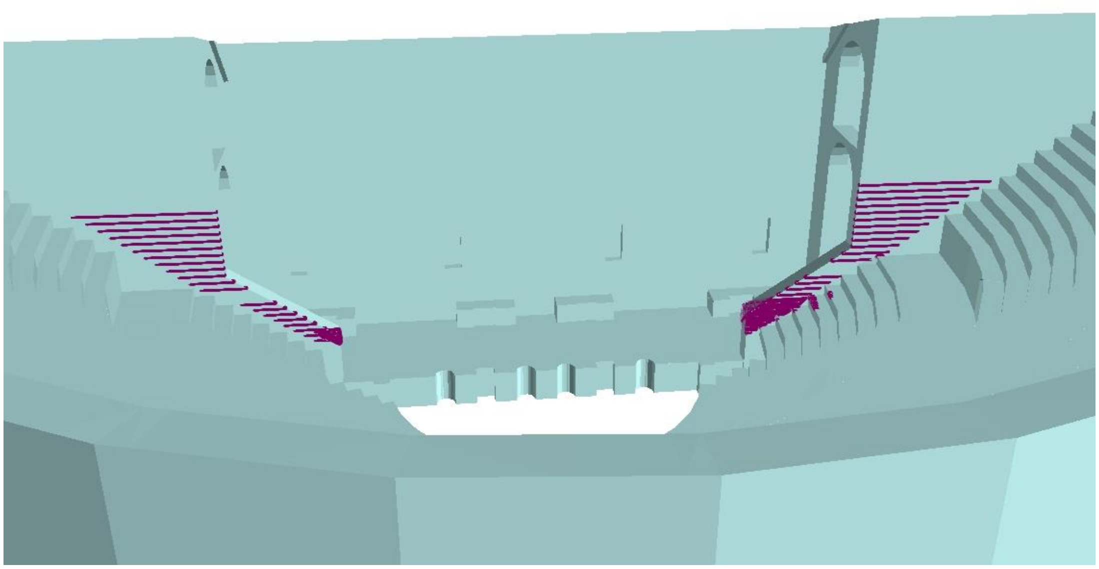


Figure 91 Obstruction points placed on the *analemmata*.

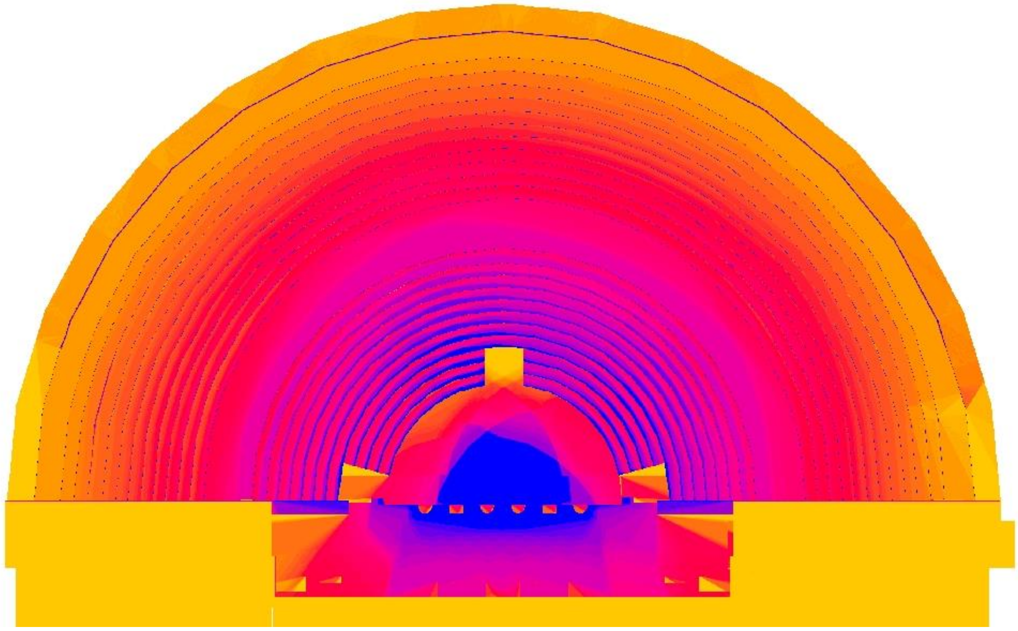


Figure 92 Map of frequency of visibility of the theatre of the Pythion at Gortyna. The colors show the different levels of visibility for the observer points, as it is explained in its correspondent graph (fig. 92).

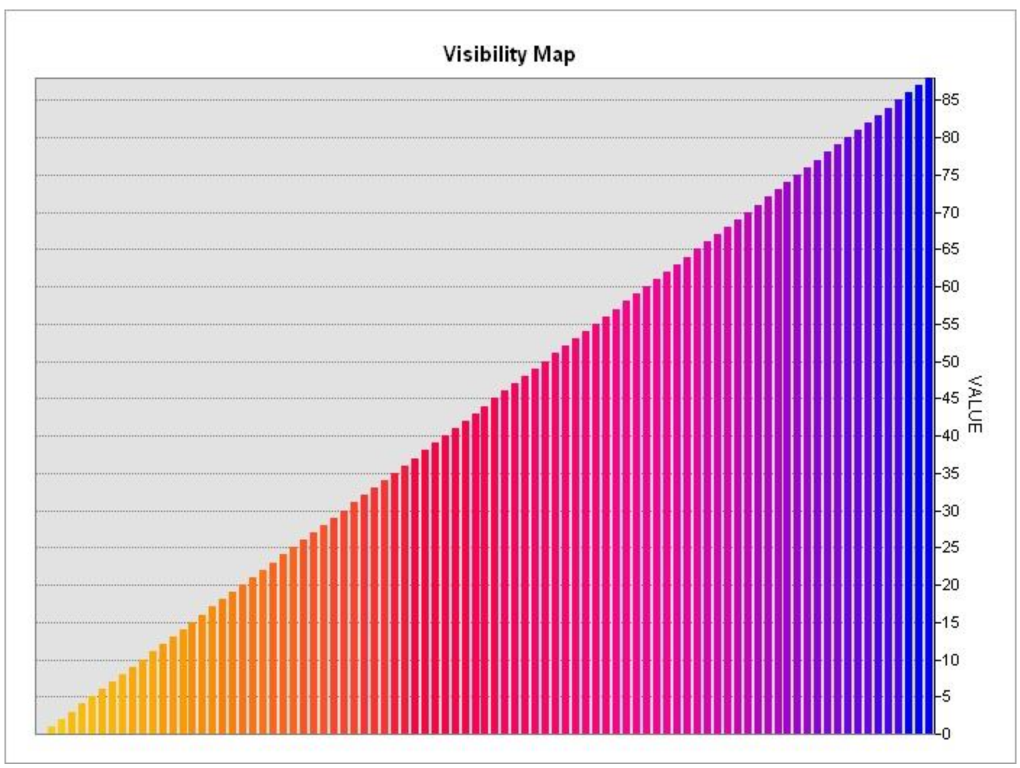


Figure 93 Graph of visibility analysis. The yellow color means that those areas are visible by none of the observer points; the blue colour indicates the area visible by all 88 observer points.

In this case, the lines of sights gave 93% visible trajectories and 7% not visible trajectories: the percentage of visibility is increased also if some obstruction points are still present on the *analemmata* of the *ima* cavea. Also the map of frequency of visibility of the second model gives better results: all the spectators have visual access not only to the orchestra but to the central part of the stage as well (fig. 94).

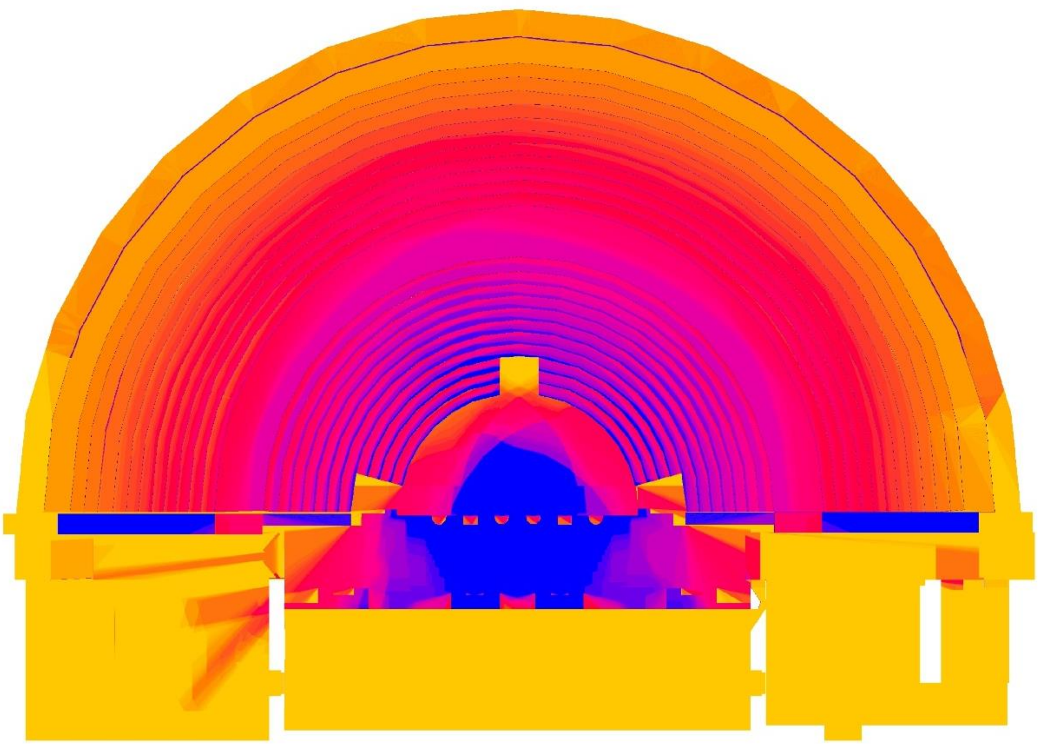


Figure 94 Map of frequency of visibility of the theatre of the Pythion at Gortyna. The colors show the different levels of visibility for the observer points, as it is explained in its correspondent graph (fig. 92).

5.5.2 Virtual acoustics analysis

In order to evaluate the quality of the acoustics in the theatre of the Pythion in Gortyna[57], 19 receivers (one each 2 or 3 rows of seats) were placed in the cavea, distributed in three lines, and a source more or less in the middle of the stage (for a detailed explanation refer to the methodology chapter, p. 65) (figs. 95 and 96).

Two versions of the theatre have been tested (choosing the structure that gave better results through the visibility analysis): one with roof above the stage (model N.1) and another without roof (model N.2).

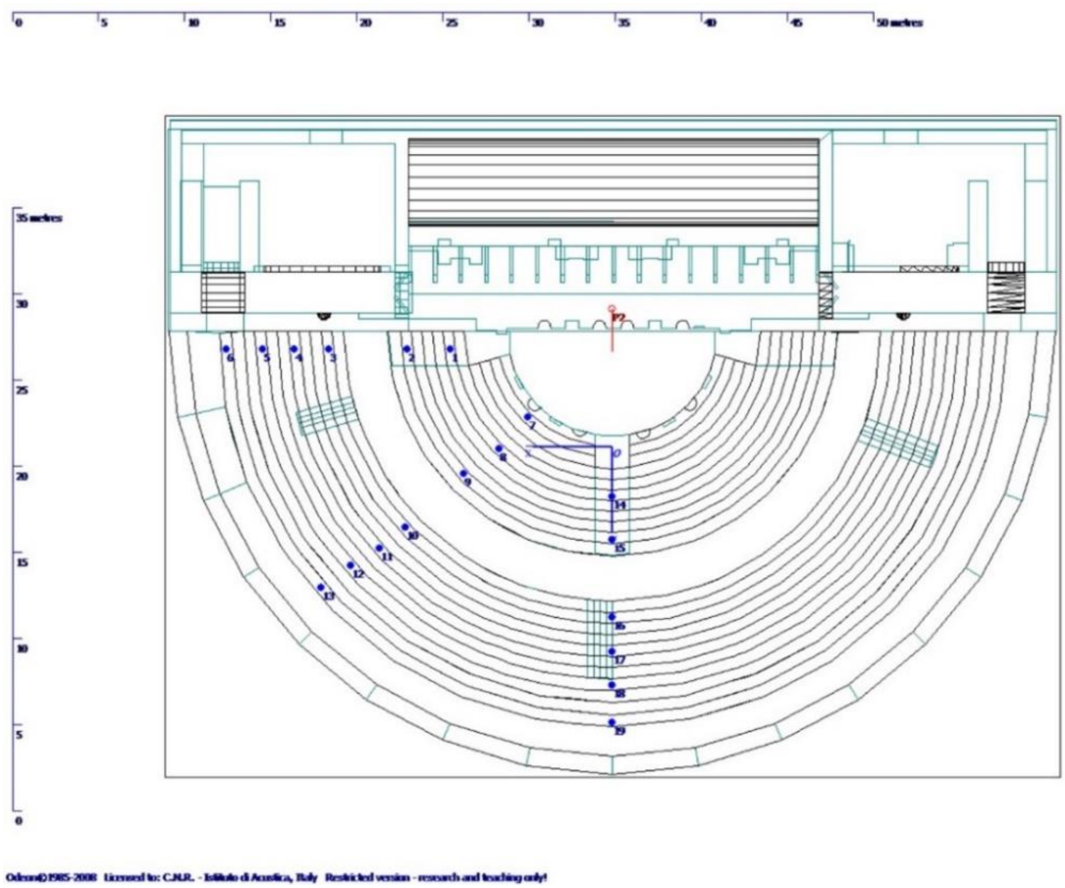


Figure 95 Plan of the theatre of the Pythion with receivers in the cavea and source on the stage.

[57] Only the 3D reconstruction representing the first phase of the theatre has been tested here. The second phase is characterized only by minor modifications that hardly would have influenced the quality of the acoustics.

Figure 96 Section of the theatre of the Pythion with receivers in the cavea and source on the stage.

The materials applied to the models, as suggested by Bonetto, Taramelli and Sanders are:

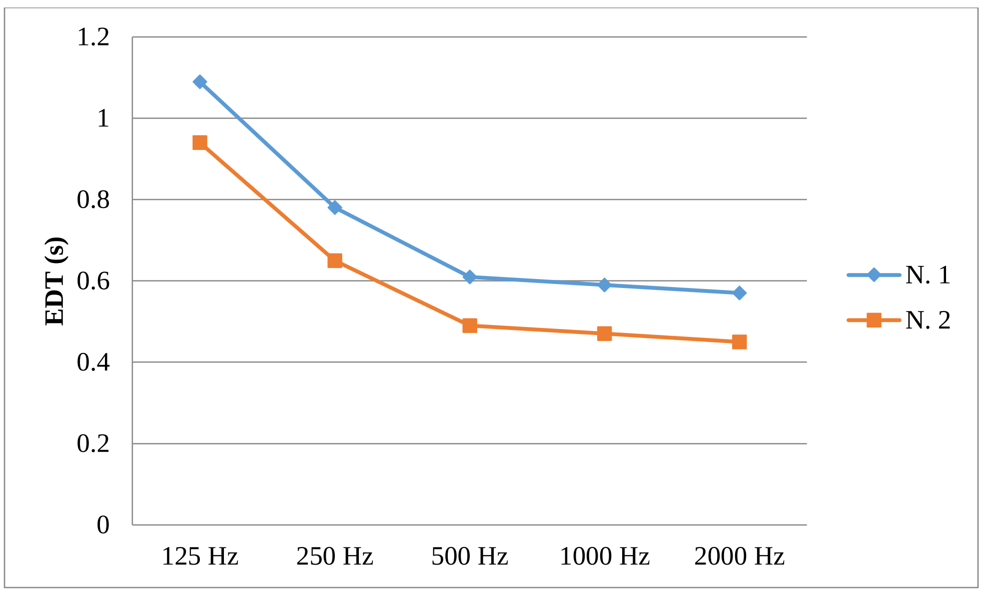
1. Bricks: *analemmata*, *ambulacrum*'s wall, *ima* cavea's wall *vomitoria*'s vaults, basilicas, *scaenae frons*.
2. Porous local stone (limestone): *diazoma*'s floor, *vomitoria*'s walls, floor and front of the stage, architectural decorations of the *scaenae frons*.
3. *Opus caementicium*[58]: orchestra's floor and the rise where the stage rests on.
4. Wood: doors of the scene building and of the *proscaenium*.
5. Wood and bricks for the roof above the stage.
6. Audience: seating area.

It is easy to note from the graphs (18-22) that the differences between the two reconstructions of the theatre of the Pythion are not too substantial and both 3D

[58] It is a building material widely used in the ancient Rome, made out of mortar and fragments of stones.

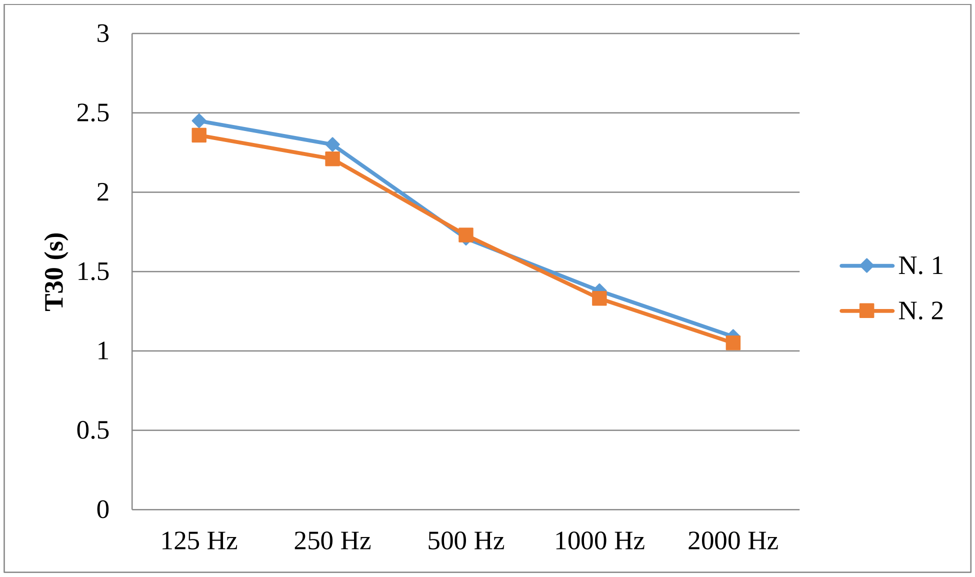
models present quite good results for clarity, definition and speech transmission index.

The reverberation time seems too high in both cases (even higher in the model N.2 with the roof) and this is an interesting aspect. Despite the quite high values of T30, the comprehension of the speech is still good, as demonstrated by C80, D50 and STI, and also by the auralisation through which no echo's problems are perceived. Indeed, the EDT, the subjective perception of the reverberation, is much shorter than T30, this may explains the absence of issues listening the auralised file[59].

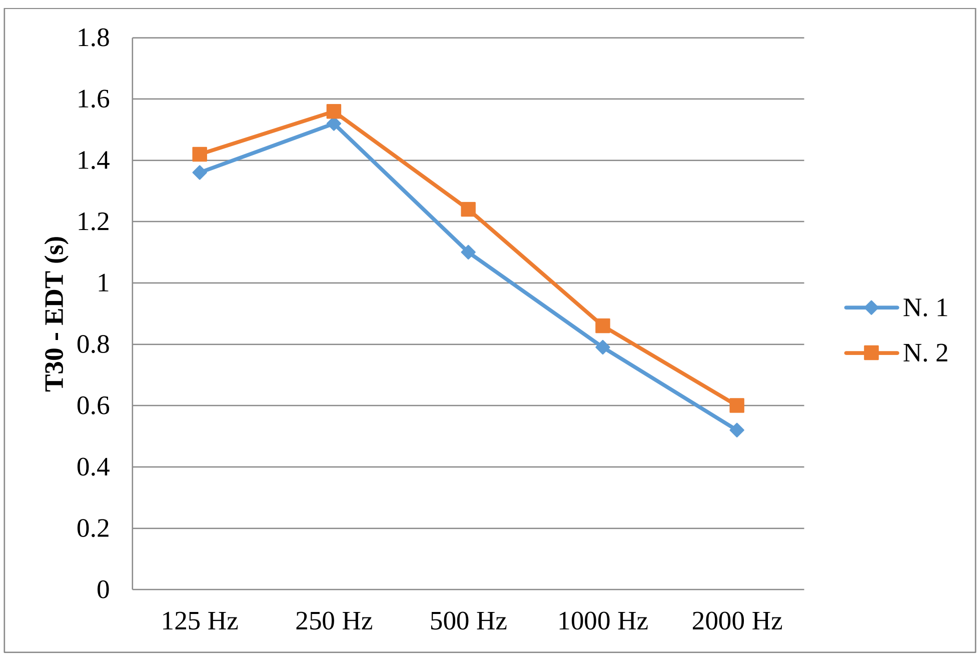


Graph 18 Average values of early decay time for all the receivers at each frequency, for both models.

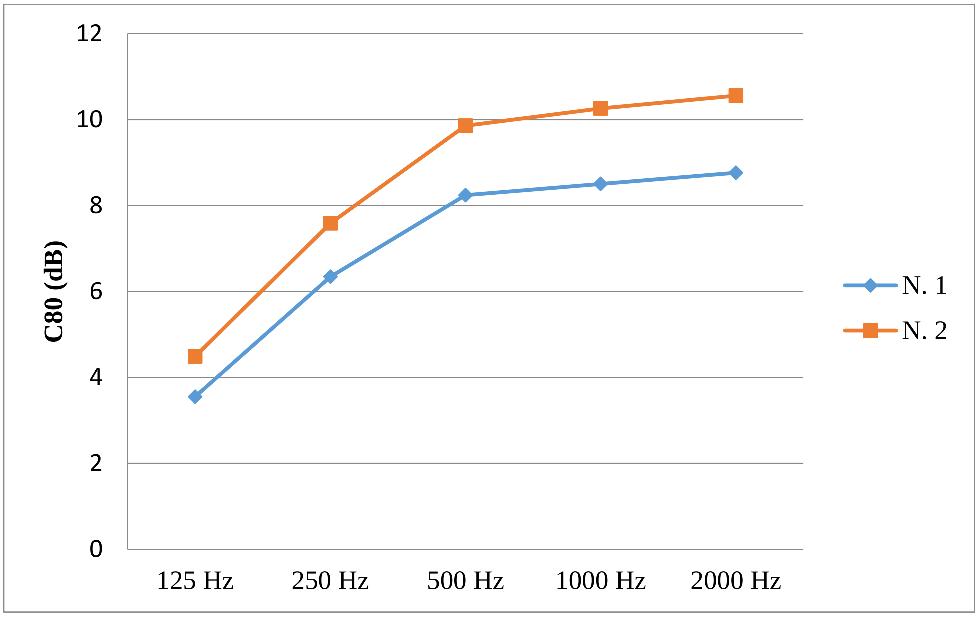
[59] The large difference between T30 and EDT may need to be investigated more in depth.



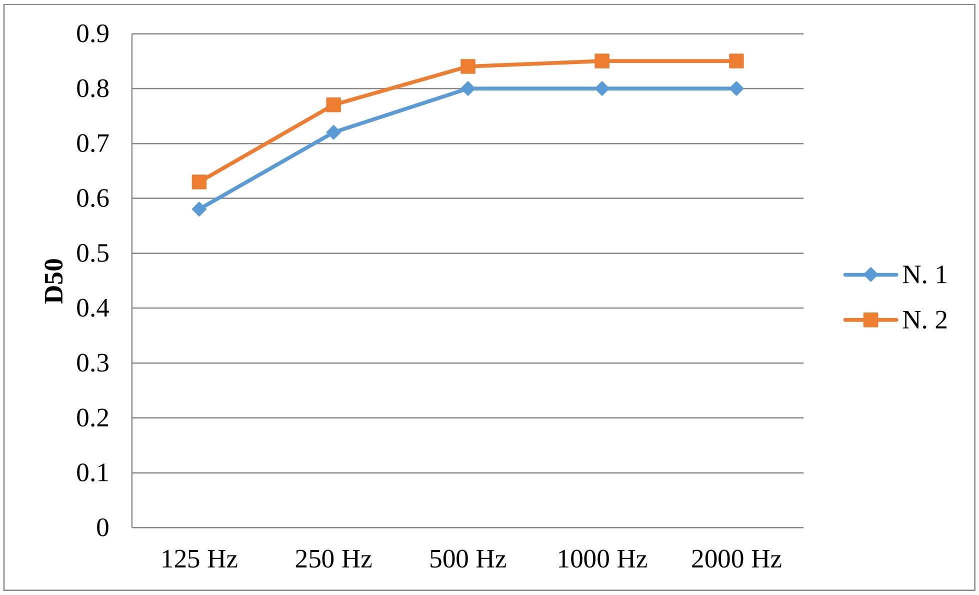
Graph 19 Average values of reverberation time for all the receivers at each frequency, for both models.



Graph 20 Average values of the difference between T30 and EDT, for both models.



Graph 21 Average values of clarity for all the receivers at each frequency, for both models.



Graph 22 Average values of definition for all the receivers at each frequency, for both models

5.5.3 Results and comments

It is possible to affirm that the interpretation of the archaeologists about the architectural structure of the theatre of the Pythion at Gortyna, is confirmed by the 3D visibility analysis (but it shows some uncertainties about the height of the *analemmata*) and by the virtual acoustics analysis[119].

The theatre of the Pythion at Gortyna had the cavea, which diameter is 52 m, divided by an *ambulacrum* and there were 12 rows of seats for each sector. The *scaenae frons* is rectilinear with three entrances for the actors. The scene building is flanked by the *basilicae*. In the 3D reconstruction columns have been added according to the witness of Belli and Sanders, but actually they were not found during the archaeological excavations (figs. 97-101).

The peculiarity of the theatre of the Pythion at Gortyna, also respect to the other theatres in Crete, are the *aditus* which lead directly into the stage, and not to the orchestra as it is the usual case (fig. 101). Only few structures have the same arrangement, and each of them is defined as *odeum*.

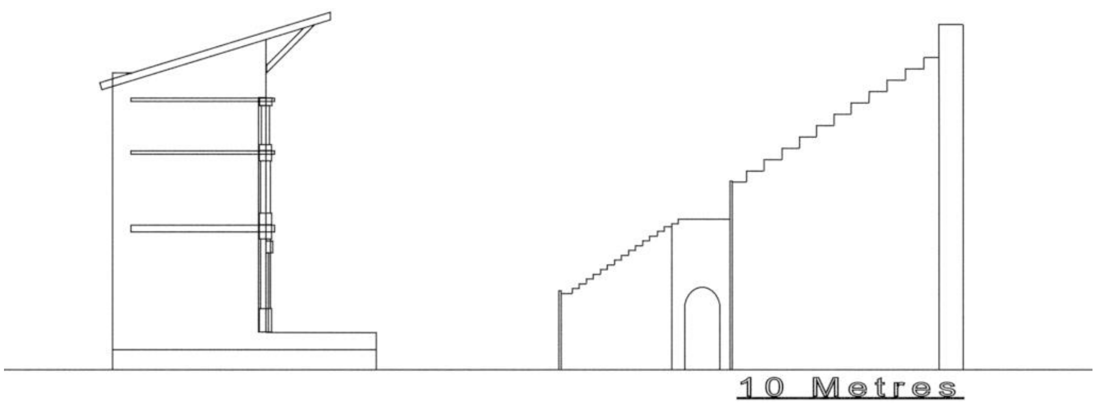


Figure 97 Hypothetical reconstructive section of the cavea and the scene building of the theatre of Pythion at Gortyna.

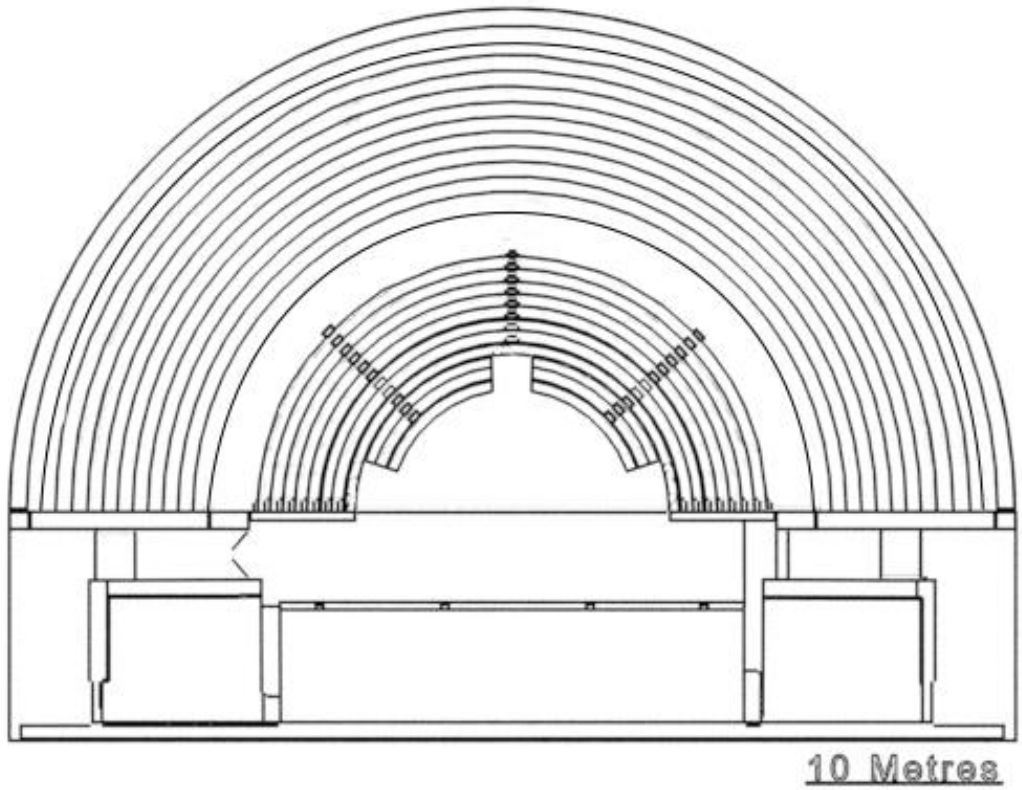


Figure 98 Hypothetical reconstructive plan of the theatre of the Pythion at Gortyna.

Figure 99 Hypothetical reconstructive drawing of the theatre of Pithion at Gortyna.

Figure 100 Rendering of the 3D model of the theatre of the Pythion at Gortyna.

Figure 101 Rendering of the 3D model of the theatre of the Pythion at Gortyna. Particular of the *aditus*.

The most interesting comparison is with the theatre at Ptolemais, in Libya. First of all, it is important to stress that it belonged to the same Roman province as Gortyna, that was *Creta et Cyrenaica*, second, it is considered as an *odeum* but it was never covered. As Ruediger Meinel well explained: *parodoi* and stage were combined and situated in front of a straight line *scaenae frons*[120] (fig. 102) as in the theatre of the Pythion. The theatre of Ptolemais is probably dated to the II century[121].

Also the Roman *odeum* in Aphrodisias (Geyre), in Turkey, presents a similar structure: *parodoi* and stage placed on the same line, in front of the rectilinear *scaenae frons*, but here the latter has five openings instead of three (fig. 103). Indeed, Meinel stated that the area of the *parodoi* in this *odeum* was used as a play area or stage, comparing it to the *odeum* of Ephesus. The *odeum* at Aphrodisia has been built between the end of the I and the beginning of the II century AD [65]. Obviously, even the *odeum* of Ephesus can be compared with the theatre of the Pythion, but the first has seven openings in the *scaenae frons* and not three (fig. 104); it is dated to the midst of the II century AD.

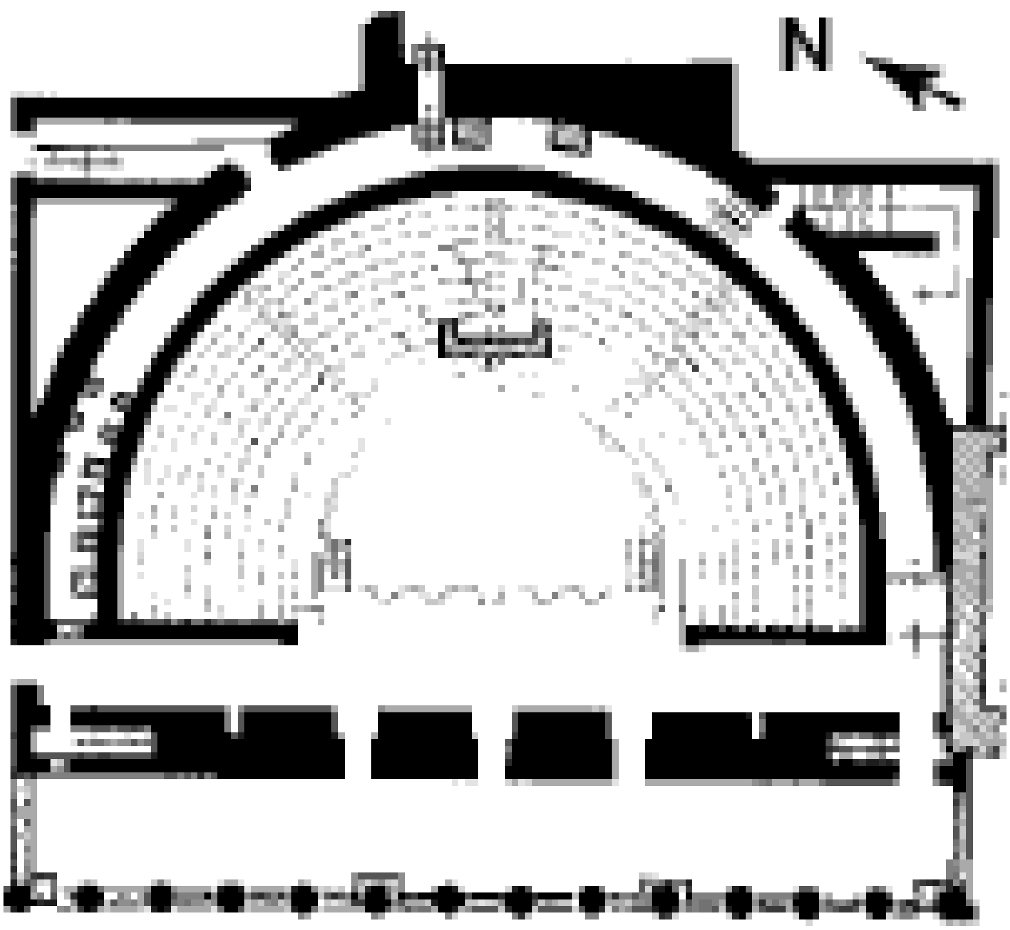


Figure 102 Plan of the theatre of Ptolemais in Libya (from Sear, 2006).

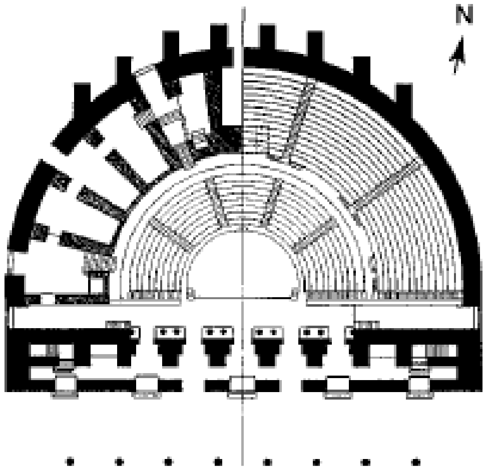


Figure 103 Odeon of Aphrodisias, Turkey (from Sear, 2006).

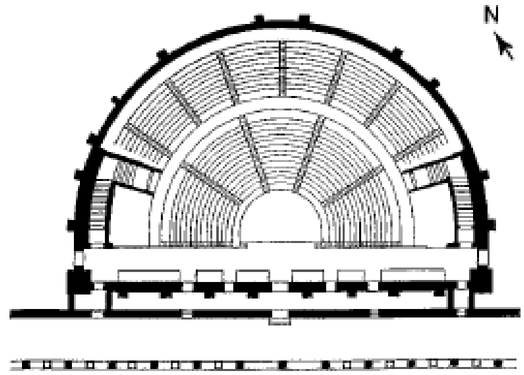


Figure 104 Odeon of Ephesus, Turkey (from Sear, 2006).

It has to be stressed that the date of construction of all the buildings above mentioned is about the same as the theatre of the Pythion (II century). They have been built in the same technique too (except for the *odeum* in Ephesus which partially lays on the natural slope), that is with blocks of local porous stone and marble; and they all have a rectilinear *scaenae frons*. It is also meaningful that Colini, at the beginning of XX century, already associated the structure of the theatre of the Pythion with the *odeon* of Gortyna.

In particular, it is interesting the similarity with the theatre at Ptolemais because it is considered an as *odeum* which was never covered, resembling in this way the theatre of the Pythion. As such it would seems pretty obvious that there was a transmission of knowledge about construction techniques and maybe a sharing of workers and architects within the same province, despite they were divided by the Mediterranean Sea. However, more generally, we can recognize a reciprocal influence in the east side of the Empire, since the other comparisons presented above are placed in Turkey.

5.6 Theatre at Kazinedes, Gortyna

This theatre is localized at Gortyna, in locality Kazinedes, around 1 Km far from the modern village of Agoi Deka, to the west side.

Although this theatre has been recently identified, the first information about it is dated back to the XVI century. Onorio Belli[26] described it as an amphitheater and till the end of the last century, its remains were interpreted as the remains of the amphitheater of Gortyna.

Onorio Belli gave a detailed description of the monument. He said that it is almost completely made out of bricks, there is a portico in *summa* cavea, two corridors running all around the building and stairs as in the amphitheater of Verona. Unfortunately, his plan is lost, but we have a description of it made by Scipione Maffei[31] that had the occasion to see it in the XVIII century. He affirms that Belli reproduced an amphitheater very similar to the Colosseum, as it was a common trend at that time, but with only 56 arches. Maffei was the first one to express his doubts about the identification of this monument with the amphitheater of the town of Gortyna: first of all Belli describes a building without decoration, which is unusual for an amphitheatre in an important town and, furthermore, the location of the remains mentioned by Belli is within the town (close to the Forum as Belli said), while the amphitheaters are usually outside the town's walls.

Later, some other travelers mentioned this monument. We can probably recognize it in the elliptical building not far from the village of Agoi Deka in the view of the ruins of Gortyna, drew by J. Pitton de Tournefort[34] in 1717. Few years after, Richard Pococke[35] suggested that the ruins of the monument close to Agoi Deka, may be identified also as a theatre, but he did not see any evident characteristics in order to affirm this with certainty. He described it as built in bricks, with arches at least on one side and with two square towers as staircase. In the successive plan of the town made by Captain Spratt[37], it is again indicated as an amphitheater (fig. 105). Not only the travelers, but also the archaeologists of the *Missione Italiana a Creta* interpreted its remains to belong to an amphitheater. At the end of the XIX century and beginning of the XX century, several archaeological excavations started in

Gortyna, and also the area of Kazinedes has been included in some investigations. Amedeo Maiuri, in 1911, was the responsible for the sector occupied by the theatre and despite the careful analysis he made, he also confused this monument with an amphitheatre. Maiuri[41] describes part of the structure of the monument, highlighting the presence of walls and vaults sustaining the cavea and two aligned towers that stick out the ellipse. He compared these towers with the four ones of the amphitheater of Pola in Croatia, attributing to them their same function that is stairs to reach the last rows of seats of the cavea. He publishes the plan of the remains made by Stefani (fig. 106), where the substructures of the cavea (at south-east and east) and the two towers in the west side are evident.

The report of Maiuri is quite accurate and it surprises that he was not able to recognize a theatre in the building he described. It is pretty clear that the two lateral towers on the west side belong to the staircases flanking the scene, whereas there are no evident traces of the elliptical structure remains on that side. Other archaeologists agree with the traditional hypothesis and they kept talking about an amphitheater, in the same period as Maiuri (Bendinelli[60][42]), and even afterwards (Golvin[61][43]).

Even in 1982, Ian Sanders[16] describes it as an amphitheater, summing up the several information given by previous scholars. This view remained until the end of the last century, when the real amphitheatre of Gortyna was discovered exactly under the modern village of Agoi Deka. This pushed the archaeologist Antonino Di Vita[51] to recognize a theatre in the remain at Kazinedes, (even though, for some years it kept to be mentioned as the amphitheatre of Gortyna). In 1994, the analytic census realized by Ciancio Rossetto and Pisani Sartorio, includes the monument among the theatres [64].

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[60] Goffredo Bendinelli studied some of the architectural fragments that should belong to the theatre, but he refers to it as an amphitheatre.

[61] Jean Claude Golvin studied a fragmented stele with a representation of Nemesis (now preserved at the British Museum) coming from the area of the theatre and he used this characteristic to confirm that the monument is an amphitheatre.

Figure 105 Plan of the ruins of Gortyna by Spratt (from Spratt 1854).

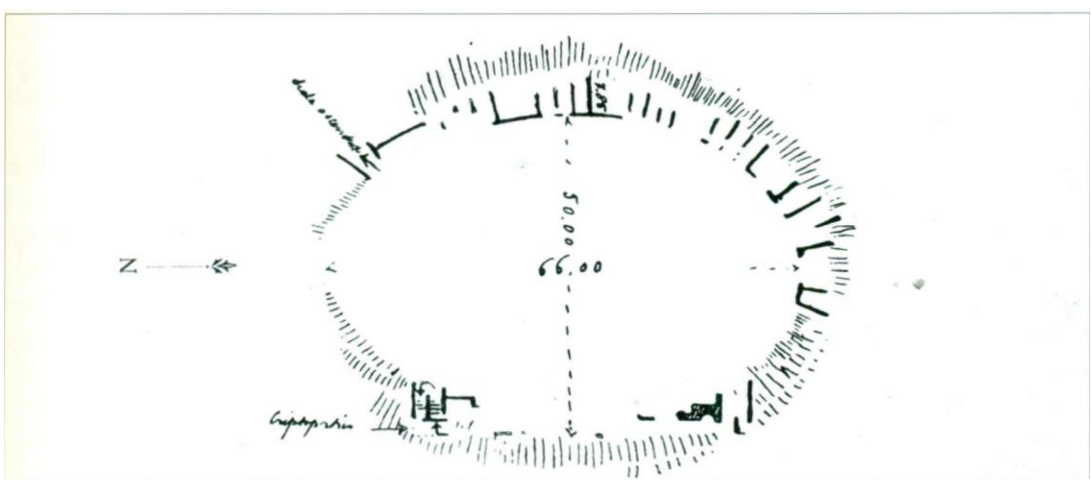


Figure 106 Plan made by E. Stefani (from Maiuri, 1912).

Since 1998, the archaeologist Gilberto Montali[52], [53] investigated and studied the site of the monument. Some of the remains, such as part of the substructure of the cavea and the lateral towers working as staircase, are still visible on the surface, and some small areas of the amphitheatre have been excavated in 1998. These are: one of the pillars of the east side of the cavea, the staircases at north, the central exedra of the *scaenae frons*, the central part of the orchestra and the central part of the stage. The plan of the survey of 1998 shows the remains brought to light through the archaeological investigations and the ones that appear on the surface (fig. 107): large part of the substructures of the cavea, the two staircases at the sides of the scene buildings, the central exedra of the *scaenae frons*, the two side corners of the *scaenae frons*, a niche in the internal wall of the *scaenae frons*, probably the external wall of the *post scaenium*, the front of the stage and some structure of the *iposcaenium*. In addition, many fragments of columns have been found in the area of the orchestra, which demonstrate at least the presence of two different sizes of columns.

Montali studied in detail the remains in order to propose a hypothetical reconstruction of the original aspect of the theatre. Unfortunately, the archaeological data are scarce so that it is pretty complicated to comprehend the architectural structure of the monument. Montali compared what he discovered in situ with other theatres well know and well preserved (Sabratha, El Jem, Tipasa, Taormina, Salamina and Potamos tou Kambou in Cyprus, Hamat-Gader, Greek theatre of Villa Adriana, Arles, Orange, Bosra, Amman, Scythopolis and many more), with the text of Vitruvius *De Architectura*, and with previous studies about the ancient Roman theatres [122]–[125] attempting to be as much accurate as possible. He also considers the necessary balance and harmony of the ancient structures in order to obtain an even more reliable hypothesis of reconstruction.

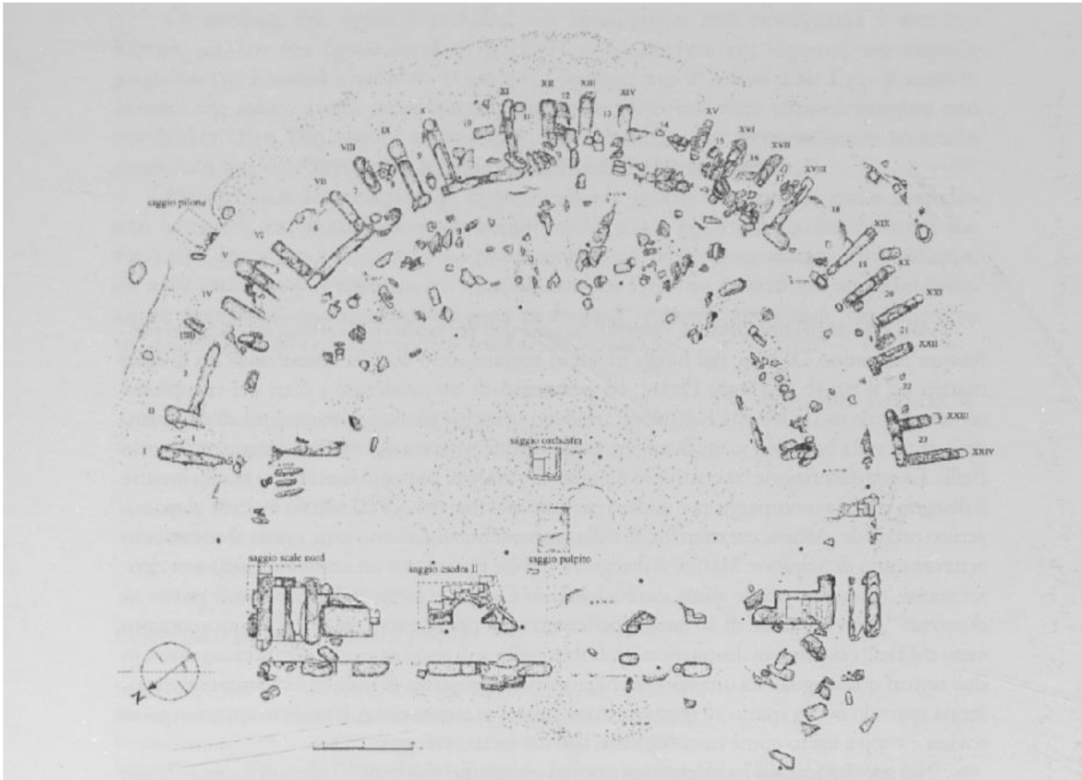


Figure 107 Plan of the remains of the theatre at Gortyna, Kazinedes (from Montali, 2006).

The reconstruction proposed by Montali is shown at figures 108 and 109. He presents it as a classical Roman theatre, with the cavea divided into three sectors, *vomitoria* and *aditus* as access for the spectators, semicircular orchestra, three entrances for the actors opened in three niches in the scene front, two storeys of columns and a portico in *summa* cavea (as already supposed by Belli). Although the archaeological remains are not enough to reconstruct the original aspect of the theatre, the reconstruction proposed by Montali is based on a solid research and on good observations. Despite this, I feel to partially disagree with his hypothesis, in particular with the reconstruction of the *versurae*. In the plan of the remains of the theatre, I do not see traces of the expansion of the staircases at the sides of the *scaenae frons*, towards the cavea or reaching the front of the *pulpitum* as Montali states. Checking the remains on the satellite picture from Google Earth (fig. 110), the same absence of structures in that area can be noticed.

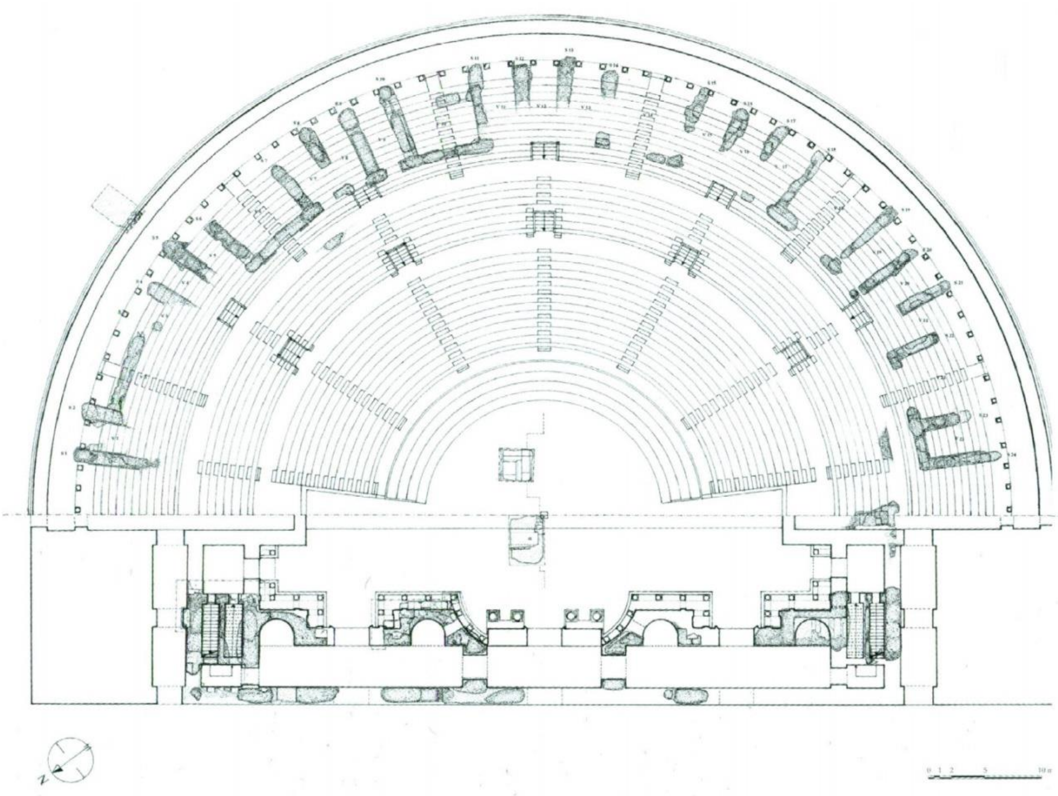


Figure 108 Plan of the hypothetical reconstruction of the theatre of Gortyna, at Kazinedes, proposed by Montali (2006), overlapping the plan of the remains (fig. 107).

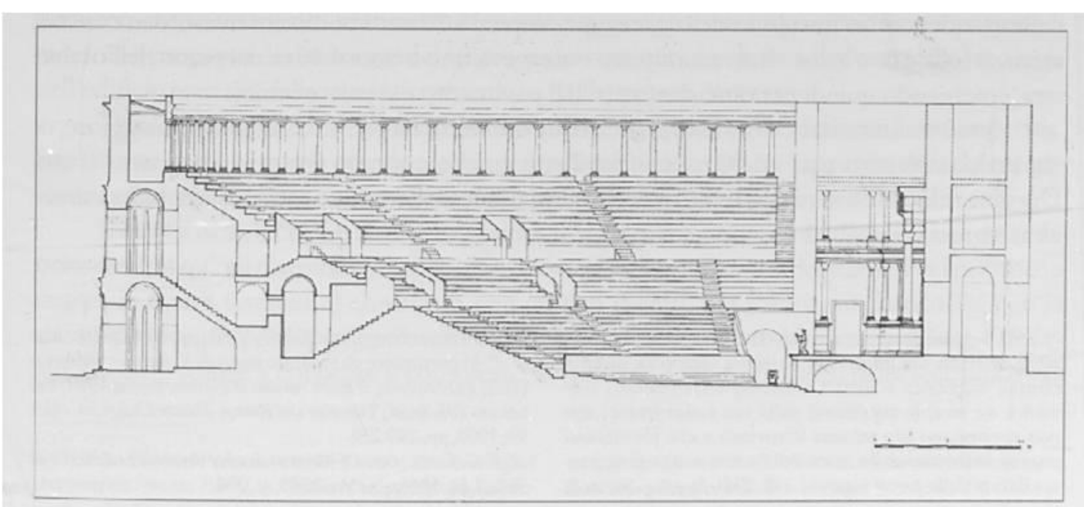


Figure 109 Section of the hypothetical reconstruction of the theatre of Gortyna, at Kazinedes, proposed by Montali (2006).

Figure 110 Satellite image from Google Earth of the area occupied by the theatre of Gortyna, at Kazinedes.

In my opinion, it seems that the sides of the stage are not flanked by any room (not even the *basilicae*) except for the two visible “towers”, corresponding to the staircases.

I am more inclined to think that there was an open, or vaulted, corridor to reach the stage from its sides, as it was the case of the close theatre of the Pythion. The figure 111 shows the reproduction of Montali’s plan in AutoCad, where the purple lines are the architectural parts I agree with, the yellow lines indicate the structures I suppose were not present in the theatre. Similarly, we can doubt about the presence of the portico in *summa* cavea. The fragments of columns that Belli saw in the orchestra, may be associate, most likely, to the decoration of the *scaenae frons*.

The 3D visibility analysis and the virtual acoustics analysis have tried to verify these hypotheses.

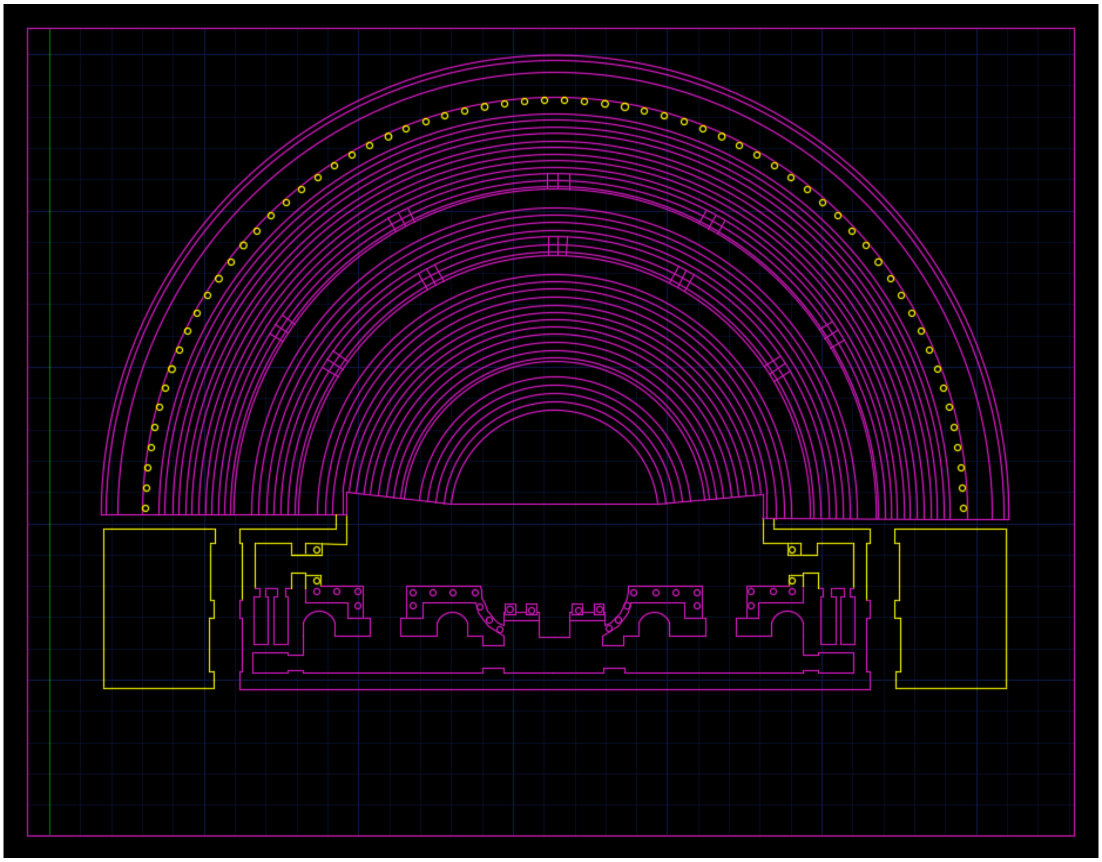


Figure 111 Synthetic representation of the hypothetical reconstruction proposed by Montali. The purple lines indicate the architectural parts which the author agreed with, the yellow lines indicates the architectural part that according to the author are missing.

5.6.1 3D visibility analysis

Two different 3D models have been used in ArcGIS in order to analyze the visibility of the stage from the spectators' seats in the cavea. The model N. 1 (fig. 112) is the reproduction of Montali's proposal (without portico in *summa* cavea because it is not influencing the visibility of the stage) and the model N. 2 (fig. 113) is the reconstruction without rooms flanking the stage. Both figures show the position of the spectators in the seating area. The grid is formed by 124 observer points (for detailed explanation refers to the methodological chapter, p. 56).

The results obtained from the calculation of the lines of sight between the spectators and the actors' location on the stage indicate that in the model N. 2 a larger number of spectators have a good visibility of the supposed actors.

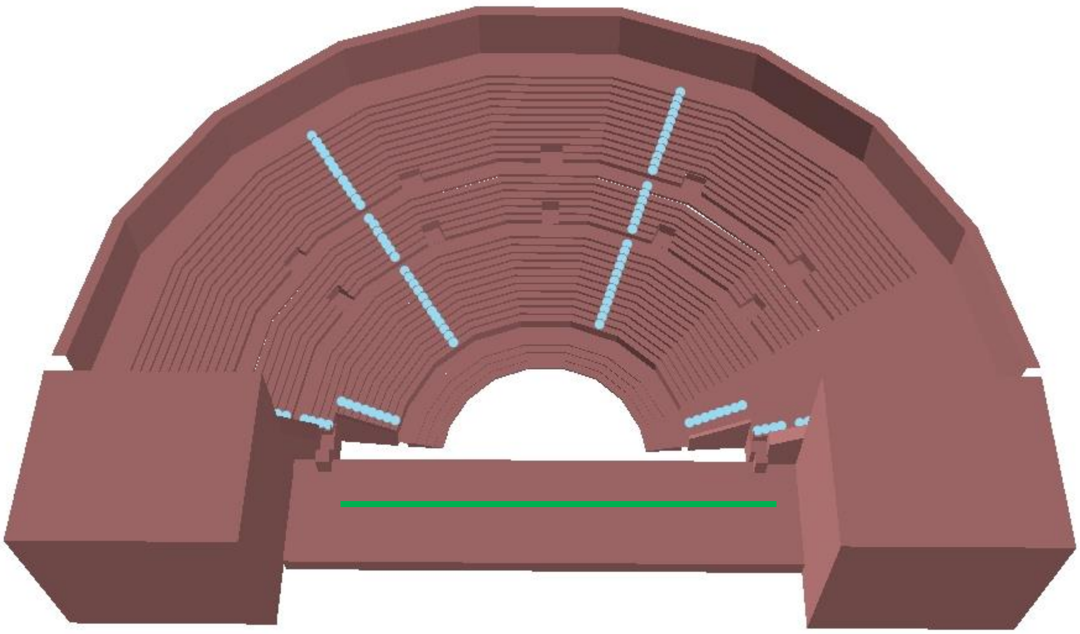


Figure 112 Model N.1 with grid of observer points.

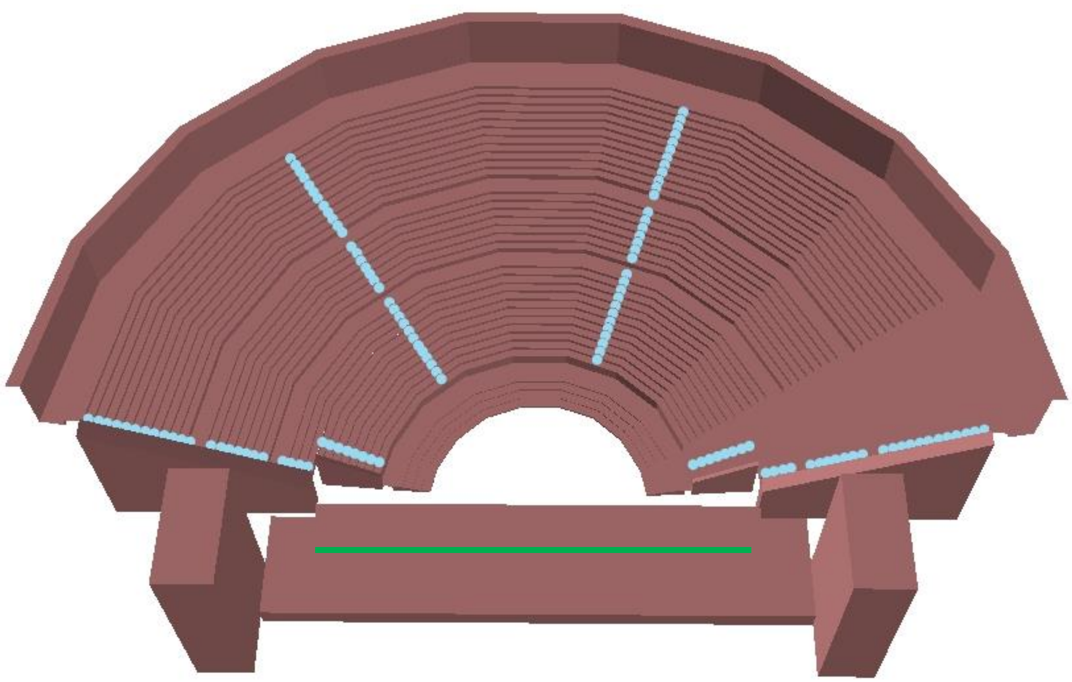


Figure 113 Model N.2 with grid of observer points.

Respectively, in model N. 1 15% of lines indicates not visible trajectories, in the model N. 2 the 8% of lines indicates not visible trajectories. In addition, the 92% of "visible lines", resulting from the model N. 2, is the same percentage obtained for the theatre of Aptera, which is well documented.
Also the frequency of visibility maps manifest that the model N. 2 is more appropriate to have a wider visibility of the stage (figs. 116 and 117), than the model N. 1 (fig. 114 and 115). Indeed, the blue color indicates the area that is visible from any point of the grid and in the frequency of visibility map of the first model, only the very frontal area of the stage is visible by everyone.

The differences between the two models may be considered negligible: it is evident that the model N. 2 allows a better visibility of the stage from the spectators' point of view, but the model N.1 does not have such a low percentage of visibility at the point to influence a large portion of spectators. Both models look acceptable, according to the 3D visibility analysis.

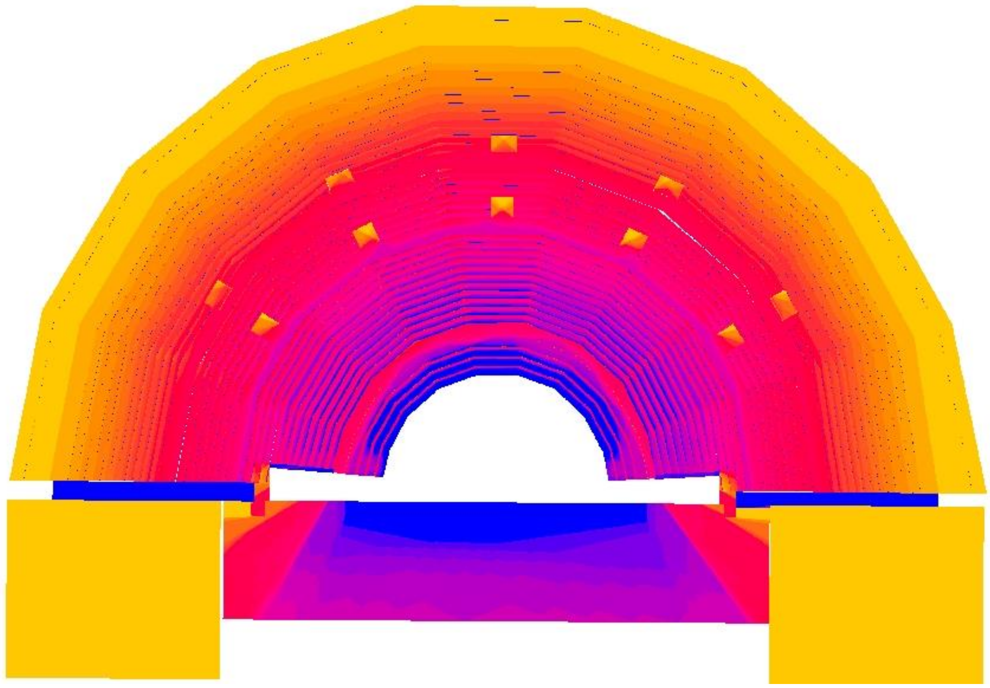


Figure 114 Map of frequency of visibility of the model N.1 of the theatre at Kazinedes, in Gortyna. The colors show the different level of visibility for the observer points, as it is explained in its correspondent graph (fig. 115).

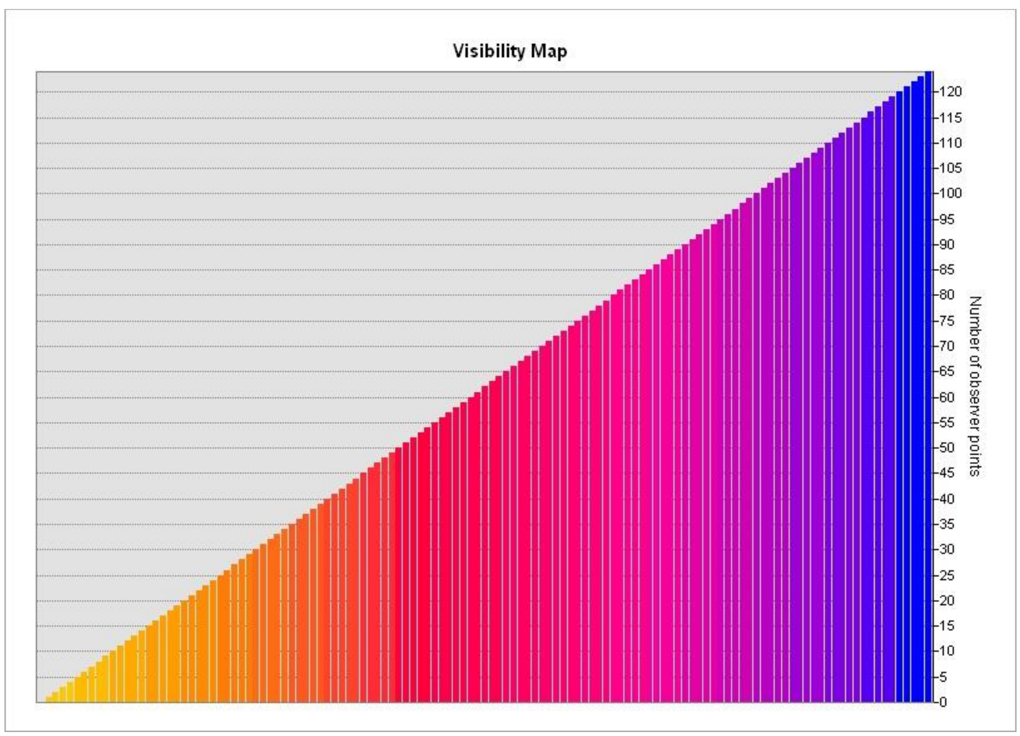


Figure 115 Graph of visibility map of the model N.1 of the theatre at Kazinedes, in Gortyna. The color scale is from yellow to blue. The yellow color means that those area are visible by none of the observer points; the blue colour indicates the area visible by all 124 observer points.

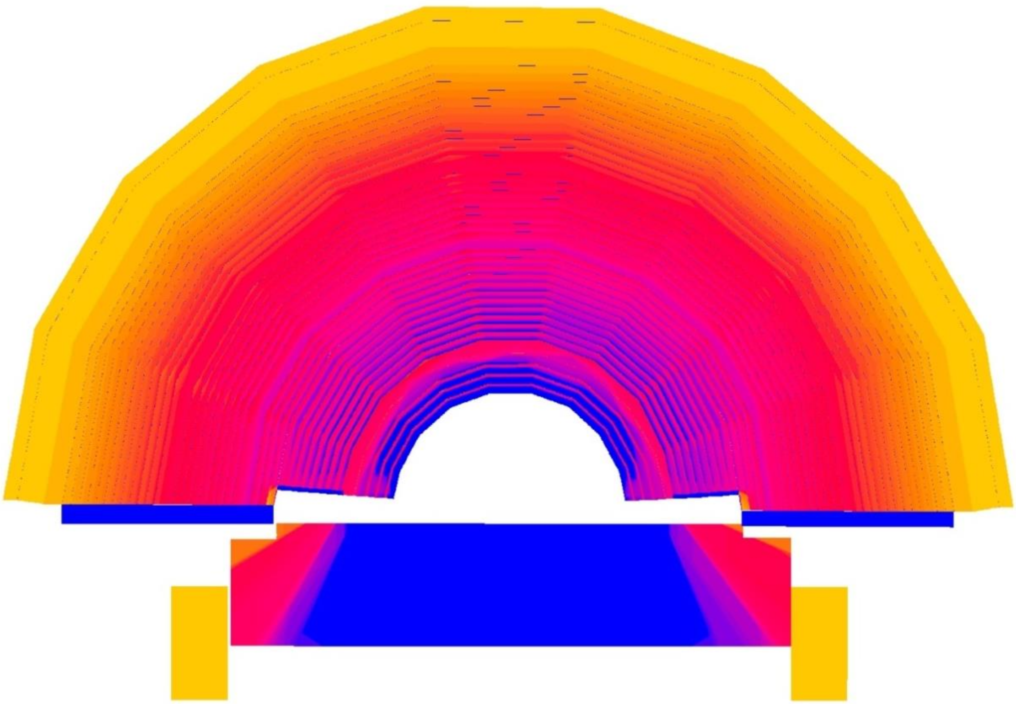


Figure 116 Map of frequency of visibility of the model N.2 of the theatre at Kazinedes, in Gortyna. The colors show the different level of visibility for the observer points, as it is explained in its correspondent graph (fig. 117).

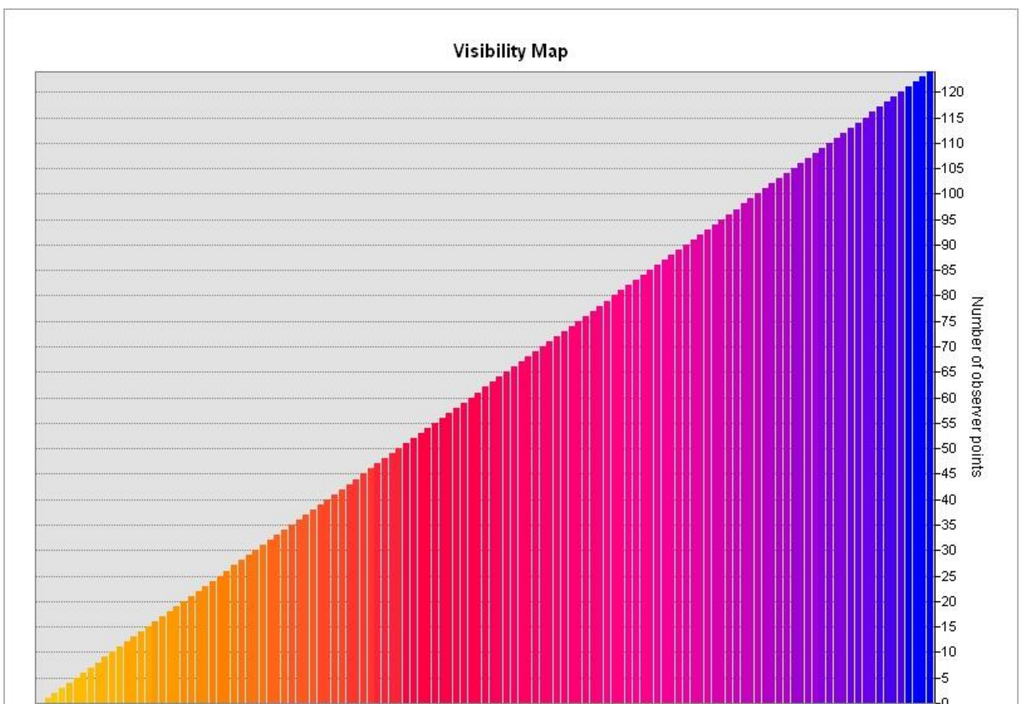


Figure 117 Graph of visibility map of the model N.2 of the theatre at Kazinedes, in Gortyna. The color scale is from yellow to blue. The yellow color means that those area are visible by none of the observer points; the blue colour indicates the area visible by all 124 observer points.

5.6.2 Virtual acoustics analysis

Three different 3D models have been tested through the virtual acoustics analysis: the model N.1 is the reconstruction proposed by Montali; the model N.2 is the same model but without any rooms at the sides of the stage except for the staircases; the model N.3 corresponds to the second model but without portico in *summa* cavea. The figure 118 shows in detail the differences of the scene building in Montali's proposal and the hypothesis formulated during this study.

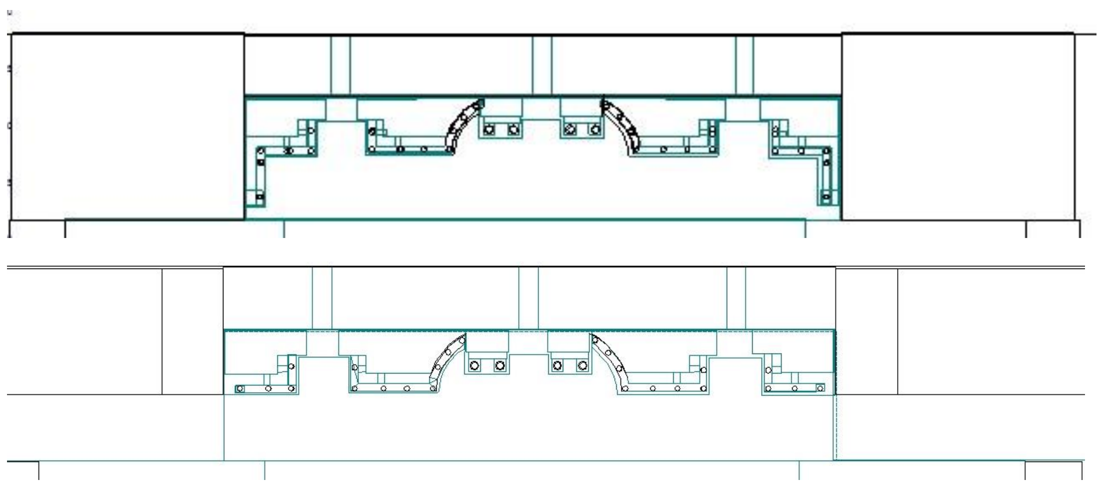


Figure 118 Plan of the two different reconstructions of the scene building.

22 receivers have been placed, forming three radial lines in one half of the seating area, one each three/four steps. A source is located at the center of the stage (for a detailed explanation refer to the methodology chapter, p. 65) (figs. 119 and 120).

The materials used in the virtual acoustics analysis of the different version of the theatres, according to the indications of Montali and the other previous scholars, are:

1. Marble: floor of the orchestra, podium, decorations of the *proscaenium*'s front, decorations of the *scaenae frons*, portico in *summa* cavea.
2. Bricks: *scaenaefrons*'s wall, cavea, *versurae,postscaenium*, diazoma's floor.
3. Stone: *versurae*, stage's floor.

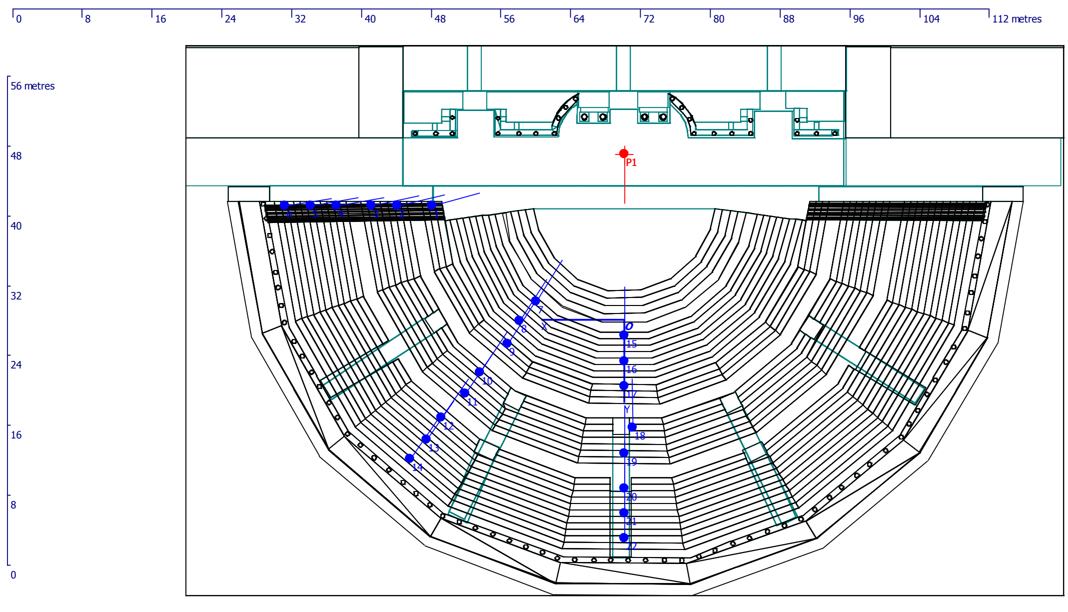


Figure 119 Plan of the 3D model N.1 representing the theatre at Kazinedes reproduced in Odeon Room Acoustics, together with receivers and source.

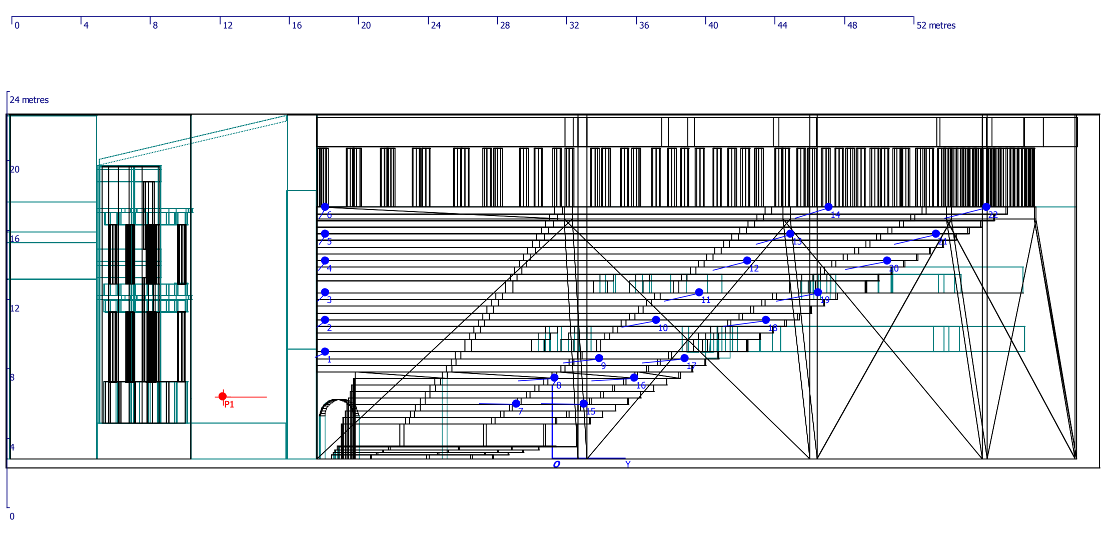


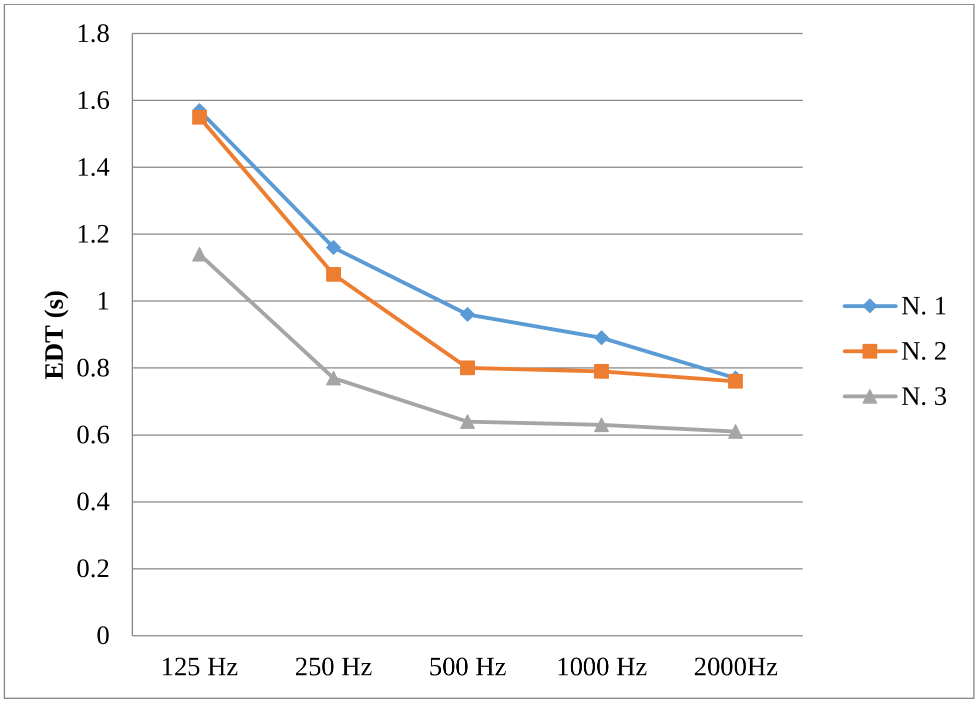
Figure 120 Section of the 3Dmodel N.1 representing the theatre at Kazinedes reproduced in Odeon Room Acoustics, together with receivers and source.

The results of the virtual acoustics analysis of the model N.1 show a level of acoustics that seems not to be acceptable: even if the reverberation time can be considered good, the clarity and definition, in numerous positions do not achieve values high enough for a comprehension of the speech and not good for enjoying a music performance. The virtual acoustics analysis of the model N. 2 gives very similar results to the first one as you can observe in the following graphs (23-28), showing the average values of all the receivers for each parameters, at each different frequency. The reverberation time (T30) at low frequencies may be considered little bit too high for a speech performance in both models. The clarity (C80) at low frequencies is under the acceptable values for a speech performance. Resulting values of definition (D50) and speech transmission index (STI) are within the acceptable range to comprehend a speech (figs. 121-122). Both model N. 1 and N. 2 present a difference between T30 and EDT higher than 0.4 at some frequencies.

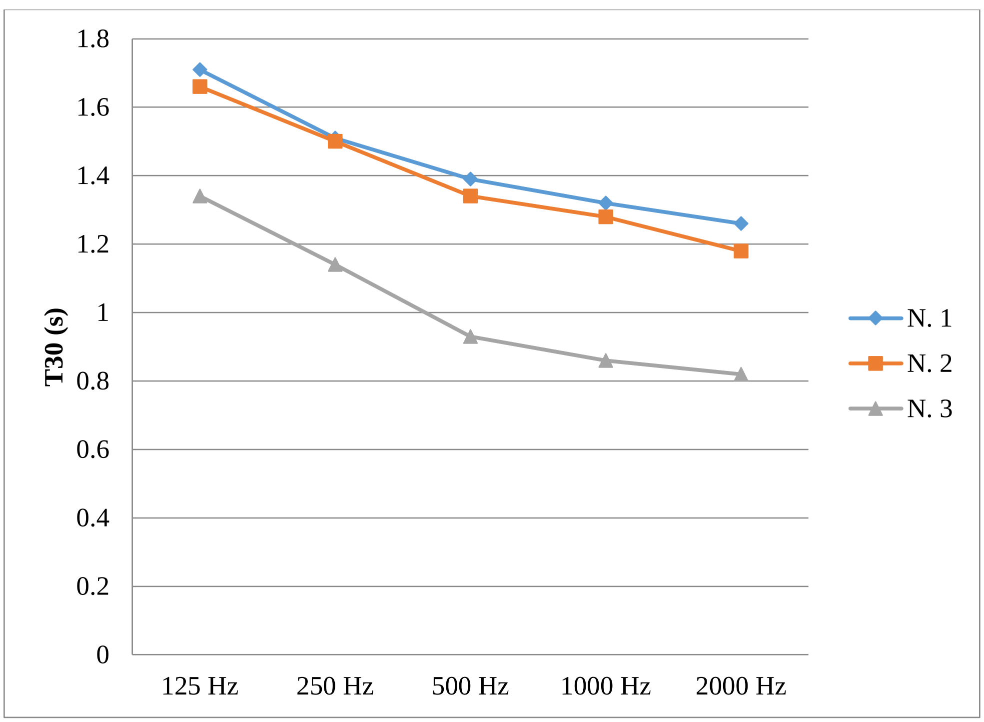
The analysis of the model N. 3 shows a better quality of the acoustics: the values of T30 are around 1 second that corresponds to the ideal value for listening a speech performance; C80 and D50 are higher than the ones of the models N. 1 and N. 2 indicating a better comprehension, and the STI as well reaches a value which indicate a good level of intelligibility (fig. 123).

More in detail, the percentages of not acceptable values from all the receivers, for clarity and definition, for each model, are shown in the table 1. It is evident that the model N.1 and the model N.2 have a substantial number of receivers that are enable to understand the performance, above all in the reconstruction including the portico in *summa* cavea, which probably produces several late reflections that have a negative influence on the quality of the acoustics. In contrast, only very few receivers in the model N.3 are not able to enjoy the performance.

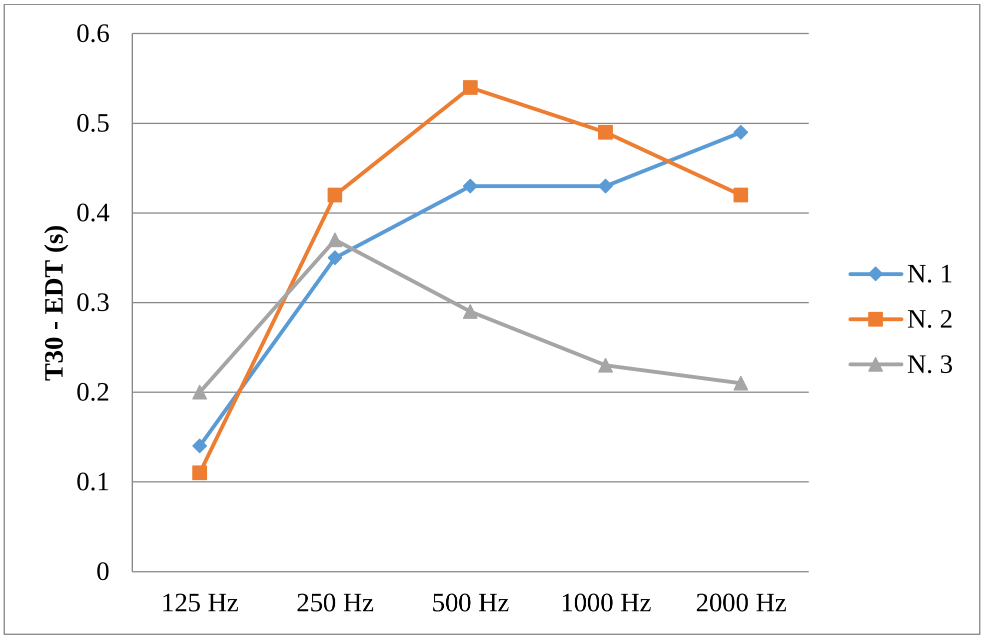
Therefore, it is possible to state that according to virtual acoustics analysis, the models N. 1 and N. 2 have some issues regarding the quality and the comprehension of the acoustics for speech performance, while the model N. 3 has a good level of acoustics' quality for speech performance.



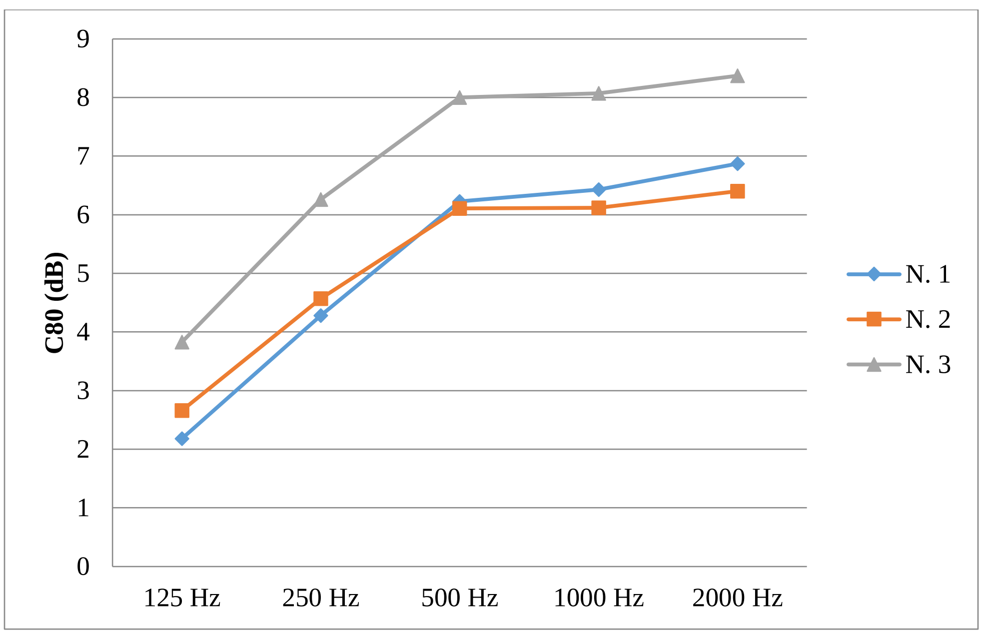
Graph 23 Average values of early decay time of the three versions of the theatre of Gortyna at Kazinedes, at each frequency.



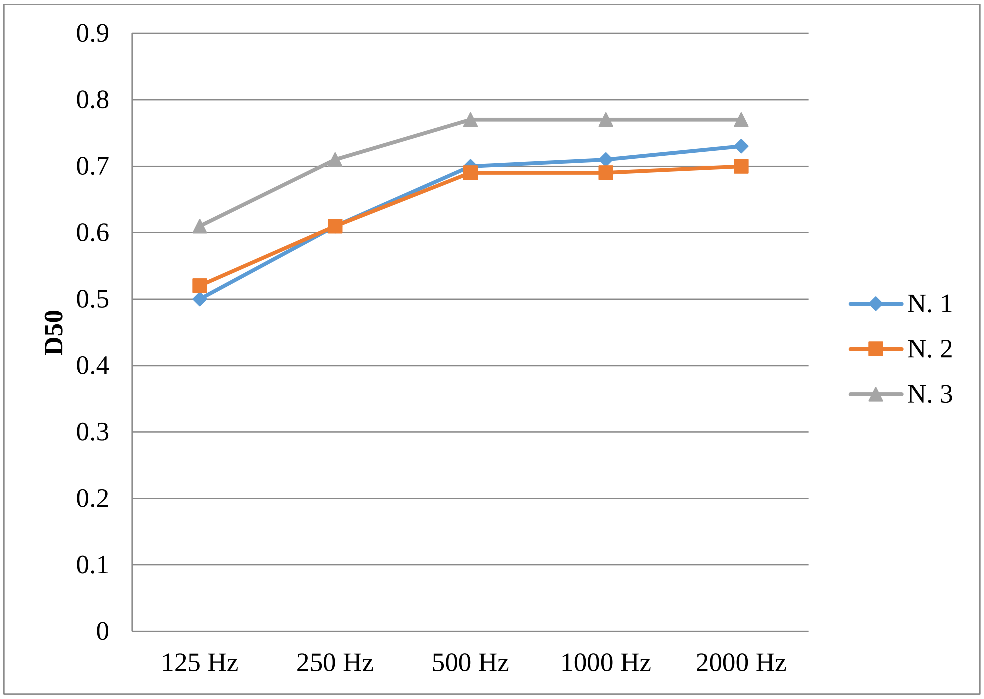
Graph 24 Average values of reverberation time of the three versions of the theatre of Gortyna at Kazinedes, at each frequency.



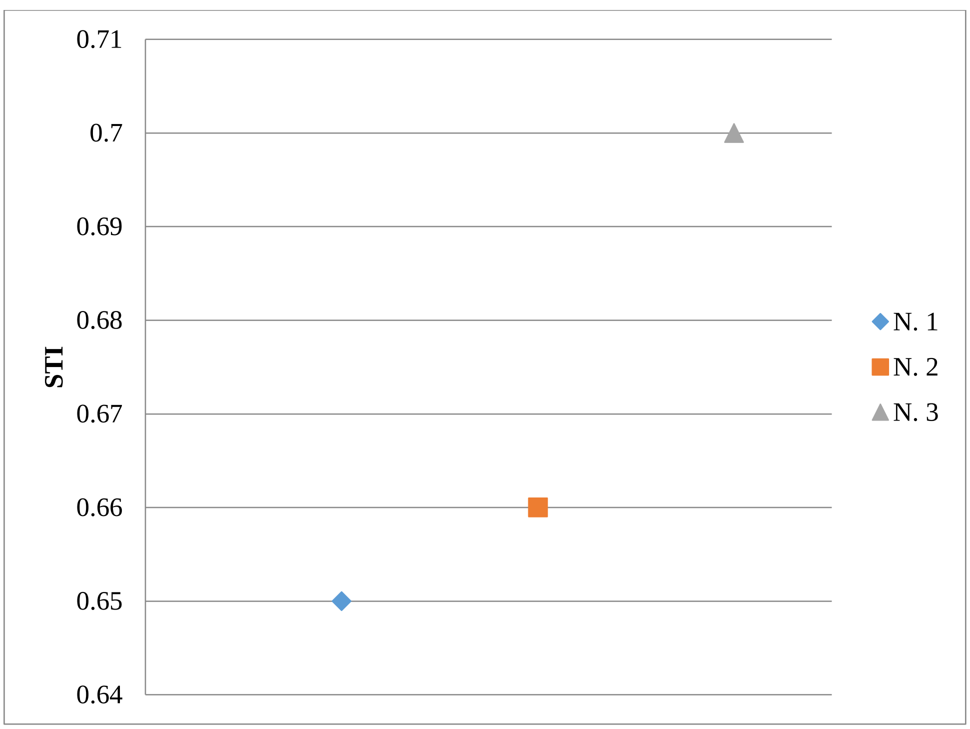
Graph 25 Average values of the difference between T30 and EDT of the three version of the theatre of Gortyna at Kazinedes, at each frequency.



Graph 26 Average values of clarity of the three versions of the theatre of Gortyna at Kazinedes, at each frequency.



Graph 27 Average values of definition of the three versions of the theatre of Gortyna at Kazinedes, at each frequency.



Graph 28 Average values of speech transmission index of the three versions of the theatre of Gortyna at Kazinedes.

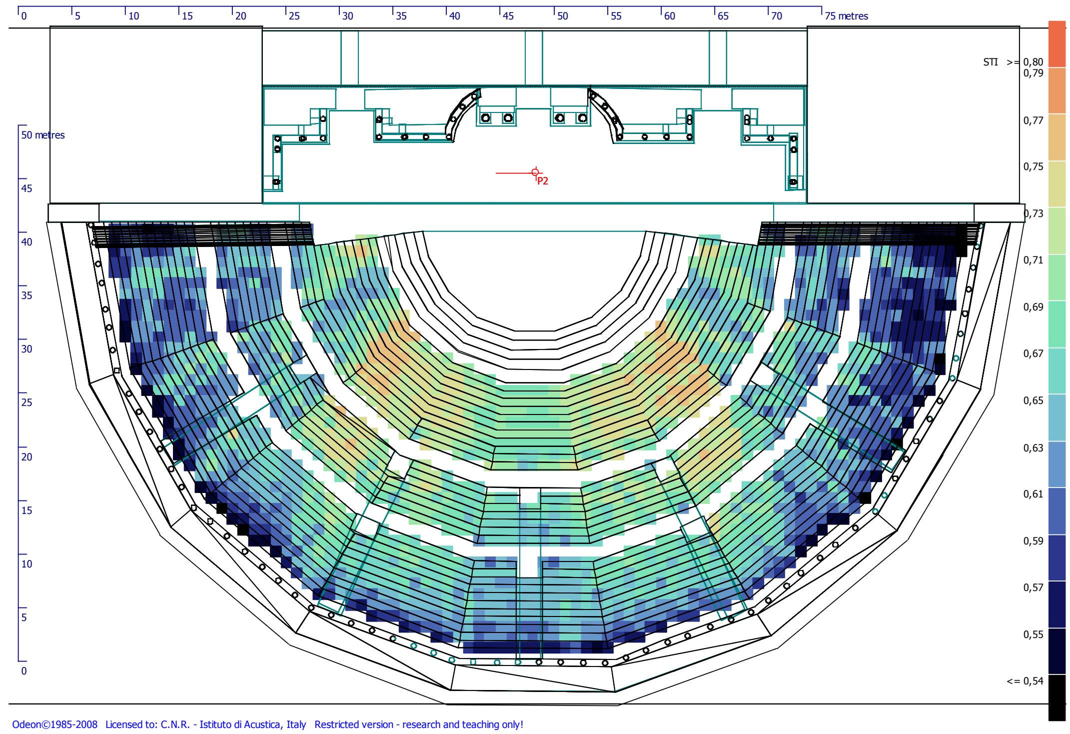


Figure 121 Grid of observers indicating the STI values for the model N.1.

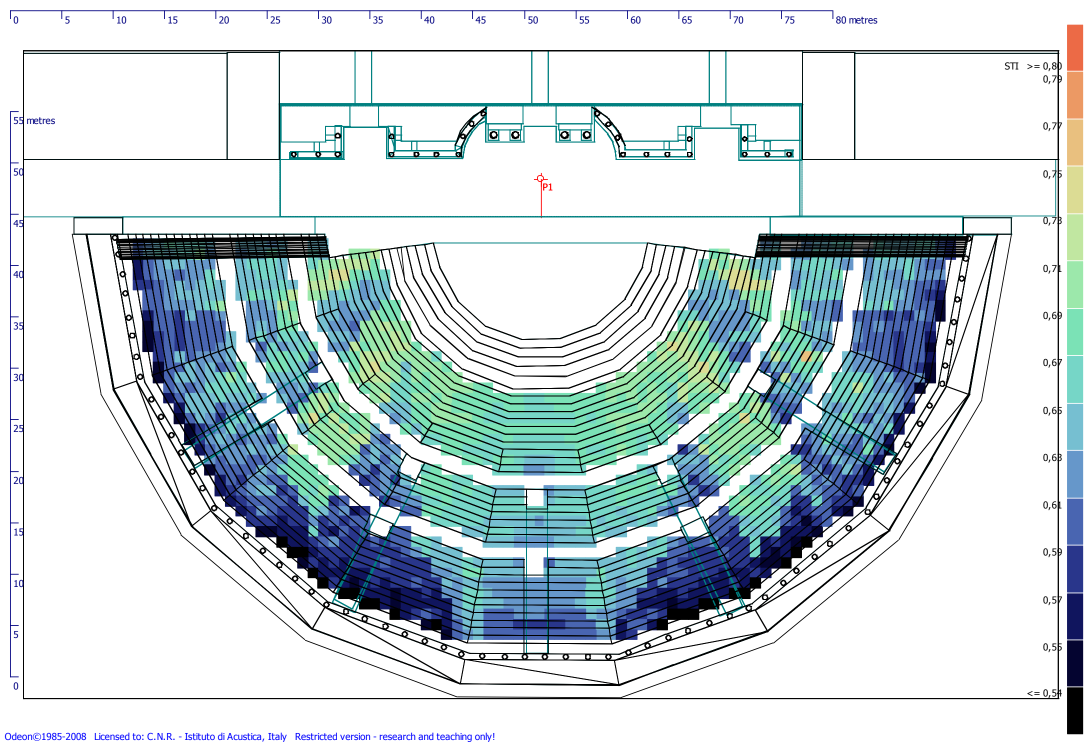


Figure 122 Grid of observers indicating the STI values for the model N.2.

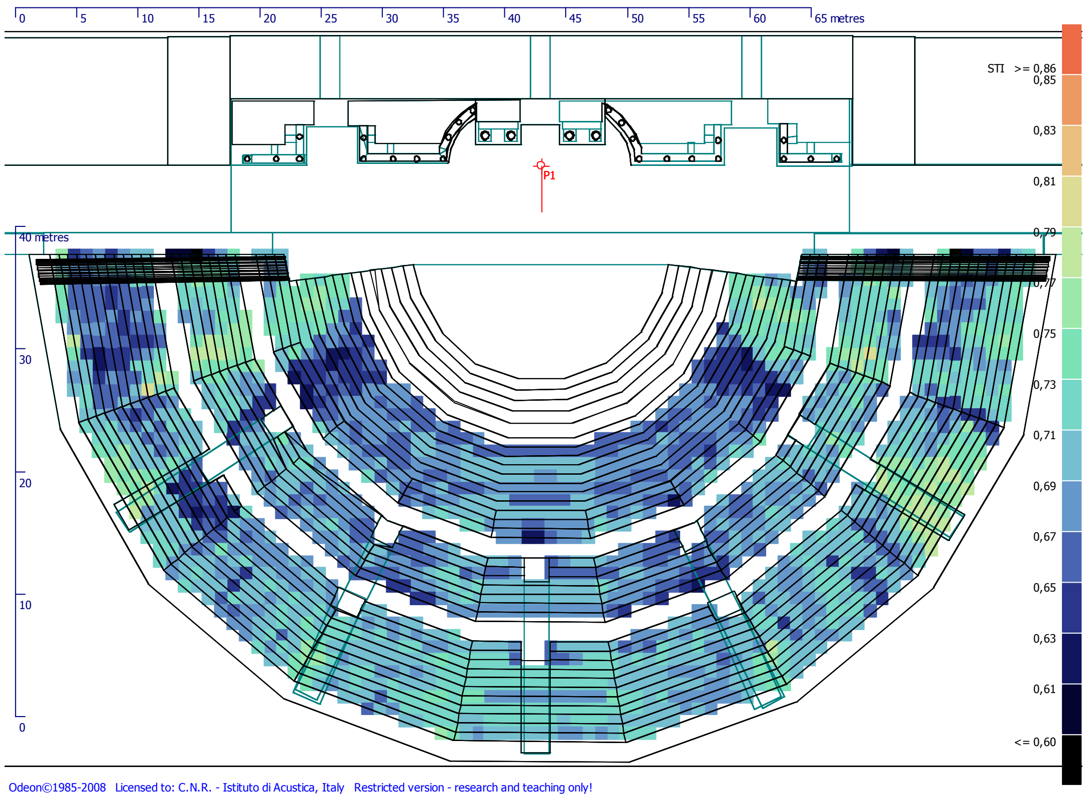
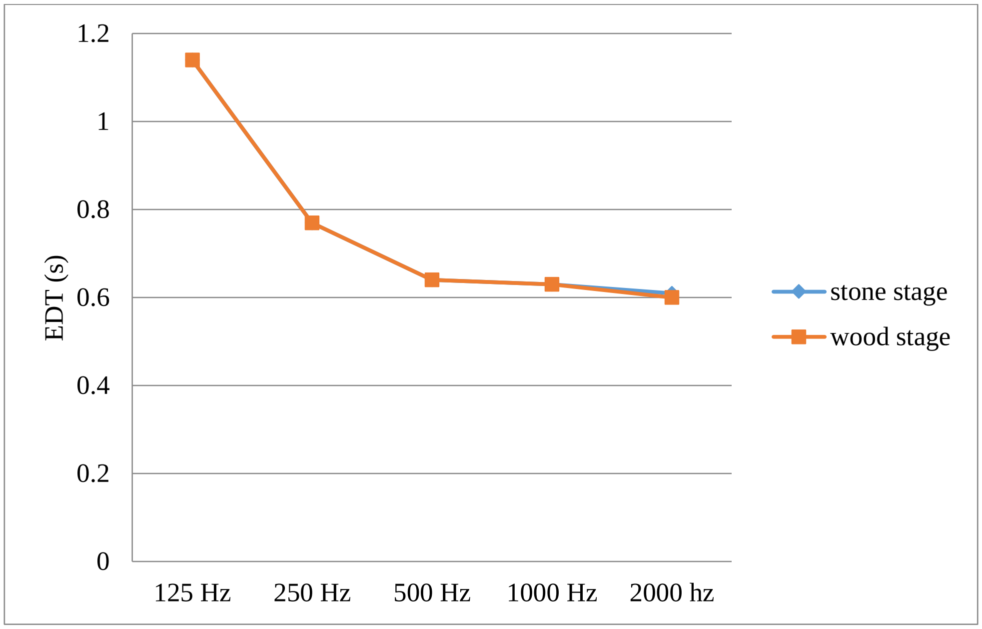


Figure 123 Grid of observers indicating the STI values of the model N.3.

	Model N.1	Model N.2	Model N. 3
Clarity (C80)	25%	19%	7%
Definition (D50)	15%	11%	1%

Table1 Percentage of the non-acceptable values of Clarity and Definition for each model, calculated on all the receivers placed.

Because there are no proofs that the stone was the material of the floor of the stage, another test has been done using a modified version of the most reliable reconstruction (N. 3): the stone material of the stage's floor has been substituted with wood. The values obtained do not show any difference between these two versions, as shown in the graphs 29-32. Also the average value of STI is the same for both versions: 0.70.



Graph 29 Average values of early decay time of the two versions, with stone stage's floor and wooded stage's floor, at each frequency.

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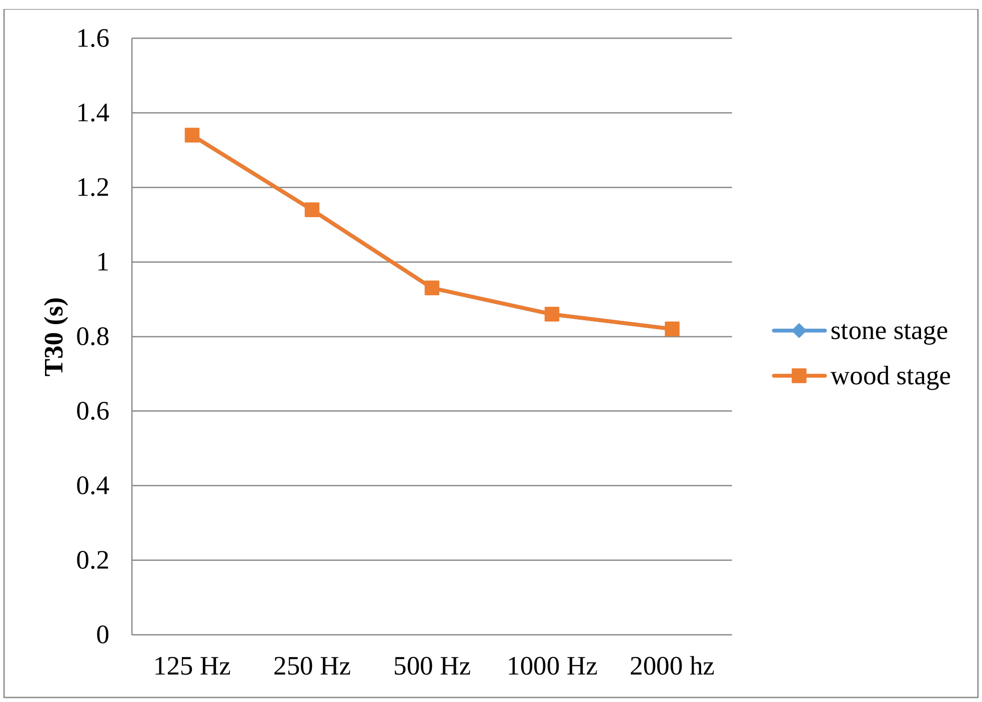
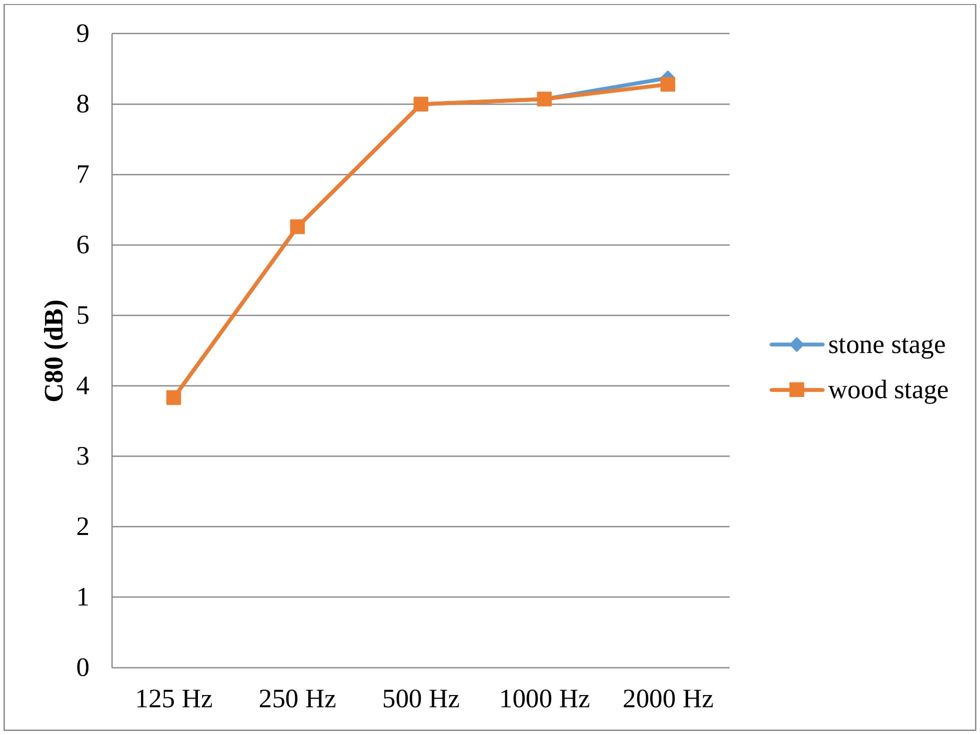
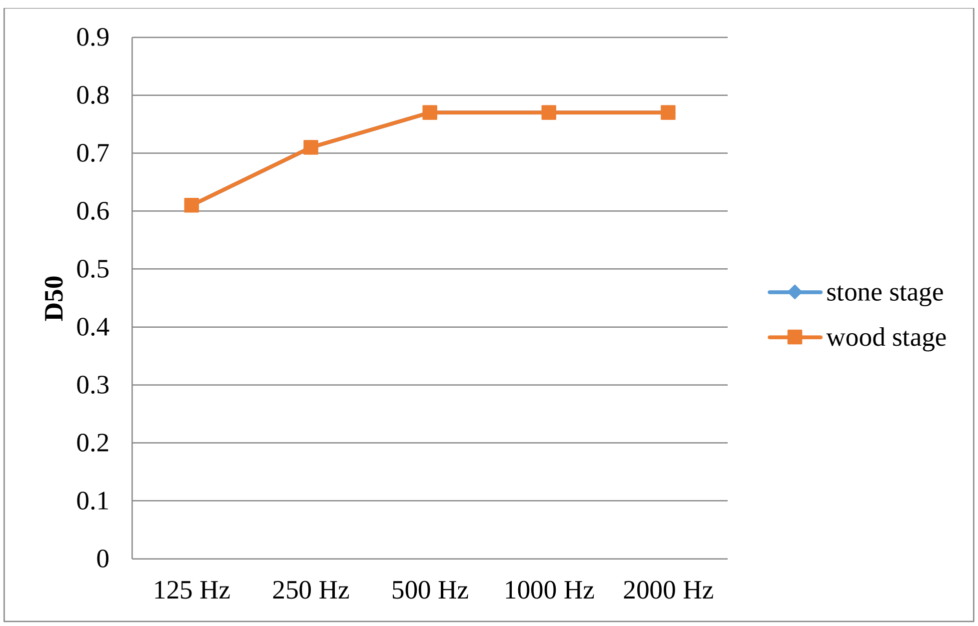


Graph 30 Average values of reverberation time of the two versions, with stone stage's floor and wooded stage's floor, at each frequency.



Graph 31 Average values of clarity of the two versions, with stone stage's floor and wooded stage's floor, at each frequency.



Graph 32 Average values of definition of the two versions, with stone stage's floor and wooded stage's floor, at each frequency.

5.6.3 Results and comments

The results collected through the analysis of archaeological plans and satellite images, the 3D visibility analysis and virtual acoustics analysis suggest that the original aspect of the theatre of Gortyna, at Kazinedes, should corresponds to Montali’s hypothesis, but without the portico in *summa* cavea and without rooms flanking the stage except for the staircases, in such case there was an open or vaulted corridor to reach the stage from its sides. The theatre at Kazinedes in Gortyna resulted to have a two storeys *scaenae frons* with three openings, a central one decorated with a semi-circular niche and the two lateral ones decorated by rectangular niches. The cavea was divided into three sectors by two *ambulacra* and it had a diameter of about 90 m (fig. 124-127).

Several Roman theatres present a *scaenae frons* decorated with a central semicircular niche and two rectangular at the sides, for example the theatre of Ercolano, the large theatre of Pompeii, the theatre of Urbs Salvia which had a deeper central niche, the theatre of Gubbio, the theatre of Fiesole which also had the semi-circular niche at the back of the *scaenae frons*, the theatre of Volterra with a larger central niche, the theatre of Verona in Italy; the theatres of Orange, Arles and Vasio (here the semi-circular niches at the back of the *scaenae frons* are present as well) in France; the theatre of Vienna in Austria; the theatre of Salonae in Croatia; the theatres of Augusta Emerita and Segobriga in Spain; the theatres of Cuicul and Thugga in North Africa; the theatre of Corinth in Greece (whom all niches are semicircular); the theatres of Petra and Philadelphia in Jordan; the theatres of Aezani, Hierapolis and Miletus in Turkey; the theatres of Apamea and Palmyra in Syria. Therefore, this kind of structure is widespread all over the Roman Empire. However, I think that it is interesting to note that of all the theatres located in Greece, only one (if we exclude the theatre at Kazinedes in Gortyna) has the *scaenae frons* decorated with semicircular entrances (the aforementioned theatre of Corinth).

Among these, the theatre of Vasio has also the open or vaulted *aditus*, separating the cavea from the scene building (fig. 128), as currently proposed for the theatre at Kazinedes in Gortyna.

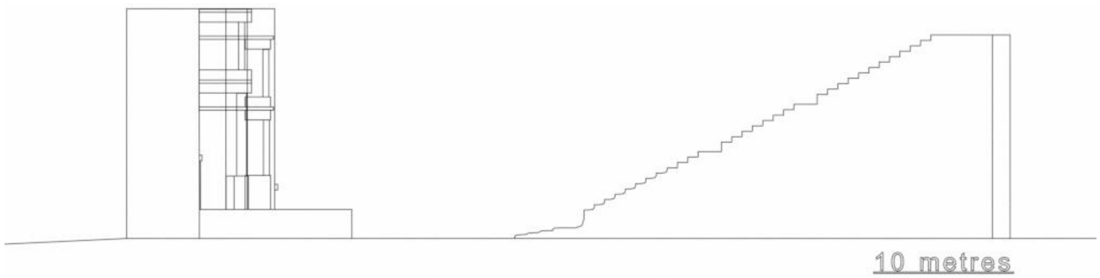


Figure 124 Hypothetical reconstructive section of the theatre at Kazinedes, Gortyna.

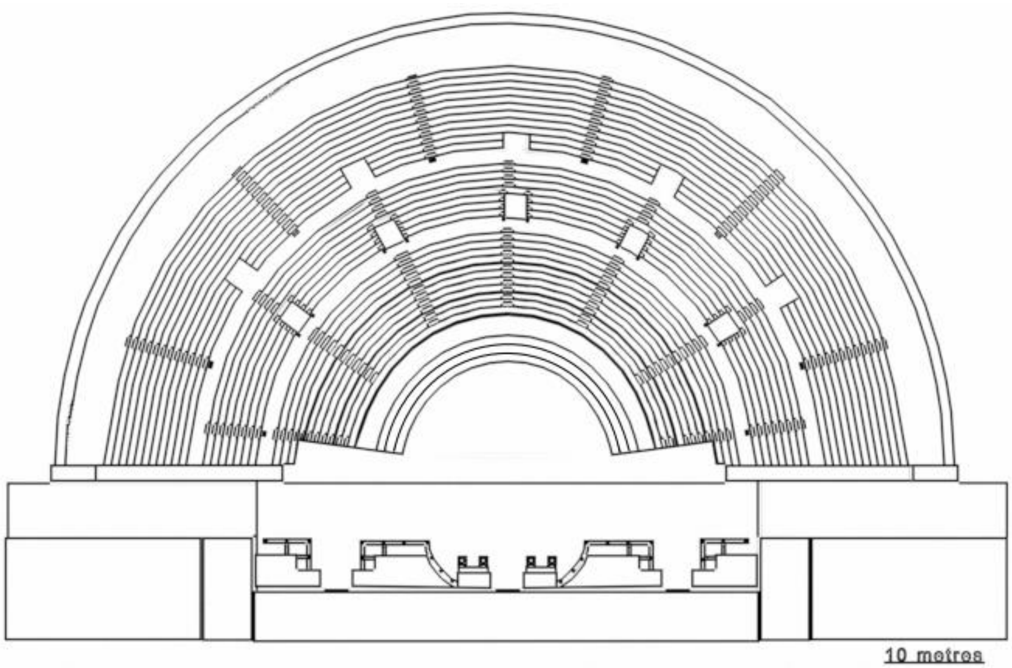


Figure 125 Hypothetical reconstructive plan of the theatre at Kazinedes, Gortyna.

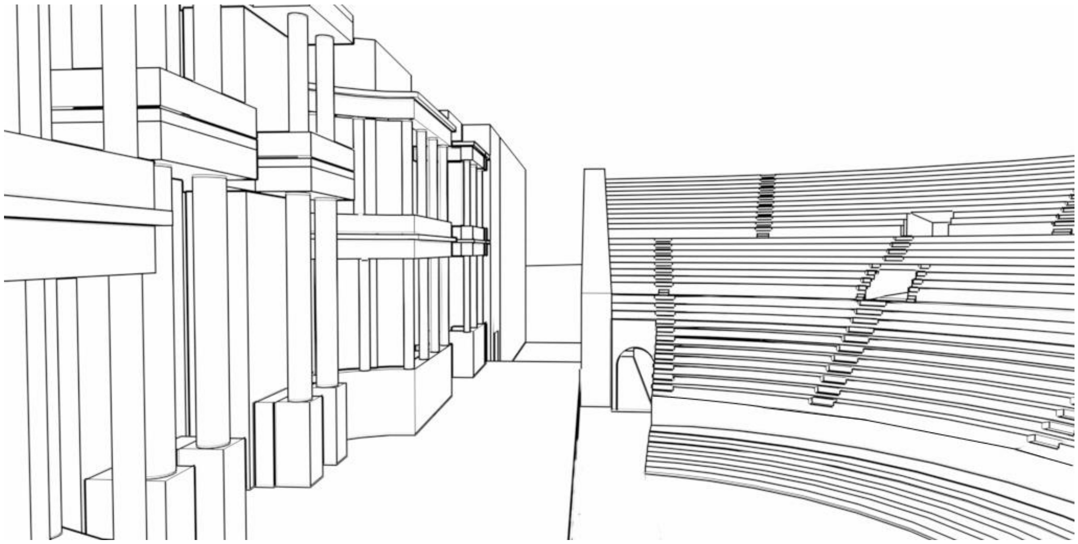


Figure 126 Hypothetical reconstructive drawing of the theatre at Kazinedes, Gortyna.

Figure 127 Rendering of the 3D model of the theatre at Kazinedes in Gortyna.

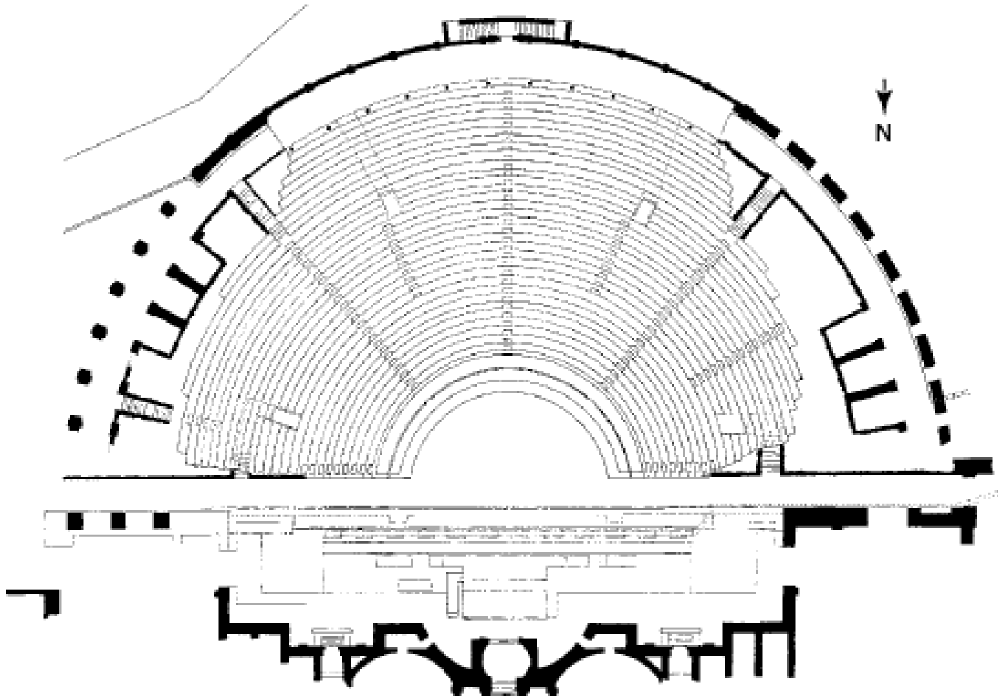


Figure 128 Plan of the theatre of Vasio in France (from Sear, 2006).

However, I have to admit that generally the theatres with such a *scaenae frons*, which is typically Roman (evident also by the few examples present in Greece and Turkey), have the cavea connected to the scene building obtaining a single closed block (which is also typical for the Roman theatres).

5.7 Theatre at Koufonissi

Koufonissi is a small and uninhabited island at south east of Crete. Its theatre is located at the north side.

The archaeological investigations in the island started in the 1970s.

The archaeologist Albert Leonard[46] from University of Arkansas was the first one to document the Roman theatre there. He describes it as a "small theatre constructed of undressed local stone and mortar". Since the area of the theatre was covered by sand and vegetation, Leonard was able to take only few measurements of the remains: the circumference of the cavea at its top that is 50 m, some of the seats, 0.80 x 0.35 m. In the same area, he also noticed fragments of three columns made out of grey conglomerate, which average diameter is 0.47 m. He did not see any remains belonging to the scene building and hypothesized that nothing is left because of the proximity of the modern beach.

Few years after, Nikos Papadakis[48] examined the remains on the island, taking pictures of the theatre as well. He did not mention the previous report made by Leonard, but he gave a very similar description. He said that the theatre is located 120 m far from the coastline, he could only see the upper part of the cavea while the rest is all buried under the sand, as shown in one of Papadaki's pictures (fig. 129).

Immediately after, archaeological excavations were initiated by the Ephorate of Classical Antiquities of Eastern Crete, and Papadakis resumed the results in a short paper[47], successively followed by a more thorough study.

Papadakis describes the structure of the theatre and the material used to build it, and he reported several measures of the remains[126]. He identified twelve rows of seats: the seats are 0.80-0.90 m wide and 0.40 m high, covered by slabs of terracotta in the area where the spectators used to sit. The cavea is made out of a white local porous stone, its diameter is around 34.40 m and the first row of seats is 21 m long. Between the cavea and the orchestra there is a short wall 0.70 m wide and 0.45 m high, decorated with multicolor plaster. The orchestra is little larger than a semicircle, its diameter is 12.50 m, and it is paved with slabs of terracotta. He identifies some ionic columns made out of white-red marble, 3.46 m high. He assumed a length of the scene building of around 20 m. The capacity of the theatre might have been around 1000 spectators. He also mentioned the presence of vaulted *parodoi.*

Figure 129 Picture of the area of the theatre dated to the early '70s of the last century (from Papadakis, 1976*).*

The theatre has been mentioned by Touchais[49], [50] too at the end of the '70s but he did not add any further information.

In more recent times, the area of the theatre at Koufonissi has been investigated also through geophysical prospection carried out by the Laboratory of Geophysical-Satellite Remote Sensing and Archaeo-environment of the Foundation for Research and Technology Hellas (FORTH)[62]. The magnetometer was used in a very large area (100x200 m), while the GPR was used to investigate only few small parts at NW, S and in the middle, up to 2-2.5 m deep. Part of the scene building has been identified, from 0.60-0.80 m up to 1.20 m deep, by the GPR, confirming the hypothetical length given by Papadakis, of 20-21 m. The GPR has located the *thymele* at the center of the orchestra as well (fig. 130). At the time of the prospection, the distance of the theatre from the sea was 90 m, 30 m less than the time when Papadakis measured it. This suggests that it is essential to intervene quickly in order to protect the structure from the sea.

In the reconstruction of the 3D model of the theatre of Koufonissi, aerial photo (fig. 131) and satellite images have been very useful. They have been imported and scaled in AutoCad. The boundary of the orchestra has been identified and 12 rows of seats have been drawn according to the dimensions given by Papadakis. The east area of the scene building is visible and thus it has been easy to create the same part on the west side (fig. 131). The plan has been extruded in 3D Studio Max, again following the indications of Papadakis for the height of the seating area. Given the average diameter of the columns that probably were decorating the *scaenae frons* (0.47 m) their height has been reconstructed according to the Vitruvian rules of harmony.

From the aerial picture, the theatre of Koufonissi does not look like a classical Roman theatre: the scene building is shorter than the full diameter of the cavea and the basilicas are not attached to the *analemmata* or the cavea.

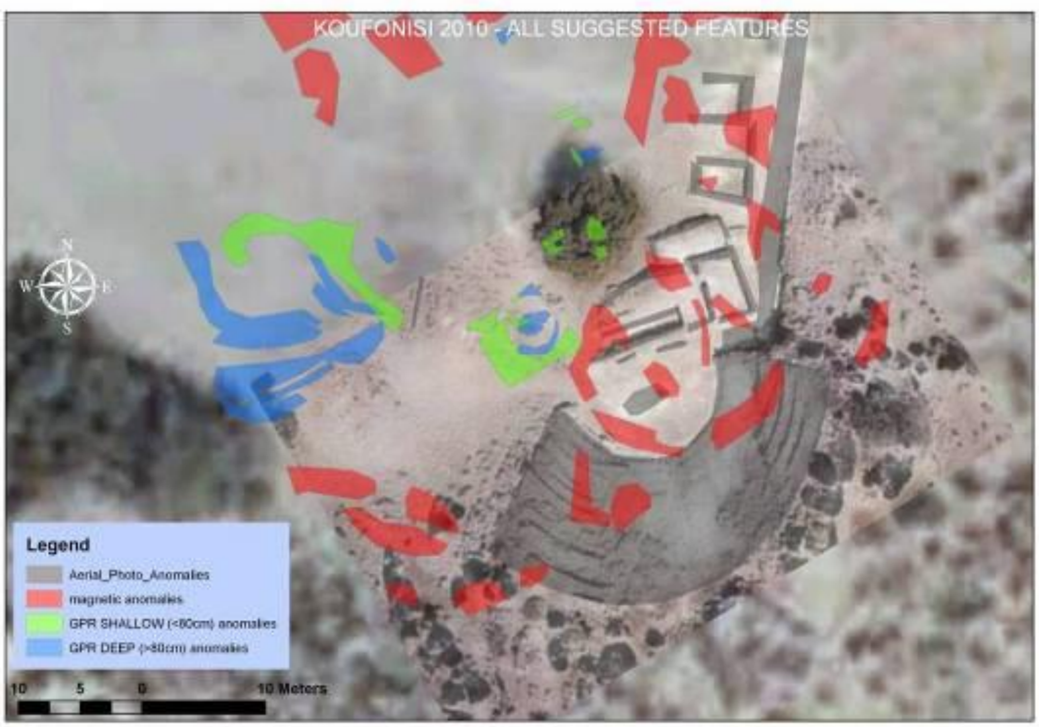


Figure 130 Resulting anomalies from the geophysical survey, superimposed to an aerial photo of the area occupied by the theatre at Koufonissi (from Papadopoulos and Sarris, 2010).

Figure 131 Aerial picture of the site of the theatre of Koufonissi (from the website Diazoma).

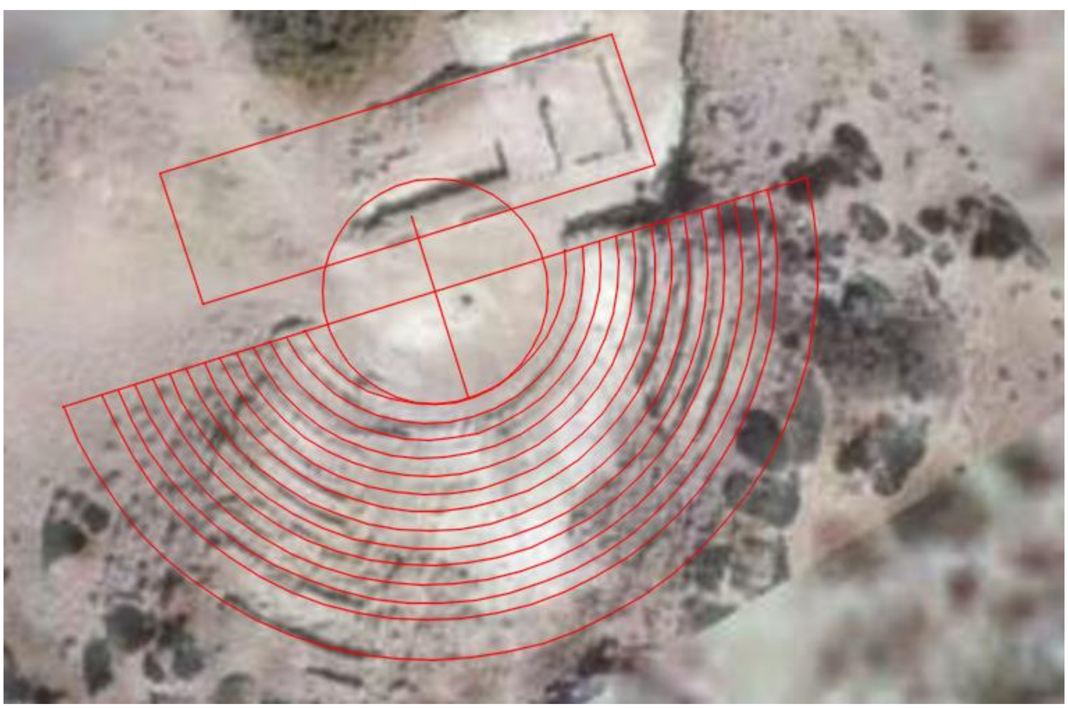


Figure 132 Aerial picture of the area occupied by the theatre of Koufonissi plus its drawn plan in AutoCad.

5.7.1 3D visibility analysis

Only one 3D model has been reconstructed for the 3D visibility analysis, since the structure of the cavea and the one of the stage are pretty clear. The grid is composed by 48 observers points located in four lines in the cavea, 0.75 m higher than the seats (for a detailed explanation refer to the methodology chapter, p. 56) (fig. 133).

The calculation of the lines of sight from the observer points in the seating area to the hypothetical positions of the actors on the stage, gave as result that 10% of the lines are not visible trajectories and 90% are visible trajectories.

As predictable, the obstruction points are located on the *basilicae* at the sides of the stage but they impede only the visibility of the sides of the stage; the central part is still visible by everyone or almost everyone, as it is shown in the frequency of visibility map (figs. 134 and 135).

The high percentage of visible trajectories between the cavea and the stage, plus the visibility of the central part of the stage by everyone, or almost everyone in some cases, suggests that this 3D model may be a correct, or partially correct, reconstruction of the structure of the theatre of Koufonissi.

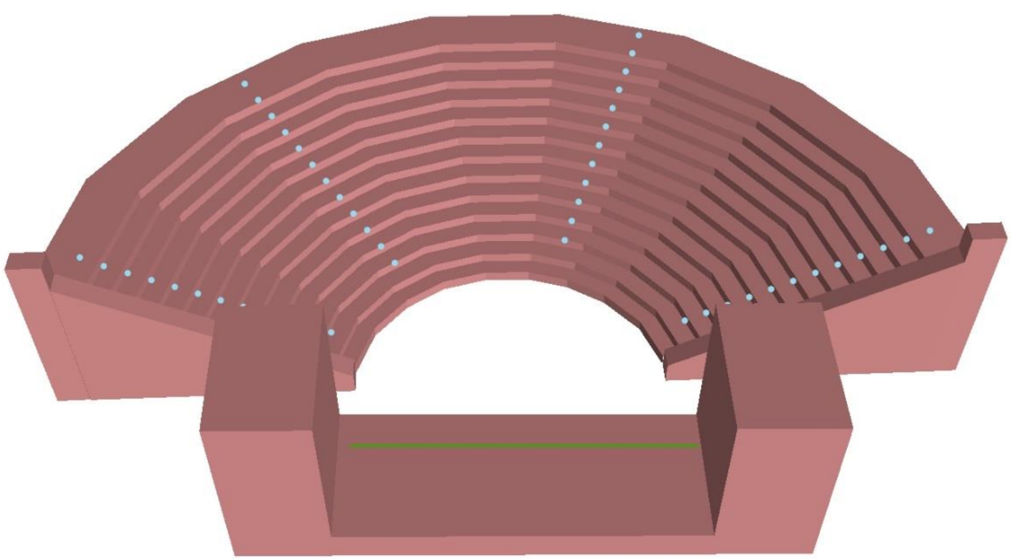


Figure 133 3D model of the theatre of Koufonissi with the observer points in the cavea.

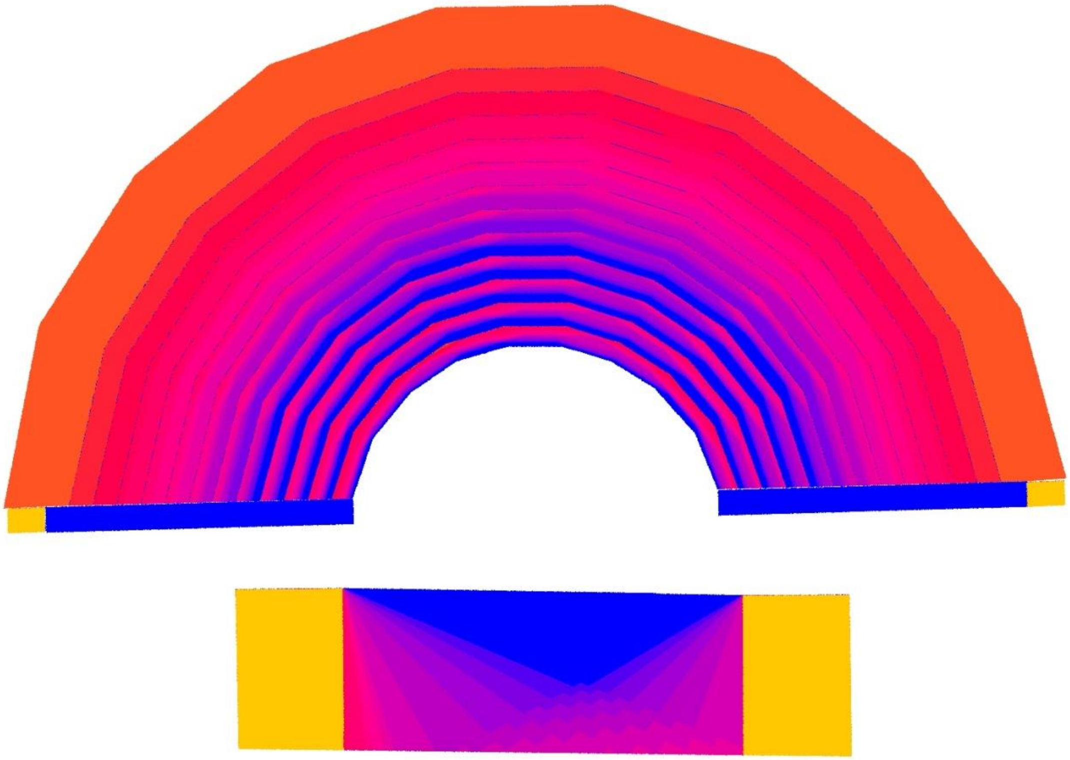


Figure 134 Map of frequency of visibility of the theatre of Koufonissi. The colors show the different level of visibility for the observer points, as it is explained in its correspondent graph (fig. 133).

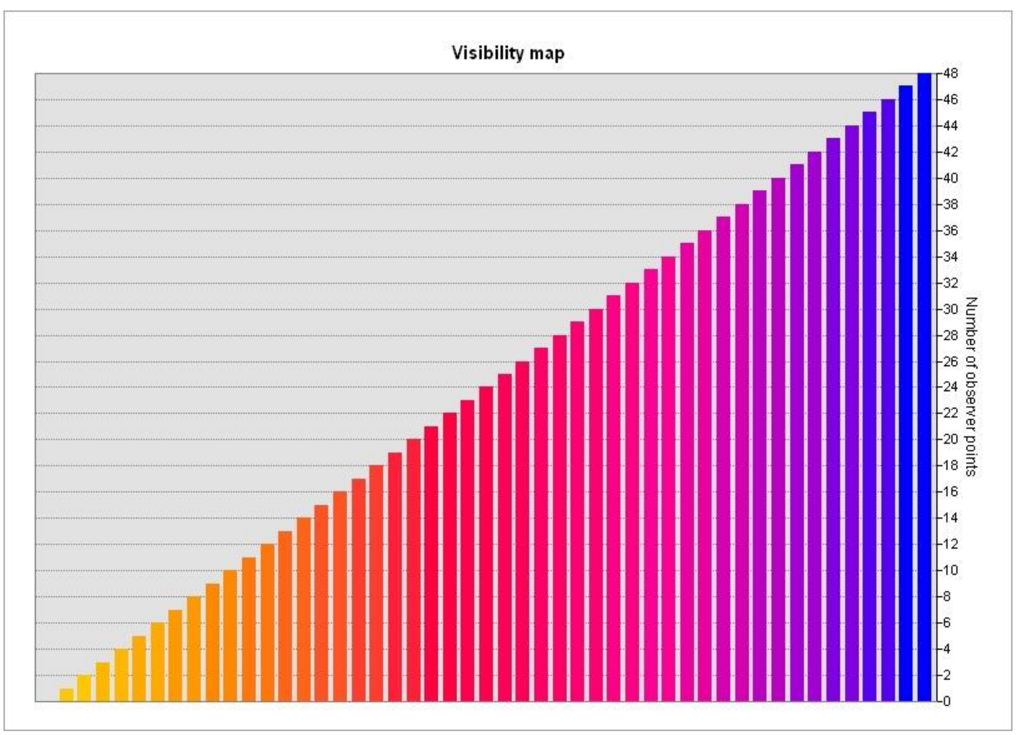


Figure 135 Graph of visibility map of the theatre of Koufonissi. The color scale is from yellow to blue. The yellow color means that those areas are visible to none of the observer points; the blue colour indicates the area visible by all 48 observer points.

5.7.2 Virtual acoustics analysis

Three different 3D models have been created to verify which is the most reliable reconstruction, according to virtual acoustics analysis: the model N.1 is based on the indication given by the archaeologists and on the visualization of the satellite pictures; the model N.2 is the same as the N.1 plus the roof over the stage; the model N.3 is the same as N.2 plus the portico in *summa* cavea[62].

Three lines of receivers have been placed in the 3D model, each one with 4 receivers (one receiver every three seats) for a total of 12 receivers. A source has been placed at the center of the stage (figs. 136 and 137) (for detailed explanation refers to the methodological chapter, p. 65).

The material applied to the 3D model, according to Leonard and Papadakis are the following:

1. Stone: cavea, *scaenae frons*, *postascaenium*, basilicas
2. Marble: columns.
3. Plaster: podium.
4. Terracotta: orchestra.
5. Wood: doors of *scaenae frons.*
6. Audience: seating area.

[62] The choice to test one model with portico in *summa* cavea is due to the fact that the classical Roman theatre is designed with it.

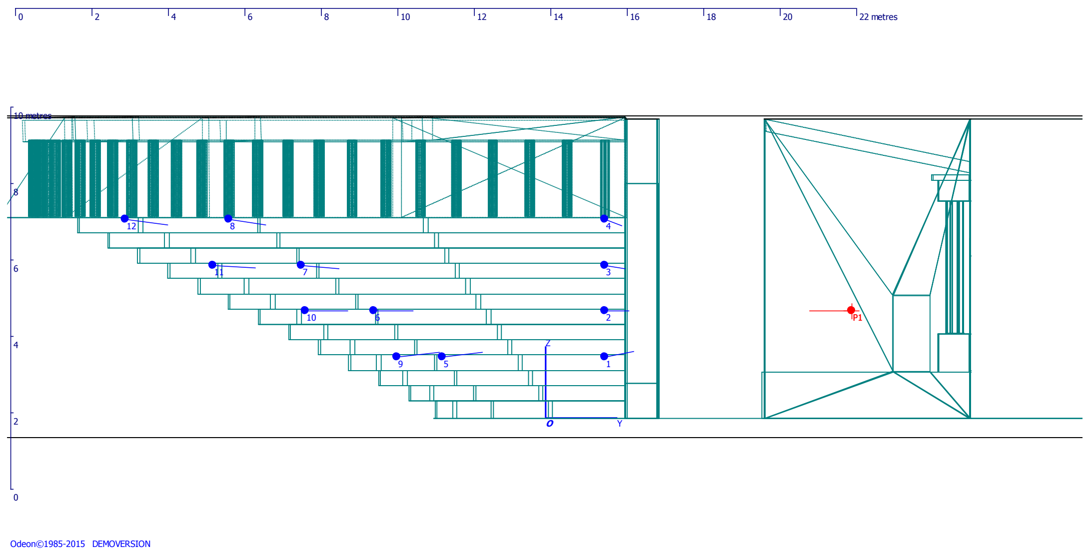


Figure 136 Plan of the 3D model of the theatre of Koufonissi in Odeon Room Acoustics, plus receivers and source.

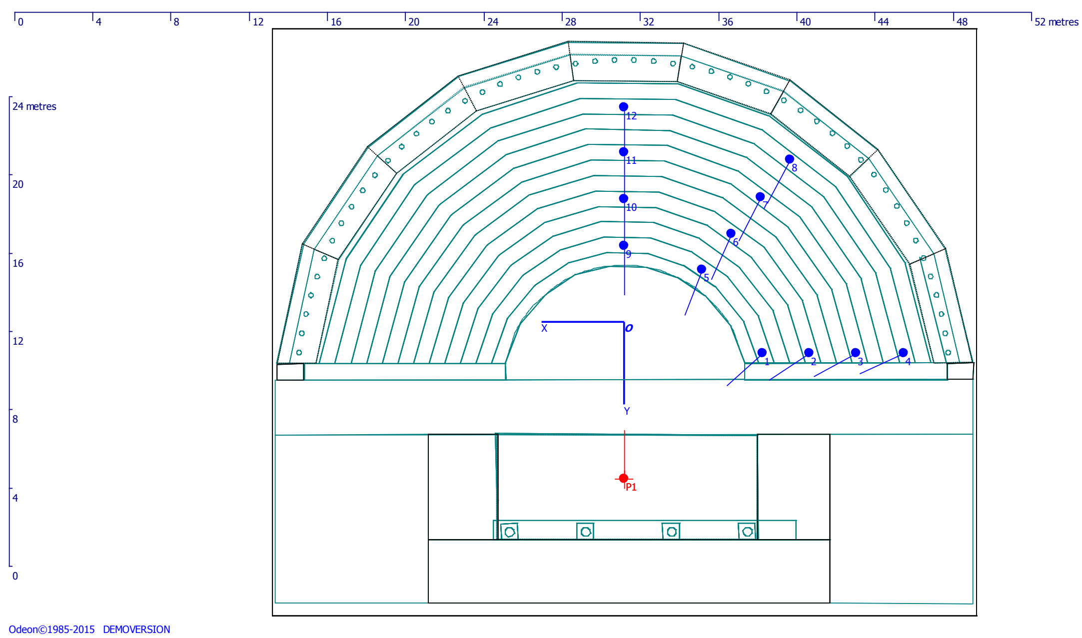
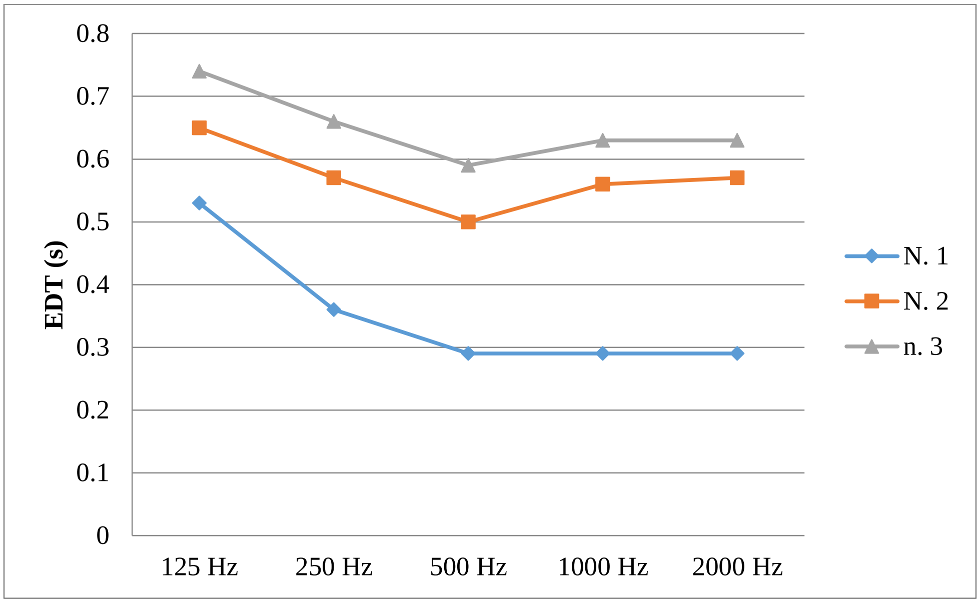
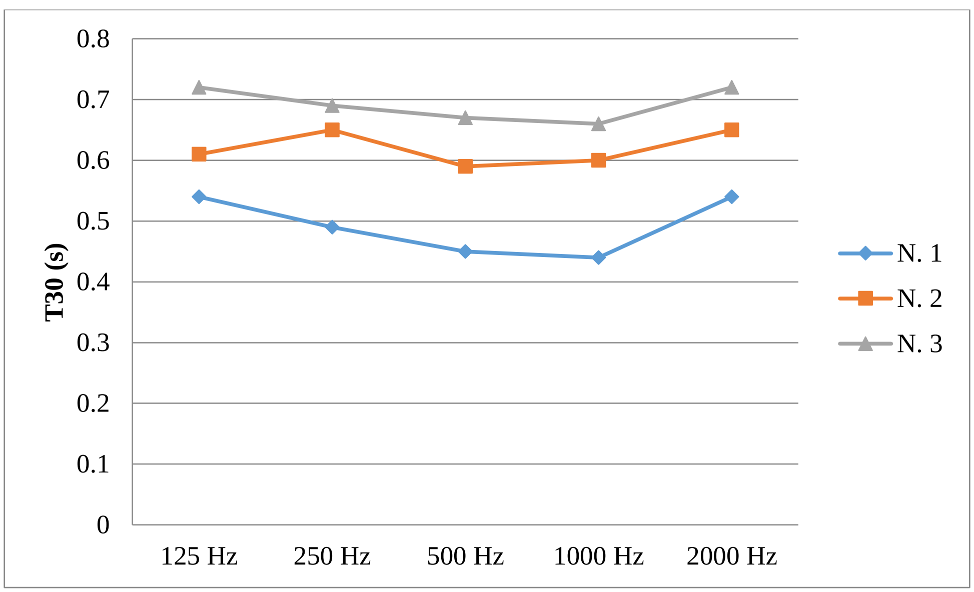


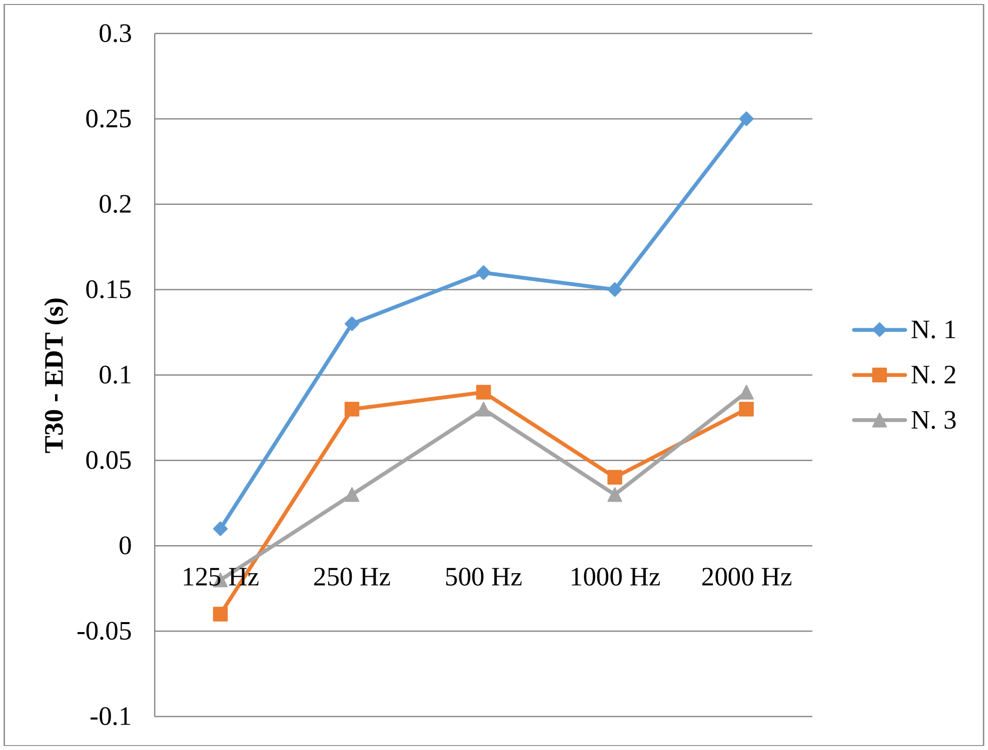
Figure 137 Section of the 3D model of the theatre of Koufonissi in Odeon Room Acoustics, plus receivers and source.



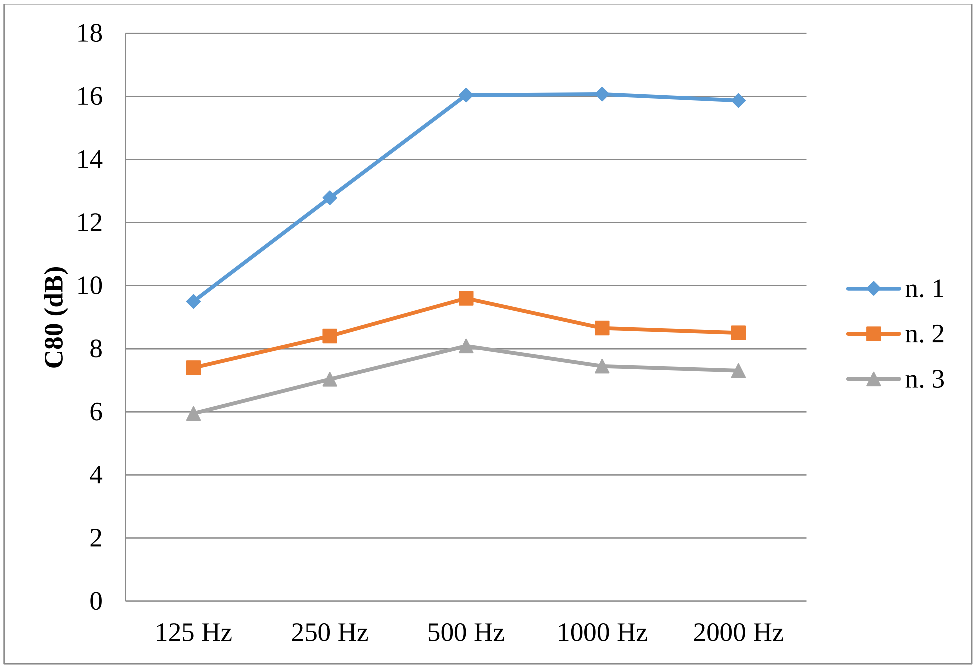
Graph 33 Average values, at each frequency, of Early Decay Time for all the receivers, for each 3D model.



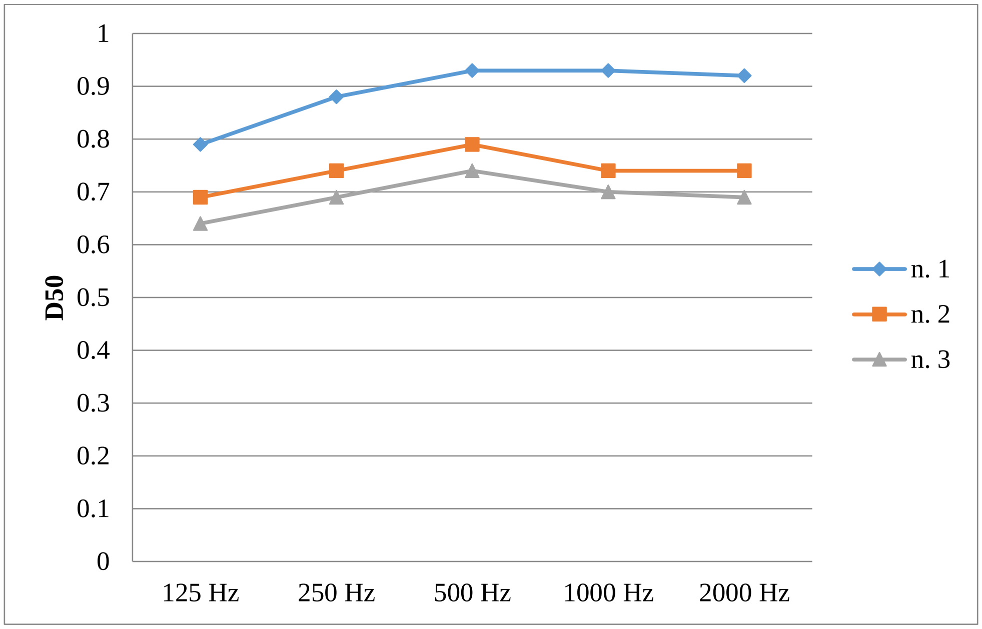
Graph 34 Average values, at each frequency, of Reverberation Time for all the receivers, for each 3D model.



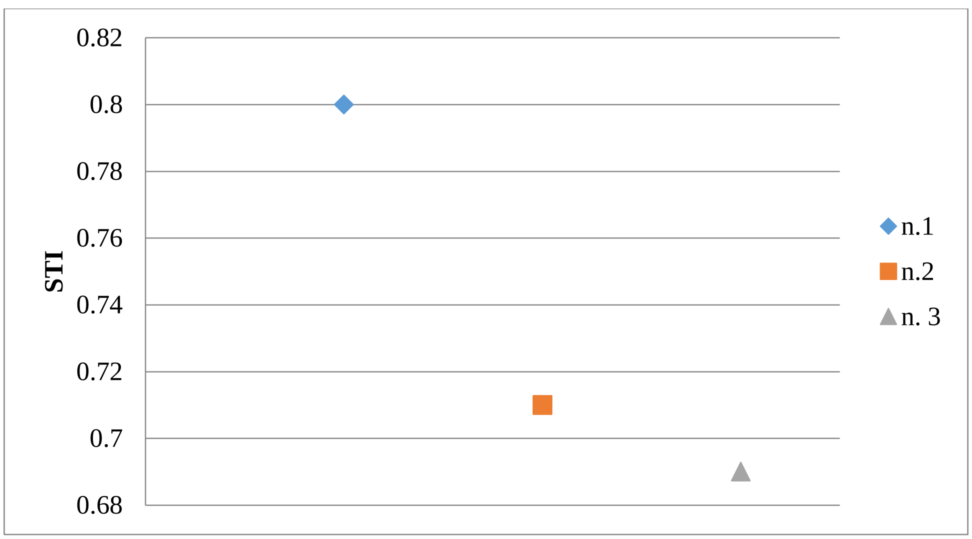
Graph 35 Average values of the difference between T30 and EDT, for each model.



Graph 36 Average values, at each frequency, of Clarity for all the receivers, for each 3D model.



Graph 37 Average values, at each frequency, of Definition for all the receivers, for each 3D model.



Graph 38 Average values of Speech Transmission Index for all the receivers, for each 3D model.

From graphs 33-38 it is evident that the values of the acoustics parameters are different for each model, but all of them are within the range of acceptable values for a good quality of the acoustics. The results of the STI suggests that the model N. 1 has an excellent comprehension of the speech, while the model N. 2 and N. 3 have a good comprehension. The T30 of the model N. 1 seems to be too low and the subjective perception of the reverberation (EDT) is of course even lower. Despite this, the values of C80 and D50 are very good, indicating the ease to understand a performance there. The models N. 2 and N. 3 presents a higher reverberation time (T30) and early decay time (EDT) but lower clarity (C80) and definition (D50).

The model N. 1 looks the most suitable for speech performance despite the low values of T30, but it might be possible that there was a roof above the stage in order to improve the latter and to obtain a fuller sound. Instead, I would tend to exclude the idea of the portico in *summa* cavea since there is not any improvement of the acoustics quality in the model N. 3, and since there is not archaeological evidence about the presence of the portico, it is more likely that it did not exist.

5.7.3 Results and comments

Archaeological data, geophysical prospection, 3D visibility analysis and virtual acoustics analysis seem to bring to the same reconstructive hypothesis of the theatre of Koufonissi. The cavea is not divided by any ambulacrum and it is composed by 12 rows of seats made out of local stone and terracotta. The *aditus* lead to the orchestra and divided the scene building from the *analemmata* at the sides of the cavea; they might have been covered by vaults. The *scaenae frons*, is rectilinear, it had three entrances for the actors and two *basilicae* at its sides. Few columns probably decorated the *scaenae frons* composed only of one storey. The length of the scene building is not the same as the diameter of the cavea, but shorter (figs. 138-141).

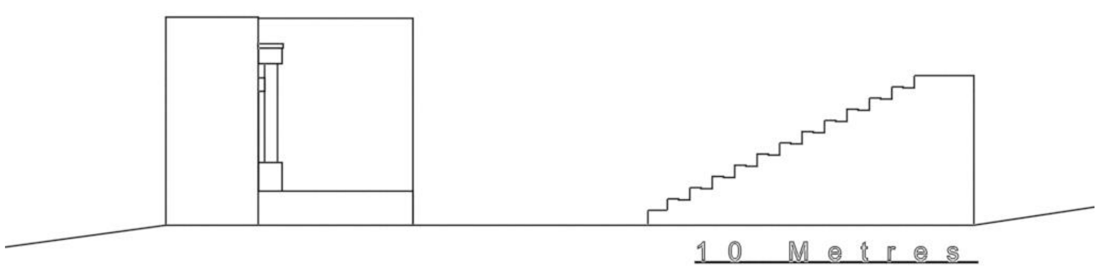


Figure 138 Hypothetical reconstructive section of the theatre of Koufonissi.

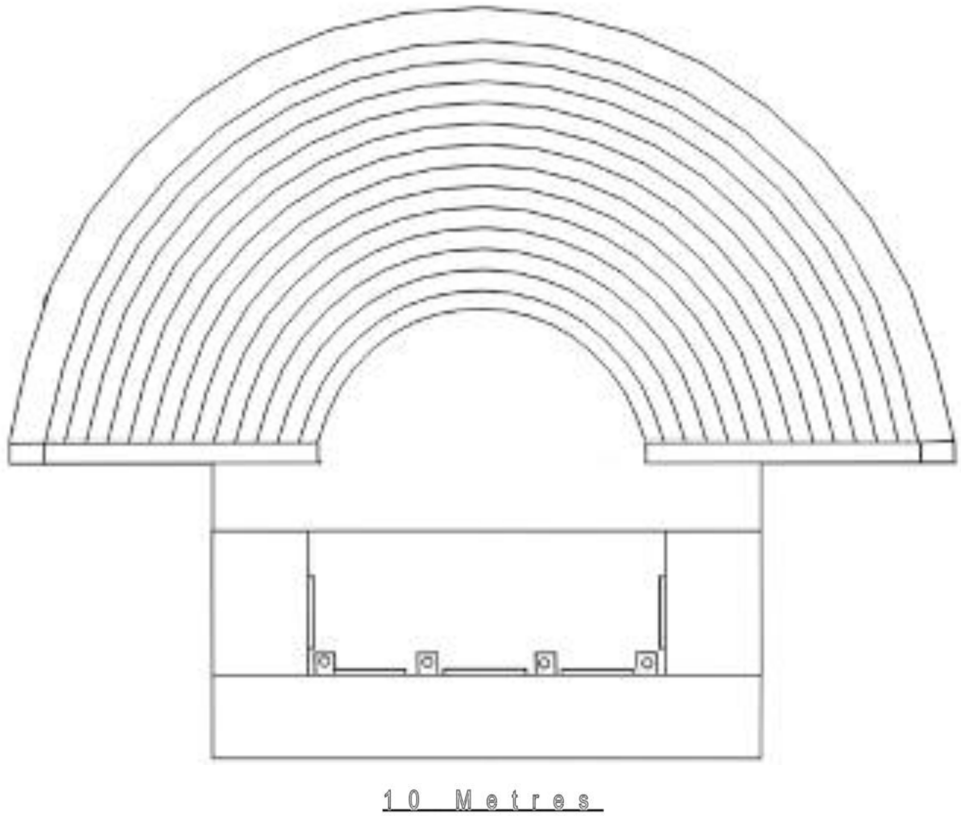


Figure 139 Hypothetical reconstructive plan of the theatre of Koufonissi.

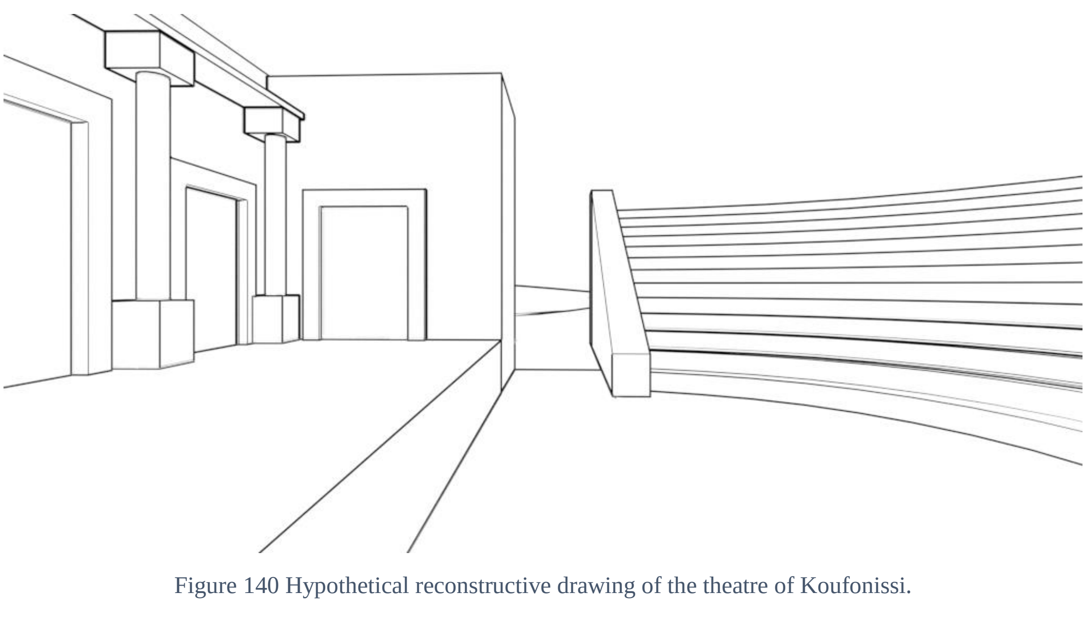


Figure 140 Hypothetical reconstructive drawing of the theatre of Koufonissi.

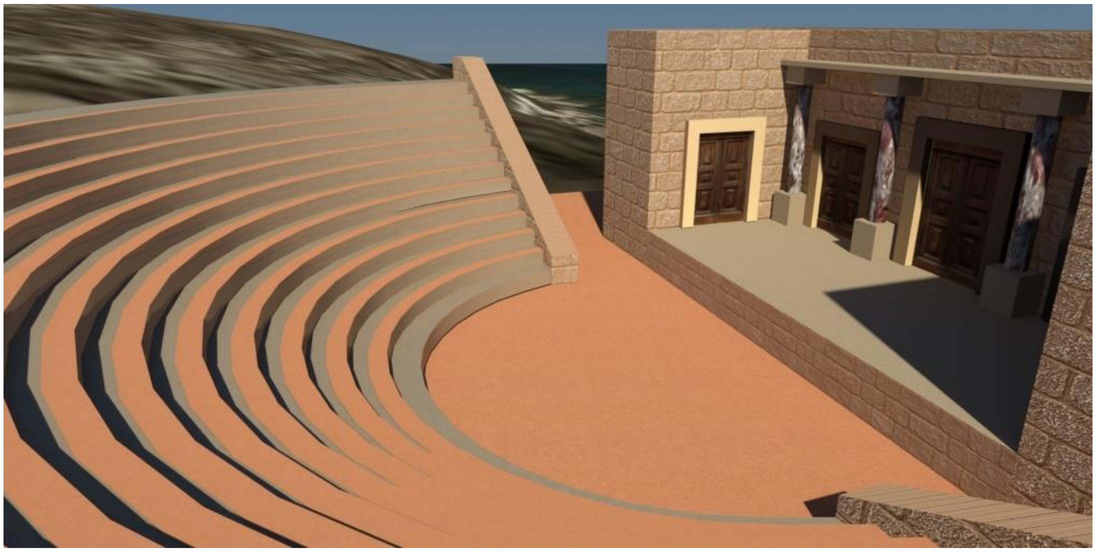


Figure 141 Rendering of the 3D model of the theatre of Koufonissi.

The structure of the theatre of Koufonissi may be compared with the one of Segesta[63] in Italy, even if the dimensions of the latter are much bigger. In both theatres the *analemmata* and the *aditus* were parallel to the stage; the stage was flanked by two *basilicae* not connected to the *analemmata*, and the scene building is shorter than the diameter of the cavea (fig. 142). The theatre of Segesta is actually a Greek theatre and its first construction is dated to the V century BC and its last phase is dated to the I century BC[65].

In Sicily there is another similar theatre, the one of Solunto[64]: here we have only one sector of seats (without separation in *ima*, *media* and *summa* cavea), but the cavea exceeds a bit the semicircle; however the scene and the cavea are separated by the *parodoi* and the scene building is shorter than the diameter of the cavea (fig. 143). Also the theatre of Solunto is a Greek theatre: built in the IV century BC, then abandoned and rebuilt within the I century BC[65].

Also in Turkey there is a theatre with such a structure. The theatre of Alinda, built in Greek time and then restored in the Augustan period, presents a cavea that slightly

[63] Segesta was an ancient colony in Sicily, which date of foundation is unknown.

[64] Soluntum is a Greek colony founded in the IV century BC.

exceeds the semicircular cavea, *parodoi* separating the cavea from the scene building, and the latter is shorter than the full length of the cavea (fig. 144). The theatre of Alinda has been built between the end of the III century and the beginning of the II century BC[65].

In Greece, exactly at Dium in Macedonia, there is a similar theatre, that it is also defined as an odeum, which is dated to the Roman times, namely the II century AD. Again we have a shorter scene building than the diameter of the cavea, a rectilinear *scaenae frons*, and the cavea slightly exceeding the semicircle (fig. 145)[65]. Another example in Greece, of a theatre with a similar structure and probably dated to the early Roman times, but rebuilt in II/III century AD, is at Nicopolis, in Epirus (fig. 146)[65].

This kind of structure clearly remind the Greek theatre, characterized in particular by open *parodoi* and the inferior length of the scene building with respect to the length of the cavea. Indeed we have similar examples in Italy, Greece and Turkey, where actually there were also Greek theatres[65]. The cases of Dium and Nicopolis are quite interesting because also if they are dated to the Roman times, they partially have a Greek aspect, exactly as the theatre of Koufonissi[66]. More in particular, we can notice that the theatre of Segesta and the one in Solunto are the most similar to the theatre of Koufonissi because they have *basilicae* at the sides of the stage too.

[65] We do not have such kind of theatres in North Africa and the western and northern part of the Roman Empire.

[66] Of course, in Greece, Italy and Turkey, there are much more of these kind of theatres (open *parodoi* and a shorter scene building) but they all have a different shape of the cavea, which largely exceed the semicircle (see the theatre of Stobi and Caunus) or a different kind of scene building (see the theatre of Telmessus).

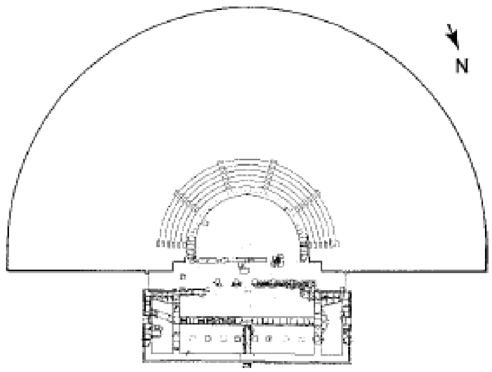


Figure 142 Plan of the theatre of Segesta in Italy (from Sear, 2006).

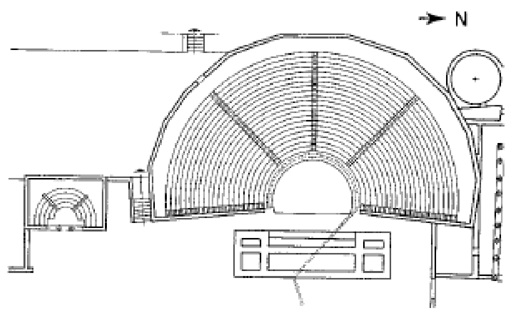


Figure 143 Plan of the theatre of Solunto in Italy (from Sear, 2006).

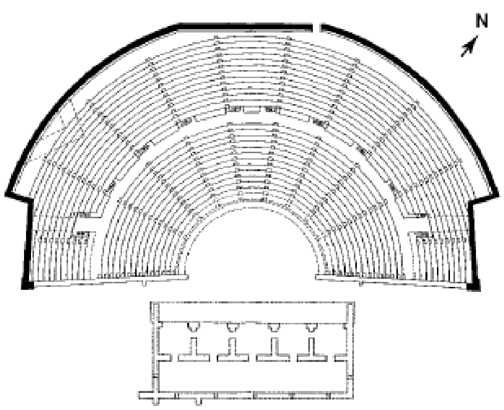


Figure 144 Plan of the theatre of Alinda in Turkey (from Sear, 2006).

Figure 145 Plan of the theatre of Dium in Greece (from Sear, 2006).

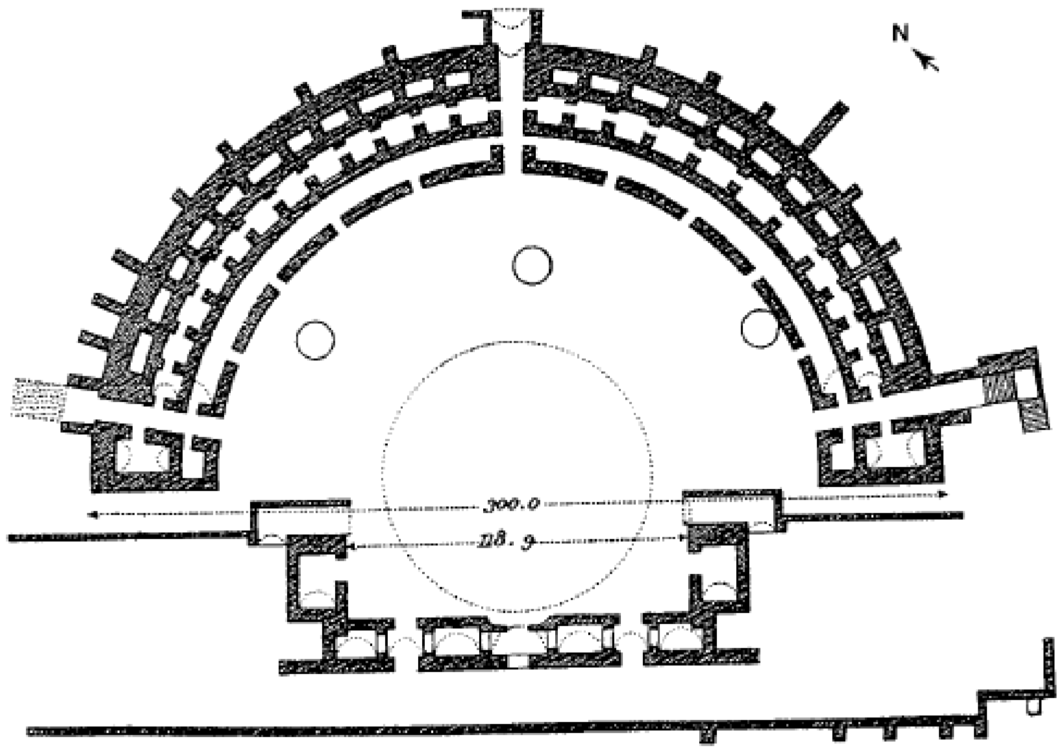


Figure 146 Plan of the theatre at Nicopolis in Greece (from Sear, 2006).

5.8 Theatre at Lissos

The Roman theatre of Lissos is localized in the archaeological site, close to the church of Agios Antonios, in the south-west of the island. It has not been excavated and the information about it is so scarce that does not allow any kind of reconstruction.

The first one that mentioned this theatre is Captain Spratt in the second half of XIX century. He only affirms that “at Lissos there are the remains of a theatre 78 feet in diameter”[37]. The second one to document the theatre is Ian Sanders[16], measuring a diameter of 15 meters, shorter than the diameter given by Spratt.

In the map of the archaeological site, it is also expressed the doubt if it is a theatre or an odeon, since it is very small, and the monument is represented with seven or eight rows of seats.

A survey has been done in the area of the theatre, with the support of GeoSat ReSeArch Lab, in order to obtain more information. Some measurements of the remains have been taken manually and through GPS, and some low aerial pictures were taken through an unmanned aerial vehicle (fig. 147). Few blocks of stone forming the seats are still visible (fig. 148), so it was easy to obtain the height of the rows of seats. The diameter of the cavea results to be of 22 m, as Spratt observed. However, it is evident from the low aerial picture that the remains are very scarce and it seems impossible to identify the scene building, without an archaeological excavation or a geophysical survey. In addition, the north side of the theatre is occupied by a modern construction.

It is not clear if the rectangular structures at both endings of the external row of seat are part of the substructure of the cavea or two basilicas flanking the stage.

Two different 3D models were reconstructed. Both of them have seven rows of seats (each rows is 0.40 m height and 0.50 m deep) as it is indicated in the plan of the site of Lissos, one has the seating area interrupted at the sides by the two supposed *basilicae*, the other one instead has the seating area overlapping the two rectangular structures. The height of the stage has been chosen with the purpose to keep harmony and right proportions in the full structure of the theatre. Both reconstructions have been tested with 3D visibility analysis and virtual acoustics analysis in order to verify their reliability.

Figure 147 Low aerial pictures of the area occupied by the remains of the theatre of Lissos (by Dr. Gianluca Cantoro).


Figure 148 Remains, perhaps, of the last row of seats of the theatre at Lissos.

5.8.1 3D Visibility analysis

Two different 3D models have been used in order to verify the visibility from the seating area to the stage and then to verify the reliability of such reconstructions. In the model N.1 the cavea is little less than a semicircle (fig. 149), whereas in the model N. 2 is a semicircle (fig. 150). A grid of 28 observer points, divided into four lines, has been placed in the seating area, and a target line has been placed approximately at the center of the stage (for a detailed explanation refer to the methodology chapter, p. 56).

As it was deducible, there are not meaningful differences between the results obtained from the 3D visibility analysis of the two reconstructions, being the *basilica* placed always right next to the stage and attached to the cavea. In both cases, the construction of lines of sight shows that the visible trajectories are the 83% of the total, therefore 17% of the lines have the visibility obstructed by the *basilicae*, as indicate by the position of the obstruction points. To be exact, the obstruction points in the model N. 2 are more numerous than the model N. 1: 6758 of the first against

6675, but it is not such a significant difference (less than 100 points of difference over more than 6000).

Also the frequency of visibility maps resulting by the two reconstructions are identical (figs. 151-153). They demonstrate that such kind of reconstructions do not allow a visibility of the central part of the stage to everyone, but only to a part of the spectators: 23-21 spectators over 28.

The 3D visibility analysis shows that the visibility in these two reconstructions is not excellent but still acceptable considering that it might be possible that few seats were not placed in a good position, or not all of them were occupied. The particular kind of analysis did not help in the identification of which reconstruction is the most reliable.

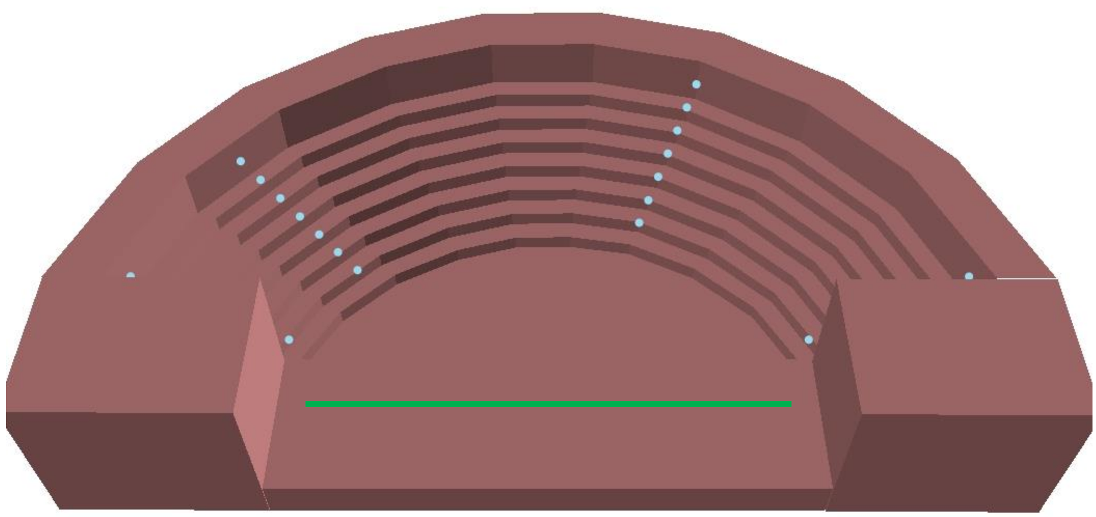


Figure 149 3D model N. 1 plus grid of observer points.

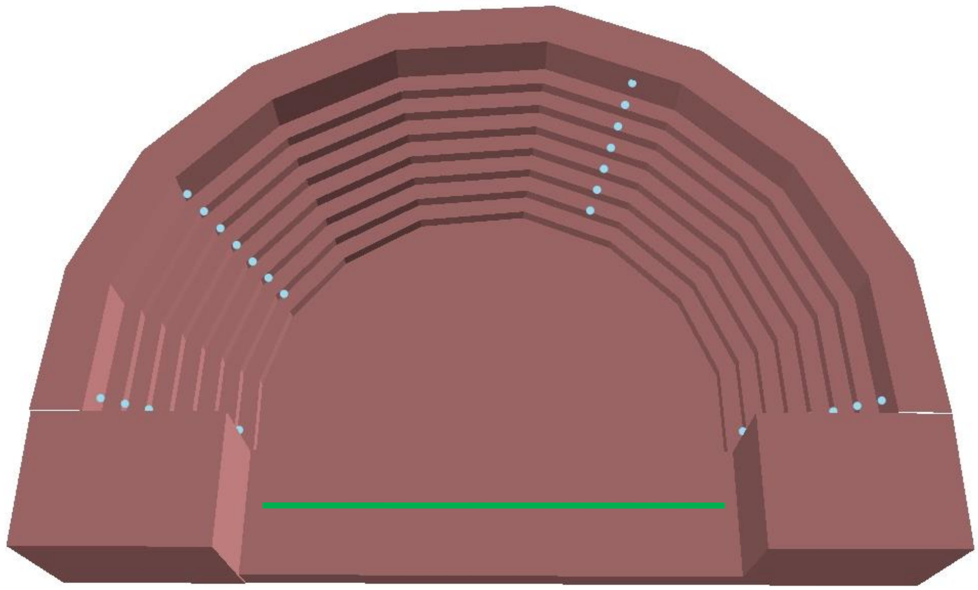


Figure 150 3D model N.2 plus grid of observer points.

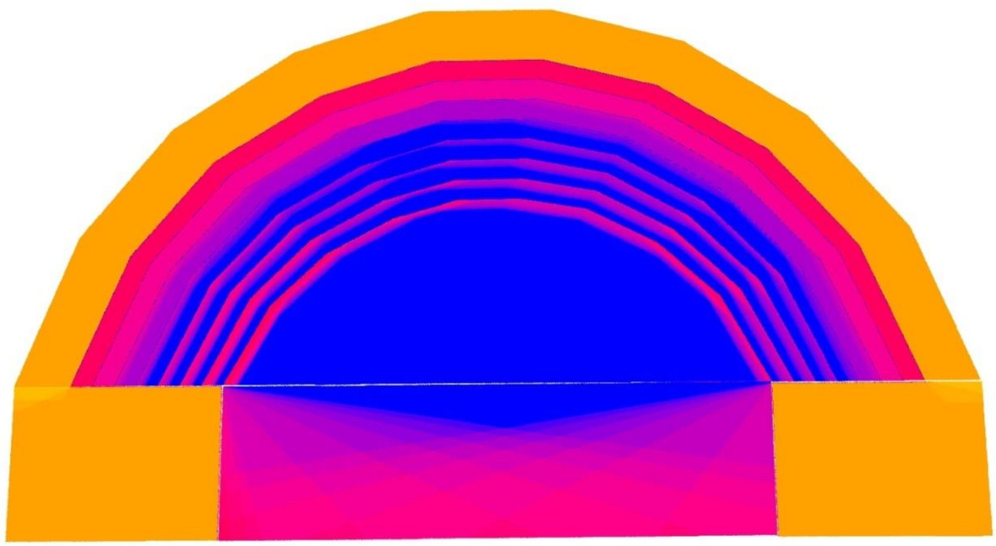


Figure 151 Map of frequency of visibility of the model N. 1 of the theatre of Lissos. The colors show the different level of visibility for the observer points, as it is explained in the correspondent graph (fig.151).

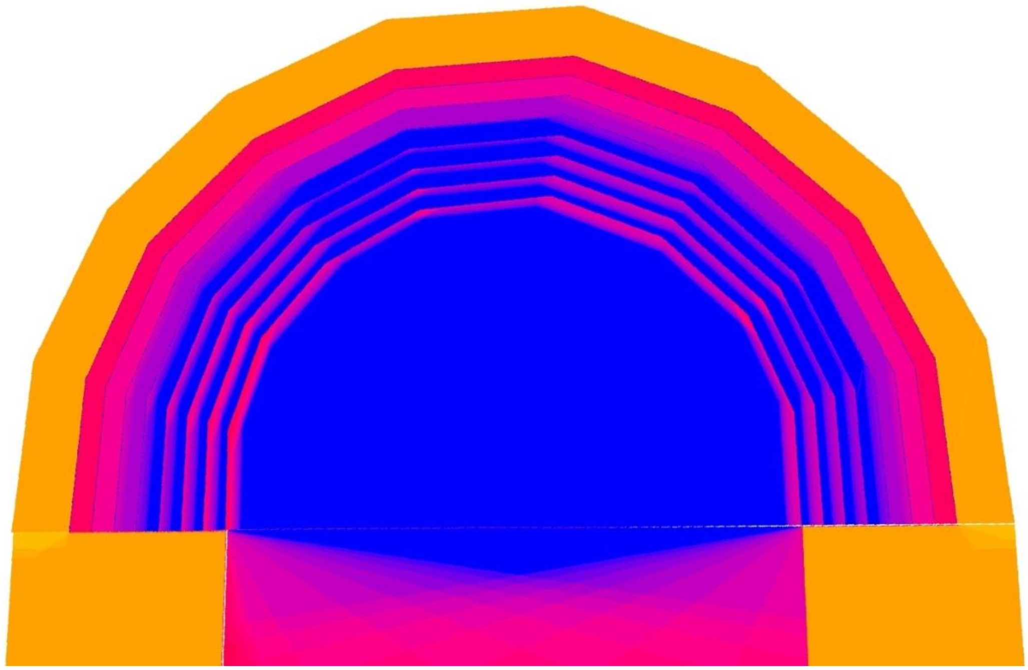


Figure 152 Map of frequency of visibility of the model N. 2 of the theatre of Lissos. The colors show the different level of visibility for the observer points, as it is explained in the correspondent graph (fig.151).

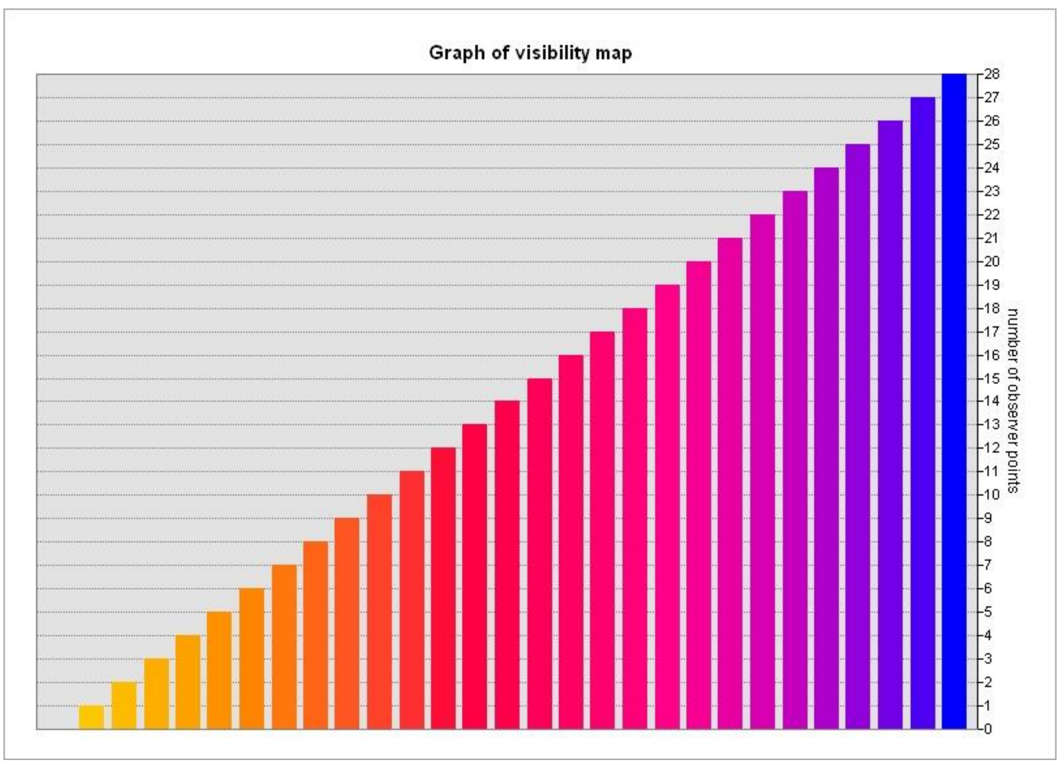


Figure 153 Graph of visibility map of both models. The color scale is from yellow to blue. The yellow color means that those areas are visible by none of the observer points; the blue colour indicates the area visible by all 28 observer points.

5.8.2 Virtual acoustics analysis

The same 3D models were tested through virtual acoustics analysis in order to verify the quality of their acoustics too.

The materials applied are:

1. Stone: cavea, *scaenae frons*, basilicas, orchestra, columns.
2. Wood: doors of the *scaenae frons*, stage's floor.
3. Audience: seating area.

Nine receivers have been placed in three radial lines of one half of the seating area, one every 2/3 seats, and a receiver at the centre of the stage (figs. 154-155) (for detailed explanation refer to the methodological chapter, p. 65).

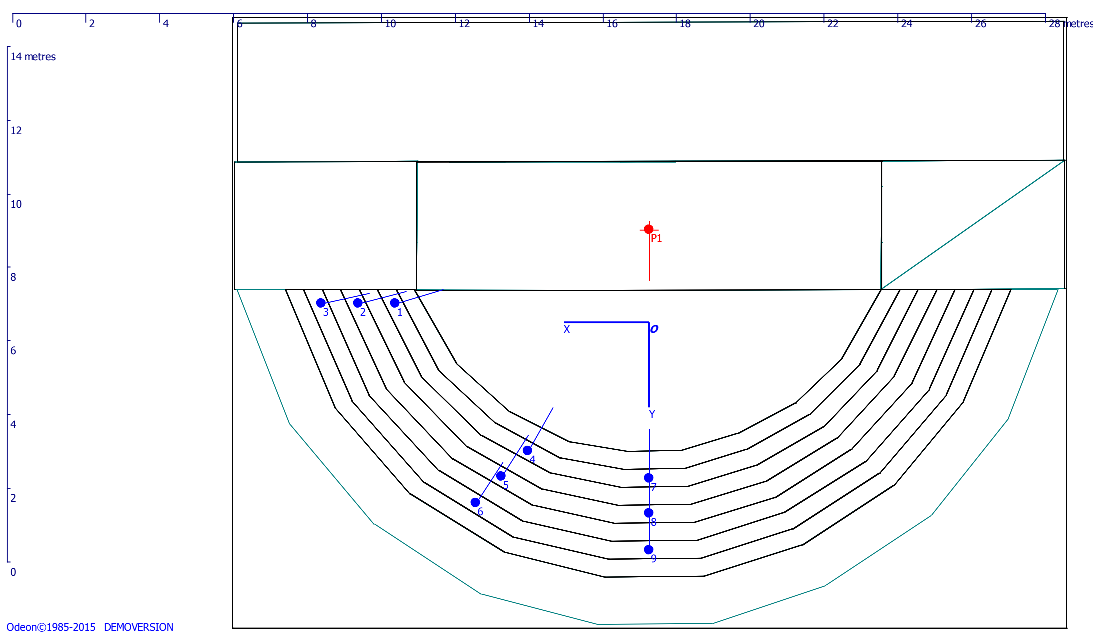


Figure 154 Plan of the 3D model N.1 of the theatre of Lissos, plus receivers and source.

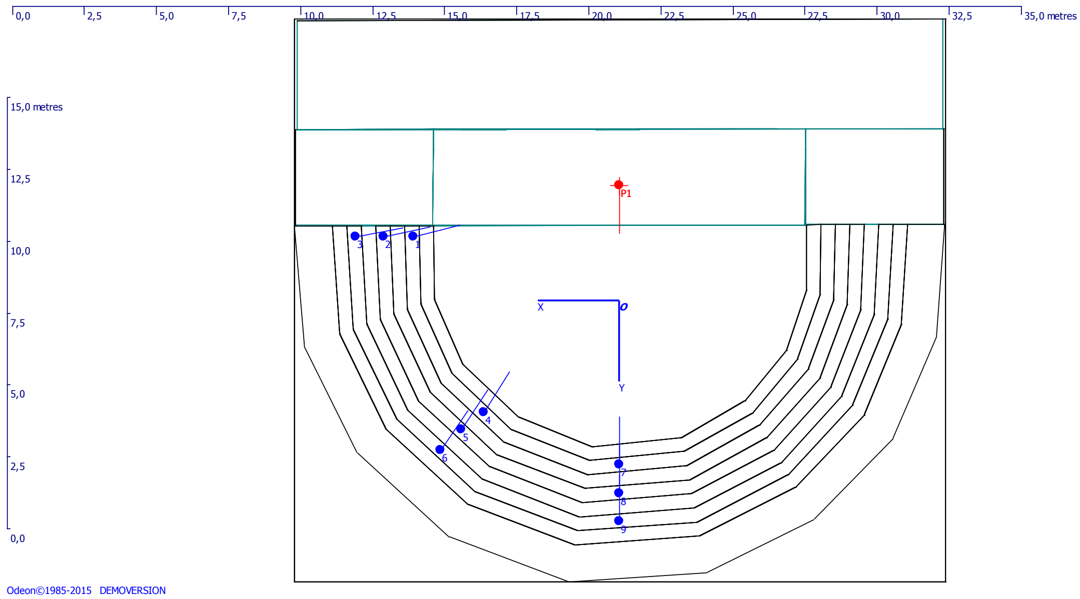
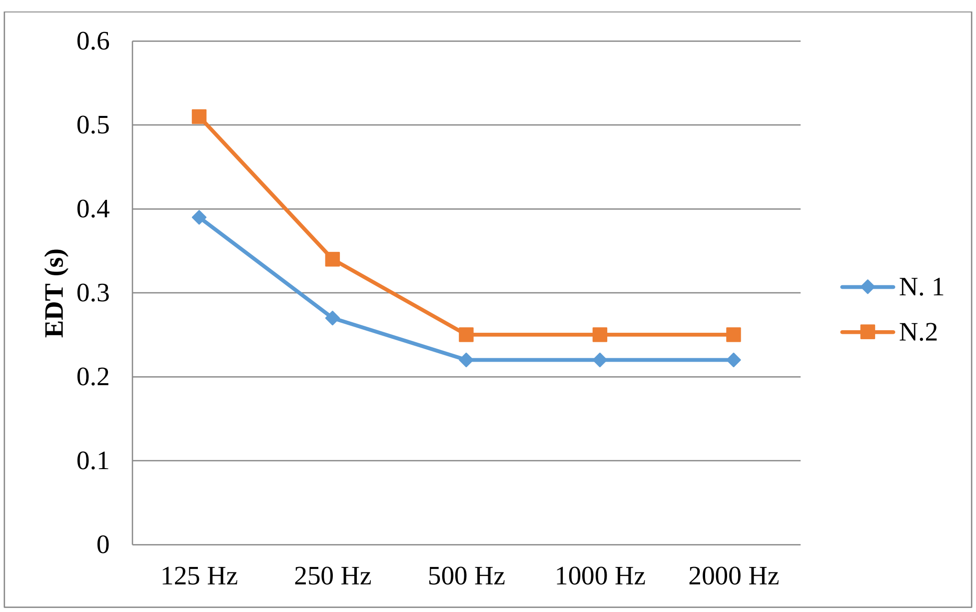
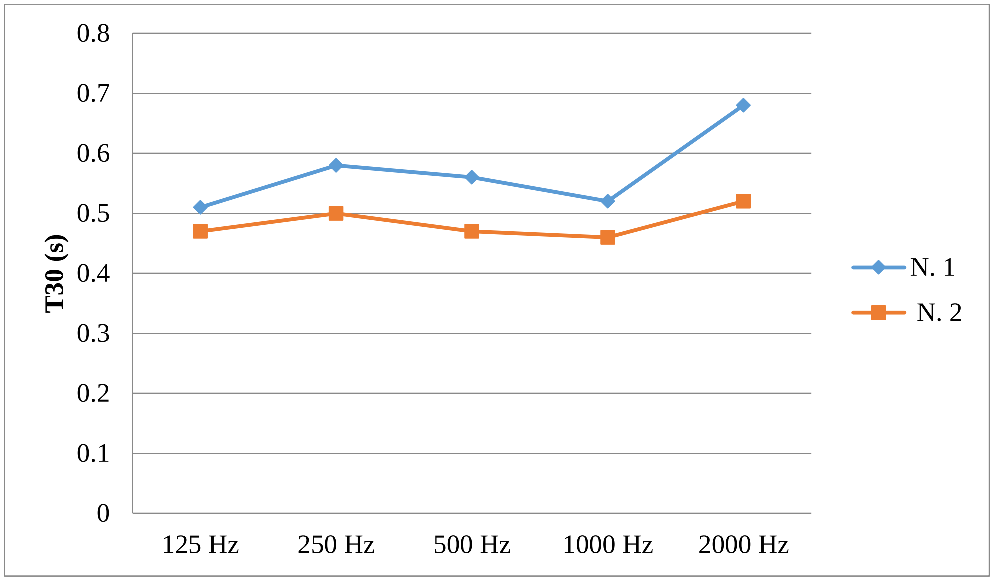


Figure 155 Plan of the 3D model N.2 of the theatre of Lissos, plus receivers and source.

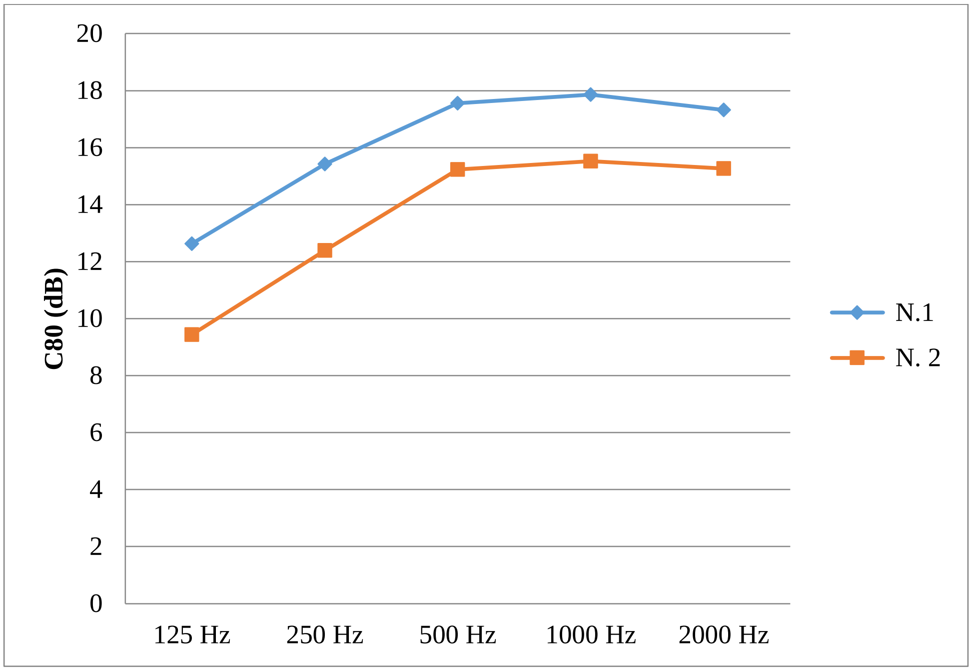


Graph 39 Average values of early decay time for both versions of the theatre of Lissos, at each frequency.

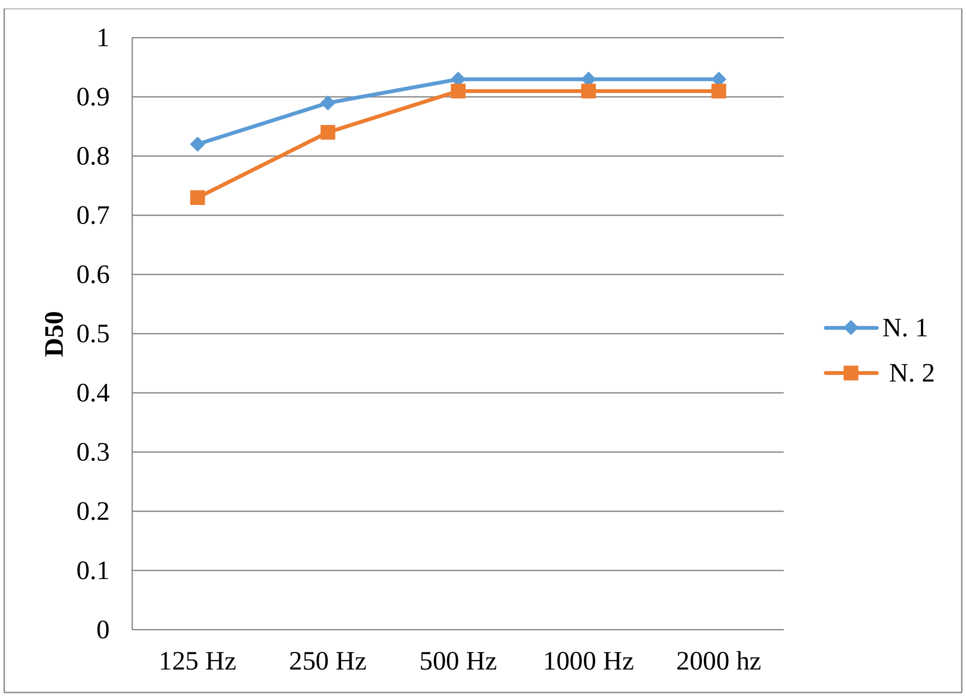


Graph 40 Average values of reverberation time for both versions of the theatre of Lissos, at each frequency.

Graph 41 Average values of the difference between T30 and EDT of both version of the theatre of Lissos, at each frequency.



Graph 42 Average values of clarity for both versions of the theatre of Lissos, at each frequency.



Graph 43 Average values of definition for both versions of the theatre of Lissos, at each frequency.

5.8.3 Results and comments

Even if the 3D visibility analysis and virtual acoustics analysis produce quite satisfying results, the available data are still too little to conclude that the original shape of the theatre was as the reconstruction N. 1 rather than the model N. 2. Furthermore, it is important to underline that generally such small theatres were considered more as *odeon*, but the obtained values from the virtual acoustics analysis suggest that this building was suitable for speech more than for music; then we may think that it could be reserved to orators and public communication more than to theatrical performances.

This theatre definitely needs to be investigate more through archaeological excavation and/or geophysical prospection because there are still many things to understand about it and a major knowledge about this building will enhance the history of the site of Lissos.

6. DIGITAL ARCHAEOLOGY

Since the first electronic digital computer appeared, about seventy years ago, the life of people changed. The impact of digital technology has been so strong in many fields and activities of our world (work environment, public life, private life and nowadays social life) that this period (still unfinished) has been defined the epoch of the digital revolution.

The word digital, as stated by Gere, “could refer to almost any system, numerical, linguistic or otherwise, used to describe phenomena in discrete terms”[127]. The digital system is now used almost in every sector and of course also archaeology has been influenced by the digital revolution. The opportunities that “digitalization” has brought to archaeology are not only the simplification of the collection, storing, visualization and interpreting data, but it also allows possibilities that would not be feasible otherwise (such as the interaction with an object, a monument or a site, remotely).

As Zubrow summarized, the impact of digital revolution on archaeology is reflected in several manners: the representation of real world in a compact and efficient way; counting, doing statistics, manipulating and evaluating measurements summarily and analytically; modelling and simulating real world processes; creation of virtual worlds; worldwide dissemination of the results and representations[128]. To generalize, the digital revolution is changing the approach of the archaeologists towards the development of the research design and implementation. It is actually curious though that digital instruments are used in archaeology since the 1960s (mainly for statistical analysis)[7], but many archaeologists are still reluctant to accept the potentialities offered by digital tools. On the other hand, luckily, there are lots of archaeologists who take full advantage of computer and digitalization, producing a workflow that goes from the indirect survey and digital photos, to databases and 3D representations, till virtual archaeology projects and digital interactive applications.

In the previous chapters (methodology and case study) it has been explained which digital tools (digitalization of plans, 3D visibility analysis, virtual acoustics analysis, 3D models) have been used to study and to obtain more accurate information about the Roman theatres of Crete. In order to have a better impact of the results of the research, it would be desirable to find ways for displaying and disseminating them. Two different media have been used: an online database and a VR application for Oculus Rift. The online database has been targeted for scholars and researchers to provide them with a tool for easily accessing information about the theatres and easily comparing them; the VR application is addressed to the general public in order to stimulate their interest toward our Cultural Heritage.

6.1 Online Database

Since the 1970's, databases were introduced in the mainstream of archaeological research. Mainly they have been used to store the huge amount of data that are collected during the archaeological excavations, but many of the archaeological databases are also used to facilitate the research, to study and compare artefacts, monuments and sites. However, the advantages of using databases is not only the possibility to store data and to study them, but also the ease of sharing information, above all through online open-access databases.

Here, I list the major online databases regarding ancient theatres, how they work, what they want to show, their pros and cons and the link to find them online.

1. The theatre database found at http://www.theatre-architecture.eu/db.html is part of a large project called European Theatre Architecture supported by the Culture Program of the European Union and by the Ministry of Culture of Czech Republic. It contains information about 2953 theatres around Europe, dated from the VII century BC till 2014. Among these, eight are Greek theatres and only seven are Roman theatres. There are three different ways to search information: a basic one, an advanced one and another one based on the personalities connected to the theatres (mainly architects, but also painters, sculptors, builders, etc.). The

basic search allow the possibility to insert the name of the theatre, the city and the country. The advanced research offers the option to search according to basic data (name of the theatre, City, Country, number of seats, type of space), historical data (the kind of event and its date, the presence of decorative painted curtain, decorative painted ceiling, historic stage machinery, historic scenery, historic costumes, historic props, if the building is still existing and if it still exist as a theatre and if it was built for other purposes) and technical data (width, height of the stage, depth of the stage, height of the stage portal, width of stage portal, flyloft, back stage, side stage, revolving stage, trap room, stage lifts, equipment for subtitles, equipment for interpretation, orchestra pit, capacity) (fig. 156). By the Persons search, it is possible to click on the name of interest and you will obtain the links to the theatre that person was involved with, plus the information about the personality.

Furthermore, there is also the map of the theatres (where the theatre are geographically located), a timeline (showing the theatres belonging to different construction periods) (fig. 157), a graphic timeline indicating the theatres opened between 1905 and 1937, the list of the countries and places where the theatres are located, tags and links, and each list is interactive and it is linked to the theatres. Selecting a theatre of your choice, information about its history, its technical data and its historic equipment, plus images, which may be pictures, drawings, plans, etc., is going to be provided. In the case of the Roman theatres, only few historical information is provided along with some images. This database is useful to understand the importance of the role of the theatre in Europe and its historical evolution, but most of the attention is paid to the theatrical buildings from the XVI century till nowadays.

2. The THEATRUM website is a project of Direktion Landesarchäologie of Mainz (Germany) and it has been created by Dr. Gert Rupprecht, together with the collaboration of Dr. Hubertus Mikler. It contains many information about numerous Greek and Roman theatres. The information content of the database is mainly focused on the inscriptions, literature and written sources related to the

theatres. In addition, for each theatre there are various descriptions and information, among others, about their dimensions, plus pictures, plans and drawings. The list of the theatres is very rich and it contains theatres that are not mentioned in other databases (such as theatres in Iran, Hungary, Romania and Ukraine) (fig. 158).

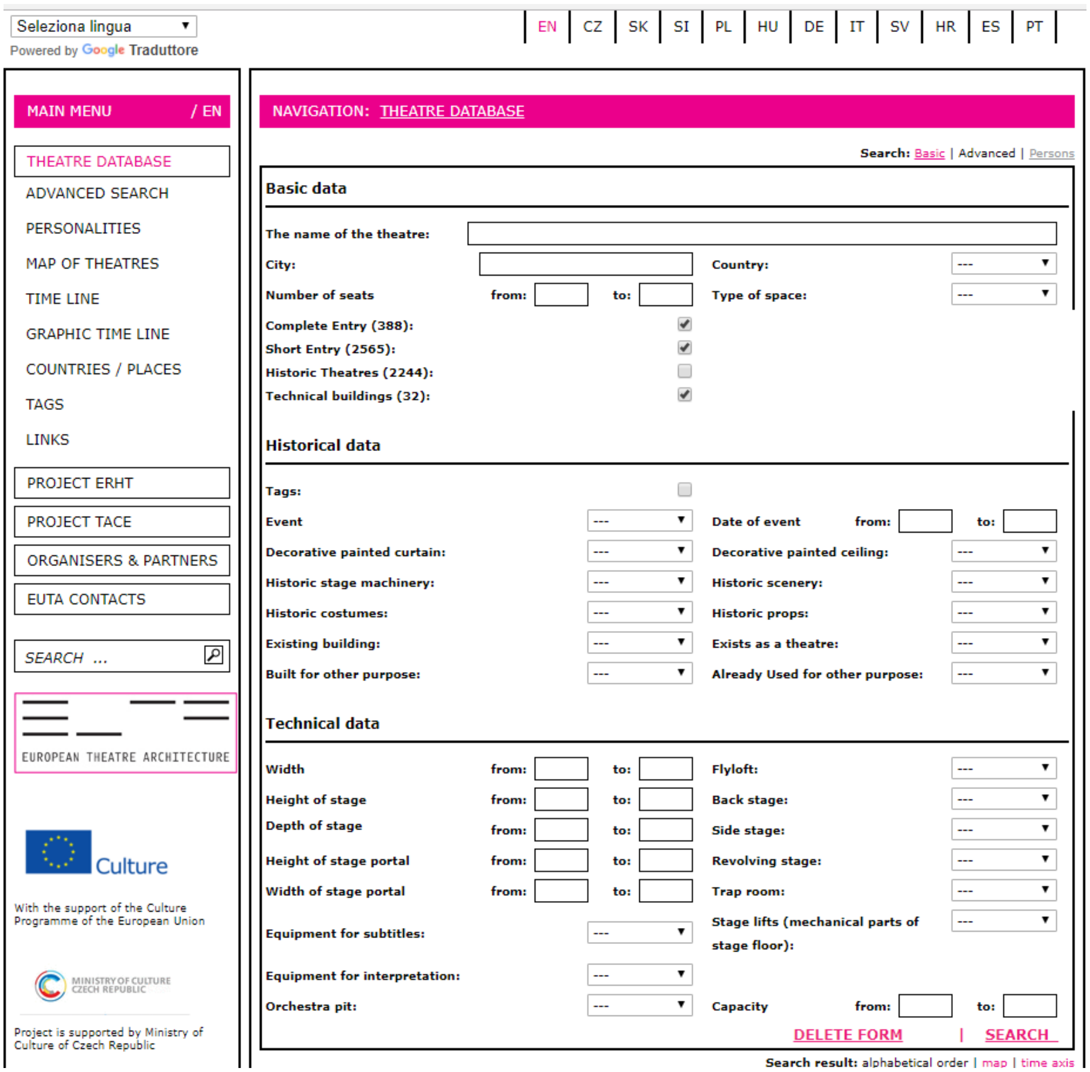


Figure 156 Advanced search options of Theatre Database.

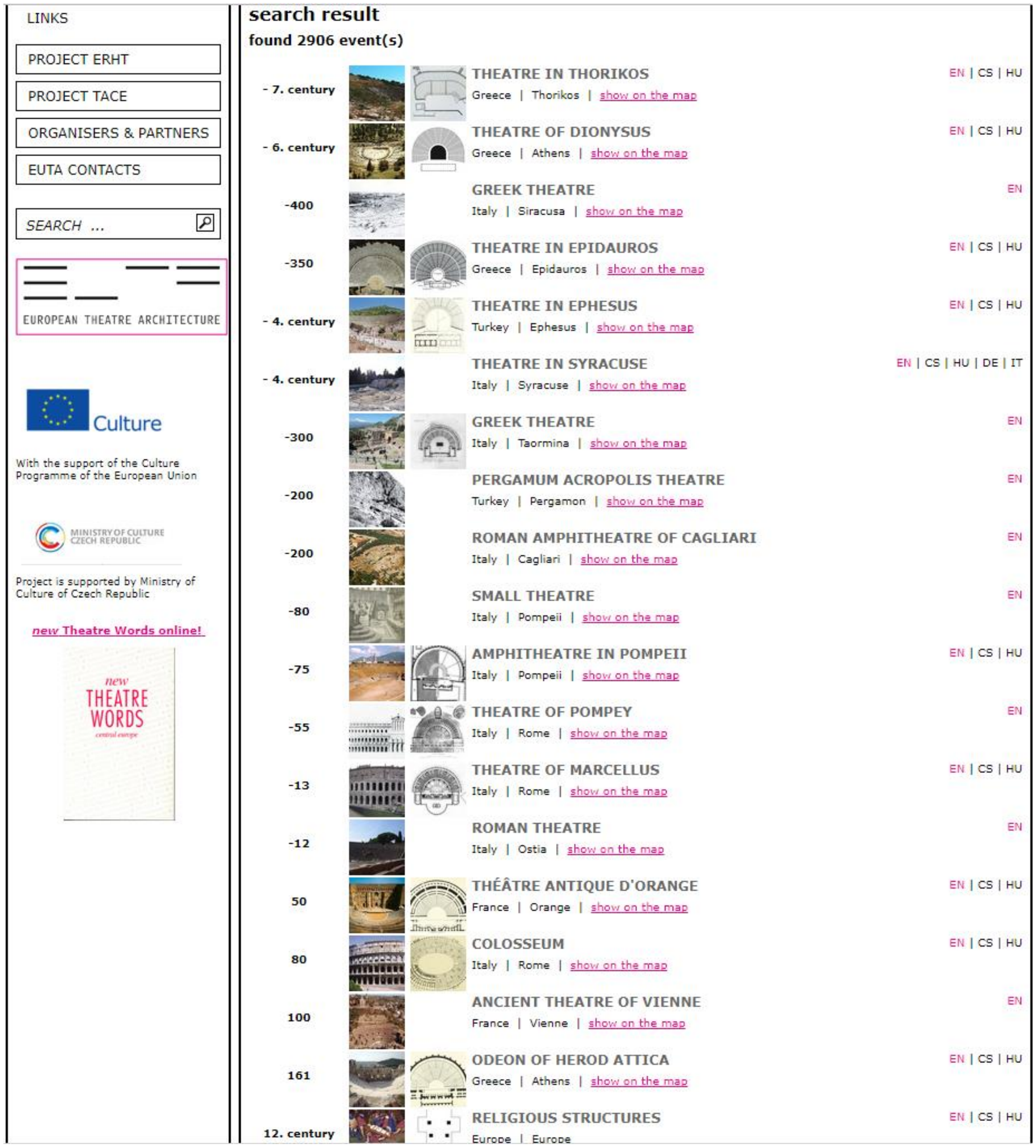


Figure 157 Timeline of Theatre Database.

Figure 158 Home page of THEATRUM website.

All the known Roman theatres of Crete are mentioned in this database, but the given information about them are very scarce; furthermore, the theatre of Gortyna in locality Kazinedes is still indicated as an amphitheatre.

The very positive aspect of this website is the very large number of theatres taken into account, but unfortunately it has only a German version without any translation in any other language.

3. The Ancient Theatre Archive (https://www.whitman.edu/theatre/theatretour/home.htm) is “an Internet resource” for Greek and Roman theatres. It is a project lead by Thomas G. Hines of Withman College in USA. Over 200 theatres are reported on the map of the Roman Empire on the homepage of the website (fig. 159). Among these, some of them have been geographically documented and it is possible to click on their position on the map to open a page containing the related information (location, theatre type, date of construction, renovation dates, excavations, dimensions, and seating capacity, architectural drawings) about the monument. In some cases, the information is accompanied by pictures, panoramic photos, videos and a more detailed description as well. In addition, it is possible to consult the relative bibliography, a glossary for the meanings of the architectural structures composing a theatre, and the theatre specification table from which the user can select any column header and sort the table data (according to: ancient name, modern name or near modern city, location, date, width of the cavea, width of the orchestra, capacity, facing direction, renovation dates, summary). It is a very useful website for doing research about ancient theatres, and hopefully it will be enriched with the addition of other theatres of the Roman Empire. The only disadvantage is that it is not possible to sort the theatres according to more than one characteristic, and this make harder the comparisons between the monuments. Furthermore, none of the theatres in Crete is mentioned in this archive.

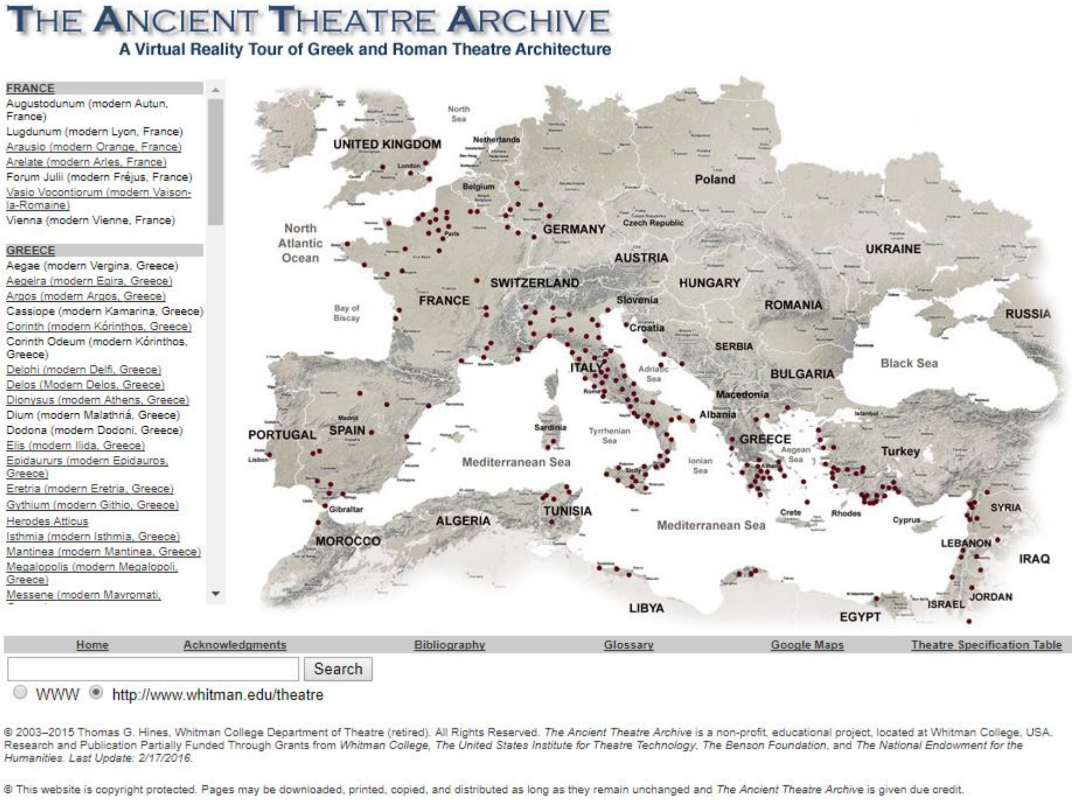


Figure 159 Home page of The Ancient Theatre Archive.

4. The website Engramma (http://www.engramma.it/eOS/index.php?id_articolo=385) cannot be considered a proper database, but it is mentioned here so that we can have a more complete list of the available online sources about ancient theatres. Engramma is an online magazine about the classical tradition present in our time. One of the articles is an indexing of the ancient theatres and *odeia* in the Roman Empire. Through four different symbols, placed on a map (fig. 160) and in a list, the state of conservation of numerous ancient theatres is indicated. The list is subdivided according to the geographical area in which the monuments are (or were, or are hypothesized to be) located and information as typology, date, dimension and notes are added.

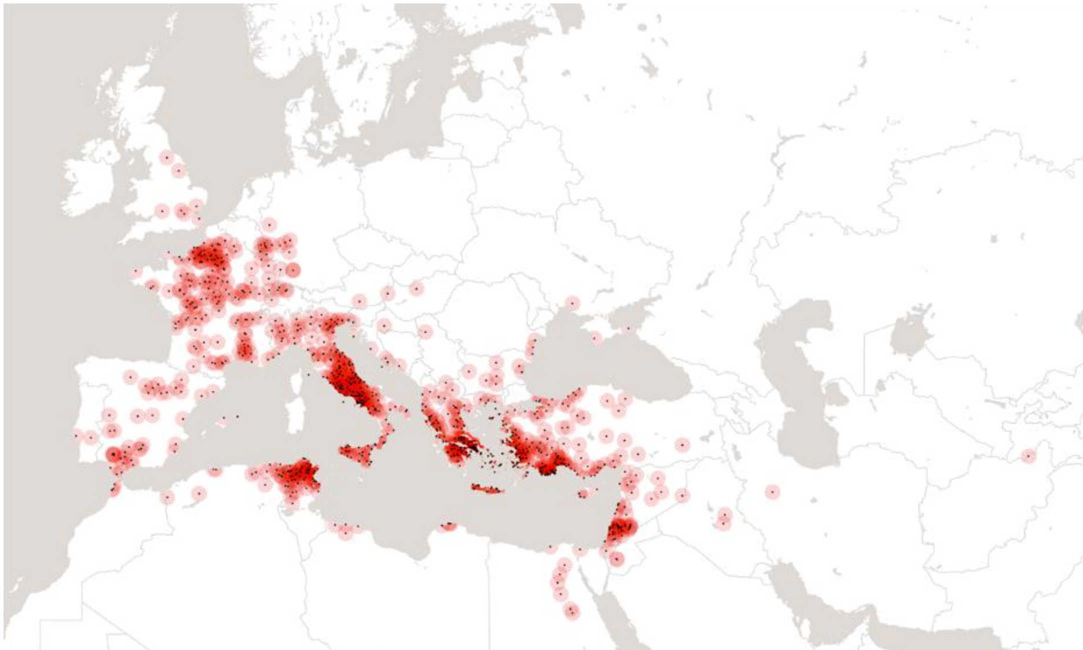


Figure 160 Map of state of preservation of theatres in the Roman Empire on Engramma website.

Based on the above experiences, a new database was realized for the particular research about the Roman theatres in Crete. The database is called Roman Theatres because the future aim is to enrich it with the rest of the Roman theatres in Greece first, till to expand it to the whole Roman Empire. The main purpose of this database is to facilitate the comparisons between theatres, according to their architectural structure.

The web database application was developed with the standard three-tier architecture model (fig. 161). At the base of the application we used MySQL for the Database Management system (DBMS) followed a classic relational model (i.e. many scholars may describe 1 theatre). The middle tier consists of the web server (in our case Apache2 on Ubuntu 16.04 LTS) and the application/client environment (written in PHP and utilizing open source libraries). The application code was furthermore developed following the Model–view–controller (MVC) architectural pattern for CRUD (Create, Read, Update, Delete) actions on the database which are ultimately presented in the top tier to authenticated users (fig. 162). The database is online at the address https//romantheatres.ims.forth.gr.

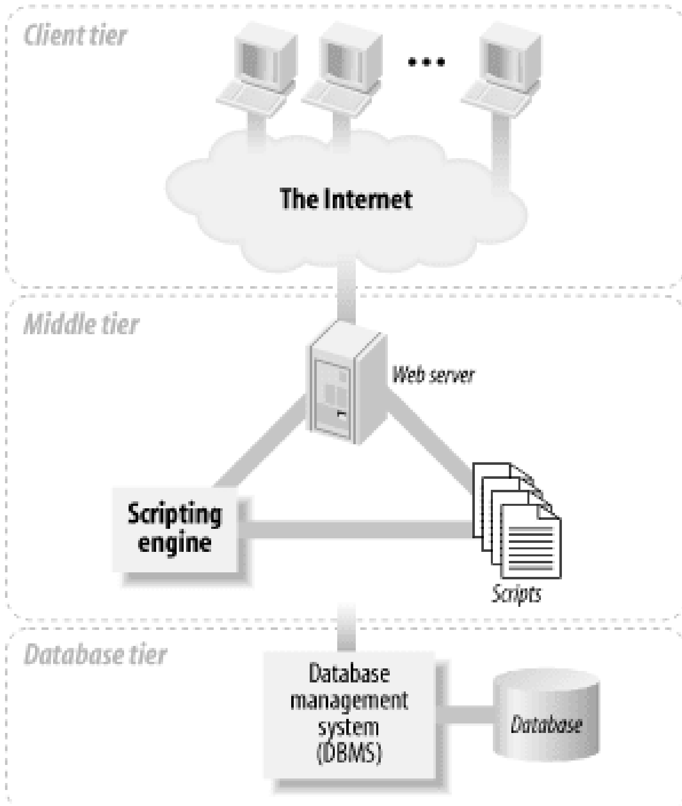


Figure 161 3-tier web database application.

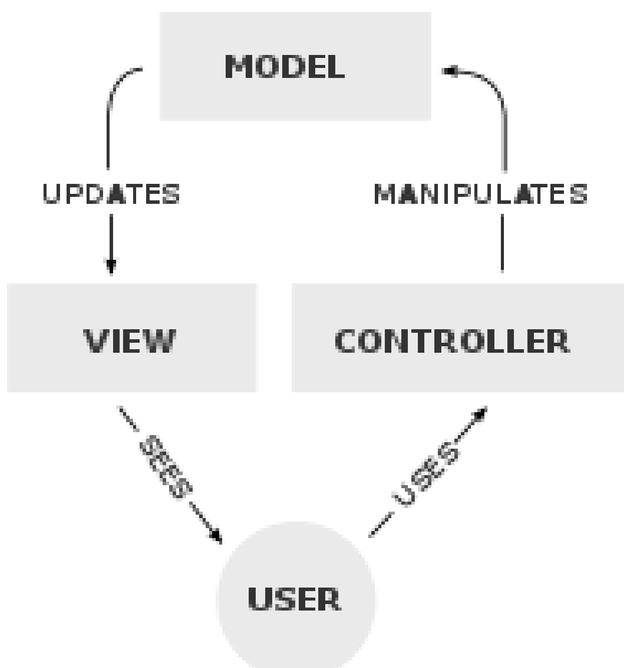


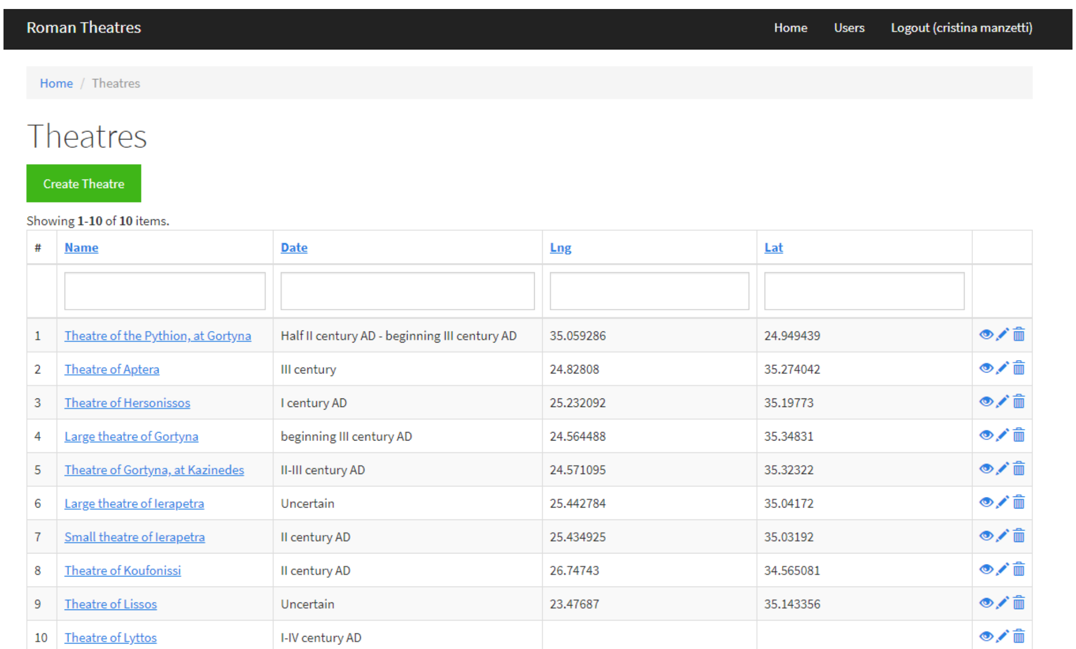
Figure 162 MVC architecture pattern for developing applications.

The home page shows that it is possible to visualize the list of the theatres (which contains general information), the list of the scholars who investigated the theatres, and the list of the theatres according to their architectural characteristics (fig. 163). Selecting “view theatres”, the list of the theatres will appear along with their date of construction, and their exact position. One has the ability to filter results by the name of the theatre, the date of construction, the longitude and the latitude (fig. 164). Selecting a theatre, will display the theatre detailed page containing general information about it (such as description, date, vicinity to the modern village, orientation, location with respect to the ancient town, proximity to the ancient town, longitude, latitude, elevation), comparisons with other theatres, the scholars who studied it, the values of the acoustics parameters (T30, EDT, C80, D50 and STI) obtained through the acoustics analysis, plus the relative bibliography (fig. 165). Selecting a scholar from the “scholars table”, will redirect the user to the detailed page of that scholar, containing the year of the publication and information about the author, plus the list of the theatres the scholar studied and the possibility to select them.

From the home page, selecting “view scholars” will display the list of all the scholars who investigated or studied one, or more, of the Roman theatres in Crete. It is possible to filter the results according to name and information about the scholar (as archaeologist, architect, etc.) (fig. 166). Also from the list page of the scholars, one has the ability to select one of them and to obtain the list of the theatres he/she has examined (fig. 167).

The third option on the home page is selecting “view data” that will display the list of the Roman theatres of Crete: there is the possibility to select each theatre and also to filter the results according to scholar, type of cavea (built or dug), number of sectors of the cavea, diameter of the cavea, and diameter of the orchestra (fig. 168). Once the user enters the detailed page of one of the theatre, he/she has all the information available regarding its architectural structure, according to each one of the scholars.

Figure 163 Home page of the Roman theatres database elaborated at GeoSat ReSeArch Lab.



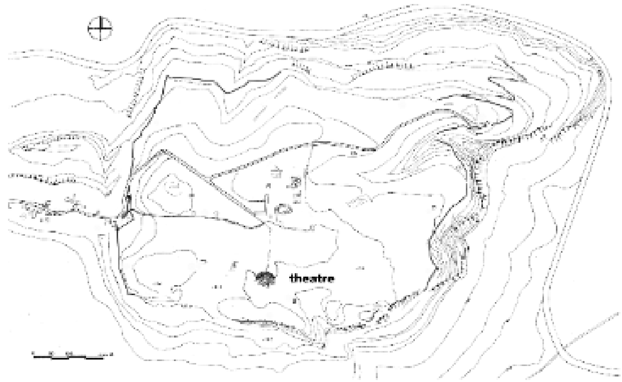
#	Name	Date	Lng	Lat
1	Theatre of the Pythion, at Gortyna	Half II century AD - beginning III century AD	35.059286	24.949439
2	Theatre of Aptera	III century	24.82808	35.274042
3	Theatre of Hersonissos	I century AD	25.232092	35.19773
4	Large theatre of Gortyna	beginning III century AD	24.564488	35.34831
5	Theatre of Gortyna, at Kazinedes	II-III century AD	24.571095	35.32322
6	Large theatre of Ierapetra	Uncertain	25.442784	35.04172
7	Small theatre of Ierapetra	II century AD	25.434925	35.03192
8	Theatre of Koufonissi	II century AD	26.74743	34.565081
9	Theatre of Lissos	Uncertain	23.47687	35.143356
10	Theatre of Lyttos	I-IV century AD		

Figure 164 "Theatres" page of the Roman theatres database.

Theatre of Aptera

Update Delete

Theatre ID	4
Name	Theatre of Aptera
Description	It had three phases: an Hellenistic one, a first Roman one and a second Roman one
Date	III century



V. Niniou-Kindeli and N. Chatzidakis, "The Roman theatre at Aptera: a preliminary report," in Roman Crete. New perspectives, Jane E. Francis and Anna Kouremenos., Oxford & Philadelphia: Oxbow Books, 2016, p. 128.

Location

Vicinity to Modern Village	it is located about 650 meters far from the modern village of Aptera, on the east side
Distance from the Sea	910 m.
Orientation	SW
Location with Respect to the Ancient Town	SE
Proximity to Ancient Town	placed within the ancient walls
Lng	24.82808
Lat	35.274042
Elevation	213 m.

Comparison

Showing **1-1** of **1** item.

Theatre	Country
Metapontum. Dated to the IV century BC.	Italy

Scholars

Showing **1-4** of **4** items.

Scholar Name
Niniou - Kindeli Vanna
Drerup Heinrich
Dilke Oswald Ashton Wentworth
Sanders Ian

Acoustic Analysis

T30 125 Hz	0.86
T30 250 Hz	0.75
T30 500 Hz	0.7
T30 1000 Hz	0.66
T30 2000 Hz	0.7

EDT 125 Hz	0.64
EDT 250 Hz	0.4
EDT 500 Hz	0.34
EDT 1000 Hz	0.35
EDT 2000 Hz	0.35

C80 125 Hz	7.58
C80 250 Hz	11.38
C80 500 Hz	13.29
C80 1000 Hz	13.4
C80 2000 Hz	13.59

D50 125 Hz	0.7
D50 250 Hz	0.8
D50 500 Hz	0.84
D50 1000 Hz	0.84
D50 2000 Hz	0.85

STI	0.79

Bibliography

Showing **1-6** of **6** items.

#	Publish Year	Reference
1	1942	Drerup H., Paläokastro – Aptara, in F.Matz, Fourschungen auf Kreta, 1942, pp. 89-98.1951.
2	1837	Pashley R., Travels in Crete. John Murray, London 1837.
3	1982	Sanders I. F., Roman Crete. An Archaeological Survey and Gazetteer of Late Hellenistic, Roman and Early Byzantine Crete. Warminster, Wilts: Aris & Phillips, 1982, Oxford.
4		Zeno A., Venezia, Biblioteca Marciana, Mss. It. CL. X. 345=7162.

Figure 165 Detail page of the theatre of Aptera of the Roman theatres database.

Scholars

Create Scholar

Showing **1-18** of **18** items.

#	Name	Description	
1	Belli Onorio	Physician, Italian traveller	
2	Barresi Paolo	Archaeologist	
3	Bonetto Jacopo	Archaeologist, University of Padua	
4	Colini Antonio	Archaeologist, Italian Mission of Archaeology in Crete	
5	Drerup Heinrich	Archaeologist	
6	Falkener Edward	Architect	
7	Leonard Albert	Archaeologist, University of Arkansas	
8	Mariani Lucio	Archaeologist, Italian Mission of Archaeology in Crete	
9	Montali Gilberto	Archaeologist, University of Macerata	
10	Pococke Richard	British traveller	
11	Sanders Ian	Archaeologist, University of Oxford	
12	Sarris Apostolos	Geophysics, Laboratory of Geophysical-Satellite Remote Sensing & Archaeo-Environment	
13	Spratt Thomas	British traveller	
14	Taramelli Antonio	Archaeologist, Italian Mission of Archaeology in Crete	
15	Niniou - Kindeli Vanna	Archaeologist, 23rd Ephorate of Prehistoric and Classical Antiquities of Chania	
16	Kanta Anastasia	Archaeologist, 13th Ephorate of Prehistoric and Classical Antiquities of Heraklion	
17	Papadakis Nikos	Archaeologist	
18	Dilke Oswald Ashton Wentworth	Philologist	

Figure 166 "Scholars" page of the Roman Theatre database

Spratt Thomas

Update Delete

Scholar ID	37
Name	Spratt Thomas
Description	British traveller

Theatres

Showing **1-3** of **3** items.

#	Theatre	Cavea Construction	Number of Sectors of the Cavea	Diameter of the Cavea	Diameter of the Orchestra
1	Theatre of Lissos			23.7 m.	
2	Large theatre of Gortyna			85.3 m.	
3	Large theatre of Ierapetra			46.9 m.	

Citations

Showing **1-1** of **1** item.

#	Publish Year	Citation
1	1865	Spratt T.A.B., Travels and researches in Crete. John Van Voorst, London 1865.

Figure 167 Detail page of the scholar Spratt Thomas of the Roman theatres database

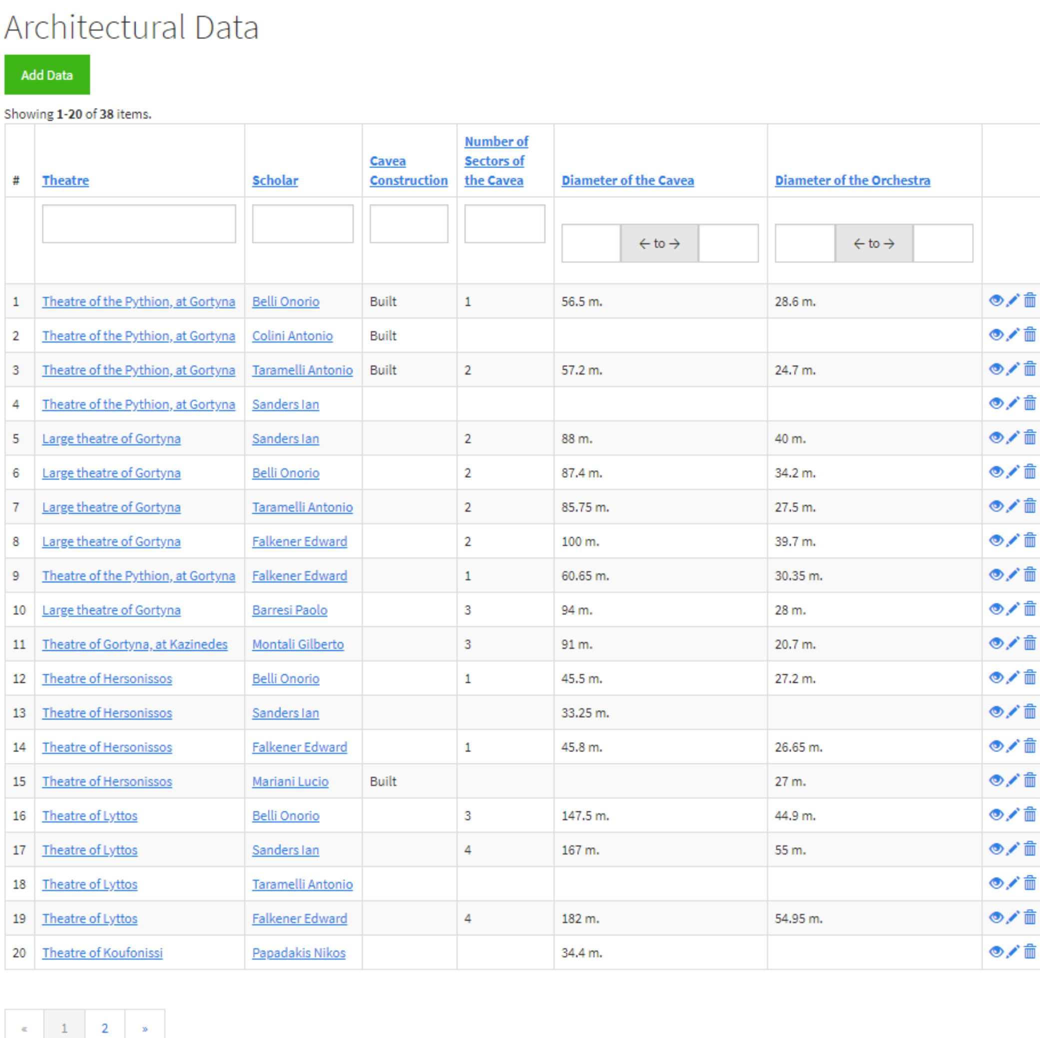
The list of data reported are the following: type of cavea, number of sectors of the cavea, diameter of the cavea, diameter of the orchestra, presence of *parodoi*, number of *vomitoria*, portico in *summa* cavea, number of columns of the portico in *summa* cavea (if present), height of the cavea, height of the scene building, number of storeys of the *scaenae frons*, number of entrances for the actors, distance between the cavea and the scene frons, presence of roof, order of columns, capacity, seats' dimensions, diameter and height of the portico in *summa* cavea columns, dimensions of the stage, diameter and height of the scene frons columns, length of the scene frons, width of the *post scaenium* (if present), number of *kerkides* for each sector, number of rows of seats for each sector and total number of row of seats. Furthermore, the material of each part of the theatre is also provided (fig. 169).

The innovative elements of this database are principally three: the addition of the acoustics values of fundamental parameters helpful to identify the kind of performance was played in that theatre; the insertion of a list of possible comparisons for each theatre; the possibility to filter the research according to the scholars who examined the monument.

The acoustics analysis should be something to do regularly whenever we are studying ancient theatres. It adds information about these ancient monuments that can help in the interpretation not only regarding their possible architecture, but also the kind of performance that was played there. Furthermore, the acoustics analysis of pretty well preserved theatres might be less fundamental for the interpretation of the remains but it helps in potential projects of reuse of the ancient theatres as venue for shows nowadays[94]. Inserting the acoustics data in the database makes possible comparisons among results obtained from different theatres, facilitating the interpretation of the acoustics characteristics of ancient places for performances.

The lists of comparisons with other theatres of the ancient world speed up the study of the architecture and the history of these monuments by other scholars as well. In addition, these lists suggest a first idea about the possible contacts among the towns of the Empire and the Roman provinces, giving a starting point for a wider research.

When the information about one monument is incomplete, mainly because of the scarcity of the remains, it is indispensable to take into account all the witnesses available regarding the monument. The possibility in the database to search information according to each scholar who investigated or studied that theatre enables other scholars to reflect on similarities and differences reported by the previous authors, facilitating formulating independent interpretations.



Architectural Data

Add Data

Showing **1-20** of **38** items.

#	Theatre	Scholar	Cavea Construction	Number of Sectors of the Cavea	Diameter of the Cavea	Diameter of the Orchestra	
					← to →	← to →	
1	Theatre of the Pythion, at Gortyna	Belli Onorio	Built	1	56.5 m.	28.6 m.	
2	Theatre of the Pythion, at Gortyna	Colini Antonio	Built				
3	Theatre of the Pythion, at Gortyna	Taramelli Antonio	Built	2	57.2 m.	24.7 m.	
4	Theatre of the Pythion, at Gortyna	Sanders Ian					
5	Large theatre of Gortyna	Sanders Ian		2	88 m.	40 m.	
6	Large theatre of Gortyna	Belli Onorio		2	87.4 m.	34.2 m.	
7	Large theatre of Gortyna	Taramelli Antonio		2	85.75 m.	27.5 m.	
8	Large theatre of Gortyna	Falkener Edward		2	100 m.	39.7 m.	
9	Theatre of the Pythion, at Gortyna	Falkener Edward		1	60.65 m.	30.35 m.	
10	Large theatre of Gortyna	Barresi Paolo		3	94 m.	28 m.	
11	Theatre of Gortyna, at Kazinedes	Montali Gilberto		3	91 m.	20.7 m.	
12	Theatre of Hersonissos	Belli Onorio		1	45.5 m.	27.2 m.	
13	Theatre of Hersonissos	Sanders Ian			33.25 m.		
14	Theatre of Hersonissos	Falkener Edward		1	45.8 m.	26.65 m.	
15	Theatre of Hersonissos	Mariani Lucio	Built			27 m.	
16	Theatre of Lyttos	Belli Onorio		3	147.5 m.	44.9 m.	
17	Theatre of Lyttos	Sanders Ian		4	167 m.	55 m.	
18	Theatre of Lyttos	Taramelli Antonio					
19	Theatre of Lyttos	Falkener Edward		4	182 m.	54.95 m.	
20	Theatre of Koufonissi	Papadakis Nikos			34.4 m.		

« 1 2 »

Figure 168 "Architectural Data" page of the Roman theatres database

39

Update Delete

Theatre	Theatre of the Pythion, at Gortyna
Scholar	Bonetto Jacopo
Cavea Construction	Built
Number of Sectors of the Cavea	2
Diameter of the Cavea	51 m.
Diameter of the Orchestra	12 m.
Presence of Parodoi	Yes
Number of Vomitoria	10
Portico In Summa Cavea	No
Number of Columns of the Portico In Summa Cavea	
Height of the Cavea	12.65 m.
Height of the Scene Building	12.65 m.
Number of Storeys of the Scaenae Frons	
Number of Columns of the Scaenae Frons	0
Number of Entrances For The Actors	
Distance Between Cavea And Scaenae Frons	5 m.
Roof	No
Order of Columns	

Capacity	1800
Seats Height	0.4 m.
Seats Width	0.65 m.
Diameter of the Portico Summa Cavea Columns	
Height of the Portico Summa Cavea Columns	
Stage Length	23.9 m.
Stage Height	0.75 m.
Stage Width	4.35 m.
Diameter of the Scaenae Frons Columns	
Height of the Scaenae Frons Columns	
Scaenae Frons Length	23.9 m.
Post Scaenium Width	4.5 m.
Number of Kerkides In Ima Cavea	4
Number of Kerkides In Media Cavea	
Number of Kerkides In Summa Cavea	
Number of Rows of Seats In Ima Cavea	12
Number of Rows of Seats In Media Cavea	8
Number of Rows of Seats In Summa Cavea	
Total Number of Rows of Seats	20

Material

Showing **1-4** of **4** items.

Material Area	Material Type	Material Structure
Orchestra floor	Marble	
Scaenae frons	Bricks	
Cavea	Poros-local	
Analemmata	Bricks	

Figure 169 Detail page of the architectural data of the theatre of the Pythion at Gortyna, of the Roman theatres database.

6.2 Virtual Reality Application

Nowadays, virtual reality is quite widespread in both sectors of Cultural Heritage and Archaeology, as demonstrated by the "new" terminologies of Virtual Heritage[129] and Virtual Archaeology[4]. Despite the diffuse implementation of virtual applications for Cultural Heritage and archaeology, there is still a long way to go in order to achieve the correct and satisfactory methodology to be applied to a virtual Archaeology project. Some of the issues have been listed in the London Charter and in the Seville Charter, respectively in 2006 for Computer-based Visualization of Cultural Heritage (http://www.londoncharter.org/) and in 2011 about the International Principles of Virtual Archaeology (http://smartheritage.com/seville-principles/seville-principles). These documents can be considered as guidelines for the production of valuable and scientific projects in the field of virtual representation of Cultural Heritage, that everyone should follow and respect. However, besides protecting and respecting the scientific accuracy of such projects, we need to take into account also the importance for the user to be engaged by these virtual representations. One of the main purposes of virtual archaeology, and more generally of 3D representations and virtual reconstructions in Cultural Heritage sector, is to disseminate the history and the knowledge which belongs to a place or a monument. New technologies constitute a powerful instrument to intrigue and attract the curiosity of a large number of people: people can explore places where they cannot go for any personal reason, places that are now destroyed, and sites that are in dangerous and inaccessible areas. If we want that such kind of virtual/cultural experience stays impressed in the memory of the people and really brings people closer to Cultural Heritage, we need to engage them and stimulate their emotions and feelings. In order to help people living a full virtual experience, to remember it and learn something from it, at least two elements are essential: interactivity and immersion. The interaction of the user with the virtual world is important in order to stimulate an active involvement which facilitates the memorization of the story he/she is living; the user needs to experience directly the virtual world, with the freedom to move around and to select the content he/she is more interested in[130], [131]. The immersion improves the feeling of presence, the perception of being really part of the scenery, and this makes the application more enjoyable and entertaining.

The Head Mounted Display (HMD) (as Oculus Rift, Samsung Gear, HTC Vive and Google Cardboard) that nowadays is getting more and more popular in several sectors (for simulations, games, education and much more), can offer both the required characteristics for fully experiencing the virtual world: immersion and interaction.

Very recently, also some applications of virtual archaeology and virtual heritage have been developed to be performed through a head mounted display[8], [11], [132]. In particular, a very good free mobile application for Google Cardboard have been made for the Greek-Roman theatre of Locri in Calabria, Italy, by digi.Art[67] (fig. 170). The 3D reconstruction of the theatre is based on the information collected by the archaeologists during the archaeological excavations and the app offers several possibilities of interactions: moving around, playing with the mechanism under the stage in order to change the scenery for different representations (fig. 171), placing or removing the veil which protected the spectators by the sun, plus listening and following the ancient characters who narrate the history of the theatre[68]. The choice of developing an app for Google cardboard is of course very convenient because the device itself is very cheap (less than 15 euros) and almost everyone has a smartphone; therefore it is an easy solution to disseminate the app, but obviously the quality and the comfort is not the same as more expensive devices.

In this research, a virtual application for Oculus Rift has been developed, in order to have a better quality, but also because it is easy to implement the same application with Samsung Gear Glasses as well, which is cheaper but still maintains a high quality result.

The main aim of this application is to virtually bring back to life six of the Roman theatres of Crete (the ones we have more information about) and to experience an ancient performance as if we were sitting in the cavea almost 2000 years ago.

[67] It is possible to download the app for free at the following address: https://play.google.com/store/apps/details?id=it.digi_art.cultura.app.TeatroGreco

[68] https://mediterraneoantico.it/articoli/archeologia-classica/teatro-greco-romano-lokroi-lantica-citta-locri-rivive-grazie-alla-realta-virtuale/

Figure 170 Mobile application of the Greek-Roman theatre of Locroi in Calabria, Italy.

Figure 171 Mobile application of the Greek-Roman theatre of Locroi in Calabria, Italy. Particular of the stage and the scenery.

The application has been created through four main steps:

1. 3D modelling of six of the Roman theatres of Crete (the theatre of Aptera, the theatres of Hersonissos, the theatre on the acropolis of Gortyna, the theatre of the Pythion at Gortyna, the theatre at Kazinedes at Gortyna and the theatre at Koufonissi);
2. Auralisation of an anechoic file from several seats spread in the cavea of the 3D models of the six theatres;
3. Creation of icons and informative panels for each theatre;
4. Development of the VR application through Unity3D, a cross-platform game engine.

<u>Step 1:</u>

The 3D models have been created after having collected and studied the available documents about their architectural structure[69]. The virtual reconstructions of these theatres are the result of a sequence of hypotheses (comparisons with other Roman theatres in Rome and in all the Empire, description of the architecture of the Roman theatres by Vitruvius) and a process of interpretation of the data acquired through the combination of several analyses (overlapping of aerial pictures with ancient plans and geophysical maps, 3D visibility analysis and virtual acoustics analysis)[70]. The ornaments, as columns, entablatures, cornices etc. are not reproduced in detail; they are very basic because the research is focusing on the architectural structure of the theatres[71]. 3D Studio Max 2016 is the software used to realize and texturize the 3D models. The materials applied to the surfaces of the objects composing the 3D models

[69] The 3D model of the theatre of the Pythion in Gortyna has been created by the University of Padua. The 3D model has been kindly offered in order to make the 3D visibility analysis and the virtual acoustics analysis of this monument as well.

[70] See “Case study” chapter for details.

[71] The collection of information about the decorations of these theatres, and their hypothetical virtual reconstruction is one of the future goals, in order to deepen and enhance the research about the Roman theatres in Crete.

are Mental Ray materials and consequently the renderer has been set on NVIDIA mental ray as well. Mental Ray materials have been preferred to others because they offer sets of materials specific for architectural rendering (as Arch&Design Material) and a kit with pre-set characteristics for some materials, as stone and hardwood, which are present in the reconstructions of ancient theatres. Furthermore, Mental Ray renderer eases the procedure of lightening of the scene, generating "correct simulation of lightening effects"[72]. Being an outdoor scene, the daylight system has been used in all the 3D reconstructions of the theatres, setting the real latitude, longitude and north direction of the position of each theatre. In order to create a more faithful reconstruction, the terrain in its real shape has been used along with the 3D models of the theatres: the contours of the terrains where the theatres are placed, have been exported from Sketch Up and imported again in 3D Studio Max. Unity is a real time engine (it renders in real time) so, in order to maintain the characteristics set through the choice of the materials, the lightening and the shadows, while the VR application is running, the baking texture option has been chosen. Through the render to texture procedure it is possible to record in an image all the characteristics of the procedural texture applied to the object, which means it records the effects of the light on the object, the reflections coming from other objects, the characteristics of the material set for that texture and it can be saved as a .JPG, a .TIFF, a .TGA and other formats. Every object in the scene of 3D Studio Max has been baked in a high resolution image (2048 x 2048) in order to maintain as much as possible the good quality of the textures applied[73]. The obtained images have been then mapped again on each object as a standard material and of course the lightening settings were not necessary anymore because the shadows and the light is store in the texture applied to

[72] https://knowledge.autodesk.com/support/3ds-max/learn-explore/caas/CloudHelp/cloudhelp/2015/ENU/3DSMax/files/GUID-484B095B-1229-4CB9-BC53-952AC40F67C2-htm.html

[73] Unfortunately, with the baking texture technique there is always a loss in the quality of the image, but it is possible to limit it.

the object (fig. 172). Then, the 3D models of the theatres have been exported as .fbx, in order to easily import them in Unity.

Figure 172 Example of baked texture of one of the columns decorating the *scaenae frons* of the theatre at Kazinedes, at Gortyna.

Step 2:

The auralisation was also performed through the same software used for the virtual acoustics analysis, namely Odeon Room Acoustics. The auralisation consists in the convolution of an anechoic file with the impulse response recorded in a specific position of a given space by a receiver. The result of the auralisation is an audio file which sounds as if the user is physically present in the space where the receiver is. For each theatre few files, from five to eight (depending on the size of the building), have been auralised in different positions of the cavea.

The anechoic file has been recorded in the laboratory of the Institute of Acoustics and Sensors “Mario Corbino” at the CNR of Rome Tor Vergata, with the collaboration of Dr. Paola Calicchia, Dr. Cristina Pace and Martina Giovanetti. The latter is a student of Classical Philology at University of Rome Tor Vergata and she played a monologue in ancient Greek from the work “The Trojan Women” by Euripides, which has been recorded in the anechoic room of the above-mentioned laboratory. The recorded file, that it is about four minutes long, has been imported in the project of each theatre in Odeon Room Acoustics and it has been automatically convolved with the impulse response recorded by the receivers placed in the cavea. Simplifying, the impulse response contains the information about the architectural characteristics of the building and this is the reason why through the auralisation it is possible to create an audio file that corresponds to the real sound in a specific position of a building.

The auralised files of each theatre have been imported in Unity, so that the user can better experience the feeling of presence in a virtual world and he/she can also understand the influence that the architecture has on the sound. The VR application allows the user to select one of the seat of the cavea from the centre of the orchestra, and automatically to move in that position and start listening to the auralised file, and then he/she can select another seat to move again and listen to the audio file from another position (fig. 173).

Figure 173 Selecting seat in the theatre of Kazinedes at Gortyna through the VR application.

<u>Step 3:</u>

In order to create a more instructive and educational application, some informative panels have been added. The added information includes: the history and the characteristics of the theatre, its location, pictures, drawings, and details. Each category of panels is represented by an icon, that when it is selected shows the corresponding panels (fig. 174).

Figure 174 Icons in the theatre of Kazinedes, at Gortyna, in the VR application.

The book icon is related to the panels about the history and the characteristics of the theatre. They are text panels and they contain very brief information about the state of art of the monument (who discovered it, when and who documented it, etc.), its architectural structures (the number of sectors in the cavea, the number of seats, etc.), its state of preservation and other typical features (fig. 175).

The images icon is connected to panels showing pictures of the theatre, ancient and new plans and sections, and aerial images (fig. 176).

The icon representing the top view of a theatre is related to the drawings panels, which means the plan, the section and the representation of the hypothetical reconstruction of the theatre according to my opinion (fig. 177).

The location icon is connected to a panel embedding a video realized through the tool Movie Maker in Google Earth Pro, which shows the full island of Crete from the top and then zooms in till the exact area where the remains of the theatre are placed (fig. 178).

Figure 175 History panel of the theatre of Kazinedes at Gortyna, in the VR application.

Figure 176 Image panel of the theatre at Kazinedes in Gortyna, in the VR application.

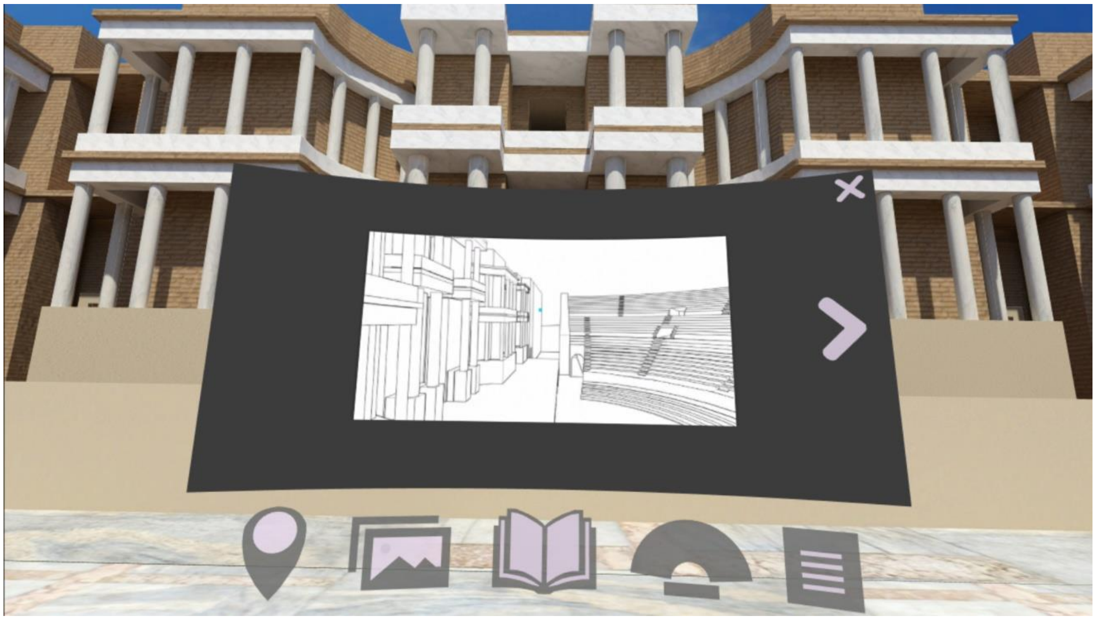


Figure 177 Drawing panel of the theatre of Kazinedes at Gortyna, in the VR application.

Figure 178 Location panel in the theatre of Gazinedes at Gortyna, in the VR application.

The details icon shows a panel about the reliability and accuracy of the 3D reconstruction of the theatre. Three images in the central part of the panel indicate three sectors of the theatre: cavea, scene and *parodoi* (corridors). On the left side of the images, the instruments used to study the theatre and helpful formulating a hypothesis about its architectural structure are listed: archaeological excavations, written sources, ancient plans, aerial pictures, geophysical maps, 3D visibility analysis, and virtual acoustics analysis. On the right side of the panel, the words "reliable, possible and hypothetical" suggest the accuracy of the 3D reconstruction for each sector of the theatre (fig. 179). The accuracy is one of the principles listed in the Seville Charter and it is fundamental in order to explain that the presented reconstruction is not the only possible. When we are dealing with destroyed buildings we can never be sure about their original structure, but some clues (as archaeological remains) bring us closer to the reality and some other can be useful only to speculate about the real aspect of a building. It must be explicitly clear if the 3D reconstruction is based on reliable data and if it is an accurate and reliable reconstruction rather than a conjecture based on information but without material evidence. This is fundamental if we want to have a scientific approach and if we want to disseminate culture rather than only attractive 3D models.

Figure 179 Detail panel of the theatre of Kazinedes at Gortyna, in the VR application.

Step 4:

The VR application of the Roman theatres of Crete has been developed through the cross-platform game engine Unity3D (its programming language is based on C#), for the device Oculus.

The reasons to opt for Unity instead of other game engines are several. First of all it is an open source software which has many functionalities and often does not need any external plugin because it has numerous libraries embedded. The other main advantage is that it can export to many platforms, more than 25 across mobile, desktop, console, TV, VR, AR and Web; this makes each application created in Unity very easy to be deployed and therefore lets more users to know it. In addition, Unity3D has an asset store from where many packages can be downloaded for free too; it is constantly updated with the latest techniques and tools developed; it allows you to distribute your applications for non-commercial reasons without any fee[74]. Furthermore, Unity is quite easy to use and the web is full of tutorials and forum to help finding solutions in programming.

Being a VR application, the best device to use is a head mounted display that allows you to have a 360° view, which enhances the feeling of presence in the virtual world and the sensation to physically live the virtual experience. In addition, some of the head mounted displays enable the user to easily interact with the objects in the virtual world. In this research, Oculus Rift is the device that has been chosen to be used for the VR application of the Roman theatres in Crete. Oculus Rift has been preferred to the cheaper Google Cardboard for two main reasons: the better quality (the screen resolutions and the quality of the lenses) and its functionalities (the orientation tracking, the gyroscope, the accelerometer and the magnetometer). Also Samsung Gear is very convenient because it has functionalities too and it has the advantage to be portable, but the quality depends on the graphic card of the mobile used along with it. By the way, once an application has been built in Unity for Oculus Rift, it can be easily exported for Samsung Gear as well, without any further modifications.

[74] More features can be visualized on the website of Unity 3D at the following address: https://unity3d.com/unity

In order to create the application, the VR library embedded in Unity has been used, without the need to import any other plugin.

The application includes six of the Roman theatres of Crete. The main menu shows six panels with the name of each theatre and with an image of the 3D model (fig. 180). Targeting the image representing one of the theatres, a video of three seconds will start, showing the path to enter the theatre. After three seconds the user will automatically enter the selected theatre and he/she will be in the orchestra facing the stage and the scene building. In this position, the five icons (book, images, drawings, location and details) are visible and they can be selected (fig. 174). After two seconds targeting one of the icons, the panel with the information or with the images will show up; through two arrows on the sides of the panel it is possible to move to the next (or to the previous) panel of the same category.

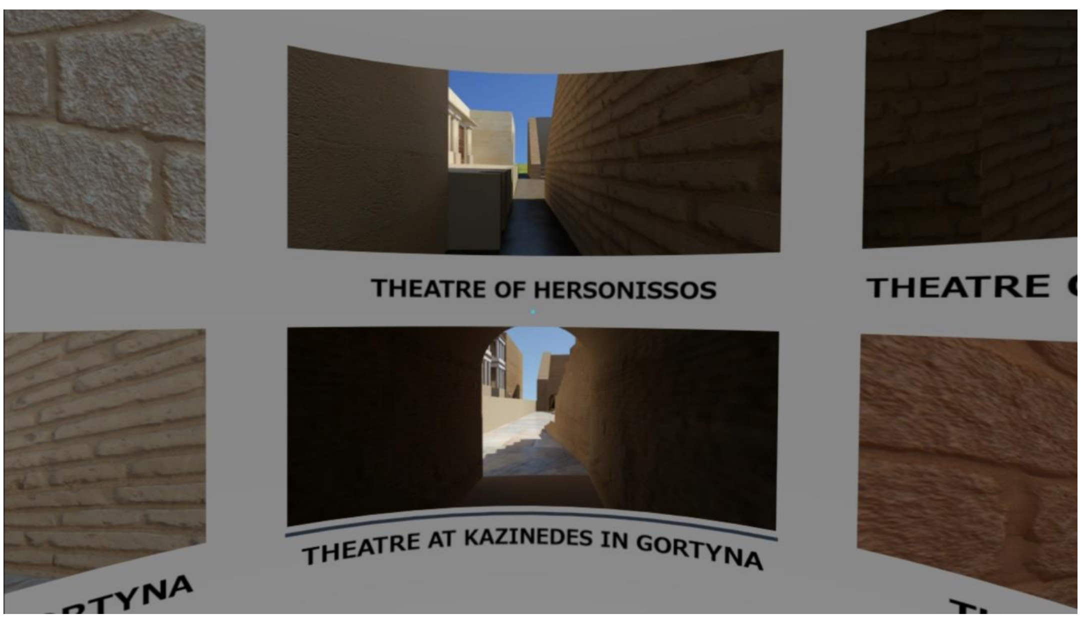


Figure 180 Main menu of the VR application of the Roman theatres of Crete.

To close the panel is enough to target at the x button placed on the upper right side, or simply selecting another icon. If the user looks around, he/she will see some icons representing two theatrical masks, used to indicate the seats of the cavea that can be selected. Targeting one of the couple of masks, the user will automatically move to the position occupied by the icon, from where he/she can look at the stage, and at the same time listen to the auralised file (fig. 181). From there, another position can be selected, in order to change seat and listen to another audio file. From any position of the seating area, the info icon is visible at the centre of the orchestra: targeting that icon, the user will move again in the orchestra in front of the stage, where the other icons will be visible again. From that position, it is possible to select also the home icon in order to go back to the main menu and then choosing another of the six theatres.

Figure 181 View of the stage from one of the seat of the theatre of Kazinedes at Gortyna, in the VR application.

During the creation of the VR application some issues arose. One of the main issues concerned the size of the application: consisting of more scenarios (six different 3D models of theatres accompanied by the correspondent terrains), plus videos, audios and images for each one of them, the application is consequently very heavy in terms of volume size. In order not to burden the application even more, some modifications have been made, as decreasing the quality and the duration of the videos, and removing trees from the 3D models. The second issue noticed is that the visualization through Oculus is not optimal, it is not completely clear, the pixels and the grid between the pixels is visible, producing the so called “screendoor effect” (the Oculus used during this research is the development kit 2). This feature makes harder to focus on details, therefore also reading texts might be annoying through Oculus.

The future step in order to improve the application created, will be to make an evaluation test about the ease of use, the ease to learn from the application, the level of entertaining, the level of comfort in using Oculus. A questionnaire will be presented to people of various age, various type of education, and various cultures.

Once the VR application about the Roman theatres in Crete will be improved and enhanced, it would be interesting and attractive to use it directly in the involved archaeological sites. Above all if the monuments are destroyed, or still buried, 3D reconstructions are a very helpful and convenient solution to illustrate to the general public the ancient aspect of that area. The 3D models along with a VR application facilitates the learning process, so that visiting an archaeological site is going to become both educational and exciting experience. Such a formative experience will motivate a larger part of the society to visit archaeological sites and museums, facilitating the economic and scientific growth of these cultural institutions.

7. CONCLUSION AND FUTURE RESEARCH

As it has been highlighted in the introduction, this study does not address a single research question, because it aims to produce new data and innovative resolutions about three different sectors (archaeology, virtual analysis, and digital media) that have been demonstrated they can be profitably combined in order to enhance the research. This thesis shows the outcome obtained from the fusion of tools belonging to different disciplines, in particular: 3D modelling, GIS (Geographical Information System) analysis, acoustics analysis, database and Virtual Reality, applied to archaeology.

The main aim of this research has been the study and the consequent valorization of the Roman theatres in Crete. As it emerges in the chapter dedicated to the state of art, the material evidence of the Roman culture in the major Greek island has been neglected for a very long time, both from the archaeologists and the citizens, who destroyed large part of the monuments to reuse the material during the centuries. After the very early information left by the European travelers since the end of the XVI century, there is a large gap in the documentation about the Roman theatres of Crete that lasted till the beginning of this century. The consistent number of theatres dated to the Roman times in the island (at least twelve), and also the remarkable size of some of them (at Gortyna, Aptera, Littos), are instead meaningful factors that indicate the prominent role and identity of Crete as a province of the Roman Empire. The geographical distribution of these theatres clearly identifies the most powerful centers in the island (as Gortyna and Aptera), but it also demonstrates that minor centers were enough evolved to have their own theatre (Hersonissos, Lissos and Koufonissi).

By means of this research, more data have been acquired about the architectural structure of the theatres thoroughly analyzed. In the chapter dedicated to the case studies, the several hypothetical reconstructions of the seven better known theatres have been listed, together with the results obtained from the different analyses which contributed to the final reconstructive hypothesis. Each theatre presents different characteristics in size, partition of the cavea, decoration of the *scaenae frons*, orientation, location, etc. At the same time some of them are more similar (Hersonissos and Koufonissi), while other have a unique shape (Aptera). The most notable common features arose from this research are two: the absence of the portico in *summa* cavea and the *parodoi*, vaulted or not, which separate the cavea from the *scaenae frons*. According to Vitruvius and several archaeological evidences (theatre of Pompey, theatre of Orange, theatre of Aspendos, theatre of Vienna, etc.), the portico in *summa* cavea is one of the main characteristics of the Roman theatre, as well as the closed structure which let the theatre looks like a unique block. The absence of a portico in *summa* cavea and the presence of open *parodoi* are typical in the Greek theatres. Indeed, the lack of these features is more common in theatres that were born from the Greek culture and that have been modified (enlarged or enriched) later on by the Romans, as the theatre of Dionysus in Athens and the theatre of Priene in Minor Asia[75]. Among the Roman theatres of Crete analyzed, only two were originally built in Greek or Hellenistic times, the theatre of Aptera and the theatre on the slope of the acropolis of Gortyna. In the case of the theatre of Aptera, the division of the cavea from the scene building by vaulted *parodoi* is documented by the archaeological excavations. This is a further reason to hypothesize the same structure for the theatre at the acropolis as well, as it has been also demonstrated by the 3D visibility analysis and the virtual acoustics analysis. The interesting aspect is that also the theaters that have been built after the proclamation of Crete and Cyrenaica as Roman province, maintained these Greek characteristics, which denote a certain independency from the Roman customs, and maybe a desire to affirm its own identity. The theatre of the Pythion at Gortyna presents this separate structure too, but with the *versurae* that give access to the stage and not the *parodoi* to the orchestra. As shown in the case studies chapter, the Roman theatres of Crete have several comparisons with Roman theatres all around the Empire: Turkey, Greece, Italy, Croatia, Austria, France, Spain, Algeria, Tunisia, Libya, Jordan, and Syria. The largest part of comparable theatres is located in Italy (Aquinum, Metapontum,

[75] There are other Greek theatres that when they have been modified by the Romans, they lost the characteristic of the open *parodoi*, as the theatre of Magnesia and Ephesus in Minor Asia.

Ercolano, Pompeii, Urbs Salvia, Gubbio, Fiesole, Volterra, Verona, Segesta, Solunto), mainly in the South, once influenced by the Greek culture. Also in Asia Minor, there are interesting similarities with some of the theatres (Aphrodisias, Alinda, Ephesus, Aezani, Hierapolis, Miletus), whereas in Greece we have only three remarkable comparisons (Corinth, Dium, Nicopolis). We can deduce that the Roman theatres in Crete clearly had a structure which reminds the typical Roman architecture, above all with regard to the semicircular shape of the cavea, the dimension of the orchestra and the scene building, but it looks like there was not a programmatic development of the theatrical structure which unified the whole island, as demonstrated by the local differences. The presence of open corridors between cavea and *scaenae frons* (probably in all the theatres examined) and the absence of a portico in *summa* cavea are indicators of the transmission and the perseverance of the Greek traditions, and it seems obvious to hypothesize that the architects and the craftsmen were local.

It is noticeable that the plans of the analyzed theatres drew by Onorio Belli at the end of XVI century, show a long distance between the cavea and the scene building. Despite his plans can be considered fanciful as stated by Isler [64], some traits of truthfulness can be recognized, for example the only sector of the cavea represented in Hersonissos' theatre plan and the identification of the pillars sustaining its cavea, the absence of a portico in *summa* cavea in the plans representing the theatre of Hersonissos and in that one representing the "small" theatre of Gortyna. It is also important to consider that he did not draw such separation between the cavea and the *scaenae frons* for all the theatres he represented, as this is evident in the plan of the theatre of Littos and the plan of the small theatre of Ierapetra [26]. The major issues with Belli's plans are the measurements and the confusion between different structural elements, but these are not good reasons to completely deny his reconstructions. Probably with that large distance between cavea and scene building, Belli simply wanted to underline that those theatres were not constituting a unique block and that indeed there were open passages. Furthermore, a similar distance between cavea and scene building is recognizable in the plan of the theatre of Boville, in Italy, made by Poletti at the end of XIX century [133], but no further investigations have been made after him in order to confirm his reconstruction.

The Roman theatres of Crete are not very well preserved and some of them have not been even excavated. In order to obtain additional information about their architectural structure, two innovative tools have been used during this research: the 3D visibility analysis and the virtual acoustics analysis. Both of them have been helpful to identify possible mistakes in the reconstructive hypotheses. In particular, as explained in the methodology chapter, the 3D visibility analysis was useful to identify elements which obstacle the visibility of the stage from the seating area, and the virtual acoustics analysis verified the acoustics quality suggesting the presence, or the absence, of some architectural structures (such as the portico in *summa* cavea) which influenced the quality of the sound, as previously demonstrated by Canac [20]. The results obtained from the implementation of these digital tools incited to rethink the various interpretations of the archaeological remains of the ancient theatres investigated, till to verify more than one reconstructive hypothesis for each monument. In other cases, this methodology confirmed the hypothesis formulated after the archaeological excavations, as for the theatre of Aptera. The virtual acoustics analysis also provided data which enable to suppose if the theatres were used for spoken performances of for music performances. As it has been presented in the case studies chapter, all the Roman theatres of Crete seemed to be reserved for spoken performance rather than for listening to music, as it was more common in the Roman theatres. Furthermore, this assumption is confirmed by the auralisation. The convolution of the impulse response and the anechoic file containing a monolog, for each receiver placed in the 3D models of the theatres, gave as a result an audio file that is clearly understandable from every considered position in every theatre.

The combination of 3D modeling, 3D visibility analysis and virtual acoustics analysis has been successful in order to acquire data that would have been impossible to obtain otherwise. It is actually recommendable and preferable to apply the same methodology to each architectural study dedicated to spaces which visibility and acoustics are fundamental. This research has re-marked that 3D modelling in archaeology is not only a solution for visualization, storing data and verifying interpretations, but it is sometimes also the only way to make analysis and to obtain new data. Of course this is not the first time that some quantitative analyses are applied to 3D models in archaeology; Lukesh calculated the distribution of artefacts in archaeological layers according to the volume of a 3D model representing the archaeological excavations, already at the beginning of the '90s[134]. However, it is important to keep underling the advantageous use of 3D models in archaeology because unfortunately I have noticed some skepticism and resistance from the more traditional archaeologists.

The reconstructive hypotheses of the Roman theatres of Crete, resulting from the interpretation of the data acquired through the study of the available documentation, the 3D visibility analysis and the virtual acoustics analysis, together with the auralised files, were used to develop a virtual reality application. As explained in the chapter dedicated to digital archaeology, the reasons to choose such kind of application to visualize the 3D models are several. Thanks to the evolution and the diffusion of digital media, such as tablets and smartphones, today it is easy to spread and share information with a vast majority of people. The high exposure of Cultural Heritage through innovative instruments and attractive reconstructions, helps to make the people aware of our precious past and hopefully to let it be more respectful of monuments and ancient sites. Furthermore, a virtual reality application distinguishes itself for the sensation of presence and immersion felt by the user, and, as demonstrated by Jacobson [21], this aids the learning process. The application of the Roman theatres in Crete has been scripted for Oculus Rift, rather than Google Cardboard, for two main reasons: the highest quality of the first, and the possibility to use the same application with Samsung Gear as well. In this way, this VR application can be addressed to museums and archaeological sites, which can enhance their exhibition and attract more visitors by the use of Oculus, but it can also be accessible to anyone else that cannot reach the sites, through Samsung Gear, or downloading the app on the PC and installing Oculus Rift.

In particular, the additional value of the application created during this research is the possibility for the user to experience an ancient performance, as it would have sounded in the specific theatre where he/she has been virtually transported. The possibility to move from one theatre to another, and to listen to the auralised file, approximately from the same relative position, also helps the user to perceive the influence that geometry and architecture have on the acoustics.

The application does not present alternative hypotheses of reconstruction because, given the scarcity of the data, it was preferable to propose one reconstructive hypothesis based on scientific data, and highlight the level of reliability for each sector of the theatres and also the data which contributed to that interpretation. Another advantage of 3D modeling is the chance of modifying the digital product so that if new discoveries will come to light and new interpretations will be elaborated, new 3D reconstructions can be easily added to the VR application.

A different digital solution has been thought for the specialists, rather than for the general public. A database about the Roman theatres has been developed, that contains all the information collected about the Roman theatres of Crete. The fundamental innovations of the particular database are the addition of the acoustics values of the parameters analyzed, and the possibility to filter the results according to the scholars who studied the monuments. The possibility to consult the acoustics values will improve the interpretation of new acoustics data acquired for other ancient theatres, as the information provided by the ERATO project has been essential for this research. The list of the data according to the different scholars can be useful for possible future thorough examinations of the same theatres because all the information is available and not only the final interpretation of only one scholar.

This research has demonstrated the fruitful interdisciplinary approach in archaeology. The ensemble of acoustics, GIS, computer science, architecture and archaeology produced valuable results both for specialists of Cultural Heritage and for non-experts. Archaeology is not an exact science and the archaeological excavation is a destructive action. Quantitative analysis and digital tools help to reduce subjectivity and to keep working on what it may not exist anymore, enabling new discoveries and stimulating new hypotheses. It is surprising to note that still many archaeologists do not know how to take advantage of what new technologies are able to offer nowadays. It is desirable that archaeology, and more in general Cultural Heritage, develops an interdisciplinary workflow in the research. The simple study of the object of the research, from the point of view of different disciplines (for example the historical aspect, the architectural aspect, the artistic aspect, etc.), that is multidisciplinary, is not enough. The different disciplines must get tuned in order to produce new methodologies and tools to achieve a more advanced and accessible result.

The downside of the interdisciplinarity is that the ability to merge different disciplines is time consuming, since our mind needs to adapt itself every time to different scientific approaches and one needs to learn from scratch the basis of all the disciplines involved. Consequently, several topics still need to be investigated about the Roman theatres in Crete. First of all it will be necessary to expand this study to the ornamental decorations of the theatres; that means analyzing the sculptures, the columns and the fragments of architectural decorations found in the area occupied by the monuments. All these elements belonging to different Roman theatres in Crete must be compared among them and among the decorations of the other Roman theatres in the Empire. The study about the decorations will enrich not only the story of Roman Crete but also the VR application, presenting more developed 3D models, and the database with additional info. The future purpose of the database is indeed to expand it further than this study has accomplished, namely with information not only about the Roman theatres in Crete, but about the theatres in the whole Roman Empire. The ideal would be to create an open access DB to all the scholars so that they can add and share their discoveries.

Furthermore, also the topographical aspect of the Roman theatres in Crete needs to be examined and it will probably bring a number of interesting conclusions with respect to the landscape context of them. In particular, it may be relevant to focus the attention in the relationship between theatres and streams, because in at least three cases in Crete (the theatre of the acropolis at Gortyna, the theatre of Lissos and the theatre of Ierapetra) we have a small river flowing at the back of the theatre.

Another interesting and necessary topic would be to apply the same workflow to the Roman theatres in Libya in order to be able to make a punctual comparison with them, because Crete and Libya (Cyrenaica) together used to form a unique Roman province.

In addition, some indirect survey, through photogrammetry and/or laser scanner, of the remains should be made and then they can be added as 3D models to the VR application, in order to show the actual state of preservation.

Finally, a serious game can be developed for didactical purposes: a 3D model of an ancient theatre can be broken down and build up again till reaching the right structure of the theatre and the right placement of its architectural ornaments; some texts of ancient performance can be read and the pronunciation can be correct; and the user can perform on the stage of the ancient theatres though Microsoft Kinect.

GLOSSARY

Absorption coefficient:the capacity of a material to absorb the energy of the sound.

Aditus**:** lateral access to the orchestra in the Roman theatre.

Ambulacrum**:** corridor that divides the sectors of the cavea in the Roman theatre.

Analemma, analemmata**:** back and lateral walls which contain the cavea of the ancient theatre.

Anechoic sound: sound that has been recorded in a room which structure reduces as much as possible the sound reflections, in order to obtain a sound without reverberation.

Augmented Reality (AR): it enriches the reality adding virtual information through digital tools.

Auralisation: is the simulation of a sound in a specific place and it is obtained by the convolution of an anechoic sound and the impulse response.

Baking texture: rendering procedure to record on an image the properties of the material applied to the object, together with the light effects.

Basilica, basilicae: two rooms placed at the sides of the stage in the Roman theatre.

Cavea: seating area of the theatre.

Clarity (C80): represents the comprehension of single sounds within a complex signal. It consists of the ratio between the energy that arrives within 80 ms, to the energy that arrives later

Cunei: sectors of the cavea delimited by the stepladders in the Roman theatre.

Definition (D50): indicates the level of clarity of the speech, the ease for the listener to understand the message of the speaker. The index of D50 is the ratio between the energy that arrives within the first 50 ms, direct sound plus early reflections, and the remaining energy of the signal.

Diazoma**:** corridor that divides the sector of the cavea in the Greek theatre.

Digital Media: all those instruments for mass communication developed after the born of computer science, that use digital electronic devices.

Direct sound: part of the sound that directly reaches the ears of a listener, travelling in a straight line from the source, and it arrives first than the other components.

Early Decay Time: indicates the diffusion of the sound and its subjective perception.

Early reflections: they derive from the sound hitting obstacles (such as walls, ceiling, floor, large objects) that reflect the received acoustic impulse; they are the first reflections that arrive after the direct sound.

Frequency of visibility map: the number of observer points which have visibility is indicated by several colors on a plan of the building investigated, showing the different access to visibility for each area of the building.

***Ima* cavea:** the lowest sector of the cavea in the Roman theatre.

Impulse response: the output from a brief input signal. It describes the reaction of the system as function of time.

Iposcaenium: the area under the stage of an ancient theatre.

Late reflections: the ones which arrive after the early reflections.

Lines of sight: lines indicating visible or not visible trajectories (respectively green and red lines) from the observer to the target.

Logeion: high stage in the Greek theatre.

Maeniana: sector of the cavea divided by the ambulacra in the Roman theatre.

***Media* cavea:** the central sector of the cavea in the Roman theatre.

Obstruction points: the points derived from the calculation of lines of sight, which indicates the obstacles that impede the visibility between observer and target.

Orchestra: area between the scene and the cavea in the ancient theatre. In Greek times the orchestra was used by the chorus for dancing, in Roman times it was partially occupied by the chairs for the senators.

Paraskenia: two rooms at the side of the stage in the Greek theatre.

Pàrodos, pàrodoi**:** lateral access to the orchestra in the Greek theatre.

Proscaenium: everything was placed in front of the scene in the Roman theatre.

Proskenion: everything was placed in front of the scene in the Greek theatre.

Pulpitum: stage in the Roman theatre.

Reverberation Time (RT): the time a sound takes to decrease by 60 dB after it stops.

Scaenae frons**:** richly decorated background of the scene in the Roman theatre.

Scattering coefficient: indicates the decreases of intensity of a signal, due to the discontinuities the signal encounters when it reaches the surfaces and their material.

Speech Transmission Index (STI): establishes objectively the quality of level of spoken, calculating the combined effect of background noise and reverberation on the intelligibility of the speech. When there are no interferences on the characteristics of modulation of the signal, there are suitable conditions of intelligibility.

***Summa* cavea:** the highest sector of the cavea in the Roman theatre.

Thymele: the altar dedicated to Dionysus usually placed at the center of the orchestra in the ancient theatre.

Tribunalia: two elevated platform placed at the sides of the cavea, above the *aditus* in the Roman theatre, reserved to praetors and Vestals.

Velarium: awning that covered the cavea in the Roman theatre.

Versurae: two entrances to the stage in the Roman theatres.

Viewshed: analysis to calculate the visibility of one or more locations in the landscape.

Virtual Archaeology (VA): defined by Reilly in 1991 asa “description of an archaeological formation or a simulated archaeological formation”, through new technologies and digital tools.

Visibility graph: analysis which calculates the inter-visibility between two or more points.

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