Методика изготовления недостающих фрагментов керамических сосудов на 3D-принтере была апробирована на ёмкостях железного века и показала определённые преимущества перед традиционными методами реконструкции керамики. Сделанные из пластика фрагменты в случае необходимости можно извлекать из сосудов. При этом не происходит разрушения ни стенок сосудов, ни пластиковых фрагментов. Также можно поменять одни пластиковые фрагменты на другие, например, изменив их окраску, что бывает необходимо сделать при разных условиях демонстрации артефактов.

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A NEW METHODOLOGY FOR ANCIENT THEATRE ARCHITECTURE HYPOTHESES VERIFICATION

Introduction

The analysis of visibility in archaeology has found widespread application, above all in landscapes' studies, since the '80s. In particular, this kind of analysis has been considered useful to investigate the distribution of sites and relationships between them (Wheatley 1995, 173–185), to understand defensive techniques of ancient populations (Loots et al. 1999), to study the likely rituals connected to prehistoric monuments and to examine the connection between monuments/sites and astronomical events (Fisher et al. 1997, 581–594).

The important information obtained through the application of visibility analysis in archaeological contexts has encouraged the archaeologists to use it more frequently, above all with the advent of GIS technology (Lake, Woodman 2003, 659–695). On the other hand, during all these years, a large part of archaeologists has left behind the other fundamental senses of the human perception: the hearing, the smell and the touch. David Wheatley has efficiently resumed the critique, developed in the last fifteen years, to the common concept that the sight is the main sense of our body and then the most widely investigated in order to understand our past culture and ancient civilizations (Wheatley 2014, 121–127).

In addition, limiting visibility studies to the landscapes and to urban-social environments (as it has been done till now) means underestimating the potentiality of this instrument. Visibility analysis can also be useful in order to interpret the architecture of ancient monuments and buildings, especially with the help of digital tools and 3D models, which allow the specialists to give a full three-dimensional shape, although virtual, to the archaeological remains. In the same way, also virtual acoustics analysis can prove helpful in enhancing hypothetical reconstructions of monuments and buildings.

The aim of this paper is to present a methodology which combines 3D visibility analysis and virtual acoustics analysis to study one of the three Roman theatres at Gortyna, the one located at Kazinedes, in order to propose a more reliable hypothesis about its original structure. In particular: through the 3D visibility analysis, the visibility of the stage from the seating area will be verified; through the virtual acoustics analysis, the comprehension of speech or music by the spectators will be taken into account.

Visibility and acoustics analysis in archaeology

During the years, several approaches have succeeded one another in order to achieve a high degree of reliability and to obtain as much archaeological information as possible through visibility analysis: isovist (Benedikt 1979, 49–65), visibility graph (Turner et al. 2001, 106–118), viewshed analysis (Fisher 1996, 1298–1301) and texture viewshed that sees the combination of GIS analysis and 3D modelling (Earl 2005; Paliou et al. 2011, 380–385).

Indeed, since the beginning of the 21st century, the main issue of visibility analysis is the need to work in a full 3D environment, in order to consider also vertical faces (for example trees and buildings), and therefore to have a more exact approach and to obtain more reliable results. In the very last years, a faster methodology has been applied in the *insula* V of Pompeii (Landeschi et al. 2015, 356–358), which consists in the possibility to calculate lines of sight (trajectories showing through different colours if the observer sees or not the target) directly within the 3D model, through the visibility toolbox of ArcGIS, in order to verify the visibility of an alphabetical inscription and of a political announcement.

Luckily, in the last years, the interest toward the hearing has been increased also among the archaeologists (and not only) as demonstrated by the word "archaeoacoustics" (Till 2014, 24–27), which indicates a multidisciplinary approach in the study of the sound of the past and its effects on our ancestors. Obviously, many acoustics analyses have been done already, in particular in ancient theatres (Canac 1967, 19–179), but very rarely these works were conducted by archaeologists. Mainly, the acoustics measurements were taken in order to know the acoustics properties of historical buildings and not really to reconstruct the history of those buildings, with very few exceptions (Chourmouziadou, Kang 2008, 514–529; Gugliermetti et al. 2008, 157–165).

Finally, Paliou and Knight proposed to combine visual data and acoustics data, in order to obtain more information about the sensations the worshippers were feeling and the stimuli they were receiving, within the Church of San Vitale in Ravenna (Italy), during the liturgy (Paliou, Knight 2013, 233–234). They created a combined map (visual data obtained by the visibility analysis, plus acoustics data derived from the in situ measurements) indicating the sensory catchment in the area of the church, in order to study which are the privileged positions in the building to assist the liturgy; in particular they wanted to examine the social differences between men and women, according to the area they occupied in the church (floor and *matroneum*).

The recent development of software, which enables to simulate acoustics measurements in a virtual environment, has allowed specialists to investigate the original acoustics properties of ancient theatres through their 3D reconstructions, with the advantage to consider all their architectural elements and not only those that have been preserved and/or modified during the centuries (Iannace et al. 2011; Lisa et al. 2006, 20–25).

Methodology

The methodology sees the use of several software, because there is not only one that combines 3D modelling, visibility analysis and acoustics analysis.

First and foremost, all the information (descriptions, plan, section and aerial image) regarding the chosen theatre has been collected, studied and analysed. A 3D model of the reconstruction hypothesis of the theatre, proposed by the archaeologist Gilberto Montali (Montali 2006, 237–289), has been created, tracing his plan and section in AutoCAD and then modelled in 3D Studio Max.

In AutoCAD, a grid of observer points (representing the spectators) has been made as well. The grid consists of four rows formed by 124 observer points located 75 centimetres higher than the corresponding seat in order to simulate the average eye-level of a seated man/woman. Four rows of points are sufficient to verify the quality of visibility, considering that from the central area of the theatre the stage is probably visible. In particular, it is important to examine the visibility conditions of the spectators seating at the sides of the cavea (the observer points here are placed 80 centimeters far from the converging walls to take into account the space occupied by the probable stepladders), where the converging walls of the

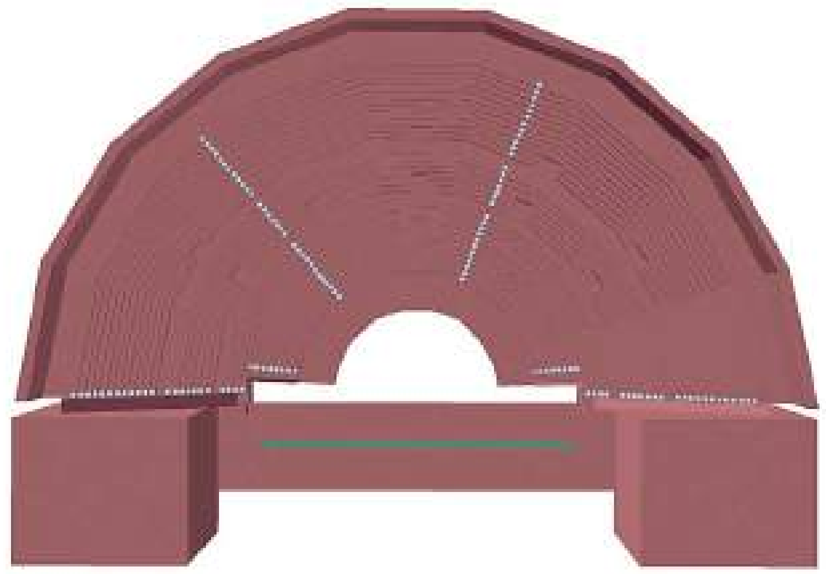

Fig. 1.
3D model of the theatre of Gortyna, at Kazinedes, plus grid of observer points and target line.
Image: M. C. Manzetti

analemma, or the basilicas, can be an obstacle. However, two rows of points are placed also in the central area to compare the results among the different locations, and to check the visibility from the first rows in case the stage would be too high, impeding the view.

The simplified 3D model and its grid have been then imported in ArcScene, the 3D visualization application of ArcGIS. A line (the target) has been drawn at the centre of the stage (almost as long as it), 160 centimetres higher than its floor with the purpose to represent the possible position of the actors/actresses (fig. 1).

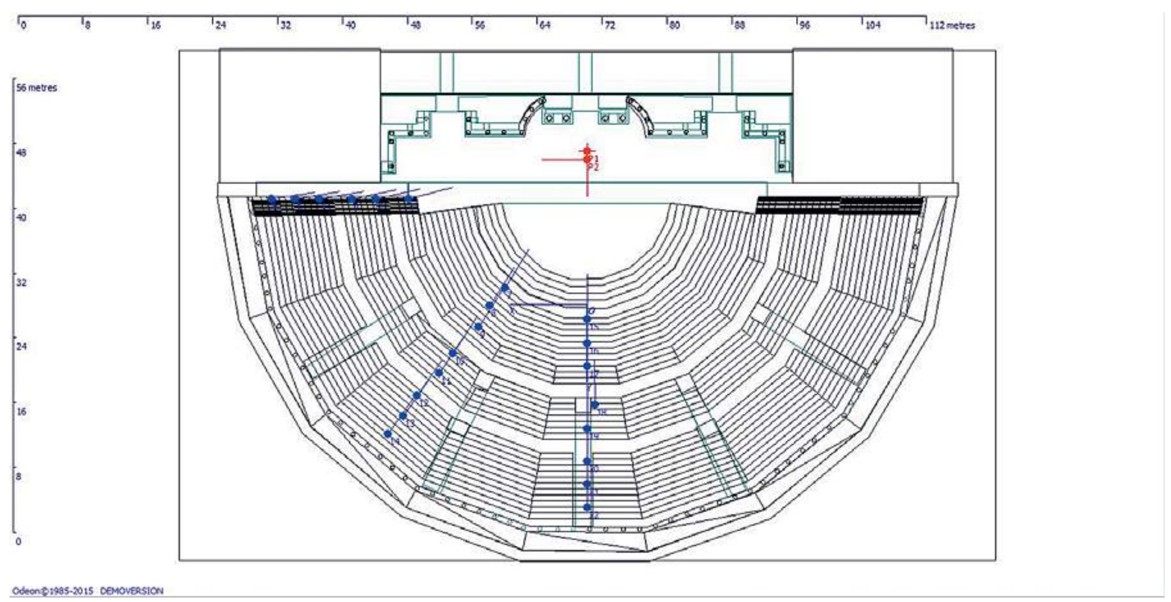

Fig. 2.
3D model of the theatre of Gortyna at Kazinedes, plus source and receivers.
Image: M. C. Manzetti

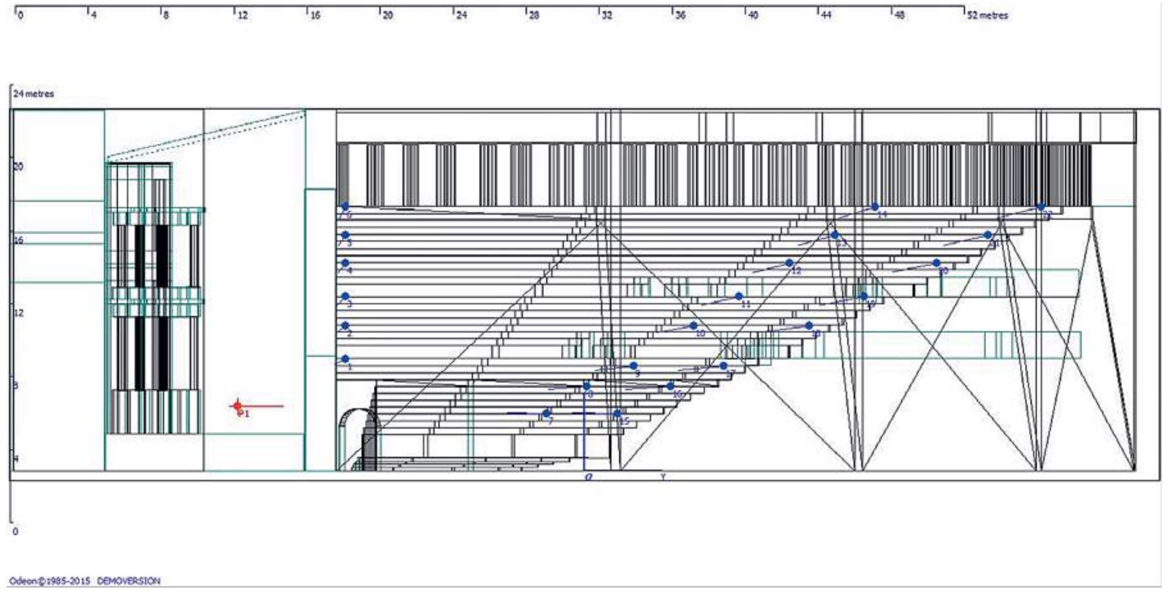

Fig. 3.
Section of the 3D model of the theatre of Gortyna at Kazinedes, plus source and receives.
Image: M. C. Manzetti

Lines of sight have been built between the grid and the line; they show through two different colours which spectators can see the actor/actress in one or many positions across the stage (green lines) and those that have no visibility (red lines) of him/her in one or more positions. Even more interesting is the identification of the obstruction points, that is the exact localization of the elements that obstruct the visibility; therefore they allow us to hypothesize which architectural parts might be wrongly reconstructed or misfit. In addition raster maps have been produced too, in order to visualize the frequency of visibility from the observer points: these maps make possible to visualize how many observer points see the stage or part of it (Manzetti 2016, 39–42).

Afterwards, the 3D model has been imported in the software Odeon Room Acoustics; a source has been placed at the centre of the stage (again 160 centimetres higher than the floor) assigning to it an overall gain of 60 dB, and 22 receivers (75 centimetres higher than the seats) have been placed in three radial lines in one half of the cavea (being this specular there is no need to place receivers also on the opposite side) (fig. 2, 3).

The appropriate materials (bricks, marble and stone), alongside the relative absorption coefficients, have been assigned to all the surfaces of the 3D models, including the seating area, where a material simulating the presence of the audience has been set. The scattering coefficient (that indicates the decrease of the intensity of a signal, due to the discontinuities the signal encounters when it reaches the surfaces and their material) has also been assigned, in order to describe the physical properties of the surface. Once all the settings have been modified and the correctness of the 3D model checked, the software can measure the impulse response for each receiver and consequently it gives the values of several parameters useful to judge the quality of the acoustics: reverberation time (T60), clarity (C80), definition (D50) and speech transmission index (STI) are the ones considered in this study.

The reverberation time is the time a sound takes to decrease after it stops; the ideal value for the speech is around one second, the ideal one for the music is around two seconds. The clarity represents the level of comprehension of single sounds in a complex signal; we have

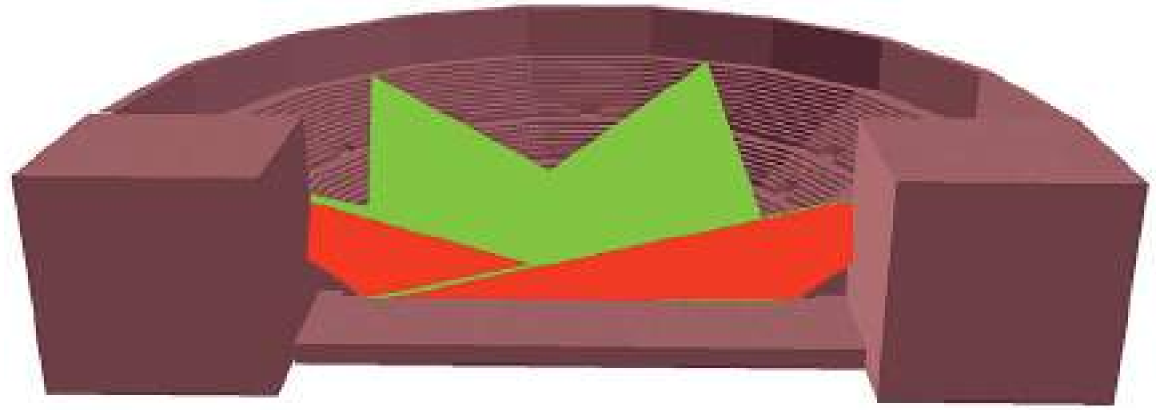

Fig. 4.
Lines of sight in Montali's hypothesis. Image: M. C. Manzetti

an appropriate acoustics for speech when the value of C80 is equal or greater than 3 dB, while for music the value should be under 3 dB. The definition indicates the level of clarity of the speech, the easiness for the listener to understand the message of the speaker; in order to have an acceptable quality of the acoustics for the speech, the value of D50 has to be higher than 0.50 (by definition it is included within 0 and 1). The Speech Transmission Index establishes objectively the quality of level spoken, calculating the combined effect of background noise and reverberation on the intelligibility of the speech; values of STI above 0.60 means a good and excellent intelligibility, under 0.60 is fair and bad (Spagnolo 2014, 760–807).

Case study and results

The theatre of Gortyna (Crete), in locality Kazinedes, is the monument chosen for application of this combined methodology. The theatre is partially visible on the surface, but it has not been excavated yet, so it is very challenging to try to reconstruct its original structure.

The first descriptions of the theatre are dated to the 16th century, but till the end of the 20th century it was confused with an amphitheatre by many scholars. Finally, when the real amphitheatre was discovered, the correct interpretation was made (Di Vita 1991). This theatre has been investigated recently only by Gilberto Montali, who has proposed his own hypothetical reconstruction, based on his archaeological knowledge and on analogies with other Roman theatres. In his reconstruction, the cavea is divided into three sectors, plus four rows for the *proedria* on the orchestra, overlooked by a portico at its very top. The *scaenae frons* is composed by two storey, a central semi-circular niche and two rectangular niches at the sides (the niches correspond to the entrances reserved to the actors) and it is flanked by two basilicas.

The resulting lines of sight obtained from the 3D model representing Montali's hypothesis, show that 15 % of these lines indicate not visible trajectories (fig. 4). It is clear, from the location of the obstruction points, that the basilicas are the main obstacle to the visibility of the stage for the spectators seating on the sides (fig. 5).

The visibility map shows that only the very frontal part of the stage is visible to everyone (blue colour), while we may suppose that the actors were playing mainly in the central area of the stage, which is visible by around 100 spectators out of 124 (fig. 6).

The results of the virtual acoustics analysis gives the following values (considering all 22 receivers and the range of frequencies between 125 and 2000 Hz): T60 between 1.10

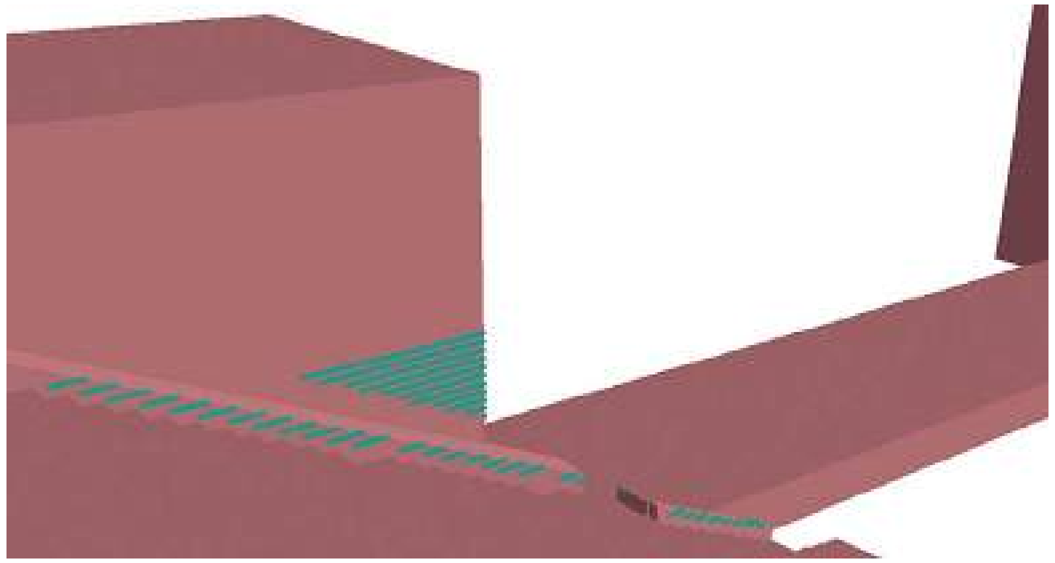

Fig. 5.
Obstruction points of Montali's hypothesis.
Image: M. C. Manzetti

and 1.97 seconds, C80 between -4.5 and 9.9 dB, D50 between 0.23 and 0.88, and STI between 0.56 and 0.76. The results show an acoustics quality that is not acceptable: even if the reverberation time can be considered good, the clarity and the definition, in numerous receivers, do not achieve values suitable for a comprehension of the speech and neither for listening to a music performance (25% of the values of the clarity are under 3 dB and 15% of the values of definition are under 0.50).

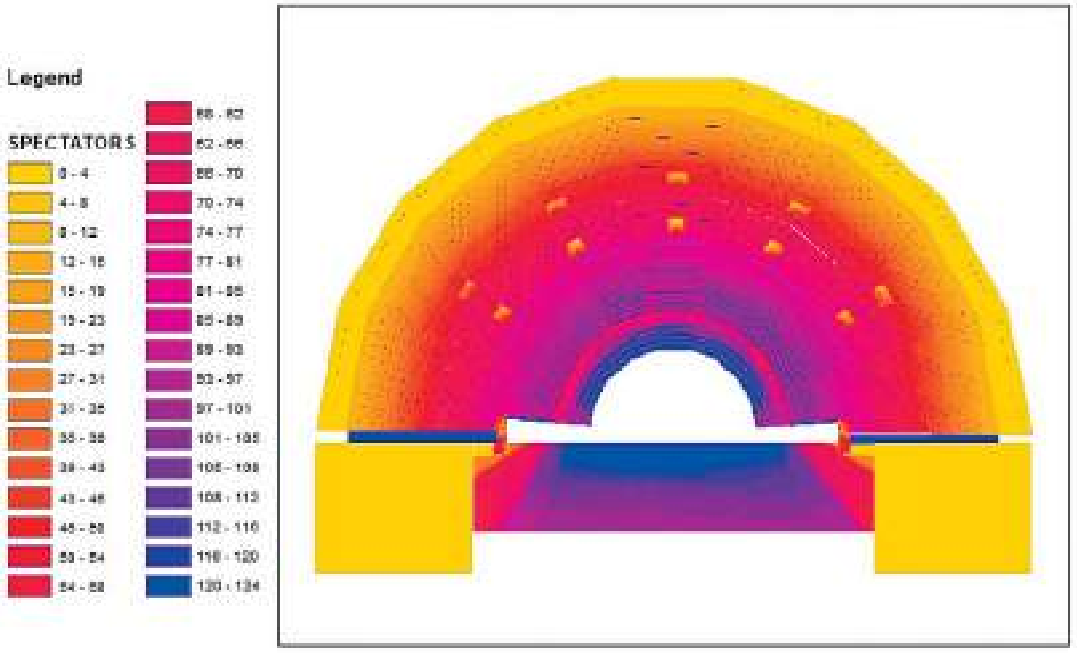

Fig. 6.
Visibility map of Montali's hypothetical reconstruction of the theatre of Gortyna, at Kazinedes.
Image: M. C. Manzetti

Fig. 7.
Satellite images of the site of the theatre of Gortyna at Kazinedes (from Google Earth).
Image: M. C. Manzetti

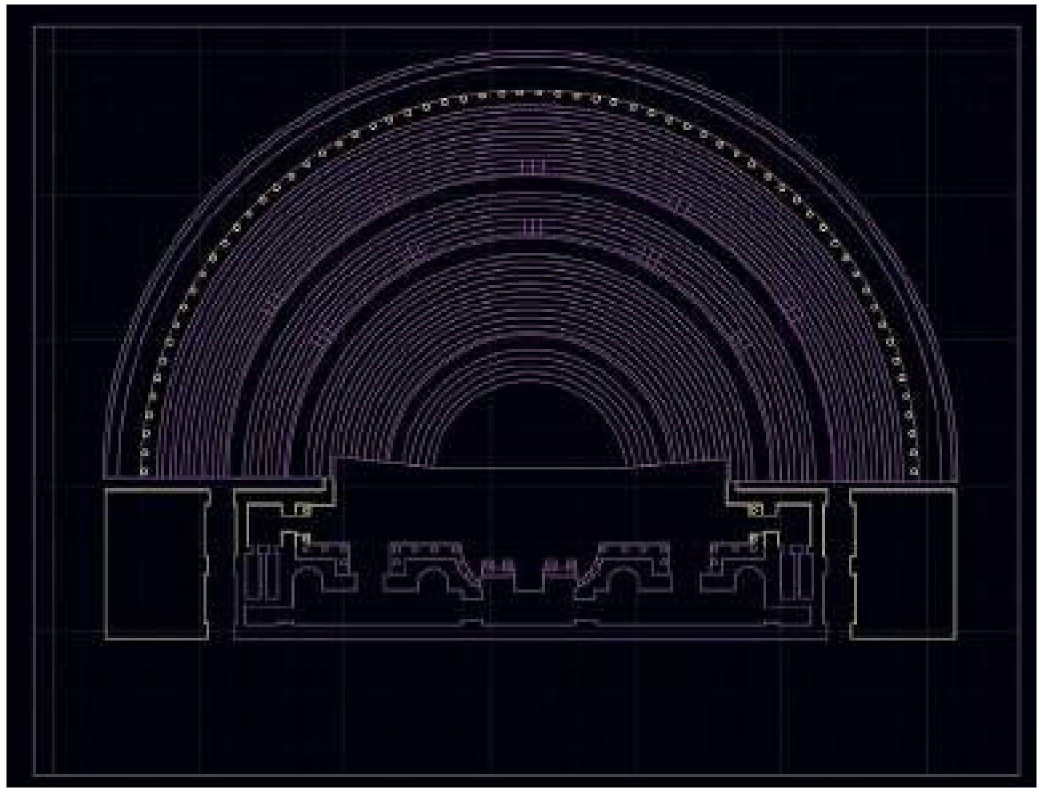

Fig. 8.
Representation of the plan of the hypothetical reconstructions proposed by Montali. The purple lines indicate the architectural parts according to the author's views and the yellow lines indicate the architectural parts that have been modified in the second model analysed.
Image: M. C. Manzetti

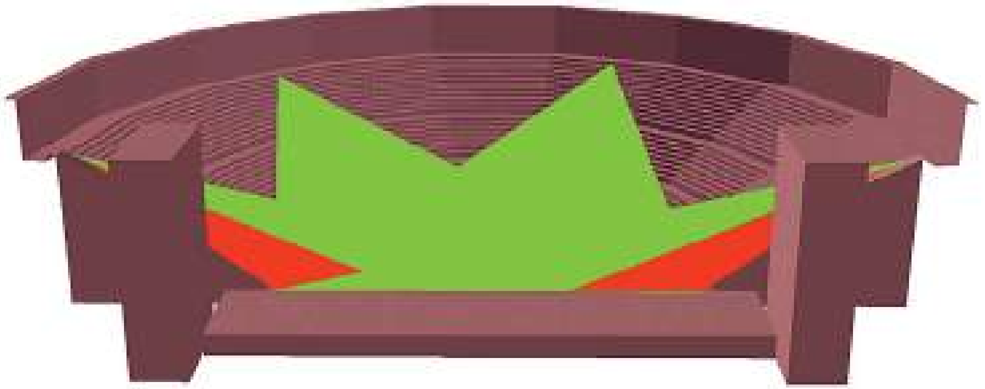

Fig. 9.
Lines of sight of the alternative reconstructive hypothesis of the theatre of Gortyna, at Kazinedes.
Image: M. C. Manzetti

Another 3D model, with some modifications in the architectural structure, has been tested. Comparing the plan drawn by Montali and the satellite image of the site (fig. 7), we have noticed some incongruities that are shown in fig. 8. It seems there are no remains between the cavea and the scene building. There actually appears to be a corridor between the two structures. Therefore, the second 3D model has been constructed with an open corridor between the seating area and the scene building, moving back and reducing the size of the basilicas that are the main obstacles to the visibility. The portico in *summa* cavea hypothesized by Montali, has been removed as well, because it generally produces late reflections which influence the quality of the acoustics, and because there are not clear proofs of it.

The 3D visibility analysis shows that 8% of the lines of sight are not visible trajectories (fig. 9) and the visibility map presents a stage, whose central area is visible by all the spectators (fig. 10).

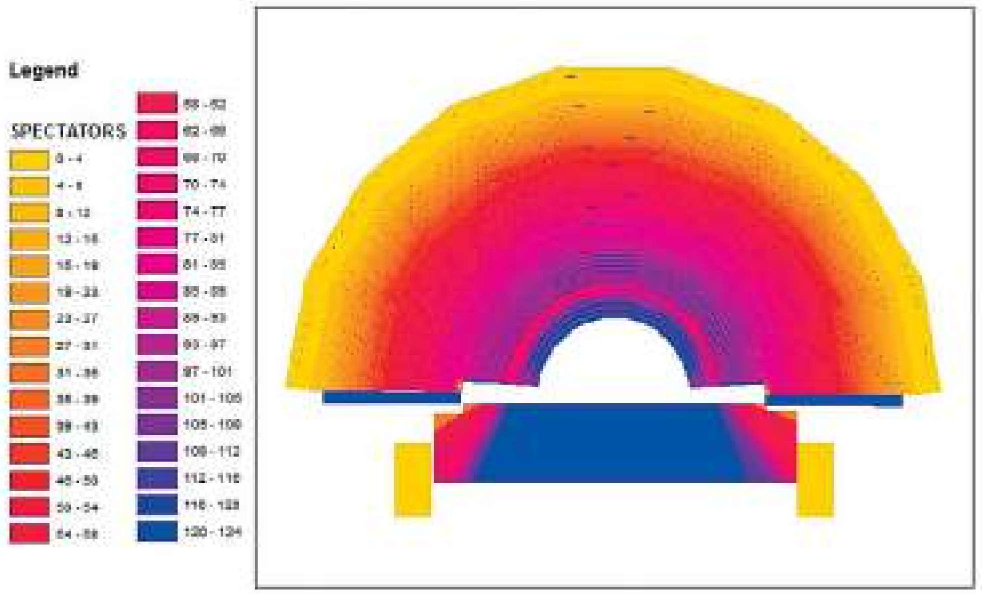

Fig. 10.
Visibility map of the second hypothetical reconstruction of the theatre of Gortyna, at Kazinedes.
Image: M. C. Manzetti

The virtual acoustics analysis of this model revealed a better quality than the previous one, for the comprehension of the speech. The values obtained are the following: T60 between 0.62 and 1.73; C80 between 1.2 and 10.9 dB; D50 between 0.48 and 0.85; and STI between 0.66 and 0.73. About the clarity and definition, respectively, only 7% and 1% of the receivers present a value under 3 dB and under 0.50. The results for all the parameters demonstrate that the architectural structure of the second model is suitable to have a speech performance.

Conclusion

This study demonstrates two main aspects which are expected to be further developed in the future and be applied more frequently to the archaeological research.

First, digital instruments and 3D models have proved to be essential in the study and analysis of archaeological sites. Without the opportunity to virtually reconstruct the theatre at Kazinedes, we could not probably have so many possibilities to know something more about it. Of course, archaeological excavations, even better if preceded by geophysical prospections, are still the best method to discover the history and the characteristics of an ancient site. Most of the time, however, it is not possible to conduct archaeological excavations in a specific site, or the remains are so scarce that do not allow specialists to formulate reliable hypothesis regarding the full structure of the buildings. It is already recognized that virtual reconstructions give the possibility to verify the correctness of a structural hypothesis, but this research manifests that the 3D models can be further analysed (and not only visualized), in order to propose more accurate architectural reconstructions.

The second aspect that is worth to be underlined is that the combination of 3D visibility analysis and virtual acoustics analysis, for monuments reserved to performances, is a more advanced approach which can raise new questions and bring forward new theories and hypotheses. It is time to focus on all the senses that were (and still are) involved in the everyday life of our ancestors, so to reach a deeper knowledge of the past. Furthermore, this approach can lead to the creation of virtual applications much more immersive than in the past and provide an engagement that will facilitate the learning and the memorization.

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