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Correlating damage condition with historical seismic activity in underground sepulchral monuments of Cyprus

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ABSTRACT

Severe and repeated earthquakes devastated Cyprus in antiquity, causing in many cases the abandonment of entire settlement sites. Yet, information regarding the level of seismic activity of historical seismicity in Cyprus is very limited and does not provide the evidence to arrive at reliable conclusions relative to hazard damage parameters such as the severity or occurrence frequency of a seismic event. Thereafter, the level of risk in which these monuments are exposed is unclear leading to an increased uncertainty regarding their safeguarding from future events.

The paper aims at investigating the correlation between damage observed in underground ancient tombs and the historical seismic activity at the area based on in situ observations and expert opinion analysis. In addition, the paper aims to simulate the current state of the tomb's structure, and predict, through a seismic scenario, the propagation of damage from future large earthquake events. Underground monuments are chosen since, due to the nature of the seismic force, they are further "protected" and capable of surviving strong ground motions as they follow the displacement of the soil surrounding them. Typical examples of such structures in Cyprus are the hypogea in the necropolis of the "Tombs of the Kings", located in Paphos area. Some of these monuments exhibit severe cracking of the rock-cut stone walls and evidence of collapse of vertical resisting members of skeleton structure. Paphos area is the most active seismic region in Cyprus based on the historical catalogue of events with evidence of a number of destructive earthquakes.

The framework presented herein utilizes information regarding the current geometry of these structures as documented from topographical surveys, their depth, area of opening, size of resisting members along with information regarding the geotechnical conditions at the site to arrive at estimates of the displacement demand under various seismic scenarios. The predicted shear strain levels on the walls are compared with the strain capacity under tension of the soil material to identify the possibility of propagation of cracking of the walls based on a specific seismic scenario.

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1. Introduction

1.1. Archaeological and literary evidence

Contrary to studies related to historical seismic activity in Cyprus for the period beginning from the end of the 19th century onwards (Christofidou, 1969-1972; Ambraseys, 1992; Ambraseys and Adams, 1992; Gajardo et al., 1998), respective studies related to the ancient one are difficult to be found, mainly due to the intrinsic obstacles of the subject. An indexing including ancient seismic events concerning Cyprus has been formed by Ambraseys (1965) comprising in some instances the basis for archaeologists as well.

Literary sources are occasionally refer to distractive earthquakes stricken Cyprus, such as the 15 CE Paphos earthquake attested by the historian and Roman consul Dio Cassius (XXIII, 24, 7), the earthquake of 76 or 77 (Hill, 1949), the 365 CE Kourion earth quake (Am. Marc.) etc., while more abstract and generic references to seismic events related to disasters affected Cyprus are to be traced in ancient literature (Seneca, 1925: 91; Seneca, 2010: 6.25, 6.26.4; Orascula Sib. 3.395–396, 4.125–126, 5.449–454; Pas.Cr. 313C).

Ancient texts alongside archaeological evidence of ancient earthquakes consist of invaluable information guiding modern scientists' research enquiries. However, both the aforementioned resources are very limited in terms of concrete information and even though contemporary archaeologists are referring to ancient seismic events as the cause

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of destructions observed in several sites on the island, only few are to be validated through excavated archaeological material and consequently, datable with a certainty in context.

Unshaken archaeological evidence connected to ancient earthquakes derives from the area of ancient Kourion related to a great seismic event that possibly took place somewhere between the middle and the end of the 4th century A.D. (appr. 364–370 CE). This final earthquake, preceded by various shocks occurred through the years, befallen in a crucial historic *momentus* when Christianity was gaining power over paganism this great destruction was considered as a landmark that stigmatized once forever the shifting from one era to another (Soren, 1981; Soren, 1988; Soren and James, 1988. On the 365 CE earthquake see Am. Marc.; Sozomenus, n.d.).

Ancient earthquake manifestation in Paphos area has been revealed and documented through archaeological excavation in the Roman villa known as the House of Dionysos due to its magnificent floor mosaics. The house seems to have been destroyed and abandoned after the earthquakes of the 4th century A.D. During excavation the removal of the wall lying as it was fallen during the seismic event, revealed the skeleton of a man with his hands towards his head, documenting in a dramatic way his last moments. The study of the twelve coins that he was carrying with him permit a secure and a more or less absolute dating of the event. Based on the archaeological material the Paphos earthquake dates in the beginning of the 2nd century A.D., during the early reign of Hadrian (he reigned between 117 and 138 CE offering thus a terminus ad and postquem) (Michaelidou-Nicolaou, 1985). The earthquake attested by the excavation in Paphos was unknown to the scientific community of Cyprus prior 1985, date of publication of the excavation's results.

More seismic events affecting Cyprus are traced in ancient texts and possibly their material aspect is awaiting to be revealed through archaeological excavations.

1.2. Historical seismic activity in Cyprus

Despite all the gaps and weaknesses of the historical data, it is estimated that from 1500 BCE and until 1900 CE there were 30 destructive earthquakes of intensity 8 and above on the Mercalli scale, resulting in a statistical frequency of the order of 1 every 120 years (http://www.moa.gov.cy/moa/gsd/gsd.nsf/dmlHistEarthquakes_en/dmlHistEarthquakes_en?OpenDocument web-site of Geol. Sur. Dep.). By using the Ambraseys (1992) recurrence relationship this gives a return period of approximately 22 years, for an earthquake of magnitude 6 or more on the Richter scale. On the other hand the German re-insurance company Munich Re, in their Universal Map of Natural Disasters, gives a probability of 20% in 50 years for an earthquake with intensity 8 or more in the Mercalli scale (equivalent to about a magnitude 6 or more on the Richter scale) to occur in Cyprus. This means that by assuming a random distribution of earthquakes the return period for such an event is 224 years.

A study of the seismicity of Cyprus based on the earthquakes that occurred in this area the last 2000 years indicates that the most earthquake stricken area of Cyprus is the south-west coast zone, which stretches from Paphos through Limassol to Larnaca and reaches Famagusta. The south coast high seismicity zone is related to the Cyprian Arc, which is regarded as a diffuse boundary between the African and the Eurasian plates (Ambraseys and Adams, 1992). The structure of the Cyprian Arc is complex and the availability of information concerning it, is very poor. There is an agreement of opinions regarding the general shape of this arc, but there is not a clear view on whether it is a plate boundary (Ambraseys and Adams, 1992) (Fig. 1), or a broad zone of thrusting (Fig. 2) (Ambraseys and Adams, 1992).

Arc is shown as a plate boundary (after Ambraseys and Adams, 1992).

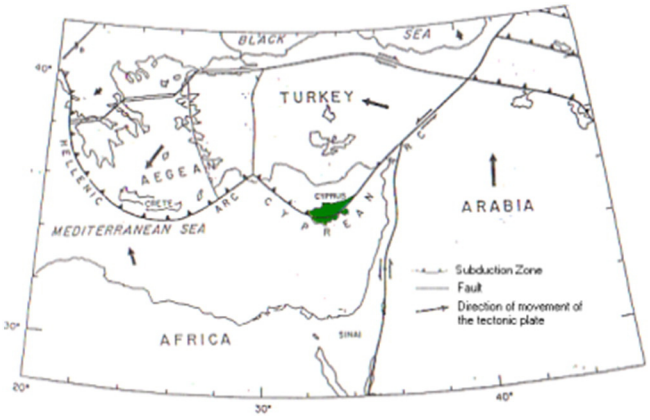

Fig. 1. Arrangement of the tectonic plates in the East Mediterranean. The Cyprian.

2. Methodology

In order to arrive at the analytical determination of the seismic vulnerability of the tomb a methodology was adopted based on the calibration of an analytical finite element model. The seismic hazard is introduced in the methodology in the form of a time-history acceleration record in order to account for its dynamic nature i.e. the frequency and magnitude of the oscillation. The adopted methodology includes both an observational part based on recordings and expert judgment and an analytical part. The first part relies on a thorough and detailed survey of the structure in order to identify its structural resisting system and map closely the cracking pattern on the walls. This investigation is conducted using a variety of methods from in situ topometric measurements, photographs, to more complicated and detailed digital image processing and standard topographic survey. The latest was accomplished with the use of the topographic equipment Leica 1203+ (accuracy < 1 cm). The total station was employed to record the current geometry and shape of the tomb, while special focus was given to some characteristic elements of the monument such as the pillars, the entablature and the entrance of the tomb. In addition, the equipment was used to capture the cracks presented in the tomb's vertical walls, as well as in the upper part of the portico. The geometry of the complex and the cracks were then drawn in a CAD environment and the retrieved product was used as a digital model for the structural stability test. Included in this part is the investigation, using the outcomes from

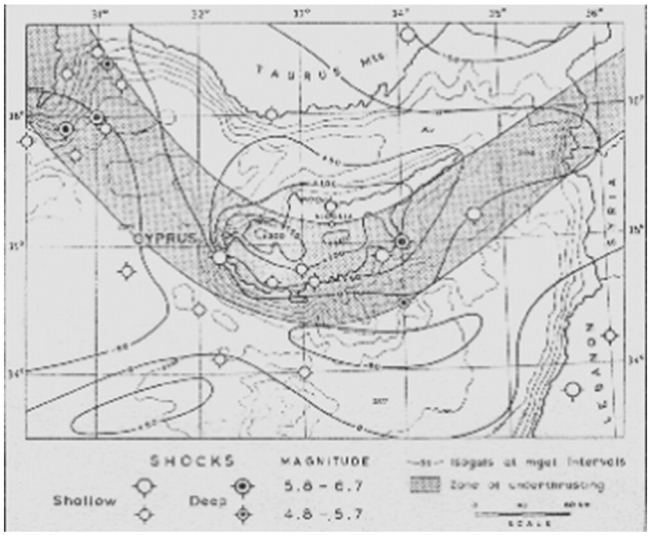

Fig. 2. The Cyprian Arc illustrated as a broad zone of thrusting (Galanopoulos and Delibasis, 1965).

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