Earthquake Archaeological Effects (EAEs) from the archaeological site of Ancient Corinth, Greece and their correlation to seismic events

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Abstract: *The archaeological site of Ancient Corinth preserves potential Earthquake Archaeological Effects (EAEs) that according to their classification in relation to intensity intervals are indicative of minimum EMS-98 intensities that range from VII to IX. Historical and instrumental seismicity records, historical archives of drawings and photographs and damage records from the earthquakes of 1858 and 1928 were investigated in an attempt to correlate recorded potential EAEs and relative minimum intensities with seismic events. The study gave the opportunity to verify the applicability of the EAEs classification in relation to the proposed intensity intervals for the earthquake of 1858, to suggest candidate EAEs for rock-hewn monuments and to suggest that the site suffered repeatedly from earthquakes of EMS-98 intensities of VII to VIII and potentially from more than one seismic events of minimum EMS -98 intensity of IX.*

Key words: *Temple of Apollo, Glauke Fountain, rock-hewn monuments, macroseismic intensity.*

INTRODUCTION

The archaeological site of Ancient Corinth is located on an uplifted Pleistocene marine terrace at 75 m altitude on the northern foothills of the Acrocorinth hill, a region characterised by active tectonics and intense seismicity (Fig. 1). Archaeological studies suggest that the site was first inhabited during the Neolithic period (6000 B.C.), its use continued during the Bronze Age and advanced in the late 8th cent. B.C. with intense landscape modification and monumental architecture serving religious, civic and market activities (Fig. 2). Ancient Corinth was razed in 146 B.C. by the Romans and was re-founded as a Roman colony that flourished till the end of 3rd c. A.D., (Crouch 2003).

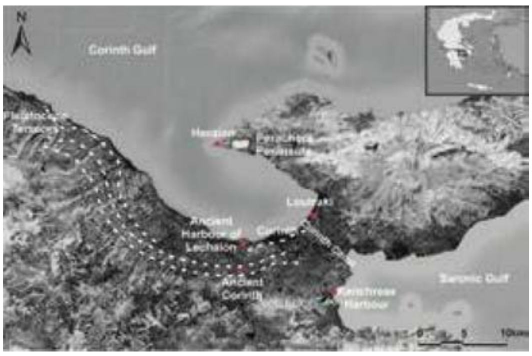

Figure 1: Location map of the study area and surrounding archaeological sites.

The proposed archaeoseismological classification of Earthquake Archaeological Effects (EAEs) and their relation to intensity intervals of EMS-98 macroseismic scale (Rodríguez-Pascua et al., 2011, 2013) was applied on the site of Ancient Corinth in order to investigate potential damage from ground deformation and transient shaking, correlate proposed minimum intensity values with existing seismic records and identify potential seismic events and their effects on the site.

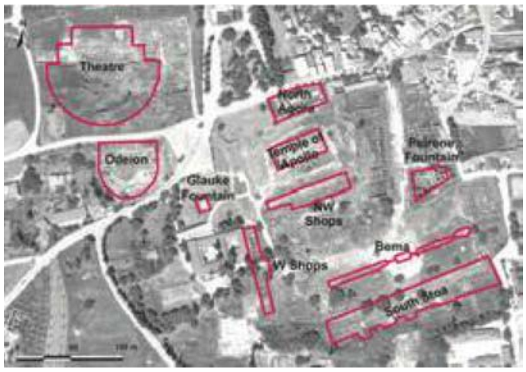

Figure 2: The archaeological site of Ancient Corinth. Monuments studied marked with red line.

METHODS

Each monument of the archaeological site was examined for its geological substratum, typology, state of preservation and potential EAEs. Monuments in a total collapsed state preserving either questionable or even no effects, were not included in the study. The potential EAEs identified on each monument were recorded following a qualitative approach, i.e. each monument was investigated for the types of effects and not for the number of each effect preserved. The EAEs records were correlated with potential EMS-98 intensity scale values as suggested by Rodríguez-Pascua et al., 2013, and minimum macroseismic intensities were constrained. The results were compared with historical and instrumental seismicity of the region and available regional historical archives and records.

RESULTS

The potential EAEs from the archaeological site of Ancient Corinth were mainly recorded on the monuments of the Peirene Fountain(6th c. B.C.), the Temple of Apollo (550 B.C.), the NW shops, the W shops, the Odeion (1st c. A.D.) and the Theatre (Roman period). Variable building fabric effects were identified summarised to penetrative fractures, rotated and displaced masonry blocks, dropped key stones, folded steps and kerbs, collapsed vaults and dipping broken corners (Fig. 3). The South Stoa, the North Agora and the Bema are mainly characterised by effects of dipping broken corners and penetrative fractures.

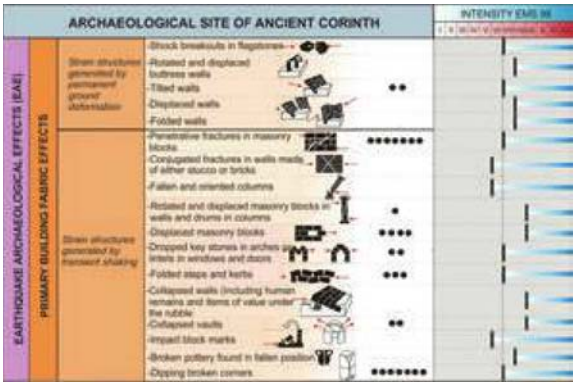

Figure 3: Potential EAEs distribution (black dots) as recorded on monuments of the archaeological site of Ancient Corinth (modified after Rodríguez-Pascua et al., 2013).

The majority of the effects recorded on the monuments of the site relate to EMS-98 minimum intensities of VII (Fig. 3). Three effects summarised to rotated and displaced masonry blocks in walls (Temple of Apollo, NW Shops, Peirene Fountain, Theatre) a displaced column (Temple of Apollo) and collapsed vaults (W shops, Odeion) relate to EMS-98 intensity of IX. Therefore, it can be suggested that the site of Ancient Corinth suffered considerable damage from earthquakes of minimum EMS-98 intensities ranging from VII to IX.
Two rock-hewn monuments of the site preserve extensive fracturing. The Glauke Fountain (Roman period), a rock-hewn monolithic monument carved on sandstone, preserves a set of V-shaped corner cracks in the upper parts of the construction (Fig 4). Peirene Fountain that is partly rock-hewn on the contact between conglomerate and marl deposits preserves extensive crashing and spalling in one of its rock-hewn underground reservoir walls (Fig. 5). Although these effects require geotechnical investigations in order to assess their origin and strain-field and examine potential non-seismic nature, they could be suggested as candidate Earthquake Archaeological Effects for rock-hewn monuments.

Figure 4: The Glauke Fountain with partial collapse that preserves V-shaped corner cracks at its SSE façade.

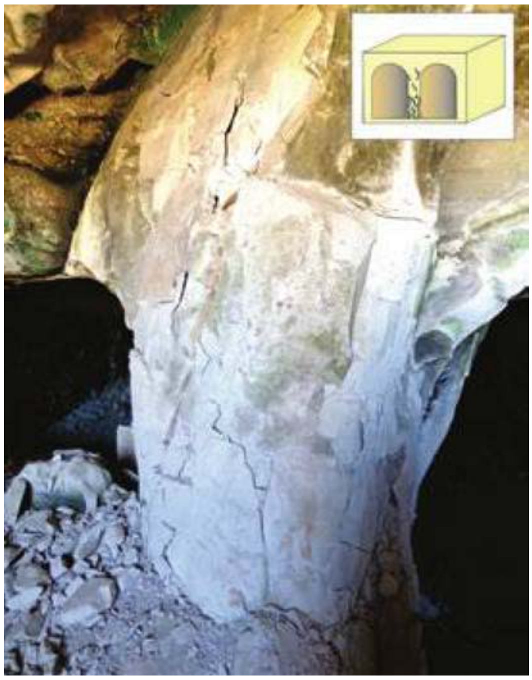

Figure 5: The NE tunnels of Peirene Fountain that preserve crashing/spalling effects on their rock-hewned tunnel wall.

Regional earthquakes with intensities that have caused extensive damage in the vicinity of Ancient Corinth according to the earthquake catalogue by Papazachos & Papazachou (1989) were examined and a number of events were identified. However, damage records for the archaeological site under investigation come mainly from two events, the earthquakes of 1858 and 1928.

The 1858 Earthquake
The 1858 earthquake represents a milestone event of the regional history since it destroyed the city of Old Corinth,

caused its abandonment and the foundation of the modern city of Corinth next to the Corinth canal. The disaster is described in detail by G. Koustas, the prefectural doctor of Corinth in his report published by Pandora journal on the 15th of August 1958. His report provides valuable information on damage distribution, fatalities, injuries and regional environmental effects, allowing a reliable assessment of the macroseismic intensity (MMI X), the magnitude (M=6.7) and epicentre (a few km to the east of Ancient Corinth), (Papazachos & Papazachou, 1989).

For the archaeological site of Ancient Corinth, Koustas (1958), reports that the temple of Apollo suffered extensive damage. One column that was lacking the capital was fractured and displaced. The corner outer epistyle was also fractured and displaced from its position while parts from the rest of the epistyle and capitals were fractured and/or collapsed. The state of Apollo temple before and after the earthquake was investigated and the damage was confirmed through available archives of drawings and photos of the period (Fig. 6).

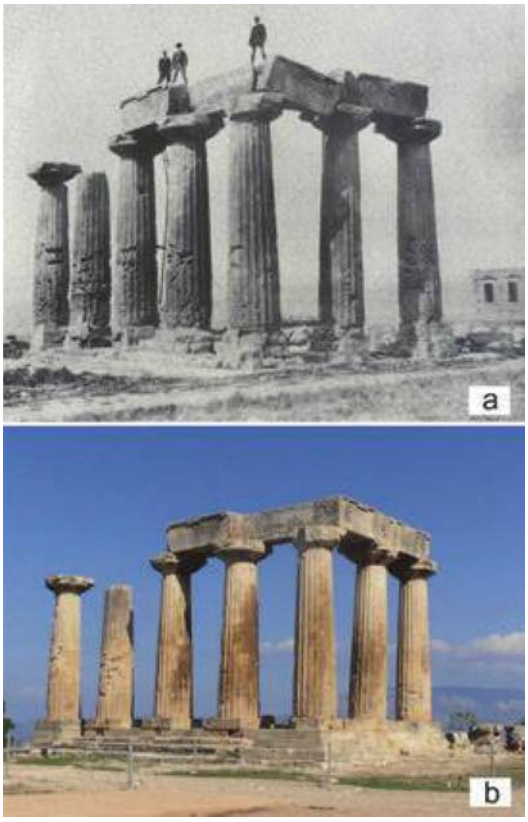

Figure 6: (a): The Temple of Apollo in 1901. Note the two metal rings that support the single fractured column without a capital, and the displaced outer corner epistyle. This figure is also indicative of the poor state of preservation of the temple base, (ASCSA Corinth Excavations). (b): The Temple of Apollo in our days with rescue restoration measures taken on the epistyle, the base and the fractured column).

During the site survey, it was observed that the middle column in the SSE façade presents horizontal displacement of approximately 10 cm towards the SSE (Fig. 7). Although it is not clear if, and to what extent, this displacement pre-dates the 1858 event, it is considered likely that this effect directly associates with the epistyle displacement. Since the historical archive does not indicate previous displacement of the epistyle, the column displacement could be considered as an additional seismic effect of the 1858 event.

Figure 7: The capital of the column under the restored epistyle that preserves a displacement of ~ 10 cm towards the SSE.

As reported by Koustas (1858), the environmental effects of the earthquake involved rockfalls around Acrocorinth where a section of the fortress walls collapsed while at the northern foothills of Acrocorinth hill, a cave collapsed. In the city of Old Corinth, extensive damage in aqueducts and reservoirs was recorded and the springs of the town dried up. Ground ruptures were dense and extensive especially in slopes. In Kenhreae 200 m inland from the coastline, water spurt in the fields through vents indicative of earthquake induced ground liquefaction. According to the ESI-07 intensity scale (Michetti et al., 2007), the earthquake environmental effects of the 1958 earthquake suggest intensities that range from VII to IX.

The 1928 Earthquake

The 1928 event is one of the first instrumental events with magnitude M=6.3, epicentre near the SE end of the Corinth canal, very shallow depth and MMI intensity of IX (Papazachos & Papazachou 1989). The event destroyed the modern city of Corinth where 3000 buildings suffered irreparable damage and 15.000 people were left homeless, (Drakopoulos et al., 1978). In Ancient Corinth according to the official governmental reports, out of the 380 inspected buildings, 300 were damaged, out of which 250 were considered as repairable and 50 either collapsed or were severely damaged (beyond repair), (Drakopoulos et al., 1978). The macroseismic intensity of the 1928 earthquake for Ancient Corinth is not known. However it can be assumed that it cannot be lower than

VIII due to its proximity to the epicentre and the extent of the damage. Environmental effects of this event were limited to ground cracks and extensive fissures mainly concentrated in the coastal regions near the Corinth canal while small scale landslides and rock falls were observed at the Gerania mountain slopes near Loutraki (Drakopoulos et al., 1978), suggesting ESI-07 intensity of VII-VIII (Michetti et al., 2007).

Figure 8: The NNW facade of the Glauke Fountain. With dashed line the section of the monument that collapsed during the earthquake of 1928.

In search of potential records of damage in the archaeological site, a repor retrieved from the archives of the American School of Classical Studies mentions the extensive damage sustained in Old Corinth and that *"part of Glauke collapsed"*, (Lord, 1947). Through the available photographic archives (E.L.I.A. Catalogue 2015), images dated in 1924 and 1930 were retrieved and compared confirming the partial collapse of the Glauke Fountain (Fig. 8). The damage sustained by the monument can be considered as quite extensive since approximately one third of the Glauke Fountain collapsed. It is notable that although the observed V-shaped corner cracks (Fig. 4) associate directly with the partial collapse of the monument, according to available photographic archives (ASCSA, 2015) they pre-date the 1928 earthquake. These fractures could relate to an earlier seismic event (e.g. 1858) but further studies are necessary in order to assess their nature and origin.

DISCUSSION

The investigations in the archaeological site of Ancient Corinth gave the opportunity to identify potential EAEs that relate to minimum EMS-98 intensities of VII to IX. It also allowed the suggestion of two candidate EAEs for rock-hewn monuments although further geotechnical studies are required. Through the study of historical and instrumental seismicity of the region and available records and archives, the EAEs recorded on the Temple of Apollo were correlated with the earthquake of 1858 (EMS-98 X) and the effects on the Glauke Fountain were partly correlated with the event of 1928 (EMS-98 IX).

It is interesting to note that the Temple of Apollo although it suffered serious damage from the 1858 event it was not affected significantly by the earthquake of 1928. Furthermore, the archaeological site appears to have suffered minimal damage during the earthquakes of 1930 (intensity VII in Ancient Corinth), 1962 (intensity VIII+ in Ancient Corinth) and in 1981 (intensity VIII in Ancient Corinth) regardless the poor state of preservation of the monuments. These observations allow us to suggest that the majority of the EAEs recorded represent a cumulation of seismic effects from numerous historical and modern earthquakes with intensities that range from VII-VIII. The partial correlation of the effects relating to minimum EMS-98 intensities of IX with the 1858 earthquake, indicates that the site potentially has suffered extensive damage from more than one earthquakes of minimum EMS-98 intensity of IX.

Further study of the potential EAEs recorded on the site's monuments and their correlation with the regional historical seismicity is a challenging task due to existing uncertainties. However, it will allow a better understanding of the relationship between site effects and macroseismic intensity, contributing to an archaeoseismological seismic hazard assessment approach for the archaeological site.

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References

ASCSA. Corinth Excavations Digital Resources. Available from: <http://www.ascsa.edu.gr>. (January 2015).

EL.I.A.. Catalogue of Archives. Available from: <http://www.elia.org.gr>. (January 2015).

Crouch, D.P., (2003) (ed). *Geology and Settlement, Greco-Roman Patterns*. Oxford University Press. New York. 2003, p. 385.

Drakopoulos, J., G. Leventakis, A. Roussopoulos, (1978). Microzonation in the seismic area of Corinth-Loutraki. *Annals of Geophysics*. 31, (1), 51-95.

Koustas, G., (1958). Corinth Earthquake. *Pandora*. 9, (202), 225-229. (in Greek).

Lord, L.E. 1947 (eds). *A History of the American School of Classical Studies at Athens, 1882-1942, an Intercollegiate Project*. Harvard University Press. Cambridge Massachusetts. 1947, p. 494.

Michetti, A.M., E. Esposito, L. Guerrieri, S. Porfido, L. Serva, R. Tatevossian, E. Vittori, F. Audermard, T. Azuma, J. Clague, V. Comerci, A. Gurpinar, J. McCaplin, B. Mohammadioun, N.A. Mörner, Y. Ota & E. Roghozin, (2007). Intensity Scale ESI 2007. In: (Guerrieri, L. & E. Vittori, eds.) *Mem. Descr. Carta Geol. d'Italia., vol. 74, Servizio Geologico d'Italia - Dipartimento Difesa del Suolo, APAT, Rome, Italy.*

Rodríguez-Pascua, M.A., R. Pérez-López, J.L. Giner-Robles, P.G. Silva, V.H. Garduňo-Monroy, K. Reicherter, (2011). A comprehensive classification of Earthquake Archaeological Effects (EAE) in archaeoseismology: Application to ancient remains of Roman and Mesoamerical cultures. *Quaternary International.* 242, 20-30.

Rodríguez-Pascua, M.A., P.G. Silva, R. Pérez-López, J.L. Giner-Robles, F. Martín-González, M.A. Perucha, (2013). Preliminary intensity correlation between macroseismic scales (ESI07 and EMS98) and Earthquake archaeological effects (EAEs). In: *Proceedings of the 4th International INQUA Meeting on Paleoseismology, Active Tectonics and Archeoseismology (PATA), 9-14 October 2013, Aachen, Germany.*

Papazachos, B. & K. Papazachou, (1989) (eds). *The Earthquakes of Greece.* Ziti Publications. Thessaloniki. 1999, p. 356.