Archaeoseismological investigation of earthquake induced ground liquefaction events at the Early Christian Basilica, Ancient Lechaion harbour, Corinth, Greece

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Abstract: *Ground deformation structures preserved on the decorated floor of the Early Christian Basilica located in the vicinity of the ancient Lechaion Harbour, Corinth, are indicative of reccurent eathquake induced ground liquefaction events. Through the study of archaeological, geophysical and stratigraphical data, the surface structures were correlated with substratum features and three potential ground liquefaction events are suggested. The results are indicative of at least one seismic event before the construction of the Early Christian Basilica that has caused considerable damages to the ancient harbour installations, a second event (524 A.D.) that caused considerable but repairable damages to the temple and a third event that relates to irreparable damages and thus the destruction of the Basilica in A.D. 551.*

Key words*: Archaeoseismology, near surface geophysics, earthquake geology, lateral spreading, sand vents.*

INTRODUCTION

The Gulf of Corinth, represents an active continental rift system in a subduction zone setting, with extensional tectonics expressed through intense seismicity and marginal uplift. The Ancient Harbour of Lechaion is located in the southern coast of the Lechaion Gulf, the southeastern sub-basin of the Corinth Gulf in an estuary enivironment (Fig. 1). It is characterised by an outer harbour edged by moles and an inner artificially excavated harbour representing one of the most important harbours of Greece during antiquity. According to archaeological surveys its construction dates back to the 6th - 7th c. B.C., its use continued during the Roman period and an Early Christian Basilica was constructed at its western part during the late 5th c. A.D., (Pallas, 1959). Geomorphological, sedimentological and geoarchaeological studies suggest episodic uplift (Stiros et al., 1996, Morhange et al., 2012), sea level changes (Mourtzas et al., 2014) and tsunamigenic impact events (Hadler et al., 2013), indicative of neotectonic and geomorphological processes expressed through seismic activity. Archaeological excavations performed by Pallas during the late 1950s to early 1960s suggest that the Early Christian Basilica was destroyed by the A.D. 551 earthquake. Recent restoration works carried out in the Basilica revealed the decorated floor of the temple preserving deformation structures indicative of earthquake induced ground liquefaction. The aim of this work is to present the results of the investigations carried out on the site in order to study and identify the triggering mechanisms of the surface deformation structures and propose a sequence of potential seismic events.

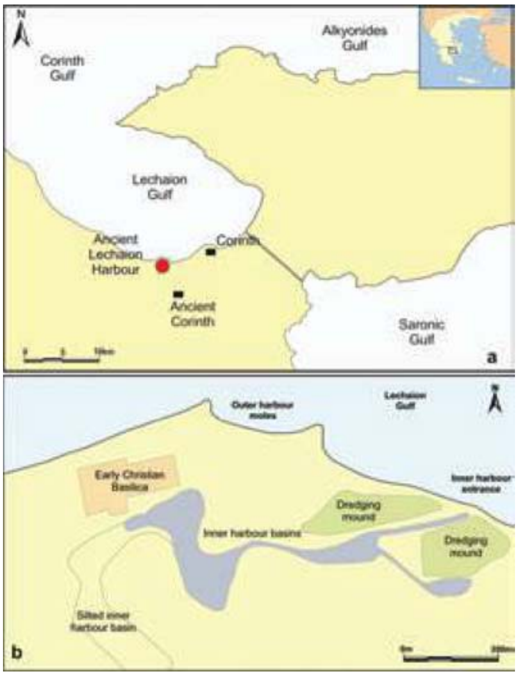

Figure 1: (a) Location map of the study area, (b) Plan of the ancient Harbour of Lechaion.

METHODS

The methods employed in this study involve the combination of field observations and established geophysical surveys through EM, GPR and ERT methods employed as a reconnaisance survey, with lithostratigraphic data obtained from four drill cores with vibracore equipment and existing archaeological records (Fig. 2). Fieldwork included mapping and cataloguing of distinct ground deformation structures in places where the floor was preserved in a good condition. The EM and GPR survey were carried out along ten ENE-WSW trending lines within the Basilica while the ERT survey included two profiles at right angles to each other along a ENE-SWS and a NNW-SSE trend. The lithostratigraphy was examined by four short depth drill cores in the central part of the southern aisle. Cores 2 and 4 were drilled in circular depressions while 1 and 3 in surrounding locations.

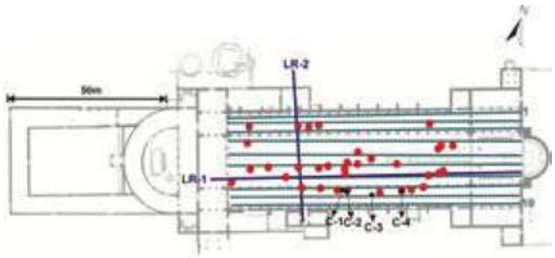

Figure 2: Location of the ten EM and GPR profiles (dashed green lines), the two ERT profiles (purple lines), the distinct deformation structures (red dots) and the drill cores (black dots) in the Early Christian Basilica.

RESULTS

The surface structures represent a cluster of linear and circular depressions and buckling structures with a primary ENE-WSW and secondary NNW-SSE trends (Fig.3). These structures correlate well with the surface expression of earthquake induced ground liquefaction (Obermeier, 2009).

Archaeological stratigraphy

The archaeological subsurface stratigraphy of the Basilica as described by Pallas during his original site excavations (1956 to 1965) includes an artificial fill composed mainly of sand and pebbles with occasional intercalations of clay, lithic and ceramic tiles fragments and mortar. This fill extends to a depth of a least 1 m below the Basilica floor and its lower layer is considered as the preparation ground for the construction of the Basilica (Pallas, 1965). The foundations of the temple are located at a depth of 1.45 m and 1.70 m in sand deposits that date to the 3rd c. B.C. As suggested by a layer of boulders at a depth of 3 m located to the SW of the Basilica, the artificial nature of the subsurface stratigraphy possibly extends to a depth of 3 m (Pallas, 1959).

Figure 3: Surface deformation structures on the decorated floor of the southern aisle of the Basilica and corresponding rose diagram with the primary and secondary trends. (a,b) Circular and linear depressions with an ENE-WSW trend. (c) a circular depression in contact with a linear structure of NNW-SSE trend, (d) linear depressions of ENE-WSW trend.

Core drilling

The sedimentary analysis suggests a mixing of high energy fluvial sediments reworked by shallow water marine processes, typical of an estuarine depositional environment. The deposits are characterised by intercalations of coarse silty-sand to very coarse-grained sand and gravel with pebbles up to 2-3 cm diameter. Three sedimentary units were identified, the artificial unit A and the sedimentary units B and C here characterised with caution as "natural" since they could represent artificial fill layers of the ancient harbour installations (Fig. 4).

The artificial nature of the upper 1 m, is confirmed by the stratigraphy in cores 1 and 2 with layers that contain up to 10% clay and bear strong analogies to the archaeological stratigraphy. The absence of artificial fill deposits from cores 3 and 4 suggests that the artificial fill was arranged mainly in the central and WSW part of the temple indicating the presence of a "paleosurface", before the construction of the Basilica, dipping gently towards the WSW.

All four cores above the "paleosurface" contain a packed layer of dark grey colour containing fragments of ceramic tiles and agglomerates that correlates well with the archaeological layer of the preparation ground. This layer appears as a base layer of the artificial fill in cores 1 and 2, while it appears as the surface layer in cores 3 and 4.

The stratigraphy below the "paleosurface" (units B and C) is again characterised by coarse to very coarse sand and gravel with pebbles with a minimal content of fines. The grain size analysis of the four vibracore sedimentary samples suggests potentially liquefiable deposits (Tsuchida & Hayashi, 1971).

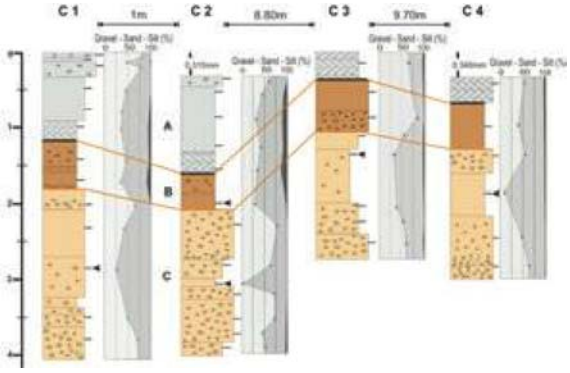

Figure 4: Lithostratigraphic columns of the four boreholes with grain size content and stratigraphic correlation. Horizontal distance between boreholes is indicated at the top of the figure. Bold black line in the logs represents the "paleosurface, black arrows indicate layers with high liquefaction potential.

Sand layers exhibiting high liquefaction potential were identified in both units B and C in cores 2 and 4 that were located in circular depressions (Fig. 4) The lack of high potential liquefaction sand layers in Unit A may be attributed to sediment mixing (Obermeier, 2009). The location and distribution of the high liquefaction potential layers, is indicative of a liquefaction source horizon below 4 m.

Geophysical survey

Substratum structures indicative of earthquake induced ground liquefaction were identified with all three geophysical methods suggesting extensive lateral spreading zones that develop along directions consistent with the two trends recorded on the Basilica floor. The survey suggests primary extensional displacement towards the free face of the inner harbour basin along at least three near vertical fissures with an ENE-WSW strike. These zones are represented in the EM second derivative of apparent conductivity map at 3 m effective depth range as high permeability zones; while in the ERT LR-2 profile they result as near vertical low resistivity zones, (Abu Zeid et al., 2012) (Fig. 5). It is interesting to note that the higher conductivity zones in the EM map are parallel to two linear relatively lower conductivity zones, possibly representing deposits related to harbour constructions pre-dating the Basilica construction.

Potential secondary substratum zones with relative moderate conductivity values oriented NNW-SSE are also indicated in the EM second derivative of the conductivity map at 3 m effective depth range, mostly in the central and southern aisle of the temple. Again, these potential zones correlate well with the upper 5 m of the LR-1 ERT profile, indicating nearly vertical discontinuities up to 2-3m wide in the WSW part of the profile, and with the surface deformation structures. Finally, the GPR profiles indicate 3 m water table depth; vertical zones of low signal amplitude in the upper 3 m that coincide with the near vertical lower resistivity zones of the ERT LR-1 profile and good correlation with the surface structures.

The lateral spreading as indicated by the ERT profiles, has been triggered along a shear zone located at approximately 4 to 5 m depth. This shear zone may represent the liquefied horizon that caused the overlying extensional fissures, allowing rapid ascent through the overlying strata, (Youd, 1984a).

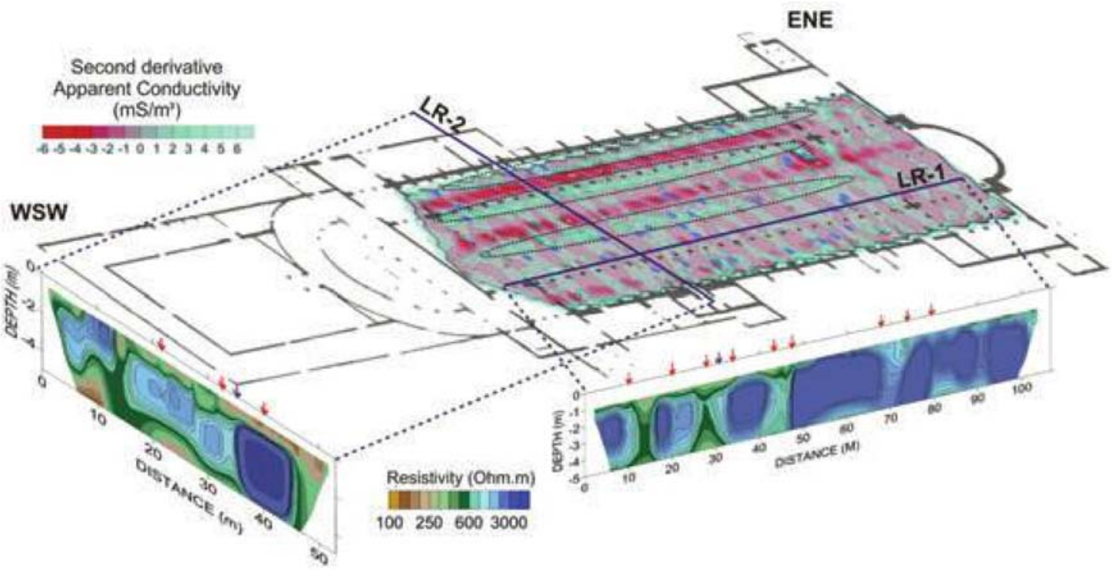

Figure 5: The Early Christian Basilica plan with the EM map of 3 m effective depth range and projections of the two detailed ERT profiles of the upper 5m (LR-1 and LR-2). The three principal high conductivity zones are circled with black dashed lines. Blue dots and red arrows indicate ground deformation structures recorded on the surface. Blue arrows indicate the intersection of the two ERT profiles.

The good correlation between the widespread surface deformation structures and the lateral spreading zones allows to establish a cause-effect relation among the earthquake induced damages of the Basilica and the archaeological findings suggesting the A.D. 551 earthquake as responsible for its destruction. Since the region is characterised by intense seismic activity and ground liquefaction is a phenomenon that generally presents reccurence (Youd, 1984b), the available data were further examined for possible indications and the following observations were made:

1. Although the preserved deformation structures correlate satisfactorily with the substratum structures,they do not present horizontal and vertical displacements of the extent suggested by the geophysical survey. This observation combined with the location of the liquefied sand samples in units B and C, that is, under the artificial fill and the "paleosurface", indicates that liquefaction and initial opening of fissures pre-dates the construction of the Basilica. Therefore, at least one seismic event can be suggested that occured on the site before the construction of the temple (late 5th c. A.D.), potentially during the operation of the ancient harbour.
2. One circular depression in the northern aisle preserves at its margins some remains of a second floor surface, including tiles and mortar, located 0.20 m under the surface of the Basilica floor. The observation is indicative that the floor of the northern aisle at some point underwent restoration. The location of the second floor remains at the margins of the depression suggest that both floors were damaged sequentially by the same process, i.e. the reactivation of a pre-existing sand vent.

The archaeological record suggests supplementary constructive works during the reign of Ioustin A' (518 - 527 A.D.) (Pallas, 1965). During the reign of Ioustin A' the earthquake of A.D. 524 destroyed Ancient Corinth and surrounding region and reconstructions were carried out under the order of the Emperor (Papazachos & Papazachou, 1989). Thus, we might infer that one liquefaction recurrence event was manifested during the earthquake of A.D. 524 causing repairable damages to the Early Christian Basilica.

Considering the recurrence of the liquefaction phenomena, the preserved deformation structures on the floor of the Basilica potentially represent a number of earthquake events and not just the damages resulting from A.D. 551 earthquake. The vicinity of the ancient harbour of Lechaion can be considered as a site valuable for earthquake science studies since it is indicative of a variety of earthquake environmental effects. Further multi-disciplinary studies would contribute to the comprehension of the regional historical seismicity and consequently to regional seismic hazard assessment.

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