Efficient Sediment Management at the Entrance of an Ancient Harbour

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EFFICIENT SEDIMENT MANAGEMENT AT THE ENTRANCE OF AN ANCIENT HARBOUR

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ABSTRACT

In this study, an investigation was carried out of the ancient harbour of Lechaion (Peloponnese, Greece), regarding its associated coastal sedimentation features. The ancient facility, established around 600 B.C., is positioned on the south-eastern edge of the Gulf of Corinth where continuous small steep alluvial fans form the shoreline profile. As for today's sedimentary state of the coast, natural forces and human pressure have produced a deltaic environment lacking inland and coastal sediment deposits. Despite decay over the centuries, the overall capability of the main features of the ancient installation in controlling sediment flow up to this day, indicates a judicious initial positioning and planning. The proposed layout is an answer in reducing downstream shore erosion, induced by conventional long groynes used today, along with avoiding sediment trapping at the port entrance. Beyond historical data and on site observations, herein the evaluation of both the efficiency of this ancient harbour design and its effect to adjacent shore protection, was verified through a widely accepted computational package.

Keywords: Lechaion, Submerged breakwaters, Inland basin harbour, Dredging.

1. INTRODUCTION

Lechaion, the harbour of ancient Corinth is probably the first dredged dug-inshore harbour in history. It is situated near the homonymous region at the south-eastern expanse of the Gulf of Corinth (Peloponnese, Greece). It is conventionally assumed that the infrastructure was founded around 600 BC (Stiros et al., 1996). Different construction phases from the original design can be noticed from the historical records. Lechaion harbour served for many centuries, along with the successive flourish and decline of Corinth city, from archaic to medieval times, when it was ultimately abandoned (Williams, 1993). In spite of the continuous historical rearrangements, the main harbour elements are still visible today. Considering that in the Gulf of Corinth nature produces one of the most dynamic coastlines in the eastern Mediterranean, the site inevitably gathers attention.

From the beginning of the 6th century B.C. two main types of seaports were developed throughout the Hellenic region. The trading and the war harbour. As for the purpose served by Lechaion facility, it is undefined. Archaeological evidence indicate that protective constructions such as rubble mound breakwaters, quays, and vertical walls, where extensively used in ancient Greece. Recent studies suggest that such features provided adequate protection when compared to modern day ports (Ziros, 2000). An overview databank of major ancient ports is available at http://limenoscope.ntua.gr. An extensive literature of historical, archeological and geological studies of the Lechaion harbour complex has been presented until now. There are also previous studies for the geotectonic activity of the region and tsunamigenic impact related with the sustainability of the harbour (Hadler et al., 2011). Despite all this scientific effort, not much can be found on the interaction of the ancient harbour layout with the wave and sediment climate of the region.

As for the geological features of the study area, the tectonic evolution of the Gulf of Corinth is characterized by horizontal as well as enormous vertical movements. While the northern coast is dominated by subsidence (Lykousis et al. 2007), the southern coast of the gulf, including Lechaion area, has been subject to ongoing major tectonic uplift. Maximum rates occur in the central part of the gulf and decrease in eastern and western direction. Thus, the amplitude of the quaternary uplift lies in between 900 m and 1600 m along the central part of the southern coast. Holocene shorelines, well preserved above the present day sea level, allow the estimation of an uplift rate of approximately 3 mm/year (Pirazzoli et al., 2004). Due to this significant ongoing geotectonic uplift of the area, rivers along the coast have been affected by gradual reduction of their hydraulic gradient. In combination with residential and road network development since the late 70s, interventions as sand extraction from river beds, destruction of the sand-dunes and extensive construction of groynes and seawalls along the southeastern coast of the Corinth Gulf, have produced a deltaic environment that does not contribute adequate inland deposits to the coastal zone. Even so, the ancient design can still control and circulate sediments at both sides of the harbour area under these eroding pressures. Today's applications of long jetties aggravating erosion on their downstream, a phenomenon that cannot be solved by the shore protection measures followed (extensive arrays of rubble-mound breakwaters and seawalls), as experience showed only locally halt of land recession. The practice of conventional large groynes, intercepting long-shore sediment transport, may intensify material loss due to sediment deflection to the deeper waters. Solving this problem, thus minimizing beach erosion induced by long perpendicular to the shore groynes or jetties, has become a major challenge for engineers along the Corinth gulf.

In this direction, the answer seems to derive from the historical record provided by the site of the ancient port of Lechaion. A record that comprises human experience gained by using the port for at least a millennium by continuous adaptation to natural forces, thus providing up to present days a still visible and rather successful solution to both sheltered docking facility and shore stabilization. Consequently and considering the granular character of the respective shore, the objective of this paper is to examine the functionality of the ancient harbour due to wave-current induced sediment transportation. As the basin of the structure has been constructed on the terrestrial area upstream of the coast, the interest is also focused on the entrance of the navigation channel connecting the basins to the sea. Herein the evaluation of the efficiency of the ancient harbor design of Lechaion, using submerged elements, was carried out through the computational model MIKE 21 (2007, DHIGroup). A direct by-product of this study was the assessment on how the ancient engineer faced siltation at the entrance of the harbour by simultaneously stabilising adversarial beach and avoiding downstream erosion, and this as an answer to the conventional also perpendicular to the shore groynes used today as docks.

2. THE ANCIENT HARBOUR OF LECHAION

The harbour seems to be in fact a product of an elaborately processed arrangement of a small natural riverbed (Figure 1). Today, certain harbour facilities are still visible constituting a complex of different type installations. A large number of evidence, lead us to suggest that Lechaion's harbour was initially formed by inland dredging, "cothon" in Greek (Morhange et al., 2012). What is to be pointed out is that, the significant ongoing geotectonic uplift of the area counterbalanced rising sea level (Kambouroglou, 1989; Mourtzas et al. 2014) and sudden subsidence events due to regional seismicity over the last 2,000 years, thus keeping present relative positioning of the harbour elements with respect to the shore close to the initial layout. This ables to assess the Lechaion harbour layout, by studying its coastal behavior according to current topography and bathymetry.

The initial intervention to the small river outlet on the harbour location was the excavation of a siding meander in order to slow down river flow velocity. Then, extensive excavation of the existing river bed, by dredging debris up to three meters deep, resulted in the construction of the inner port basin. Last dredging operation, was digging of the navigable entrance channel and connecting the port with the sea. Before and after construction of the inland port, the estuary of the river was separated from the sea with a narrow band of land. This narrow sandy shore was full of sand dunes.

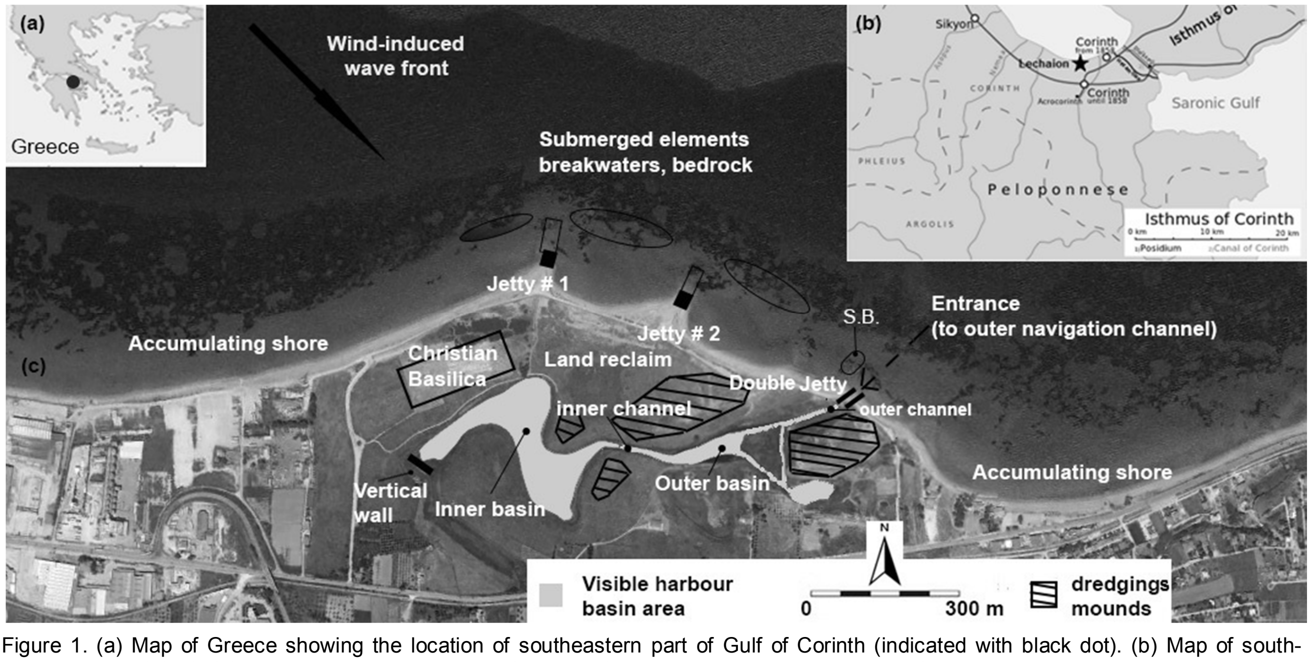

Figure 1. (a) Map of Greece showing the location of southeastern part of Gulf of Corinth (indicated with black dot). (b) Map of south-eastern edge of Gulf of Corinth showing the location of Ancient Corinth and the ancient harbour of Lechaion (indicated with black star). (c) Map of Lechaion's ancient harbour area based on Google Earth Imagery. The grey area corresponds to the visible today inland harbour basin connected to the sea by the outer channel and comprises the outer and the inner basins connecting between with the inner channel. On the eastern side, the ancient harbour's access channel is delineated. Dredgings mounds and other features as jetties are also indicated. The feature indicated as S.B. are the remains of a protective to the entrance submerged breakwater. In general submerged elements are located to the north of the main basin littoral area.

To acquire vital space outside the inner harbor (second construction phase), by putting rubble mounds placed in piles, above the existing narrow band of land and into the sea. Over these stones, layers of sand were spread creating new land (Papafotiou, 2008). As for the scale of the land reclaim, between the inner harbour basin and the present beach, the remains of an early Christian basilica 186 m long dating since the late 5th century A.D., were excavated. A third construction phase included two outer short-length groynes (jetties # 1, #2,), illustrated below in Figure 2, made of ashlar blocks connected with conjunctions. Along with beachrock and archaeological data, Mourtzas et al. (2014) compared present submergence of the coastal structures of the ancient harbour with roman times. From the aspect of coastal engineering, in antiquity the structures (jetties #1, #2) could be characterized as low crested groynes while today they are described by a mean submergence of 1 m below sea level and are partly emerged on their base (Figure 2). Numbers as #1 and #2 are given conventionally in order to avoid confusion with the double jetty located on the mouth of the entrance, to the inner harbour channel, mentioned in this work as the west and east jetty of the entrance channel.

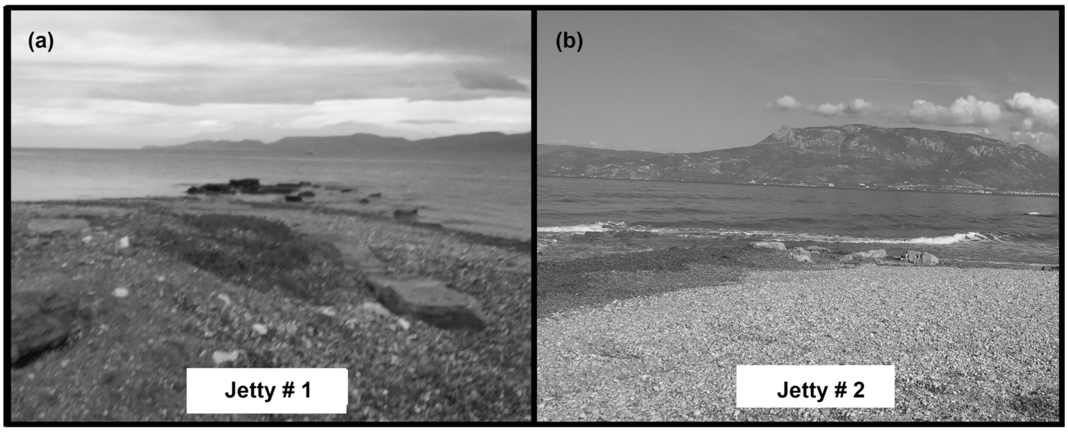

Figure 2. (a), (b) View of emerged remains of Jetty #1 and Jetty #2.

The arrangement of the edges of the access channel, of about 8 meters wide (Figure 3a), was formed by two rows of ashlar blocks on each side, the west and the east jetties (Figures 3b, 3c). Observation of the remains of these narrow jetties (ranging from 1.2-1.6 m wide) indicates that these blocks were interlocked with conjunctions (Figure 3d).

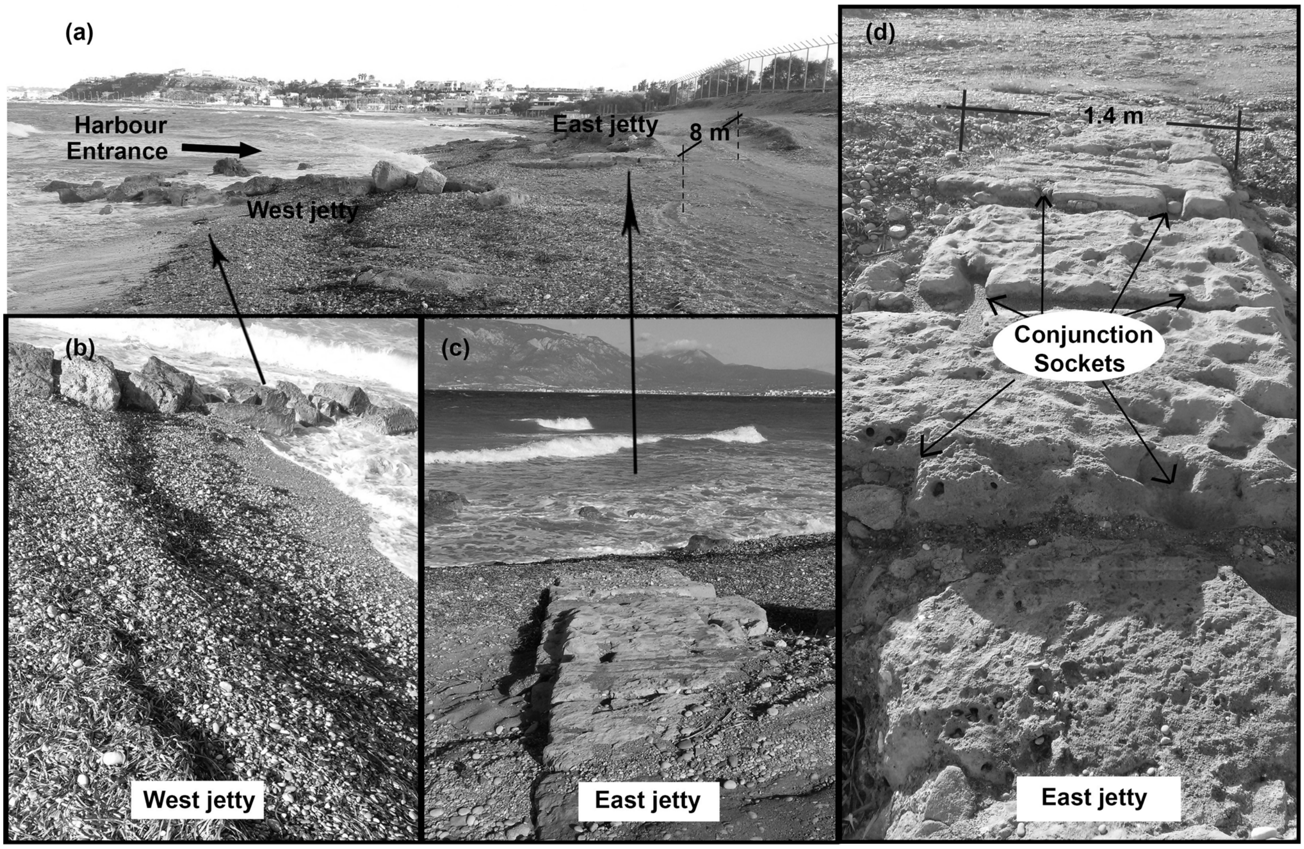

Figure 3. (a) The arrangement of the edges of the access channel, of about 8 meters wide. (b) The west jetty on the entrance of the harbour. (c) The east jetty of the entrance. (d) Interlocking of ashlar rectangular blocks with conjunctions.

On the north-eastern extension of an entrance quay, 33 m west of the entrance channel, the remains of a short submerged breakwater (denoted as S.B. in Figure 1), low crested in roman times (Mourtzas et al. 2014), as for jetties #1, #2, can be found. This submerged breakwater occupying an area of 250 m^2, composed by rectangular blocks, probably and in combination with the double jetty, served as a protective element to the entrance channel as well for easing navigability by protecting vessels from wave impact when entering the harbour as well as minimizing sediment entrapment at the entrance. In combination with the partly submerged groynes located upstream (Jetties #1, #2), the layout proved to perform satisfactory.

Today, large mounds of sediments dredged in ancient times from the riverbed form present topography around the inland basin. In Fig. 4, a view of the inner harbour as well as the dredging mounds is given. Excavated in an existing river depression, Lechaion's inner harbour was a basin whose serpentine configuration was an efficient sediment trap that was particularly problematic for ancient engineers. This sediment management leads us to favour the hypothesis that harbour dredging was needed to create and to maintain the basin over centuries. According to Pâris (1915), a cross wall (denoted as vertical wall in Figure 1) was built in order to control the river flow, serving possibly as a diaphragm to inland sediment. Along with the "cothon" forming the inner basin, most river incoming sediment was deposited on the west side of the basin and thus preventing river-induced siltation at the inner channels of the outer basin and the entrance. There is mounting evidence for harbour formation through inland dredging technology throughout the Mediterranean (Pomey, 1995; Morhange & Marriner, 2010). Lechaion was probably one of the first harbours to be excavated in Greece by dredging soft rocks formed on an alluvial deposit background (Georgiadès, 1907; Pâris, 1915). Today no major stream or river flows towards the harbour area, so such sediment supply source does not exist. Finally, it must be pointed that the excavated harbour basin when constructed was covering a larger area than the visible remaining today, and there is no doubt that massive harbour works and warehouses once stood in this region (Rothaus, 1995). Despite archaeological effort, several aspects of the diachronic development of the ancient harbour are still obscure.

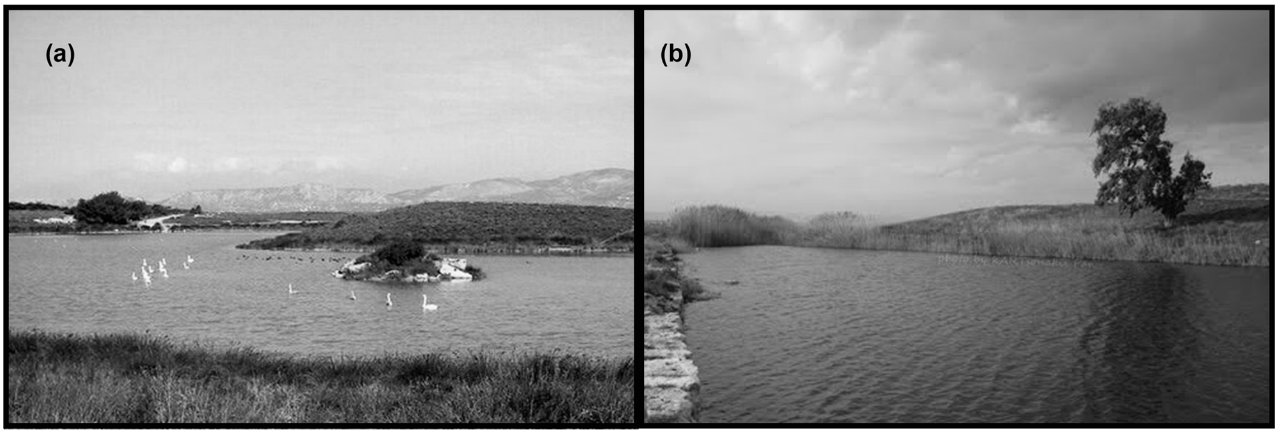

Figure 4. (a) View of small hills of sandy mounds dredged from the harbour basins. (b) View of the Inner basin.

3. THE SUBMERGED BREAKWATERS SYSTEM OF THE ANCIENT HARBOUR OF LECHAION

Formation of bedrock, tectonic and wave forces over the centuries, have also created submerged elements (small natural reefs) parallel to the shore resulting in the formation of two-T shaped submerged system (Figure 5b).

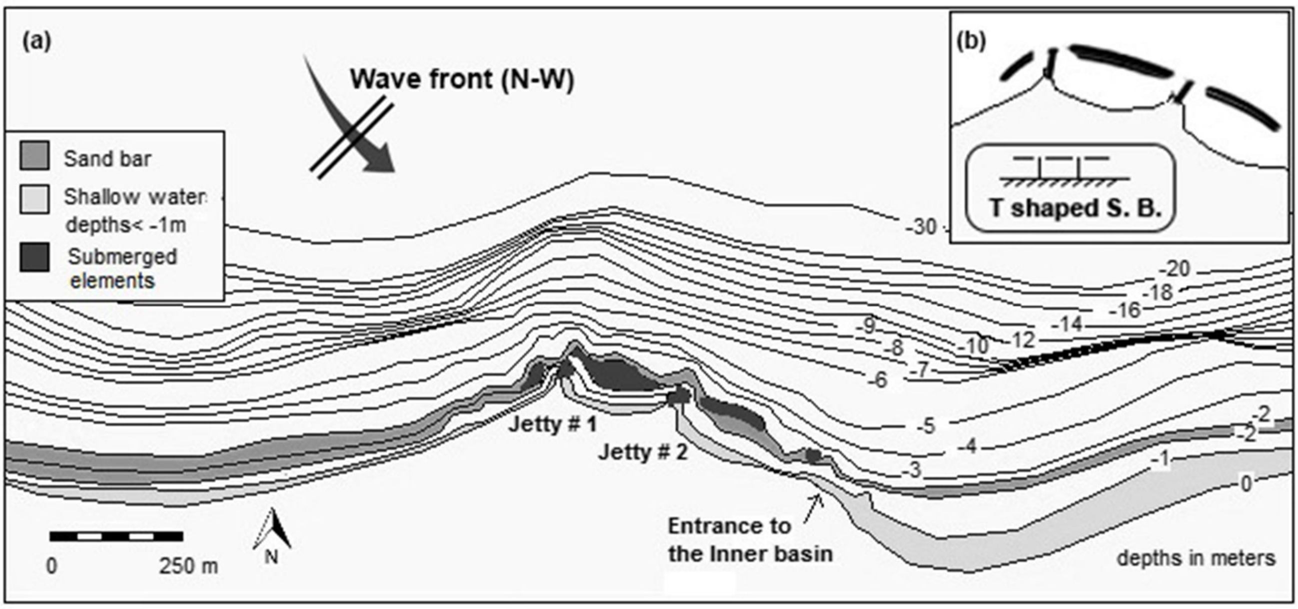

Figure 5. (a) Bathymetry and location of the submerged structures and natural reefs, functioning as sediment transport controllers. (b) Configuration of the T- like shaped plan of the submerged breakwaters system. Image plotted by adjusting two bathymetry maps, i) from the Hellenic Navy Hydrographic Service (scale 1:100,000), ii) (scale 1:10,000), by a study of Papafotiou (2008).

Adjustments of bathymetry maps available, as well as on site observations (subaqueous investigation) revealed the system of the two-T shaped submerged system with the parallel to the shore features detached from the perpendicular to the shore main structures.

The change of gradient due to the slopes of the submerged breakwaters has been smoothed by the creation of a sand bar all along the coast. Two basic maps where used in order to plot bathymetry of the port area. The first one from the Hellenic Navy Hydrographic Service (scale 1:100,000), and the second one (scale 1:10,000), was recovered from the study of Papafotiou (2008) which was digitally adjusted to the first one. As for the section of the two moles (jetties #1, #2), they are constructed of large stones (ashlar blocks) laid in rows, ranging in dimension from 1.9 x 0.9 x 0.4 m to 0.5 x 0.4 x 0.25 m (Pâris, 1915). The perpendicular to shore submerged formations are probably a projection of bedrock functioning likewise an impermeable submerged breakwater section. It seems that siting of the harbour was also selected in order to take advantage of the natural rocky reefs functioning like submerged (partly impermeable) breakwaters for shore protection. It is noteworthy that the artificial jetties #1, #2 were placed at the gaps of the parallel to shore bedrock, pointing out the knowledge of ancient engineers with regard to the "weak" points on the shoreline behind detached breakwaters. An aspect of the partial transposition of the breaking zone resulting from the system of the submerged breakwaters, under waves coming from the north-west, is given in Figure 6.

Figure 6. View of the breaking zone relatively to shore, for the T shaped submerged structure developed around jetty #1. Similar conditions are observed also for jetty #2.

As for coastal sediment transport, Google earth imagery gives a clear view of the sediment transport tracks along the adjacent to the harbour coast during a wind storm event (Figure 7). Due to the grayscale illustration of the figure, sediment tracks on the eastern to the harbour area, are indicated with dashed lines. The mechanism of sediment entrapments and the creation of a wash-out current in front of the navigation channel on the entrance to the inner basin, can be spotted. The bypass of sediments around the T shaped submerged breakwaters and their deposition in the nearby beach, a few hundred meters east of the channel mouth, is also visible. What can be well observed is that positioning of the entrance on the convex at the eastern part of the site, was aiming to benefit from maximum wash-out currents drawing away the bypassing sediment in order to prevent siltation. Last, refraction and diffraction phenomena around the berms of the jetties (jetties #1, #2), import to their lee, sufficient quantity of sediment, then trapped and circulating between the detachments of the submerged elements. Despite the accurate positioning of each structure, the basis for the success of the hydrodynamic mechanism described above, seems to be the "exploitation" of shoreline shape. Indeed the harbour entrance was placed at the least prone to sedimentation section of the shoreline.

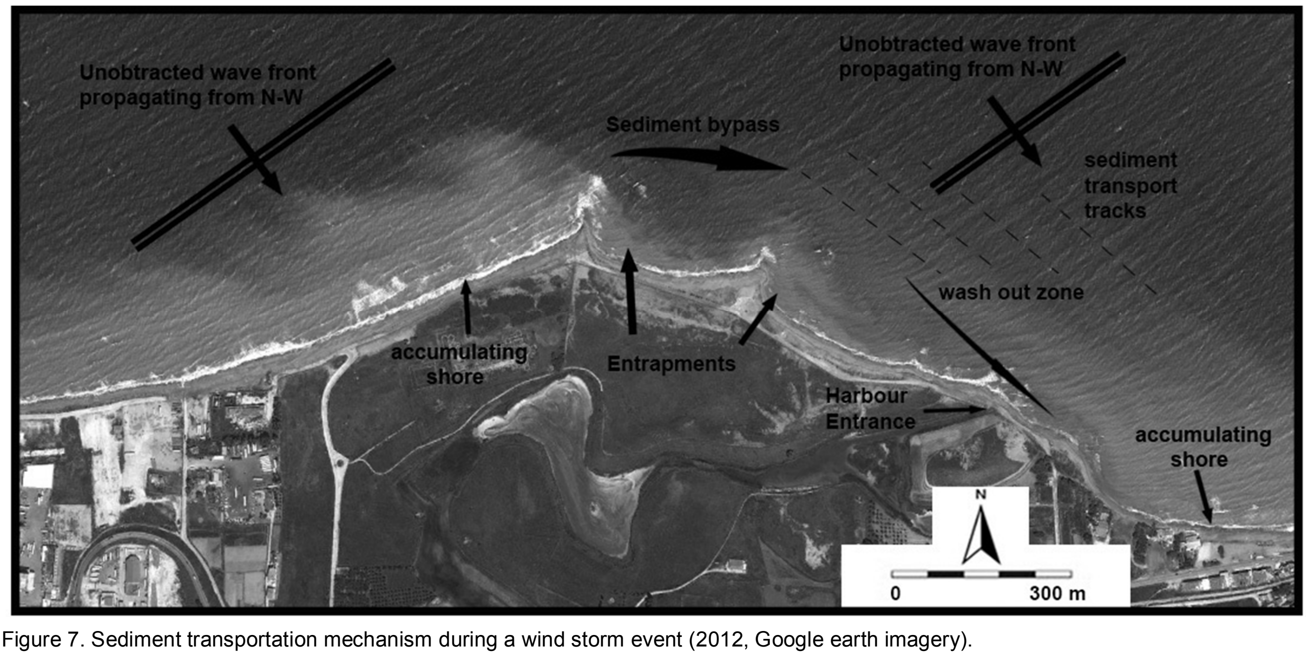

Figure 7. Sediment transportation mechanism during a wind storm event (2012, Google earth imagery).

Summarizing and in accordance with the previous chapter, a wide range of technical works have been applied, resulting in the layout of the harbour that is still visible. Site selection and positioning of the facility dealt with the arrangement through dredging of the once existing river bed, and took advantage of the natural bedrock forming small reefs in the nearby shore. Coastal constructions and land reclaim, produced an adequately sheltered inland harbour, by solving both the problem of siltation on the entrance end ensuring adjacent beach with sediment supply. The combination of partly submerged groynes, the natural reefs serving as detached submerged breakwaters and submerged double jetty on the entrance of the harbour positioned on a convex shore, shows that sediment flow can be partly bypassed to the downstream area while at the same time a percentage of momentum creating a wash-out effect in front of the entrance, minimizes entrapments in front of it.

4. NUMERICAL SIMULATION

In order to study the efficiency of the examined harbour layout, the computational model MIKE 21 (2007, DHIGroup) was used, aiming at furthering investigation on the hydrodynamic conditions developed due to wave-induced currents. These conditions were simulated using numerical models that predict wave propagation, horizontal velocity of wave-induced currents and transport of bottom sediment. The main goal was to investigate the impact of the coastal structures on sediment transport along the ancient harbour. Mild slope equations are used by the respective model (PMS), to simulate all phenomena which transform wave characteristics under the effect of solid boundaries. Calculation of radiation stresses being developed in the region, serves as an input to the hydrodynamic model (HD), which in turn feeds the sediment transport model (ST).

4.1 Simulation input

As orientation of the harbour makes it vulnerable mainly to the north-west sector, where sufficient fetch is developed (Fetch = 34 kms), the numerical model was applied for one incident wave scenario. The wave scenario was defined according to wind data gathered from the Hellenic National Meteorological Service. Data used for the estimation of maximum wave characteristics evolving in the area, were those of the nearest station available. Due to lack of data in the north shore of the Corinthian gulf, the station of Preveza was selected as it is located on the west coast of mainland Greece above the northwest edge of the Gulf of Corinth and gives representative data for north-westerly winds blowing towards the gulf. In table 1, the calculated characteristics of the incident wave (H_s, T_p) input can be found.

Table 1. Characteristics of the incident wave input.

NORTH-WEST SECTOR	
H_{mo} (m)	T_p (sec)
1.65	4.8

Bathymetry maps mentioned in chapter 3, were adjusted and digitized in order to produce the bathymetry input, used as a basis for the rest of the simulations. Taking into account the data of Figure 5 and for depths ranging from 0 to up to -70 m the model was developed as shown in Figure 8. The characteristics of the submerged structures as well as of the sand bar extending along the coast were included. Due to the scale of the simulation grid of the examined area, these features, though included, are not visible in the bathymetry model of Figure 8. The bathymetry is representative of the modern shore profile.

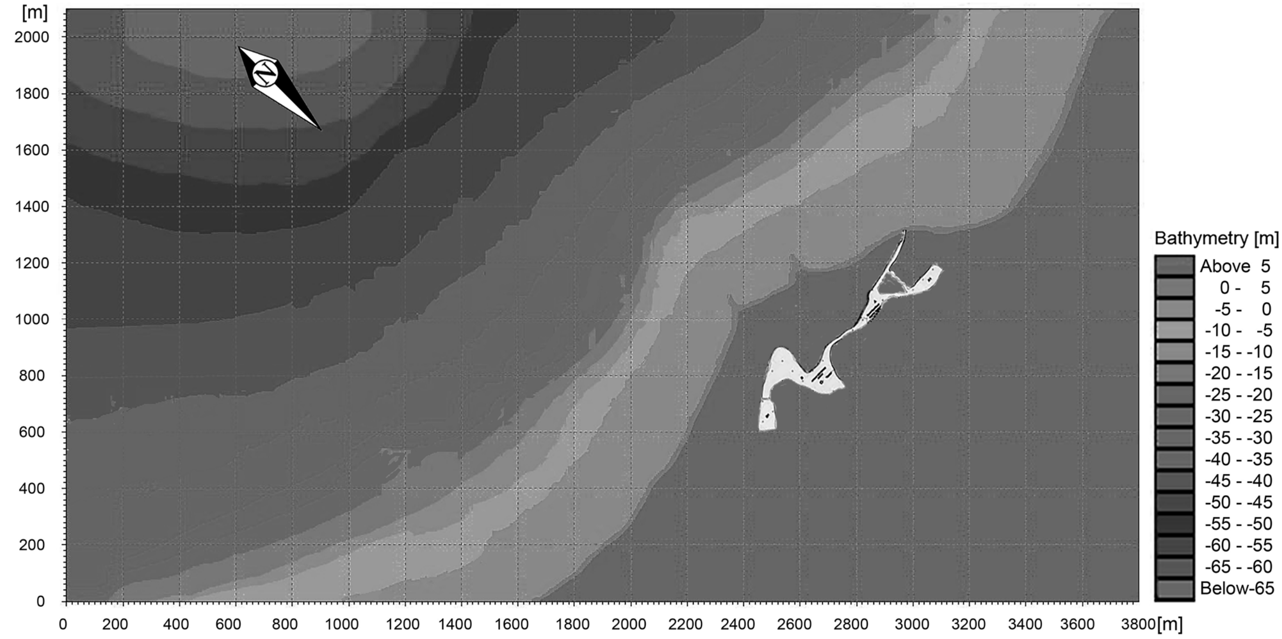

Figure 8. Bathymetry model turned by 45° anti-clockwise. Area of the inland basin and the entering channel are also shown.

4.2 Simulation results

Assessment of the resulting hydrodynamic field and sediment flow simulation was set mainly under qualitative evaluation. Specifically for simulating sediment transportation conditions two basic assumptions have been made: it was assumed that (a) infinite fine-grain sediment quantity is available for transportation and (b) the thickness of the sediment layer is also infinite. The model is capable in capturing phenomena as diffraction due to vertical wharves of jetties (partly submerged), shoaling and wave breaking leading to wave energy dissipation along the coast as well as refraction changing the initial direction of the incoming propagating wave-front. These simultaneously developed conditions can be easily observed around the harbour for a real time storm event producing waves approaching from the north-west sector. All simulations were produced for today's existing bathymetry profile and this for north-west wind.

In Figure 9, simulation of the developing wave field is shown as simulated by PMS module, for north-west wind.

Figure 9. Simulation of wave field (PMS) for north-westerly wind. Area of the inland basin and the entering channel are also shown.

In figure 10, simulation of the associated hydrodynamic field in terms of horizontal velocities U follows.

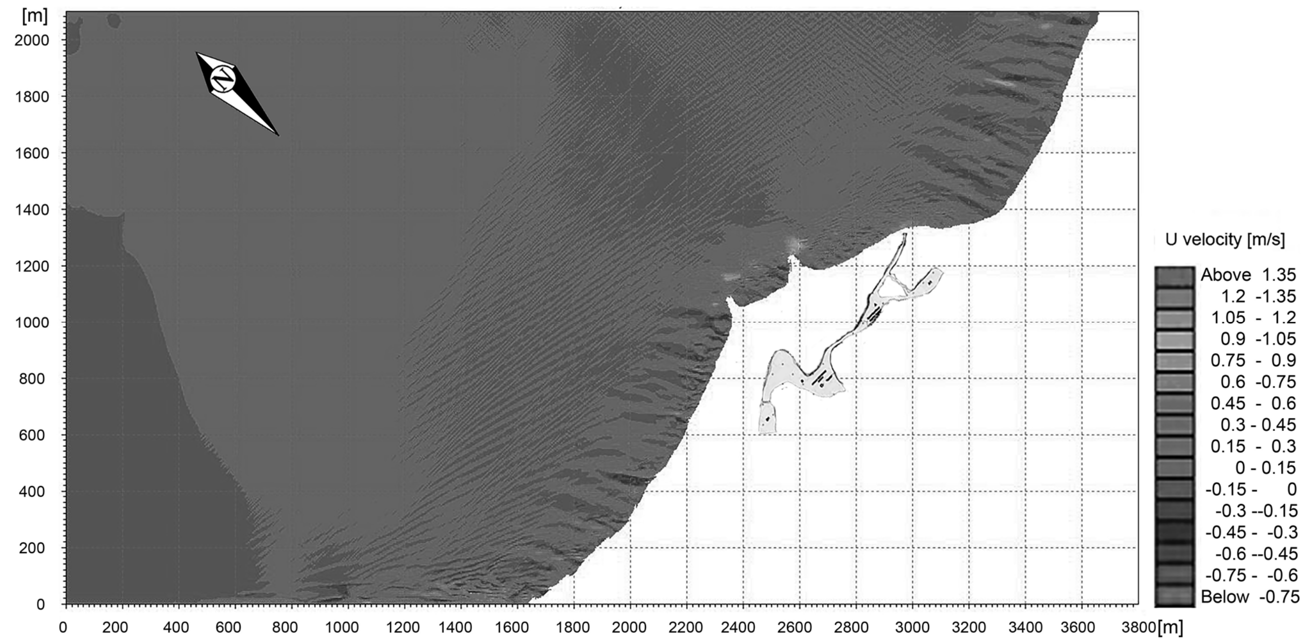

Figure 10. Simulation of horizontal hydrodynamic velocities (U), for north-westerly wind. Area of the inland basin and the entering channel are also shown.

Wave energy dissipation in quantitative terms of wave heights due to the phenomena described above, is well displayed. To the lee of the two partly submerged jetties (jetties #1, #2), wave height is considerably reduced while upstream of the entrance of the harbour a significant portion of wave energy is still approaching and wave breaking happens mostly on the coastline. In contrary, immediately eastward of the channel mouth, wave height is rapidly decreased before reaching the beach (Figure 9).

Abnormalities and wave height fluctuations on the edge of the south-west area near the coast were caused by the simulation procedure that assumed boundary conditions around the borders of the computational field. However, these did not affect substantially the results around the harbour area. The same abnormality pattern was also observed in all of the simulations but actually did not impair the model results in the study area.

As shown in figure 10, in relevance to the mean wave direction, apart from the edge of the submerged part of jetty #1, horizontal velocities maximize right after the leeward side of the jetty #2, while significant horizontal velocity rates are repeated a few tens of meters on both sides of the inner harbour channel entrance. This observation along with indications of the hydrodynamic behaviour of the harbour layout mentioned above fits quite reasonably with the mechanism described as wash-out zone in front of the channel entrance in figure 7. Similar result was taken by the model simulating the hydrodynamic field in terms of vertical velocities of a lower quantitative amount when compared with the respective horizontal velocities (not shown here).

Last, in figure 11 an overall assessment of the sediment transportation model (ST) indicates that the north-west wind creates long-shore currents directing from west to east. In contrast for the adjacent to the harbour area (east of the harbour entrance), the direction of sediment transportation is mainly perpendicular to the shore-front (cross shore sediment transport). The system of the submerged breakwaters functions as a sediment flow bypass and mainly conducts it around by following the shoreline. Despite the fact that sediment entrapments can be spotted behind the jetties (jetty #1, #2), significant sediment transportation occurs in front of the harbour entrance, drifting material to the downstream beach.

The basis for the success of the hydrodynamic mechanism is undoubtedly the shoreline planar shape with respect to the harbour entrance section, as underlined previously. Along the convex part of the shorefront where the port entrance is positioned, adequate hydrodynamic momentum creating a wash-out effect in front of the entrance is maintained, amplifying long shore currents, right after the leeward side of the partly submerged groynes and small natural reefs.

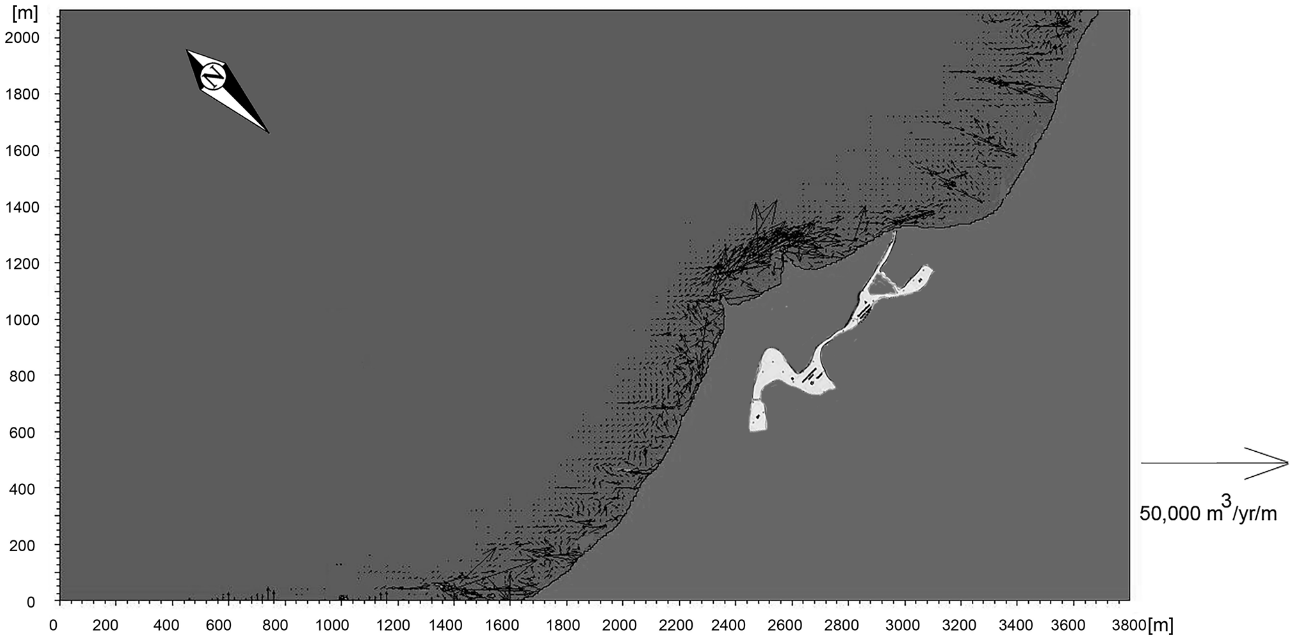

Figure 11. Simulation of sediment transportation, for north-westerly wind. Area of the inland basin and the entering channel are also shown.

Finally and in relevance to Figures 9-11, it can be deduced that deflection of sediment to the open sea, downstream of the harbour, is controlled as the bypassing of the submerged breakwaters material follows a path close to the coast and then is received by cross-shore currents finally disposing it to the east beach. For a better observance of Figures 9-11 due to grayscale rendering, enlargements of the model results for the port area are given in Figure 12 (also for mean wave direction).

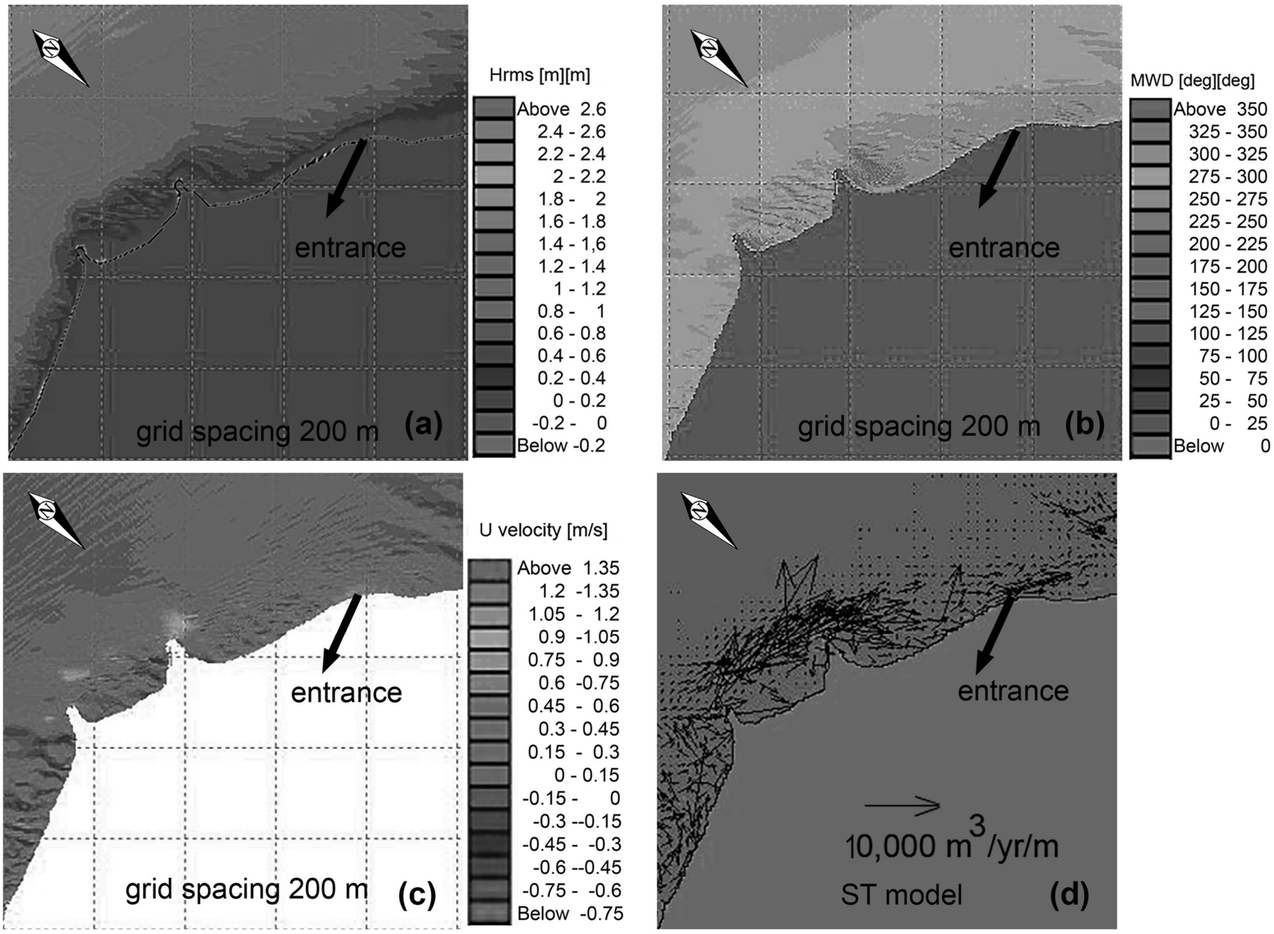

Figure 12. (a) Wave heights, (b) Mean wave direction change, (c) Horizontal velocities field, (d) Sediment transportation flow, for north-westerly wind.

5. CONCLUSIONS

This study showed that the adopted layout in the Lechaion ancient port design was able to control and retain sediments, at both sides of the harbour entrance. Simultaneously, siltation in the entrance channel is minimized increasing its navigational efficiency. The system of the partly submerged groynes and natural small reefs functions both as a sediment trap as well as a sediment flow bypass to the adjacent shore and thus resulting in stabilization of the nearby coast. Comparison of sediment transportation conditions as extracted by assessing on site observations during a wind storm event and Google earth imagery with model results shows good agreement with the simulation output.

Overall assessment of the layout of the harbour considering positioning, arrangement of the existing river bed in controlling incoming sediment from land, coastal constructions and inclusion of natural reefs along with intervention to the shape of the coastline through land reclaim, shows that the ancient engineer succeeded in maintaining functionality of the harbour entrance by minimizing siltation, while at the same time ensuring sediment supply. The combination of partly submerged groynes and submerged detached breakwaters on the upstream convex profile of the shore and double jetty on the entrance of the harbour positioned on the edge of this shore convex, shows that this arrangement is able to manage sediment flow by bypassing a part of it on the downstream area and simultaneously maintaining a percentage of momentum creating a wash-out effect in front of the entrance.

Because of the fact that the success of the ancient harbour seems to derive mainly by its orientation to one main sector (north-west), possible application beyond the south coast of Corinth Gulf, requires further investigation on similar layouts for two (or more) main wind directions.

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REFERENCES

DHIGroup (2007). MIKE 21, Parabolic Mild-Slope Wave Module, Scientific Documentation.
DHIGroup (2007). MIKE 21, Flow Model, Hydrodynamic Module, User Guide.
DHIGroup (2007). MIKE 21, ST, Non-Cohesive Sediment Transport Module, User Guide.
Georgiadès, A.S. (1907). Les Ports de la Grèce dans l'antiquité qui subsistent encore aujourd'hui, Athènes, *N.Taroussopoulos.*

Hadler H., Vött A., Koster B., Mathes-Schmidt M., Mattern T., Ntageretzis K., Reicherter K., Sakellariou D., Willershäuser T. (2011). Lechaion, the ancient harbour of Corinth (Peloponnese, Greece) destroyed by tsunamigenic impact. *2nd INQUA-IGCP-567 International Workshop on Active Tectonics, Earthquake Geology, Archaeology and Engineering, Corinth, Greece.*

Kambouroglou E. (1989). "Eretria. Paleo-geographical and Geomorphological evolution during the Holocene", *Department of Geology, National and Kapodistrian University of Athens, PhD Thesis. Athens*, p. 168. (in Greek).

Lykousis V., Sakellariou D., Moretti I., Kaberi H. (2007). Late Quaternary basin evolution of the Gulf of Corinth: Sequence stratigraphy, sedimentation, fault–slip and subsidence rates. *Tectonophysics*, 440, 29-51.

Morhange C., Pirazzoli P., Evelpidou N., Marriner N. (2012). Late Holocene Tectonic Uplift and the Silting Up of Lechaion, the Western Harbor of Ancient Corinth, Greece. *Geoarchaeology*. 27, 278-283.

Morhange C., & Marriner N. (2010). Roman dredging in ancient Mediterranean harbours. *Bollettino di ArcheologiaOnline*, vol. spe. IAAC, 23-32.

Mourtzas, N.D., Kissas C., Kolaiti E. (2014). Archaeological and geomorphological indicators of the historical sea level changes and the related palaeogeographical reconstruction of the ancient foreharbour of Lechaion, East Corinth Gulf (Greece). *Quaternary International*, 332, 151-171.

Papafotiou A. (2008). The management in time of the coastal zone between ancient harbour of Lechaion and north end of Diolkos of Corinth. *4th National Conference on Coastal Zone Management and Improvement, Mytilini, Greece.* 291-297. (in Greek).

Pâris, J. (1915). Contributions a l'étude des ports antiques du monde grec. *Notes sur L´echaion. Bulletin decorrespondance hellénique,* 39, 5-16.

Pirazzoli P.A., Stiros S.C., Fontugne M., & Arnold M. (2004). Holocene and Quaternary uplift in the central part of the southern coast of the Corinth Gulf (Greece). *Marine Geology*, 212, 35-44.

Pomey, P. (1995). Les épaves grecques et romaines de la place Jules Verne à Marseille. *Comptes-Rendus de l'Acad´ emiedes Inscriptions et Belles Lettres*, 2, 459-482.

Rothaus, R. 1995. Lechaion, Western port of Corinth: A preliminary archaeology and history. *Oxford Journal of Archaelogy* 14(3), 293-305.

Stiros S., Pirazzoli P., Rothaus R., Papageorgiou S., Laborel J., Arnold M. (1996). On the date of construction of Lechaion, western harbor of Corinth, Greece. *Geoarchaeology*, 11, 251-263.

Williams C.K. (1993). "Roman Corinth as a commercial center, The Corinthia in the Roman Period", (*Gregory T.E, (ed) JRA Supplement 8*), pp.31-36.

Ziros, G.A. (2000). "Ancient harbors in the Aegean sea". *School of Civil Engineering*, *National Technical university of Athens Thesis. Athens*. (in Greek).

http://limenoscope.ntua.gr