Submarine and coastal sediment failure triggered by the 1995, Mₘ = 6.1 R Aegion earthquake, Gulf of Corinth, Greece

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Abstract

On June 15th, 1995 a locally destructive earthquake of magnitude Mₘ 6.1 on the Richter scale occurred offshore, 7.5 km NNE of the town of Aegion, in the western Gulf of Corinth (Greece). An offshore survey using 3.5 kHz subbottom profiling system and a remote operated vehicle (ROV) has shown that the earthquake caused small sized subaerial to submarine sediment failure in at least four sites, in three fan delta deposits: the Rododafni; the Eliki and the Tolofonas. The fan deltas were located within a radius of about 9 km from the epicentre. The areal size of the four sediment failure sites ranged from 2 x 10⁴ m² to 6 x 10⁵ m², whilst the volume of the failed masses ranged from 4 x 10³ to 3 x 10⁶ m³. The sediment deformation types identified at the failure sites consist of ground cracking, rotational slides, elongated slides, sediment gravity flows and extrusion of mixtures of water and sand (sand boils). The sediment failure in the four sites affected the upper 5-6 m of well layered Holocene (?) topset and foreset fan delta deposits. The failure occurred on slopes ranging from 0.2° to 23° and the slip planes were all bedding planes which have a gradient from 0.2° to 21°.

The dominant instability mechanism that caused the sediment failure in the Rododafni and Eliki fan deltas is considered to be liquefaction of a shallow sub-surface horizon. The liquefaction was caused by elevated pore pressure enhanced perhaps by the presence of gas, resulting from the cyclic loading induced by the earthquake. The liquefied layer is assumed to have temporarily provided a failure surface for sliding to take place on and caused movement of sand that was ejected onto the surface.

In the Tolofonas fan delta the causative mechanism in the case of the multi-block rotational slide is considered to be deformation of the underlying sediments caused by remoulding and/or liquefaction while in the case of the elongated slide it is considered to be the result of a combination of shear stress increase and/or strength degradation of the unconsolidated sediment. Both of these conditions could have been generated during the cyclic loading resulting from the Aegion earthquake.

The study of historical documents reveals that sediment failure like those described above have also occurred at least four times during the past 2500 years in the same locations. Therefore, it is suggested that they could be repeated in the future by any earthquake event with a magnitude greater than 6 R, depending upon the proximity of the site to the earthquake epicentre.

Keywords: submarine landslides, earthquake hazards, Gulf of Corinth, Mediterranean Sea
1. Introduction

Sediment failure caused by earthquakes, on land, has been studied in detail but very few offshore ones have been documented or studied. Seafloor failure caused by earthquakes whose times and conditions (i.e. magnitude, focal depth, epicentre) of occurrence are well known, can be counted on the fingers of one hand. These are: (1) the Grand Banks offshore slump caused by the synonymous $M_s = 7.2$ earthquake in 1929 (Heezen and Ewing, 1952; Piper et al., 1988); (2) the subaerial to submarine slides at Port Valdez and Seward caused by the $M_s = 8.3$ Alaska earthquake in 1964 (Hampton et al., 1993); (3) the Alkyonidhes mass flow caused by the synonymous $M_s = 6.7$ earthquake in the Corinth Gulf (Greece) in 1982 (Perissoratis et al., 1984); (4) the liquefaction of shelf and nearshore sediments off the Klamath River mouth (northern California) (Field and Hall, 1982) and at the head of the Monterey Canyon in Moss Landing spit (central California) (Greene et al., 1991), respectively. The former was caused by the $M_t = 6.5$ ($M_s = 7.2$) Eureka earthquake of 1980 and the latter by the $M_t = 7.1$ ($M_s = 7.8$) Loma Prieta earthquake of 1989 and (5) a number of turbidity currents all over the world which have caused damage to submarine cables like that in the Ionian Sea in 1908 (Ryan and Heezen, 1965), the western New Britain trench in 1968 (Krause et al., 1970), and the Algerian shelf and slope in 1954 (El Robrini et al., 1985).

This paper presents the results of a series of detailed, small-scale geological studies which were carried out in order to examine sediment failure that occurred along the coastal zone in three fan deltas: the Rododafni, the Eliki and the Tolofonas that are located in the western Gulf of Corinth, Greece (Fig. 1). The sediment failure was caused by the “Aegion earthquake” on June 15th, 1995. (Fig. 1). The earthquake had a $M_s = 6.1$ R magnitude with a hypocentre at a depth of about 20 km (Carydis et al., 1996) and caused much structural damage to buildings in the nearby towns of Aegion, Tolofonas and Eratini.

2. Regional geomorphological and geological setting

The Gulf of Corinth is a WNW–ESE trending, 100 km long and 25 km wide active asymmetrical graben bounded by a major fault system along its southern margin (Brooks and Ferentinos, 1984; Doutsos and Piper, 1990; Roberts and Jackson, 1991; Doutsos and Poulimenos, 1992 and Poulimenos, 1993) and an antithetic submarine fault system along the northern margin (Brooks and Ferentinos, 1984; Ferentinos and Papatheodorou, 1995) (Fig. 1a). The onshore and offshore slope morphology in the southern margin is a direct result of footwall uplift and hanging wall subsidence of a number of discrete fault segments (Fig. 1a). Coarse grained, footwall-sourced alluvial fan deltas have been developed in the southern shoreline whose submarine part is currently prograding. The Eliki and Rododafni fan deltas on the southern shoreline consist mainly of cobble- and pebble-sized material interlayered by sand and silty sand (Schwartz and Tziavos, 1979; Leonards et al., 1988). The fans are located in the hanging walls of the Eliki and Aegion active faults, respectively (Fig. 1b). Both fans are banked against the footwall scarp of these faults. The Eliki fan delta has resulted from the coalescence of three large rivers, the Selinountas, Keranitis and Vouraicos and has a total area of 35 km$^2$. The Rododafni fan delta has resulted from the coalescence of two much smaller rivers, the Meganitis and the Erineos and has a total area of about 20 km$^2$. The Tolofonas fan delta on the northern shoreline (Fig. 1b) was formed at the mouth of a mountain valley in an emerging coastline located in the footwall of the Eratini active fault. The subaerial part of the fan delta is cone shaped, covers an area of about 3 km$^2$ and is incised by two rivers.

3. Methods

Fifteen days after the main shock, the Laboratory of Marine Geology and Physical Oceanography of Patras University conducted a reconnaissance survey of the area to map onshore
Fig. 1. (a) Map showing the regional faultlines of the study area; all offshore faults are active or potentially active (from Brooks and Ferentinos, 1984; Papatheodorou and Ferentinos, 1993 and Ferentinos and Papatheodorou, 1995). (b) Detailed bathymetric map (depth in metres) of the western Gulf of Corinth showing: (1) the areas surveyed; (2) the modern fan deltas; (3) the location of the epicentres (*) of the June 15, 1995 Aegion earthquake and of selected earlier events which have caused coastal failures and (4) the location of the shorelines which have slid and submerged as a direct result of the earthquakes shown in the figure; (c) sketch map of Greece showing the study area.
and offshore sediment failures along the coastline. The offshore survey was carried out using a 3.5 kHz seismic profiling system and a Benthos MKII Remote Operated Vehicle (ROV) for the visual inspection of the seafloor. The ROV survey was limited to the Rododafni fan delta site where, on the basis of the 3.5 kHz seismic profiles, three dive sites were selected to ground truth the seismic information.

**4. Data presentation**

**4.1. Morphological setting of the investigated areas**

The submarine topography of the fan deltas investigated is described below and the detailed bathymetry is presented in Fig. 2a–c.

The Meganitis river fan delta is located on the eastern side of the Rododafni fan complex. The Meganitis River has built its fan into water 300–350 m deep (Fig. 2a). The delta has a well developed planar bar composed of pebble/cobble and sand sized material. The delta-front sloping seawards from the bar is very narrow (≈150 m) and inclined at an angle of about 14°. The delta-front is bounded by a cone shaped prodelta-slope with an average gradient of 8° and a fan apron with an average gradient of 2°.

The delta front and slope is covered by a sequence of alternating parallel reflectors with a total thickness of about 20 m (Fig. 3a, b). The upper 8 m of the sequence consists of parallel, sharp, continuous reflectors which probably represent descrete deposits from seasonal fluctuations in river discharge. These reflectors conformably overly a transparent horizon about 8 m thick. At the base of this transparent horizon there are two or three high amplitude parallel reflectors. Drilling for harbour works in the area has shown that these high amplitude reflectors represent more porous layers within a muddy horizon (transparent) where gas, under pressure, has accumulated. The strong reflectors are abruptly terminated (Fig. 3a, b) suggesting bed truncation. The truncation surface is interpreted as a slump scar which has been refilled with sediments exhibiting transparent acoustic character indicating mass transportation.

An active submarine channel extends from the Meganitis river mouth to about a 200 m water depth (Fig. 2a). The channel floor is incised to a depth of about 40 m below the delta slope surface (Fig. 3a, b) and the bounding walls have an average gradient of 15°. The strong and prolonged surface reflector observed in the profiles across the channel, indicates that the floor is covered by coarse material. The ROV inspection of the channel floor showed that it is covered by abundant, scattered pebbles and cobbles which are blanketed by a film of silt and clay (Fig. 4). The pebbles and cobbles seem to have been deposited as inertial flows (Prior and Bornhold, 1990), during high magnitude river discharge. The silts and clays have been deposited by river suspension plumes.

The Eliki delta front is about 2 km wide and extends as far as the 150 m isobath (Fig. 1). It slopes seawards very gently with a gradient of less than 1.5°. The delta front is covered by a well stratified topset sequence which has a total thickness of about 30 m, thinning seawards and downlaps onto basal unconformity. This sequence represents Holocene high stand prograded coastal deposits.

The Eratini river fan delta is located on the eastern side of the Tolofonas fan. It extends as far as the 50 m isobath (Fig. 2d). The delta front has an average gradient of 11°, the delta slope has an average gradient of 4° and the fan apron a gradient of less than 2.5°.

**4.2. Coastal sediment failure**

Observations on the coastal zone have shown evidence that the earthquake caused three types of...

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Fig. 2. Detailed bathymetric maps (depth in metres) showing the location and areal extent of the sediment failure sites in: (a) Meganitis river delta front/slope; (c) Eliki delta front and (d) Eratini river delta front/slope. Continuous and dashed lines are 3.5 kHz profiles and ROV dive traverses, respectively, described in the text.
Fig. 4. ROV photo of the seafloor in the submarine river channel, showing that it is covered by scattered gravels, pebbles and cobbles mantled by a thin film of mud.

sediment failure: (1) ground cracks; (2) liquefaction and (3) rotational sliding.

In the Meganitis River mouth bar, ground cracks were the most prominent earthquake generated ground deformation. Most of the cracks were parallel to the shoreline, indicating an apparently seaward spreading. The cracks were 10–15 m long and about 0.1 m wide (Fig. 5). Sand and water was ejected from most of the ground cracks. The sand that emanated along the cracks formed a sheet of about 1–2 cm thick and 1–3 m wide (Fig. 5). The spread of the sand over the ground and the presence of flow structures around obstacles (i.e. cobbles) indicate that the sand flow was viscous (Fig. 5).

In the Eliki fan delta, between the Selinous and Keranitis rivers (Nikoleika Beach) the surficial sediment, consisting of pebbles and cobbles, was affected by shallow rotational slides as is indicated by the formation of rotated and landward tilted blocks which are separated by scarps with a height of 0.5–1 m (Fig. 6). The scarps were parallel to the shoreline and the blocks have dimensions of 10 15 m and 30 70 m, perpendicular and parallel to the shoreline, respectively. Landward of this zone of deformation, ground cracks and liquefaction features were also observed.

In the Eratini river fan delta no sediment failure was reported except for the sinking by about 30–40 cm and tilting of the jetty at the marina, which was built on loose sand and gravel beach deposits. A possible cause of the sinking is considered to be failure or liquefaction of the underlying layers induced by seismic shock.

4.3. Submarine sediment failure

4.3.1. Meganitis river Fan Delta

The offshore geophysical survey in the Meganitis river fan delta has shown evidence of slope instability associated with the layered Holocene (?) sequence which covers the fan cone (Fig. 3a,b). The sediment failure affected the eastern wall that bounds the active submarine channel (Fig. 2a). The failure has an arcuate shape in plan-view, with a maximum width and length of about 150 m and 1200 m, respectively. The total area of the failure zone is 200,000 m². Representative profiles, which run in the dip direction show that the uppermost part of the layered foreset unit, which has a total thickness of about 5 m and a dip of 21° to the west, has been affected by two styles of sediment failure (Fig. 3a,b). The same profiles show that the failure took place above a well defined surface lying parallel to the seafloor.

Profile 1 (Fig. 3a) in the southern part of the failure shows that the upper 5 m of the well layered surficial sediment has been affected by a multi-block rotational slide. The discrete and coherent blocks have tilted backwards by 22°, thus forming a step-like morphology on the seafloor. The individual failure planes are spaced on average every 5 m and extend below the seafloor to a depth of

Fig. 3. (a) High resolution seismic profile (see Fig. 2b for location) showing (1) the head scarp; (2) the bathymetric expression and internal structure of the rotated blocks and (3) the slip plane which is exposed on the seafloor directly downslope from the leading block. (b) High resolution seismic profile (see Fig. 2b for location) showing that the upper 5 m of the layered (Holocene) sequence terminates abruptly at a scarp indicating that masses have already dislocated themselves downslope which have been deposited as sheet/lens like deposits over the evacuated zone. **ER** = enhanced reflectors; **SI** = slip-plane.
Fig. 5. Ground cracks in the subaerial fan delta of the Meganitis river. Sand and water forced out from the cracks as a result of liquefaction.

Fig. 6. View east along the Eliki fan delta (Nikoleika beach) between Selinous and Keranitis rivers showing rotated blocks separated by en-echelon scarps.

5 m where they form a well defined glide plane, which is parallel to the seafloor and the sediment bedding planes. On the seismic profiles it is difficult to assess whether the failure planes are planar or listric. The gross horizontal displacement estimated, as suggested by Wernicke and Burchfiel...
(1982), assuming that the failure planes were planar, is 161% whilst the vertical displacement from block to block ranges from 1 to 2.5 m. The leading blocks in the downslope direction appear to have become detached and disintegrated as is indicated by the exposure of the basal glide plane on the seafloor (Fig. 3a), thus leaving enough space to accommodate the large amount of horizontal displacement upslope. This suggests a retrogressive type of failure which was caused by the absence of side support allowing the upslope blocks to move and rotate towards the unconfined direction of the bluff.

An ROV transect made along the 3.5 kHz profile 1 (Fig. 3a) for visual inspection of the seafloor over the multiblock rotational slide from a water depth of 20–70 m, showed the following features on the seafloor: (a) Scarps with outcrops of slightly consolidated stratified mudstone or lithified sand along the faces (Fig. 7a,b). The lack of any biogenic cover and bioturbation features as well as the absence of any sediment draping suggest recent formation of the scarps. At the base of the scarps in many locations poorly imbricated conglomerates in a mud matrix were observed, indicating sediment collapse. The clasts consist of angular to subrounded cobbles many of which are freshly broken with polished surfaces; (b) parallel bands of greyish colour sand locally covering the seafloor on the backtilted surface of the rotated blocks (Fig. 8). These sandy bands have less than 1 cm relief and have spread over firm sediments and seaweed. Small craters with a radius of less than 5 cm were also observed protruding through the sandy bands. Their resemblance to those sand sheets observed on land suggest that their formation was caused by the release of sand due to liquefaction of a subsurface horizon.

Profile 2 (Fig. 3b) in the northern part of the failure shows that the basal glide plane is covered by stacked sheet and/or lens-like deposits which are characterised by high amplitude surface reflectors and are acoustically transparent. These deposits are small in size, slightly larger than the resolving capability of the 3.5 kHz profiling system used. They overlap each other and onlap the lower part of the head scarp surface. This slide morphology suggests that after initiation of the main slide, the detached sediment apparently disintegrated during its downslope transport. Following the formation of the initial headscarp, upslope retrogression took place with the formation of small gravity flows, which in turn were deposited over the glide plane, thus forming a multiple sediment gravity flow deposit.

An ROV transect was made along the 3.5 kHz seismic profile 2 (Fig. 3b) for a visual inspection of the head scarp and of the sheet and/or lens-like deposits downslope reveals that the headscarp has a scalloped appearance with chutes (Fig. 9) indi-
Fig. 8. ROV photo of the seafloor upslope of the main scarp line, showing a dense covering of parallel and elongated tensile cracks with sandy bands along them.

Fig. 9. ROV photo of the main scarp face in the multi debris flow deposit area (for the location of the photo see Fig. 3b) showing a freshly cut chute.

cating that sediment flows is the dominant process. On the side walls of the chutes consolidated and well stratified sediment crops out. An overall view of a small size gravity flow deposit, seen through the ROV’s video camera, shows that the deposit is mound shaped and overlies the seafloor (Fig. 10a). The source scarp and corresponding chute of this deposit, which is further upslope, is beyond the viewing range of the ROV camera. The lack of biogenic cover on the surface of the deposit suggest that it is a recent event. A close-up view of this deposit shows that it consists of angular to subrounded cobbles in a mud matrix, many of which are freshly broken with polished surfaces (Fig. 10b). The absence of grading in the mud matrix together with the fact that the deposit came to rest a short distance from the scarp and cover a steep slope of about 20° indicates that a flow of relatively high strength value was the most probable flow type. These deposits resemble those described by Postma (1984) in the Abrioja and Espiritu Santo Gilbert-type fan deltas.

Profiles 1 and 2 (Fig. 3) show a distinctive difference in the deformation style of the failed
sediment in the northern and southern parts of the failure. In the southern part the sediment response was brittle whilst in the northern part the sediment lost its strength and disintegrated into sediment gravity flows. This is apparently a result of the differences in the composition and the physical and mechanical properties of the sediments.

4.3.2. Eliki Fan Delta (Nikoleika Beach)

High resolution seismic profiles in the offshore area of Nikoleika Beach (between the Selinous and Keranitis rivers), which has been affected by rotational slides (Fig. 2c), show that the onland instability spread offshore and affected the uppermost part of the topset sequence in the delta front (Figs. 11 and 12). The failed part of the delta front, in plan view has an almost horizontal amphitheatrical shape and extends parallel to the coastline and the general bathymetry (Fig. 2c). The failed sediment covers a seafloor area of about 600,000 m². The volume of the failed mass is estimated to be $3 \times 10^6$ m³. Examination of high resolution seismic reflection profiles, together with land observations, show that the slide is a complex low-angle translatory slide less than 5 m deep (Figs. 11 and 12) and that the sliding took place over a single basal glide plane which is also a bedding plane, dipping at about 1°.

Profile 3 (Fig. 11) in strike direction shows that within the slid body there are belts exhibiting various patterns of acoustic character indicating that the failed mass has undergone different styles of deformation during transport suggesting segmentation of the failed mass into linked discontinuous minor slides. The northern and southern margins are highly disrupted and deformed as is
indicated by the highly irregular seafloor topography and the chaotic to transparent acoustic character, whilst the central part remains almost intact as it is indicated by the undisturbed parallel reflectors in the seismic profiles. Local fishermen reported that many of the moored boats in the slide area drifted from their anchorages immediately after the earthquake. We suspect that this occurred because either the anchors of the boats were dragged by the slid sediment or the mooring lines were suspended due to changes on the seafloor topography caused by the sliding.

The presence of a high amplitude reflector and the opaque acoustic character of the underlying sediments all over the Eliki delta front (Figs. 11 and 13) indicate the presence of bubble phase gas and/or sharp changes in the sediment type. Supporting evidence for gas are: (1) a pockmark field which was detected in the nearby area in 1988 (S. Soter, pers. comm., 1995) and (2) the rising of bubbles onto the sea surface directly after the earthquake, as reported by local fishermen. The high amplitude reflector is well preserved within the central part of the slide where the surficial sediment are almost undisturbed, but is absent or masked in the margin of the slide where the surficial sediment are deformed (Fig. 11).

Profile 4, in the dip direction, in the northern flank of the slide, shows a poorly developed (about 40 m long) translated main body (Fig. 12) fol-
Fig. 13. A 3.5 kHz seismic reflection profile (for location see Fig. 2c) across two mounds illustrating that they consist of undisrupted parallel internal bedding and that conformably overlie the undeformed subsurface strata. The high amplitude reflector and the acoustic turbid zone (A.T.Z.) beneath it indicate the presence of gas in the sediments.

lowed in the downslope direction by a well developed compressional toe zone (Fig. 12). The up-slip part of the compressional zone is characterised by thrust faulting with the fault planes dipping about 11° in the upslope direction. The riding blocks between the faults, in the lower part along the gliding plane, have been deformed plastically and homogenization of the sediment has occurred as is indicated by the reflection free zone in the seismic reflection profile (Fig. 12). In the upper strata of the blocks, the reflectors are almost undisturbed, indicating rather brittle deformation (Fig. 12). The down-slip part of the compressional zone is characterised by a hummocky seafloor, whilst the internal strata is disturbed and folded indicating plastic deformation (Fig. 12). We suggest that the folds have been formed as an accommodation of stress created by the sliding masses and that the hummocky features on the seafloor resemble the pressure ridges described by Prior et al., 1984. The gross horizontal displacement within the slide, across the extensional zone in the headward part of the slide, is estimated to be about 106% and is broadly comparable by the contraction as estimated in the overthrusting zone. In the southern flank of the slide the study of the profiles in the dip direction show no evidence of any obvious translation and thrusting as observed in the northern flank. Instead the failed sediment was plastically deformed, more severely than in the northern flank, as is indicated by the widespread appearance of the transparent chaotic acoustic character in the profiles and the highly undulating topography on the seafloor (Fig. 11).

Individual sediment mounds less than 1 m high and measuring from 2 to 10 m across were also observed in some profiles (Fig. 13). The largest of the mounds exhibit almost undisturbed internal bedding and conformably overlie the undeformed seafloor. The diffraction hyperbolae associated with these mounds suggest sharp edges. These mounds are interpreted as block slides detached from the leading margin of the slide and translated over the seafloor as rafts.

4.3.3. Eratini River Fan Delta

On the Eratini river delta front and slope the geophysical survey showed that two sites have been affected by sediment failure (Fig. 2d). At the first site an area of about 60,000 m² has been affected by a multi-block rotational slide (Fig. 2d). At the second site an elongated type slide developed which covers an area on the seafloor of about 20,000 m². Representative seismic reflection profiles which are oriented in the dip direction and cross the multi-block rotational slide, show that the uppermost part of the Holocene (?) layered foreset unit, which has a thickness of about 6 m and a dip of 4°, has been broken into discrete and coherent blocks by listric planes (Fig. 14). The
Fig. 14. A 3.5 kHz sub-bottom seismic reflection record showing a series of rotated blocks affecting the surficial sediments. The detachment zone underneath the rotated blocks appears undulatory and the underlying horizon displays an overall transparent acoustic character.

Listric planes definition is lost in the underlying seismic horizon which has an undulating upper surface with an overall transparent acoustic character that also includes a few scattered, weak to strong parallel and discontinuous reflectors (Fig. 14). This acoustic pattern may indicate disturbed bedding and sediment homogenization. Furthermore, the undulating morphology of the surface implies softening of the sediment and minor mobility. Disturbed bedding in thinly interbedded siltstones and sandstones in shallow water gravity deposits was attributed, by Myrow and Hiscott (1991), to partially liquefied sediment in which little or no downslope motion took place.

Seismic profiles across the elongated slide show that it consists of a bowl-shaped depression, an elongated gully and a depositional lobe, thus resembling those slides described by Prior and Coleman (1978) in the Mississippi river. Profile 7 (Fig. 15a) which runs parallel to the subsided jetty a few tens of metres away (> 20 m) and crosses the bowl shaped depression, shows that the surficial sediments in the surrounding walls are truncated, thus indicating removal of material. The average thickness of the removed sediments is about 2 m and the total volume about $1 \times 10^6$ m$^3$. The removed sediment cut a channel which is now filled with sediments and formed a depositional lobe on the seafloor further downslope (Fig. 15b). The chaotic acoustic character seen in the seismic profiles and the uneven topography of the deposit indicate a debris flow type failure. Further offshore the smooth seafloor is interrupted by individual sediment mounds that exhibit similar morphological features and acoustic characteristics to those observed in the Nikoleika Beach. Therefore these mounds are interpreted as glide blocks translated over the seafloor as rafts. The source area of these rafts has not been defined.

5. Discussion

High resolution seismic profiles and ROV visual inspection of the seafloor have shown that the $M_s = 6.1$ R Aegion earthquake caused sediment failure simultaneously in at least four different sites located within a radius of 9 km from the epicentre. The areal size of the four sediment failure sites ranges from $2 \times 10^4$ to $6 \times 10^5$ m$^2$, whilst the volume of the failed masses ranges from $4 \times 10^3$ m$^3$ to $3 \times 10^6$ m$^3$. Earthquake triggered sediment failure, which has occurred simultaneously in two or three localities within the wider
area of the Gulf of Corinth has taken place twice during the last century (Heezen et al., 1966; Ferentinos et al., 1988). This suggests that the Aegion earthquake might have triggered sediment failure, not only in these three surveyed localities, but elsewhere as well.

The sediment failure deformation types identified within the surveyed sites are ground cracks, rotational slides, gravity flows and ejection of sand/water mixtures. All this sediment failure has affected the Holocene (?) age fan delta deposits. Through the analysis of high resolution seismic profiles it was found that in all the three sites the observed sediment failure was characterised by a shallow surface failure at about 5–6 m below the seafloor and has taken place over bedding planes which are parallel to the seabed with a dip ranging from 0.2 to 21°.

The postulated instability mechanism, based on the data presented here, which seems to have caused the sediment failure in the Meganitis River and Nikoleika beach could either be liquefaction or loss of shear strength due to fabric collapse of a shallow subsurface. This subsurface, which lies about 5 m below the seafloor, has temporarily provided a failure plane for sliding to take place. The extensive presence of sand and water injection features onto the beach surface and seafloor in close association with the sediment failure sites favour the liquefaction as the transport
mechanism. This is further supported by the results of a liquefaction potential geotechnical analysis for the Eliki fan delta that shows the presence of liquefaction prone horizons at depths between 5–10 m and 17.5–18.5 m (Leonards et al., 1988). The liquefaction was caused by the sudden increase of pore water due to the cyclic loading caused by the earthquake. Liquefaction was probably enhanced by the expulsion of gas from the deeper layers. This is suggested by bubbles rising to the sea-surface during the earthquake as was reported by the fishermen.

In the southern part of the Meganitis river failure site, where the surficial sediment have been affected by the multi-block rotational slide, the absence of side support and the steep slip plane allowed the blocks to move and rotate towards the unconfined direction, thus permitting the slide to retrogress. Furthermore, the availability of space created by the removal of the leading blocks, allowed for the large amount of extension observed and permitted the rotated blocks to remain undeformed. In the low angle translational slide off Nikoleika beach, the buttressing effect of the downslope bounding stable sediment has resulted in the thrusting and severe deformation of the failed sediment in the toe area. We speculate that this occurred because there was not enough space to accommodate the extension caused by the rotation of blocks in the headwards end of the failure. The highly irregular topography and the transparent character of the sediment below it, shown in Fig. 11 implies that the transported sediment has undergone pervasive deformation and was locally fully homogenised. The ridges formed on the seafloor may be the result of upward extrusion of sediment masses from the base of the slide whilst the complete homogenisation of the transported sediment masses was assisted by water and gas expulsion from the liquefied horizon. The latter is supported by fishermen who described witnessing the rising and bursting of air-bubbles on the sea-surface.

In the northern part of the Meganitis River failure site, the lens shaped gravity flow deposits which cover the glide plane, seem to represent products of consecutive debris flows, as is indicated by the mounded relief of the deposits and the presence of angular to subrounded cobbles in a mud matrix. The landslide morphology in the northern part suggests that the whole detached sediment body was initially translated over the liquefied horizon and that it was desintegrated during the translation. The responsible mechanisms for the initiation of the consecutive debris flows in the head scarp area following the initial failure can be attributed to one or to a combination of the following: (1) increase of stresses or reduction of strength either through remoulding or high pore water pressure caused by the cyclic loading induced by the earthquake shocks and (2) increase in shear stress upon loss of support as a result of erosion. The above suggests that the debris flows could have been triggered by the numerous aftershocks which followed the main shock and/or self-activated during the 15 day period which laps between the main earthquake and the time of the survey.

In the Eratini river delta slope, the multi-block rotational slide, which affected the surficial 6 m, was probably caused by the deformation of the underlying horizon, as is indicated by the acoustic character and the undulating geometry of the upper boundary. The deformation of the underlying sediments could be attributed to the partial loss of sediment strength due to either remoulding or excess pore fluid pressure caused by the cyclic loading induced by the earthquake.

The elongated slide was probably initiated by sliding and remoulding of the translated sediment mass. The sliding could have been caused either as a result of the stress increase acting on the sediments, or as a result of the shear strength reduction in the sediment through remoulding and/or liquefaction. Both of these conditions could be induced by ground shaking. The above mentioned mechanisms for sediment failure have also been considered by Prior and Coleman (1978) to be responsible for similar types of sediment failure in the Mississippi delta.

Historical observations give evidence that sediment failure, like those described above, has also occurred in the areas surveyed in the past (Fig. 1). In 373 BC, the ancient town of Eiki, which was situated around the area of Nikoleika beach and about 2.5 km inland, was submerged after an
earthquake (Papatheodoropoulos, 1981). The estimated magnitude of the earthquake was about 7.3 R (Papazachos and Papazachou, 1989). In 1817, a coastal strip at the mouth of the Meganitis River was submerged during an earthquake of \( M = 6.5 \) R and the land around Aegion town was covered by thick silty material. (Papazachos and Papazachou, 1989). In 1861, discontinuous coastal strips which had a width of about 150 m and a length ranging from 2 to 4 km were submerged over an area extending from Meganitis River to Vouraicos River after an earthquake of \( M = 6.7 \) R (Papatheodoropoulos, 1981; Leonards et al., 1988). In 1965 a coastal strip in the Eratini fan delta sunk under the sea after an earthquake of \( M = 6.5 \) R (Ambraseys, 1967).

Pausanius (2nd century AD, Achaika, Book 7 Κεφ, XXIV, 12, in Ancient Greek, Athena), writing about the destruction of Eligia in 373 BC said that “the sea invaded much of the land and encircled the whole town and that only around the temple of Poseidon the trees remained visible”. Strabo (68 BC – 25 AD, Geographica H’, 7, 2, pp. 384–385, in Latin, Roma), 150 years later, writing about Eligia, said that the statue of Poseidon was still upright but tilted under the water for many years and the fishermen nets were caught and damaged by it. Similarly, Schmidt (1887), referring to the 1861 earthquake, said that the landstrips were slowly submerged overnight and it took some days for the olive trees to be covered by the water. He further said that behind the submerged beach, sand volcanos appeared in many places. Based on the above descriptions it is suggested that in all cases the earthquakes have induced liquefaction of a subsurface horizon which provided a surface for the translation and subsidence of the overlying sediments.

The size of the historic sediment failure appears to be comparable to those studied in the present survey. The recurrence failure interval in this area cannot be estimated with any degree of accuracy nor can the likelihood of the size. This type of sediment failure is expected to occur when the seismic shock exceeds a certain threshold intensity i.e. more than 6 R (Kuribayashi and Tatsuoka, 1975). In the wider area of the Gulf of Corinth, on land, earthquakes with magnitude of more than 6 R have triggered such types of sediment failure (Ambraseys and Jackson, 1990). The interval time for earthquakes exceeding the aforementioned magnitude in the Corinth Gulf is as follows: earthquakes of magnitude 6 R are expected to occur every 22.7 years; earthquakes of magnitude 6.5 R every 82 years and earthquakes of magnitude 7 R every 410 years (Papadopoulos and Kijko, 1991). Therefore, it is expected that the recurrence interval for sediment failure events to be about the same. However, over a period of 2400 years only four sediment failure events, which are known to us, have occurred. This suggests that the epicentral distance is a very important factor in inducing sediment failure due to liquefaction. The epicentral distance of the 1965 and 1995 earthquakes, from the sediment failure sites, fits well to the empirical equation given by Kuribayashi and Tatsuoka (1975) which combines the maximum distance of liquefied sites versus magnitude.

References


Ferentinos, G. and Papatheodorou, G., 1995. Active normal