

## Landslide phenomena related to major fault tectonics: rift zone of Corinth Gulf, Greece

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**Abstract** Landslides in the Gulf of Corinth rift zone, Greece, are mainly in the vicinity of major active faults. The current study reports a representative landslide in this structurally controlled region which periodically moved, triggered/reactivated by heavy rainfall and earthquake activity. The composite landslide developed on structurally complex formations including sheared and weathered flysch—the most landslide-prone geological formation in Greece. The experience on the site during the last thirty-five years has contributed to a better understanding of the particular landslide mechanism and helped in the consideration of the effectiveness of various remedial works.

**Keywords** Fault-related landslides · Landslide reactivation · Remedial measures · Corinth Gulf · Greece

**Résumé** Les glissements affectant la zone de rift du Golfe de Corinthe, en Grèce, se situent principalement au voisinage de failles actives. L'étude concerne un glissement représentatif d'un secteur où périodiquement de fortes pluies ou l'activité tectonique déclenche ou réactive des mouvements de terrain. Le glissement composite se développe dans des formations de structure complexe comportant des flyschs cisailés et altérés: la formation géologique de Grèce la plus propice aux glissements de terrain. Le suivi du site durant les dernières trente cinq

années a permis une meilleure compréhension des mécanismes particuliers de glissement et aidé à la définition de divers travaux de confortement.

**Mots clés** Glissements associés à des failles · Réactivation de glissement · Mesures de confortement · Golfe de Corinthe · Grèce

### Introduction

Large landslide-prone areas affected by slow movement represent a complex and often poorly understood phenomenon. Their characteristics are difficult to determine and the prediction of their behavior is a delicate task. Large mass movements controlled by lithological, geomorphological and structural features are often not easily recognized simply by site investigation. In geologically complex areas, the relationship between lithology and tectonic history may obscure the actual cause of the mass movement. With structurally controlled landslides the type and frequency are mainly related to tectonic and lithological anisotropy (Guzzetti et al. 1996; Crosta and Zanchi 2000; Baron et al. 2005; Ambrosi and Crosta 2006; Margielewski 2006; Hradecký et al. 2007). Triggering mechanisms include:

- (a) excessive rainfall generating high pore pressure (Onodera et al. 1974; Nilsen et al. 1976; Guidicini and Iwasa 1977; Canuti et al. 1985; Kim et al. 1991; Ayalew 1999; Sidle and Dhakal 2002; Ahrendt and Zuquette 2003; Ibsen and Casagli 2004; Fiorillo and Wilson 2004; Sabatakakis et al. 2005; Ayalew et al. 2005; Hong et al. 2005; Borgatti et al. 2005; Salciarini et al. 2006) and

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- (b) strong earthquakes resulting in dynamic loading conditions at the failure surface (Jibson et al. 1994; Schuster et al. 1996; Esposito et al. 2000; Bommer and Rodríguez 2002; Keefer 1984, 2000; Khazai and Sitar 2004; Fukuoka et al. 2004; Sassa 2004; Sato et al. 2007).

Progressive creep over a period of months to years has also been documented as a predisposing factor in some larger slide displacements.

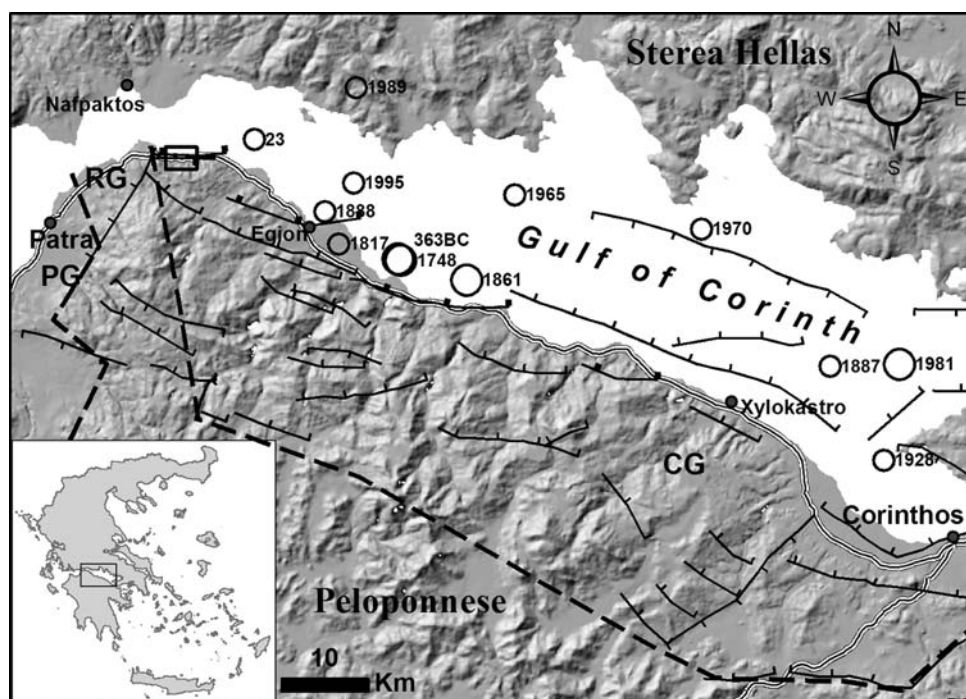
Slope instability in the southern segment of the Gulf of Corinth, Greece, is ubiquitous and ranges from deep-seated bedrock failure involving whole catchments to the generation of secondary earth flows in the marl formations. In this part of Greece, the periodically induced landslide events triggered by heavy rainfall, earthquake and anthropological activity are frequently closely related to active fault tectonics and to the existence of geodynamically active graben. The resultant geotechnical problems for

transportation routes, rural land-use and urban development are such that a large number of geotechnical appraisals have been carried out and a variety of remedial works have been implemented.

A case study has been undertaken to assess the risk of instability to the motorway connecting Athens with the city of Patras in western Greece, with particular emphasis on the geological composition and structure of the area. Failure surface geometry, geotechnical considerations and landslide evolution were examined. Significant factors related to the triggering mechanism are discussed, as well as the prevailing seismotectonic and climatic conditions of the area.

The paper outlines the significance of active fault tectonics for the development of landslides which could affect the transportation routes. It highlights the importance of expert knowledge of the local engineering geological conditions when designing proper remedial measures to reduce landslide risk in fault-related unstable slopes.

**Fig. 1** Map of Corinth Gulf showing major faults and historical seismicity in the area (Kokkalas and Koukouvelas 2005), the black box refers to the location of Panagopoula landslide study area



### Legend

- Major fault
- - - Seismically active fault
- - - Boundaries of tectonic grabens (approximate)
- "Panagopoula" Landslide
- == Motorway

### Historical Earthquakes

- M<sub>s</sub> (Richter)**
- 5.0 - 6.5
  - >6.5

## Geological setting and tectonics

The Gulf of Corinth is often considered as a typical example of a relatively simple asymmetric half-graben, with major border faults to the south and a flexure of the northern shore. The southern segment occupies the coastal area of the northern Peloponnese and was elevated about 1000 m above the present day sea level. With spectacular outcrops on its southern shore and being one of the most tectonically active and rapidly extending regions in the world (6–15 mm/year) with surface features clearly associated with seismic activity, this feature has been extensively studied (Koukouvelas and Doutsos 1996; Kokkalas and Koukouvelas 2005).

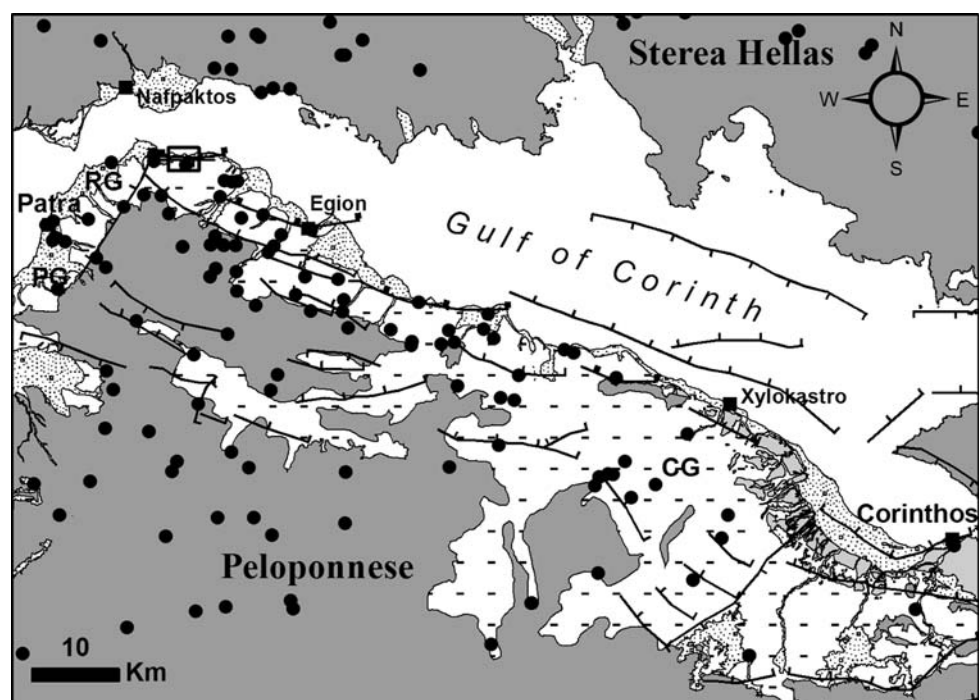
The Corinth Gulf rift zone is 100 km long and 40 km wide. Trending WNW–ESE, it crosses the Hellenic Mountain range approximately perpendicular to the structural pattern, and is an area of rapid isostatic subsidence which separates continental Greece from the Peloponnese (Fig. 1). Geodetic measurements and seismological and fault-slip analysis indicate a roughly N–S extension (Davies et al. 1997; Clarke et al. 1998). The rift zone accommodates most of the extension associated with the active subduction

of the African plate beneath the Eurasian plate. As shown, in essence there are two WNW–trending grabens—the Corinth graben (CG) in the east and the Patras graben (PG) in the west—with the NNE–SSW Rio graben (RG) passing between them (Doutsos and Kokkalas 2001).

The area, which is situated between 38°0′ E and 38°20′ N and 22°0′ E to 22°30′ E, has been recognized as one of the most rapidly developed inter-continental rifts in the Mediterranean region. Onshore and offshore normal faults in the rift zone trend WNW–ESE with a maximum surface trace of about 25 km (Koukouvelas and Doutsos 1996; Stefatos et al. 2002; Moretti et al. 2003). The faults dip north, typically at 50–60° and rarely up to 80°. The rift was developed in two stages:

1. The first stage was characterized by a shallow fault-controlled basin filled with fresh water sediments, 1000–2000 m thick; (Ori 1989; Doutsos and Piper 1990).
2. The second stage was characterized by Gilbert-type fan deltas and coarse-grained terrestrial sediments with a maximum thickness of 1200 m. Several offshore and

**Fig. 2** Simplified engineering geological map of Corinth Gulf also showing the distribution of recorded landslides that caused financial damage between 1950 and 2005



### Legend

— Major fault	Recent Quaternary deposits
- - - Seismically active fault	Pleistocene sediments
● Landslide site	- - - Pleio-Pleistocene sediments
□ "Panagopoula" Landslide	Alpine basement

onshore studies of the Patras graben (Doutsos et al. 1987; Ferentinos et al. 1985; Zelilidis et al. 1988) and the Rio graben (Kontopoulos and Doutsos 1985) have shown that the mean trend of the faults is NE–SW and NW–SE respectively.

Uplifts rates calculated for Quaternary terraces differ along the Patras–Corinth rift from 0.8 to 1 mm/year in the Patras sub-basin (Stamatopoulos et al. 1994) to 0.3–0.4 mm/year near the town of Corinth (Keraudren and Sorel 1987; Armijo et al. 1996; Dia et al. 1997). The highest uplift rate of about 4.4 mm/year was calculated for the Rio sub-basin (Kontopoulos and Zelilidis 1997; Zelilidis 2000). Active deformation along the Gulf is also documented by major active fault zones dipping NNE, uplifted shorelines, revers of drainage patterns, sub-aerial and submarine earthquake-induced landslides and historical and recent seismic activity (Ambraseys and Jackson 1990; Burton et al. 2004; Ferentinos et al. 1988; Jackson and McKenzie 1988; Papadopoulos et al. 2000; Papazachos and Papazachou 1997; Roberts and Jackson 1991; Sakellariou et al. 2001).

The Alpine basement of the Corinth Gulf rift zone (Fig. 2) is dominated by the Olonos–Pindos geotectonic zone. The normal sedimentary sequence includes schists and cherts of Triassic to Jurassic age which constitute the lowermost unit in the area, covered by thinly bedded limestones with radiolarites of Cretaceous age. A transition zone is developed above, including limestones, shales, cherts and marls, leading to the typical flysch sequence sediments of the Upper Eocene.

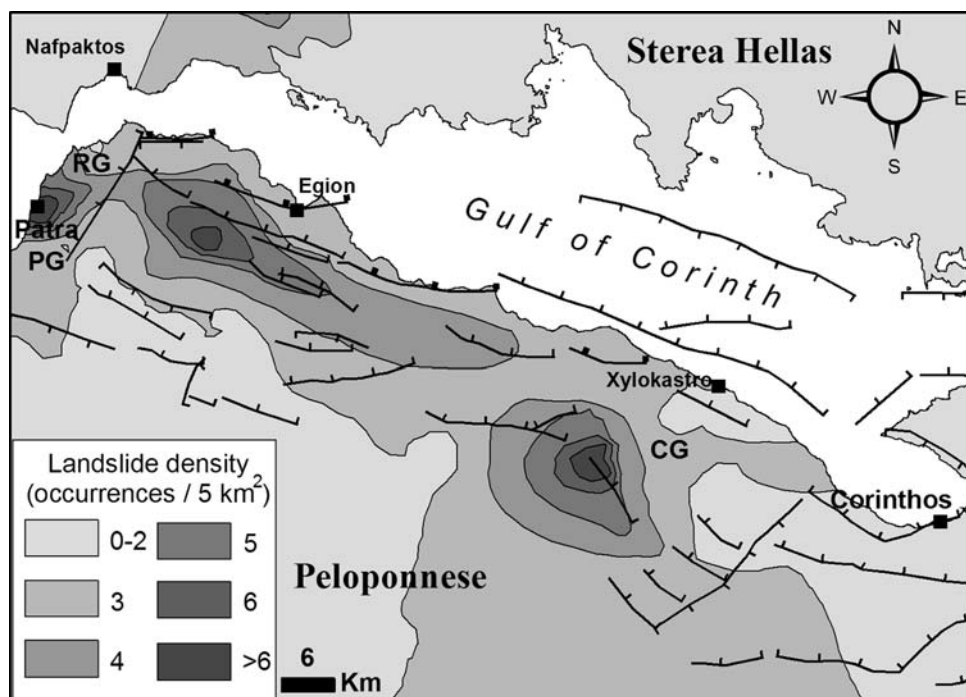
The post-Miocene tectonism of this upper zone is distinguished by the presence of strong E–W tangential tectonic movements, resulting in a westwards ductile thrusting and intense folding and fracturing of the Alpine formations (Doutsos et al. 2000). The phase of faulting which followed the initial folding caused major vertical movements (normal faults) and fracturing of the rocks. During the Pliocene and Pleistocene lacustrine and marine-lacustrine sandstones and conglomerates accumulated in the trenches created by the faulting. Subsequently, Quaternary alluvial fans were deposited and where the relief was sufficient, breccia/scree was formed.

### Landslide distribution and critical engineering geological conditions

In the last decade, the frequency of landslides in Greece seems to be increasing with progressive urbanization leading to the construction of roads, dams and reservoirs and industrial/urban activities taking place in landslide-prone areas. In addition, the continued deforestation and the occurrence of extreme meteorological events may also play a part. Since the late 1990s, there has been an increase of about 20% in the number of landslides recorded (Poyatzi et al. 2005), all of which had serious socio-economic consequences, although fortunately the only fatality was in Crete in 2003 (International Landslide Centre).

To mitigate the problem, the Department of Geology of Patras University and the Institute of Geology and Mineral

**Fig. 3** Landslide hazard zonation map of Corinth Gulf rift zone



Exploration (IGME) were commissioned to undertake an extensive study regarding landslide hazard zonation at a national scale, as recommended in the IAEG Commission Report (1976). The work included (a) detailed inventory of landslide events and their engineering geological setting, (b) analyses of underlying and triggering factors and (c) spatial distribution of these factors.

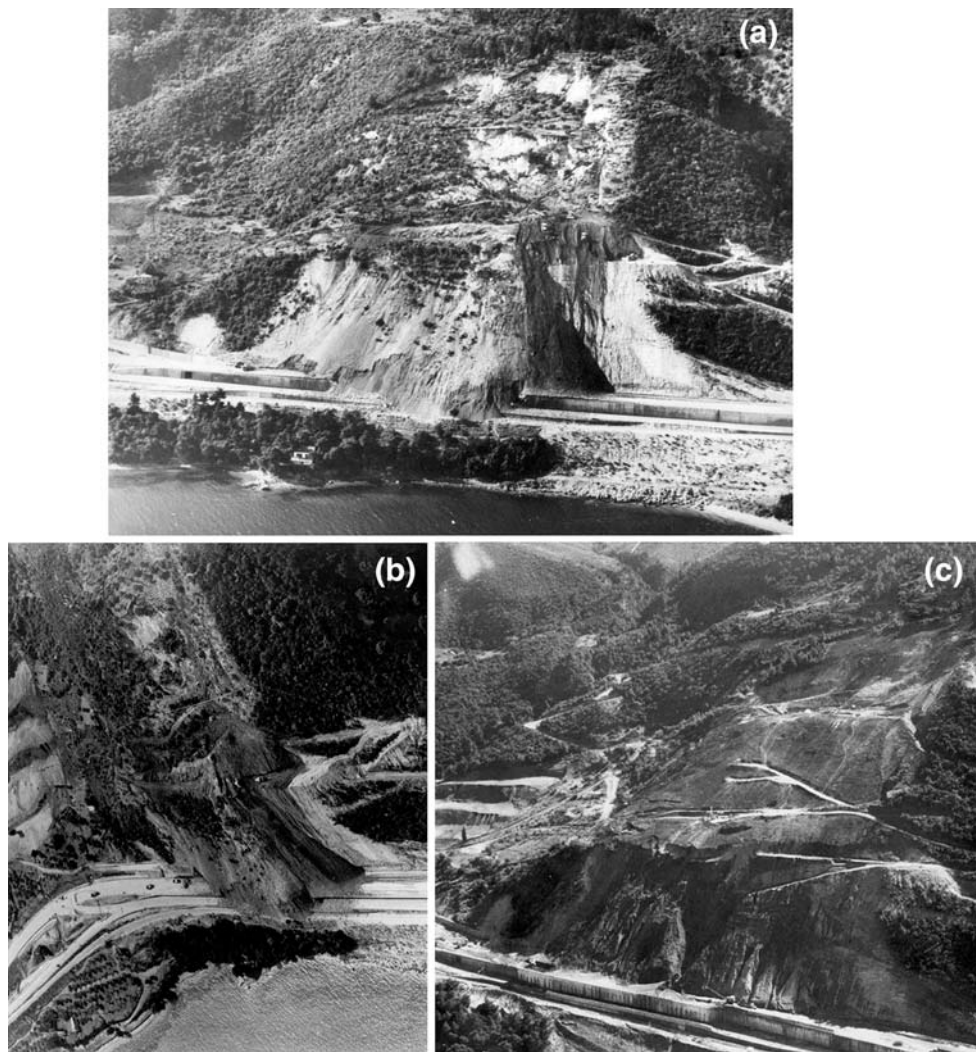
The mapping methodology was based on the experience-driven approach, employing data from existing landslide sites. A large number of technical reports and studies including landslide occurrences in the vicinity of the Gulf of Corinth were analyzed. After modifications, mainly to standardize the terminology, 218 landslide occurrences between 1950 and 2005 were recorded and digitally stored. A Statistical Inventory Form (S.I.F) modified from that initially proposed by Koukis and Ziourkas (1991) was used for data codification, mainly based on the Landslide Report (WP/WLI 1990) incorporating the former suggestions regarding the activity (WP/WLI 1993), landslide causes (WP/WLI 1994), rate of movements (WP/WLI

1995) and remedial measures (WP/WLI 2001). All data were encoded in a relational database management system designed in MS Access and managed in a Geographical Information System (GIS).

The geographical distribution of the recorded cases and the evaluation of the processed data led to the compilation of a landslide hazard zonation map (Koukis et al. 2005) at a national scale. Figure 2 shows the spatial distribution of landslides with socio-economic consequences. The scale of this map was intended to give a general inventory to inform the various stakeholders. Figure 3 shows the location of 218 landslides in the vicinity of the Gulf of Corinth between 1950 and 2005, indicating that in some areas the risks are high—up to 8 landslides per 5 km<sup>2</sup>. Not surprisingly, the landslide distribution is consistent with the main WNW–ESE trend of the onshore and offshore normal faults in the rift zone, while on a regional scale they are related to the faults/grabens.

The majority of the occurrences can be recognized as fault-scarp retreating processes which can be intensified during heavy rainfall and/or earthquake activity. The

**Fig. 4** Views of the Panagopoula landslide taken by helicopter showing (a) and (b) April 1971 event, (c) February 1972 event

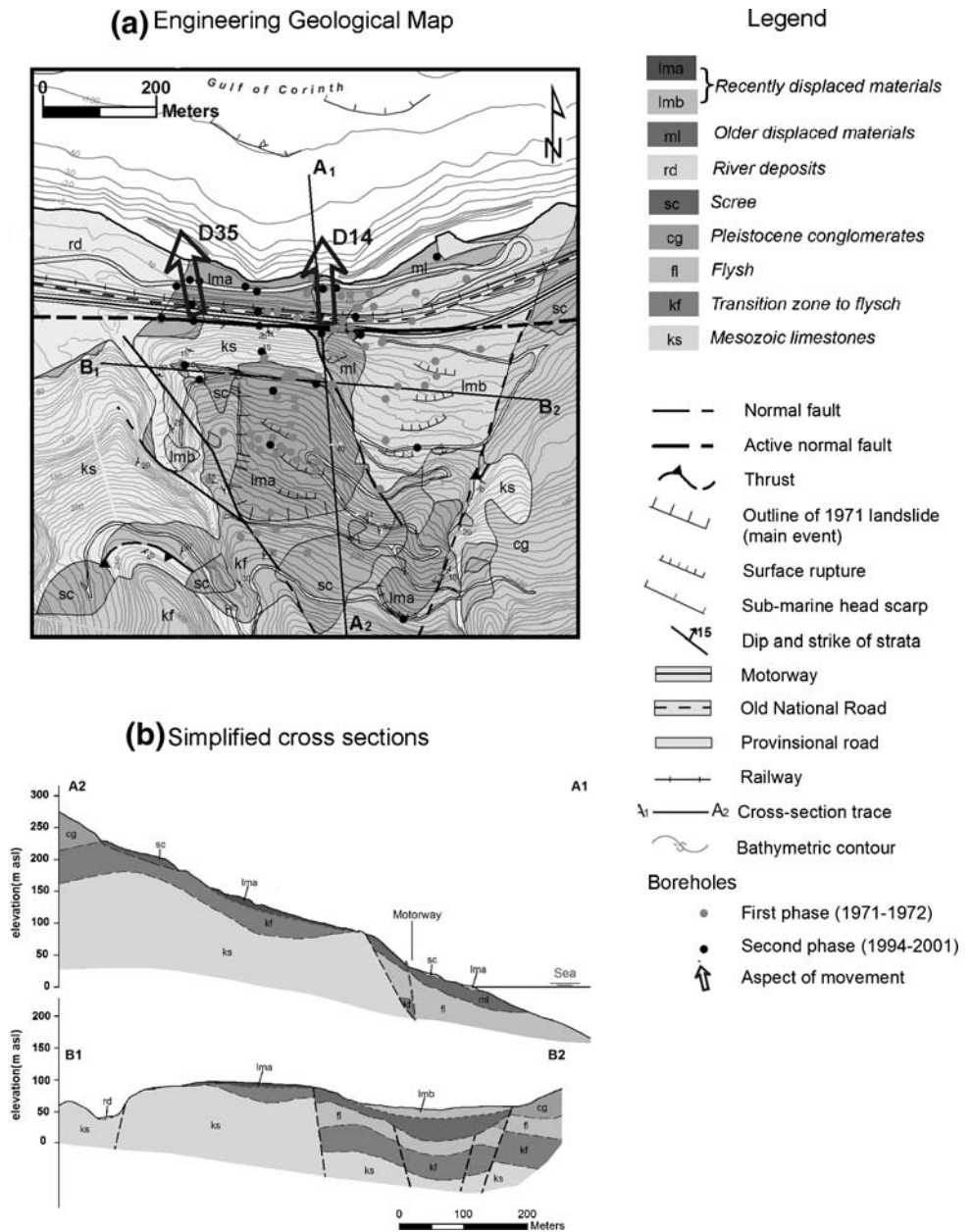


presence of the tectonically highly sheared and weathered geological formations, including Alpine basement and Neogene sediments, was a major contributory factor in the periodically induced instabilities. As a consequence, the Olonos–Pindos geotectonic zone exhibits the highest frequency of landslide occurrences in Greece, exceeding 40% of the total cases recorded. The most critical landslide-prone geological formations are flysch (30%) and fine grained Neogene sediments/marls (28%); see Koukis et al. (2005).

**Case record and analysis**

The studied case constitutes the most “famous” landslide in Greece. Its name, “Panagopoula”, refers to the coastal area situated between the cities of Aigio and Patras at the northwestern end of the elongated graben of the Corinth Gulf (Fig. 1). It is also a fault-related landslide. The area is considered to be one of those most prone to slope instability within the part of the E95 motorway connecting Athens with the city of Patras.

**Fig. 5** a Simplified engineering geological map of the Panagopoula landslide. b Simplified slip sections through instability zone



## Historical review

The area comprises an extensive instability zone where periodically induced landslide events have been interspersed with creep activity. Before the 1970s the movements were identified using aerial photography. Although in March 1970 local failures took place in the cut slopes of the motorway, the first significant failures were recorded on 25–27 April and 3 May 1971 (Fig. 4a, b), (Andronopoulos 1982). This resulted in the total destruction of the newly constructed highway connecting Athens to Patras while the old road and the railway line, running in parallel, also failed over a zone of about 350 m. As land transportation to western Greece was interrupted, a marine deviation using ferry boats was employed for several months.

The upper slide was characterized by a translational movement (Fig. 4a) on structurally sheared and weathered flysch sediments. This not only affected the upper part of the motorway slope but developed into an earth flow in the lower part where the material was tectonically highly sheared and weathered flysch. The volume of the displaced material was in excess of a million cubic metres.

In May 1971 a rotational slide occurred in the adjacent area within the displaced mass of recent debris material. The transportation lines (highway, old road and railway line) failed again over a distance of about 250 m.

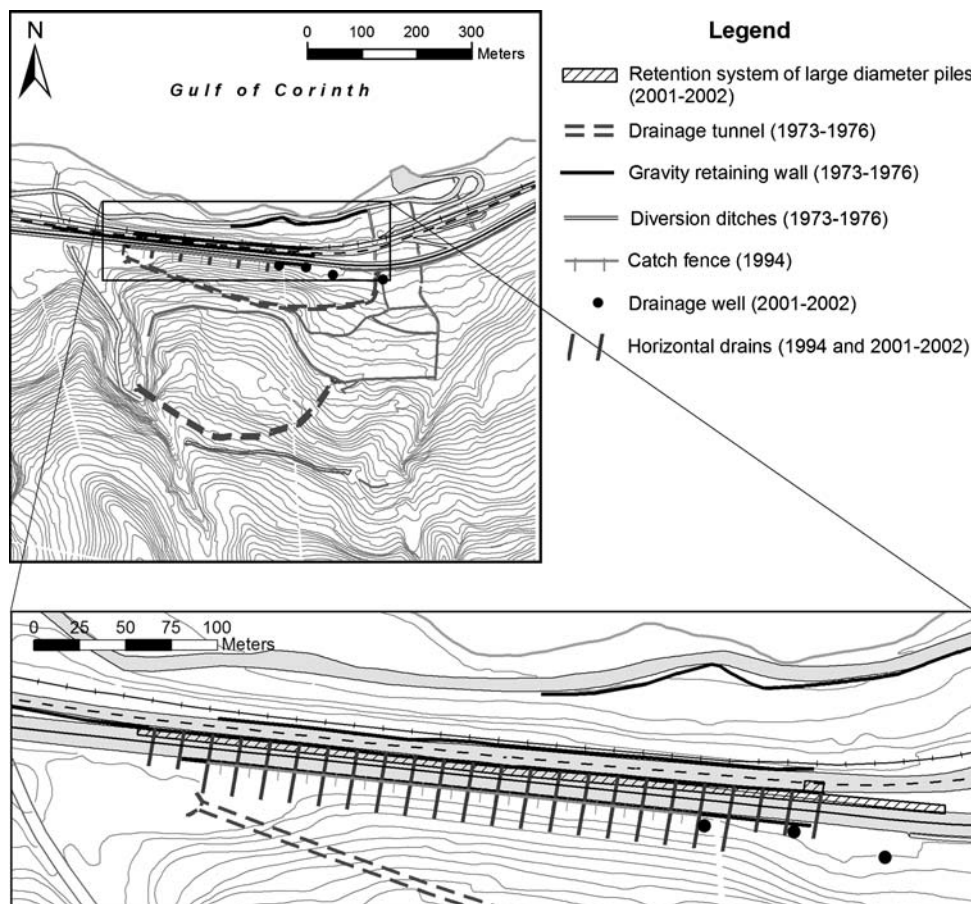
A program of geological and geotechnical investigations was carried out to find the causes of instability, design appropriate remedial measures and draw conclusions for future design. Twenty-eight boreholes were drilled (Fig. 5a) and piezometers and inclinometer tubes installed. Samples were retrieved for laboratory testing. A program of geological mapping took place along with offshore mapping (sonar images). Finally a geodetic network was installed in order to monitor the surface movements.

In February 1972, a sudden mass movement occurred in the weathered zone of the upper flattened slope (Fig. 4c).

The final design of the remedial measures focused to a great extent on the drainage of ground and surface water. The arrangement of the proposed works, which were constructed during the period of 1973–1976, is illustrated in Fig. 6. They included:

- (a) two (460 and 390 m long) drainage tunnels constructed at 30 m and 95 m a.s.l using conventional

**Fig. 6** General plan of the constructed remedial measures for the Panagopoula landsliding



- tunneling techniques with small-diameter sub-horizontal side drains;
- (b) a network of diversion ditches to remove water and reduce weight on the sliding mass and control erosion from large volumes of runoff;
- (c) removal of some of the displaced material and slope flattening;
- (d) construction of retention systems, consisting mainly of gravity and cantilevered concrete walls.

In February 1983, further ruptures occurred in the motorway pavement and settlements of an underground crossing were recorded. Again, in November 1993, fissures on the motorway and old road pavements were observed along a 300 m section. As a consequence of these warning signs, three inclinometers were installed.

In February 1994, after 56 mm of precipitation fell in five days, significant ground movement was recorded at a depth of about 8 m below the motorway pavement. This resulted in the distortion of the reinforced concrete cantilevered wall.

During the summer of 1994, further remedial works were implemented including the construction of a catch

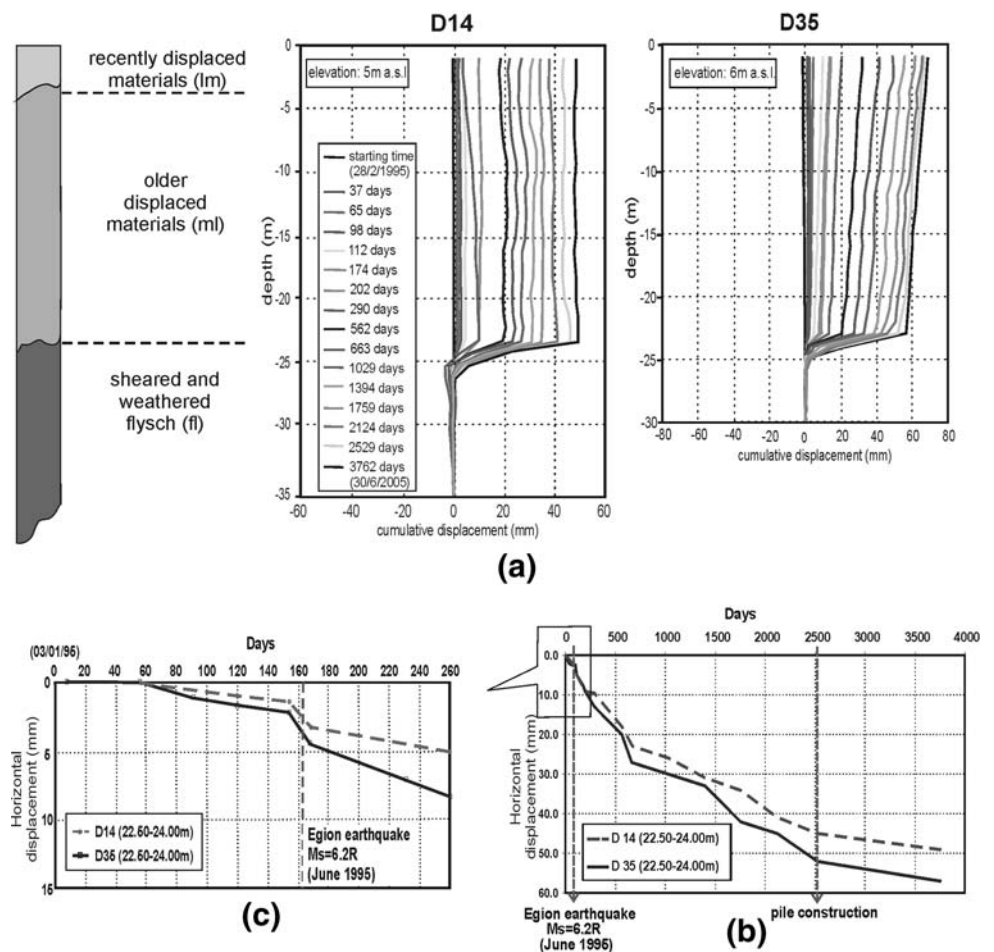
fence 270 m long, located in the ditch beside the motorway, and a large number of 150 mm diameter and 15–25 m long horizontal drains, drilled to intercept the drainage tunnels (Fig. 6). Inclinometer data indicated continuous movement after the remedial measures were completed, suggesting they were only partially effective.

An extensive program of additional geotechnical work (both in situ and laboratory) was planned, including an additional nineteen boreholes (Fig. 5a) with inclinometers and piezometers installed. The monitoring provided evidence that the constructed works generally contributed to the stabilization of the upper slope (above the motorway) but significant horizontal displacements were still being recorded in the lower part (below the highway). With new cracks in the motorway pavement recorded in September 1997, it was noted that the cumulative measured horizontal displacements between April 1995 and May 1999 were 18–62 mm at depths between 7 and 23 m.

The final remedial measures (Fig. 6) were designed to stabilize the lower part of the landslide zone and included:

- (a) construction of a retention system consisting of a double row of 256 cast in situ vertical driven piles.

**Fig. 7** a Ground profile and inclinometer readings between February 1995 (first reading after installation) and June 2005 at G36 and G14 boreholes. **b** Cumulative ground displacement measured at G36 and G14 inclinometers, **c** acceleration of ground displacement measured at G36 and G14 during the strong seismic event of Egion in July 1995





The 20–25 m long piles were 1.5 m in diameter and spaced at 3 m intervals;

- (b) improvement of drainage ditch system;
- (c) construction of four drainage wells.

These remedial works were constructed during 2001 and 2002 while the long term behavior of the stabilized slope continued to be monitored by inclinometers.

Ground conditions and landslide features

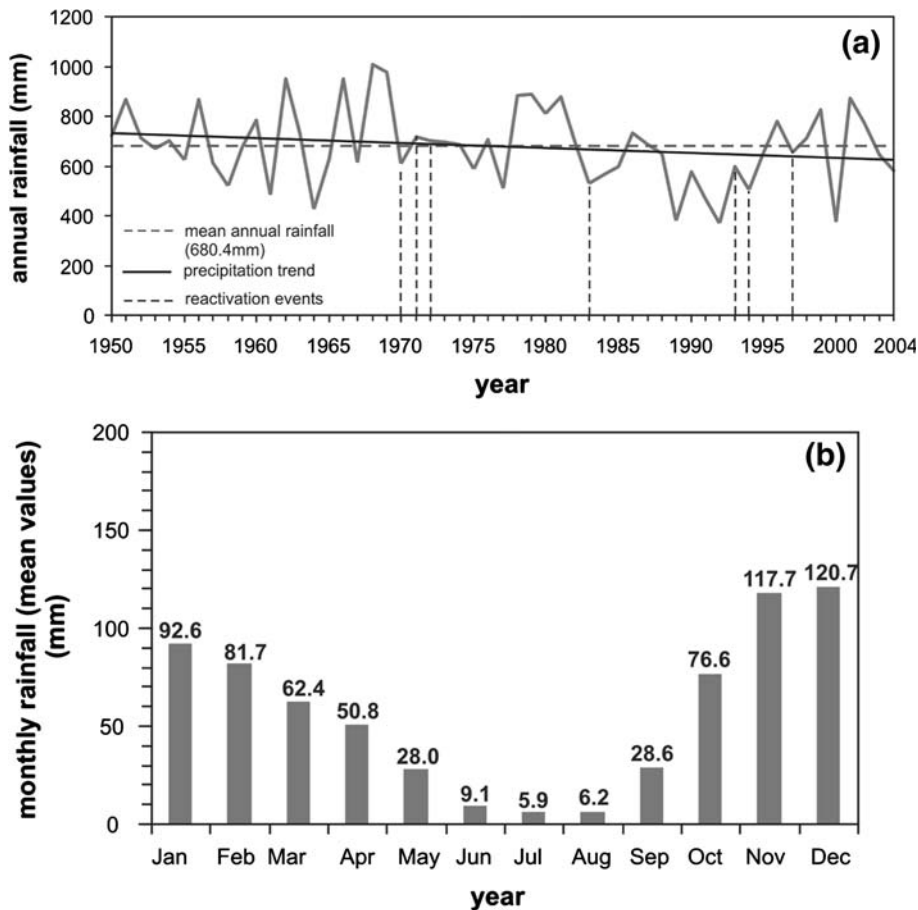
The geology maps of Fytrolakis and Antoniadis (1974) and Andronopoulos (1977) were updated using the borehole data. As noted above, the geology includes the Olonos–Pindos Alpine basement which has suffered intense folding and faulting, with medium-bedded Mesozoic limestones (ks) and occasional chert intercalations constituting the lowermost unit. This is covered by thinly bedded Cretaceous limestones (kf) with intercalations of red shale-chert, greyish shales, mudstone and sandstone which form the transition zone to the typical flysch sediments. The flysch (fl) is highly sheared and hence behaves as an argillaceous soil.

The intense past tectonic activity has resulted in a complex structure depending on the mechanical behavior (rigidity/plasticity) of the rocks and the local intensity of the tectonic stresses. The stresses have caused fracturing of the bedrock formations and loosening of the near surface rocks.

Neogene coarse grained fan delta facies consisting of conglomerates (cg) overlie the basement materials. Over 40 m of Quaternary sediments are also present including a “mélange” of older displaced clastic deposits and debris (ml) which consist of a mixture of intensively fractured, angular, calcareous—cherty—sandstone clasts/boulders with a sandy—clayey matrix. The Quaternary also includes recently displaced landslide materials from transition zone formations and from scree (lma and lmb respectively), scree materials (sc) and river deposits (rd).

A WNW trending normal fault (dipping northwards) runs almost parallel to the coast. This fault belongs to the Pspathopyrgos–Rodini fault zone, which is considered to be active (Flotte et al. 2005). The engineering geological map of the area and two representative geological cross sections are shown in Fig. 5.

**Fig. 8** **a** Mean annual precipitation for the period 1950–2004. **b** Average monthly rainfall (1950–2004)



The ground water system is influenced by the complex geological setting, including different lithological units, alternations of permeable and impermeable formations, intensively fractured rock masses etc. Twenty piezometers were installed during the second phase of the geotechnical investigation. The piezometric data indicate different groundwater levels have developed in the landslide zone (perched) compared with those in the underlying bedrock. The intense fracturing of the basement rocks allows water to infiltrate freely into the rock mass. During heavy and intense rainfall conditions, the ground water level rises and reaches the surface, probably acting as a triggering mechanism.

The first recorded landslide event in April 1971 was a large translational multiple slide in the upper slope material, which extended to depths of 25 m (Fig. 4a, b). The length was some 350 m and the width about 300 m. The second slide, in May 1971, was a rotational slide some 250 m long, 150 m wide, with a 5 m high backscar. Andronopoulos (1977) noted that this movement “resulted in the appearance of numerous cracks in the slope, the road pavement and the various points of the coastal area, where local small ridges were observed. Serious damage was caused to the road construction and the neighboring houses”.

The remedial measures constructed between 1973 and 1976 have contributed to the slope stabilization, with no ground displacements recorded for fifteen years. Some years later, a rotational slide extending to 8–25 m depth, disturbed the material in the road embankment.

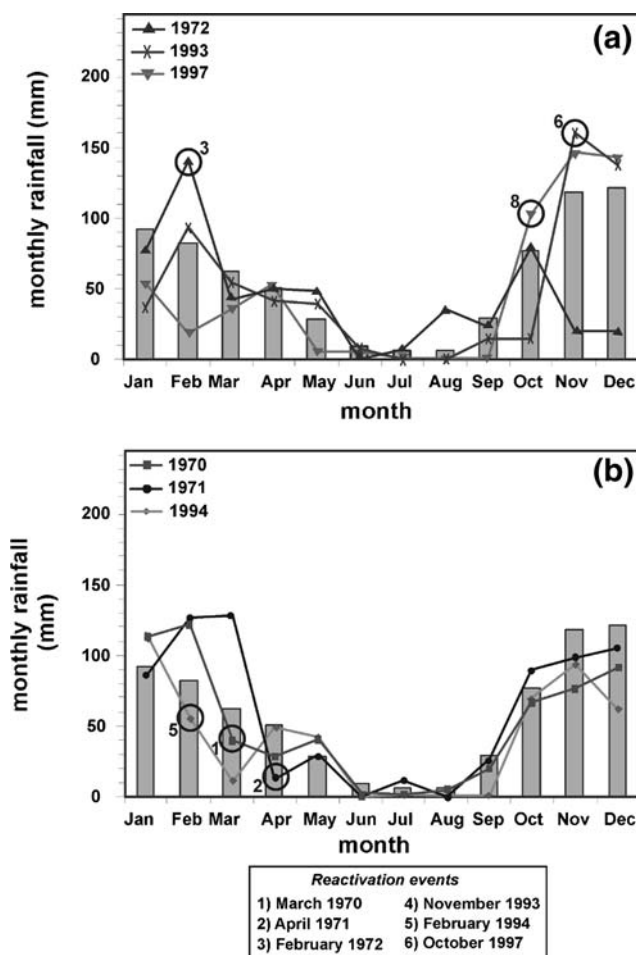
#### Monitoring—inclinometer measurements

Based on representative inclinometer readings from 1995 and 2005 (Fig. 7a) the average landslide velocity was between 5 and 12 mm/year. Monitoring of the movement indicated an almost linear relationship between displacement and time (Fig. 7b). The average velocity is classified as Class 1 according to the WP/WLI Report (1995), which suggests construction is possible, with precautions.

It is of note that a seismic event of  $M_s = 6.2$  occurred within 25 km on 15 June 1995 and was recorded by the inclinometers with a sudden movement of about 3 mm (Fig. 7c).

#### Precipitation data

Based on the precipitation data obtained from Patras station (Lat  $38^{\circ}13'55''$ , Long.  $21^{\circ}44'52'$ , elevation 6 m asl), the mean annual rainfall (1950–2004) was 680 mm (Fig. 8a). However, there appears to have been a decrease in the precipitation after 1983. As shown in Fig. 8b, the annual



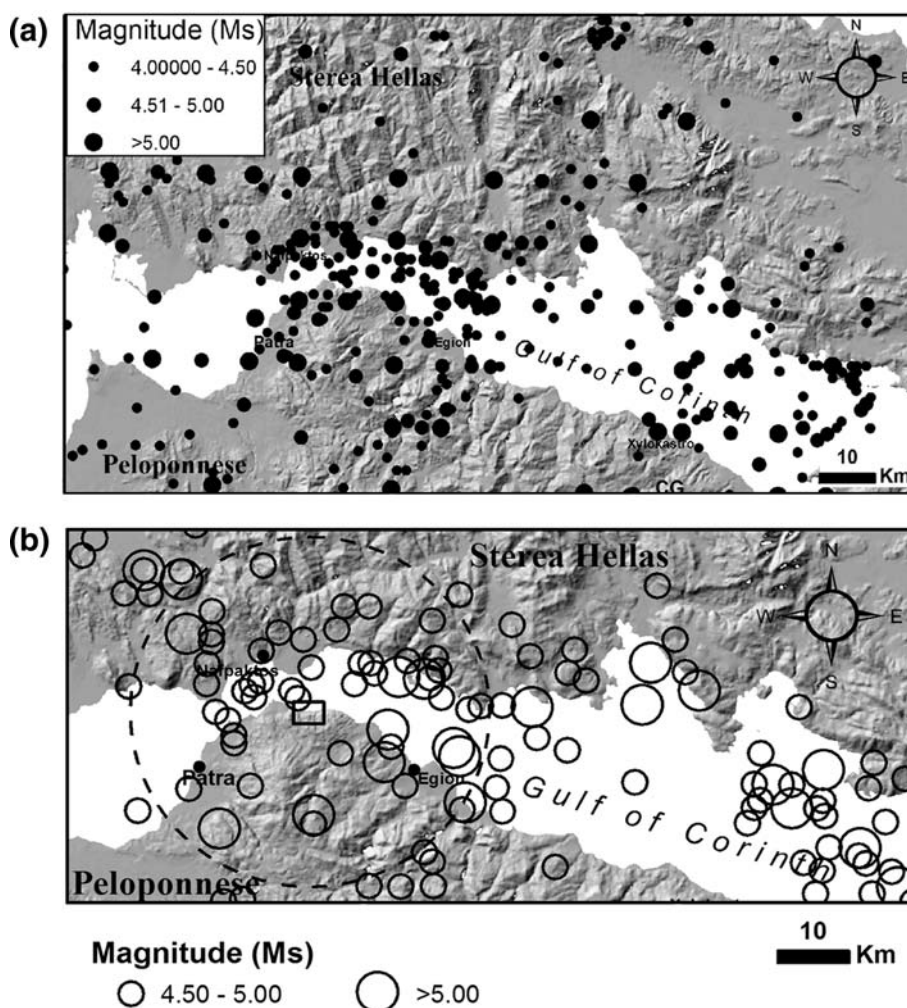
**Fig. 9** a Average monthly rainfall (1950–2004) and rainfall during 1972, 1993 and 1997. b Average monthly rainfall (1950–2004) and rainfall during 1970, 1971 and 1994

rainfall pattern is characterised by dry summers and mild wet winters, with more than 80% of the precipitation falling between October and April.

Statistical analysis of the monthly rainfall records during periods of reactivation shows that three of the events (February 1972, November 1993 and October 1997) can be related to high monthly rainfall (Fig. 9). During these periods, the monthly rainfall was higher than the mean values while 1–2 months before the events, there was only a small amount of rain. For example, during November 1993, the monthly rainfall was about 140% higher than the mean value for November, but during the 2 months prior to the slide, it was only 29 mm—about 75% lower than the mean value.

In contrast, as seen in Fig. 9b, during March 1970, April 1971 and February 1994 the monthly rainfall was lower than the corresponding mean values, but in the preceding months, heavier rainfall than usual was experienced. For instance, during the first main event (25–27 April 1971),

**Fig. 10** **a** Epicentre distribution of earthquakes with surface magnitudes  $M_s \geq 4$ , which occurred from 1900 to 2003. **b** Recent seismic activity (1981–2006) with surface magnitudes  $M_s \geq 4.5$  in an area of about 25 km around the Panagopoula landslide (Seismological Network of the University of Patras)



the rainfall was only 12.2 mm (24% lower than the mean value for April) while the March 1971 rainfall was almost double the mean value for that month.

#### Seismicity

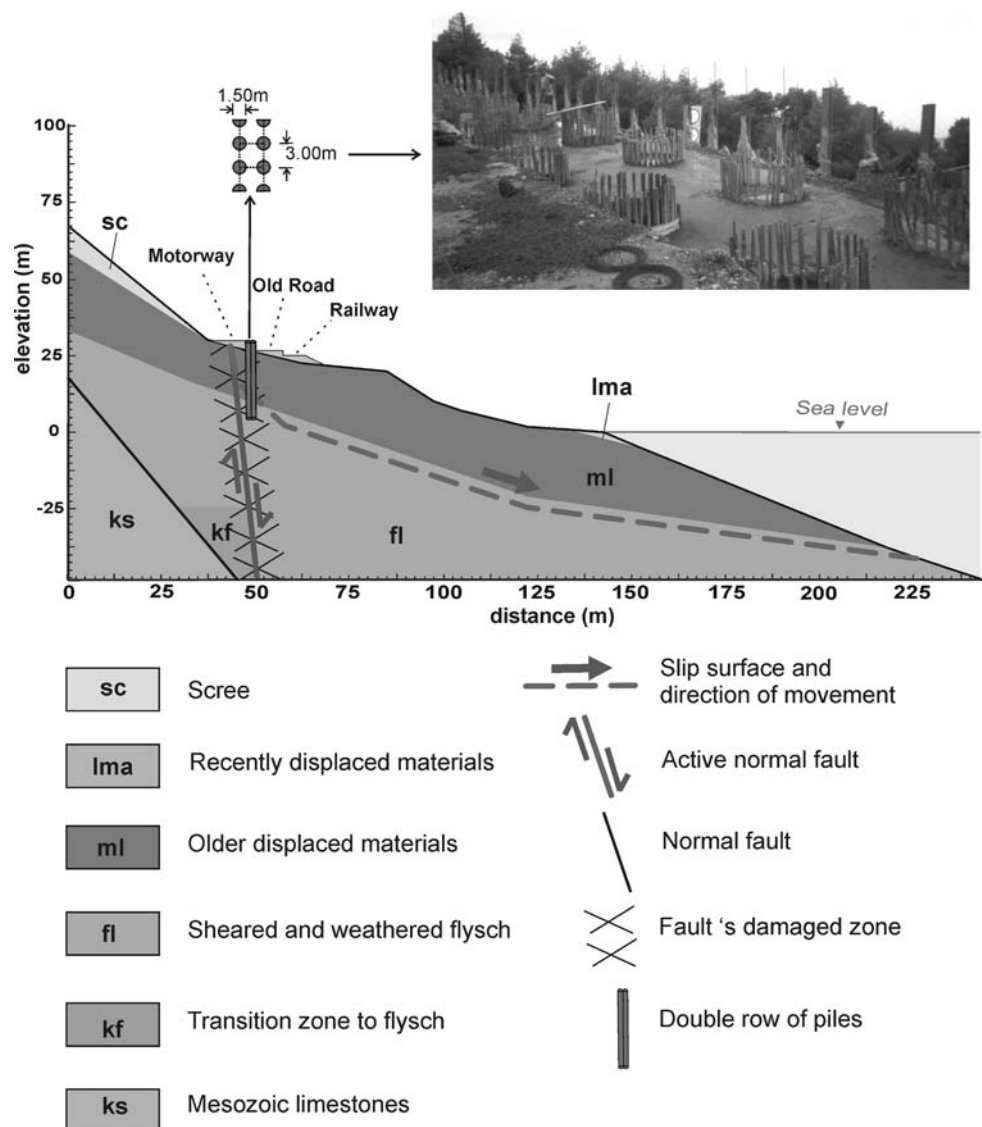
The seismicity of the area is closely related to the fault tectonics and recent geodynamic evolution of the grabens. Figure 10a shows the distribution of seismic shocks with magnitudes  $M_s \geq 4$  recorded in the Corinth Gulf rift zone between 1900 and 2003. The map indicates that the wider area of the Panagopoula instability zone is the most seismically active region of the total rift area and is associated with a high density of epicentres. The more recent seismic activity which occurred some 25 km from the study area between 1981 and 2006 includes an average of 71 shocks per year with magnitudes  $M_s \geq 4$ . The distribution of moderate and strong shocks in the area ( $M_s \geq 4.5$ ) is shown in Fig. 10b.

Triggering mechanism—pattern of landslide activity—slope stability analysis

Analysis of the data suggests that the main triggering mechanism of the landslide events was the intensity and duration of the precipitation. The increased permeability due to fissuring of the clayey formations (transition zone to flysch and older landslide materials) produced by earthquakes that disturbed the surface contributed to the instability (Cotecchia 2006). Such disturbed/loose material left behind on the slopes can be quickly infiltrated by rainfall and induce high pore pressures/landslides. In addition, the main active normal fault that traverses the already disturbed strata has caused an intensive loosening of the ground formations through an extended zone of fracturing.

The instability is also affected by anthropogenic activity, including slope excavation and loading during motorway construction, changing the slope from a marginally stable to an actively unstable state. Given the

**Fig. 11** Representative, simplified slip section through the instability zone of the Panagopoula landslide including the principal landslide body considered for back analysis and the constructed double row of piles



geological and structural complexity of the slope, the application of shear strength parameters obtained from laboratory tests for slope stability analysis is rather difficult and sometimes questionable. The mechanical behavior of a slope formed of composite materials and containing zones of reworked material due to the presence of pre-existing sliding surfaces is not controlled only by its intrinsic strength. Back analyses were carried out for the slip section shown in Fig. 11 based on the simplified slip section through the instability zone in Fig. 5b. These imply the main landslide body is effectively in a condition of limit equilibrium.

A non-circular slip surface was assumed and Janbu's simplified method applied. The sliding surface was located, for the most part, within the pre-sheared and weathered flysch, in a slope that had undergone substantial tectonic pre-slide displacement. For the analyzed surface, the

geotechnical, morphological and piezometric conditions were reconstructed using the data obtained from the detailed appraisals and long-term monitoring. The estimated shear strength parameters for the flysch were found to be  $c' = 0$  and  $\varphi' = 25^\circ$ . The values are quite similar to the laboratory residual values for the fine-grained flysch material obtained from ring shear tests (Bromhead 1979, 1986).

The remedial measures constructed during the period 1973–1976 and in 1994 contributed to the stability of the upper part of the slope as they concentrated on controlling the surface and ground water using appropriate drainage measures (drainage tunnels, diversion ditches and horizontal drains). Although their contribution to the stabilization of the slope was generally effective, their value has been over-estimated as it was shown that during their long-term operation only small quantities of water

were discharged through the drainage tunnels, even in the wet season.

In the works constructed during the period 2001–2002, however, priority was given to the stabilization of the E95 motorway. These works mainly consisted of a structural retention system with piles constructed in the slope between the motorway and the old road. Data obtained from the inclinometers, however, showed a continuous movement, indicating the constructed works were only partially effective.

## Conclusions

During the construction of the Corinth to Patras motorway, a number of landslides were crossed. Re-activation events have caused periodic destruction of the adjacent road and railway lines. Several schemes of remedial measures were implemented and their effective contribution to ground stabilization assessed by monitoring inclinometers.

From the studies undertaken, a number of conclusions can be drawn:

- (1) There is a clear spatial distribution between the main normal fault traces and landslide density in the rift zone of the Gulf of Corinth. This means that the landslide events are closely related to the active fault tectonics and to the existence of geodynamically active grabens.
- (2) The presence of tectonically highly sheared and weathered geological formations, including Alpine basement (mainly flysch) and Neogene sediments, contributes to the instability of the area.
- (3) The seismic activity causes a loosening of the near surface strata.
- (4) The weathered and tectonically highly sheared flysch contributes to the reactivation when seismic activity and/or heavy rainfall occurs.
- (5) A study of the relationship between rainfall and the individual landslide events shows two contradictory trends. In some cases heavy rainfall following a relatively dry period appears to have triggered the mass movement, while in other cases it is the cumulative rainfall over the month/months prior to the failure; the movement itself appearing to take place in a relatively dry month.
- (6) A series of remedial measures were undertaken. The initial works involved mainly drainage while between 2001 and 2002 piles were installed downslope of the motorway.
- (7) The landslide is still “active” and has a high potential for further development in the lower part of the unstable zone between the motorway and the coastline.

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