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ORIGINAL PAPER

Assessment of stability problems at southern engineered slopes along Mersin-Tarsus Motorway in Turkey

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Abstract This paper describes the cut slope stability problems of southern engineered slopes along 57 km long Mersin-Tarsus Motorway. While the northern slopes were slipping during and following construction, the stability problems occurred at southern slopes after heavy rains in December 2001. The most recent slope stability problem took place on chainage at the km 10+800 embankment on 9 April 2009. About 3.62×10^6 m^3 soil materials have currently slipped at 60 different location. After the occurrence of slides, different remedial methods (reshaping slopes, soil improvements, etc.) have been applied to stabilize the slipped slopes. The slope stability studies were carried out using back analysis to determine the slope failure mechanisms and to estimate effective shear strength parameters. Pore water pressures increase following intense rainfall events and cause reduced resistance to shear strength at the engineered slopes. In addition, the affects of the static and dynamic parameters to analyse the state of the slope after excavation were investigated and possible remedies to improve the state (toe rockfill and retaining wall) were assessed for motorway slopes through determining the slope stability with water parameter and seismic loading, separately and together. The results of the stability analysis have exhibited that a good drainage system and retaining wall prevents the motorway slope slides.

Keywords Engineered slope · Landslide · Motorway · Rainfall · Slide mechanism

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Introduction

This study aims at determining the causes of landslides occurring at different times at southern slopes along 57 km long Mersin-Tarsus Motorway (hereinafter as "MTM"). The study area extends between Mersin and Tarsus, a region near the Mediterranean Sea in southern Turkey (Fig. 1). Since Turkey is an important hinterland which is located in Asia, Europe and the Middle East within a triangle, MTM has a prominent role in transportation activities for the Mersin hub port, the Middle East, and Central Asia.

The present manuscript summarizes large-scale field surveys and laboratory works carried out by the authors to scrutinize the mechanisms of typical slope failures along the MTM. The motorway construction was started in 1992 and is currently used for transportation. The total amount of 3.62 million m^3 soil material has slid from 1995 to 2009 into the motorway corridor (Fig. 2a). Slope failure is a familiar issue on natural and cut slopes. Rainfall-induced slope failure is a common occurrence in many parts of the world. A great number of researchers have investigated the landslides triggered by rainfall (Canuti et al. 1985; Azzoni et al. 1992; Finlay et al. 1997; Polemio and Sdao 1999; Zezere et al. 1999; Paul et al. 2000; Ocakoglu et al. 2002; Petrucci and Polemio 2003). It is generally recognized that the rainfall-induced landslides are caused by excess pore pressures and seepage forces during periods of intense

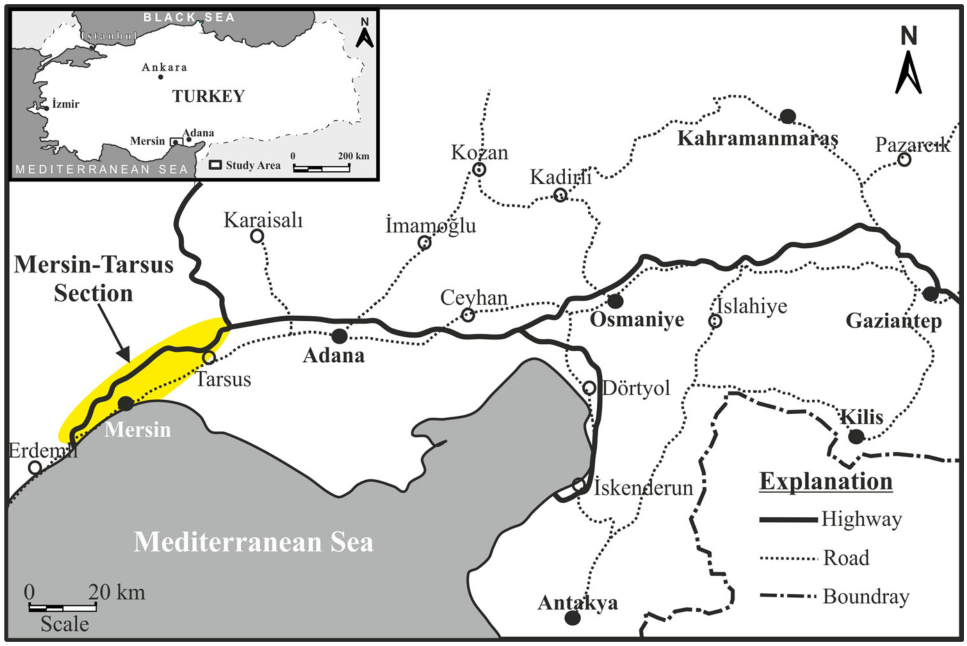


Fig. 1 Location map of the study area

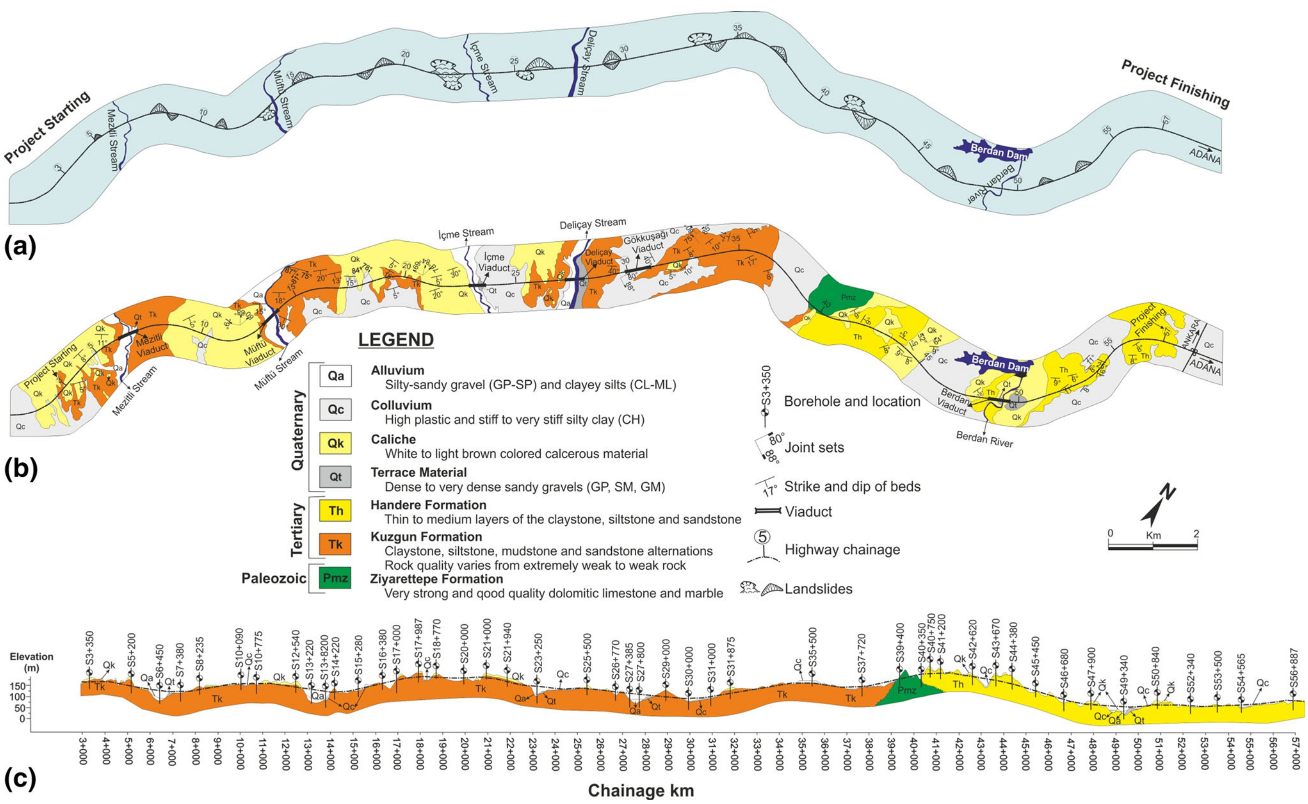


Fig. 2 Distribution of the landslides along 57 km long Tarsus-Mersin Motorway (**a**), Geological map of along motorway corridor (modified from Hoş 1995) (**b**) and Geological profile along motorway and distribution of boreholes (Modified from Hoş 1995) (**c**)

rainfall (Sidle and Swanston 1982; Sitar et al. 1992; Anderson and Sitar 1995). Accumulation of excess pore water pressure along the slopes decreases the effective stress in the soil and, thus, reduces the soil shear strength and consequently resulting in slope failure (Brenner et al. 1985; Kayadelen et al. 2007). Investigations performed in many parts of the world (Kenney and Lau 1984; Urciuoli 1998) have presented that pore pressure at shallow depths are strongly controlled by seasonal atmospheric conditions. The rainfall was characterized by short and intense rainfall throughout the first ten days in December 2001. The high rainfall intensity and accumulated rainfall triggered these landslides located on the chainage km 12+250 and chainage km 22+320.

Geotechnical laboratory tests have been conducted on disturbed and undisturbed samples in the Geological Engineering Department, Mersin University and General Directorate of State Hydraulic Works, Turkey. Specific gravity (ASTM D854-10 2010), water content (ASTM D2216-05 2010), unit weight (ASTM D4254-00 2006), grain size distribution (ASTM D422-63 2007), Atterberg limits (ASTM D4318-10 2010), and consolidated undrained triaxial compression (ASTM D4767-11 2011) tests were conducted in accordance with current standards.

Setting of the MTM

Geological setting

The study area is located on the western flank of the Adana Basin, which is one of the major Neogene basins in the Tauride orogenic belt (Yalcin and Görür 1983). In the basin, a thick sedimentary package ranging in age from Burdigalian to Recent unconformably overlies Palaeozoic and Mesozoic basement rocks (Yetiş 1988; Yetiş et al. 1995).

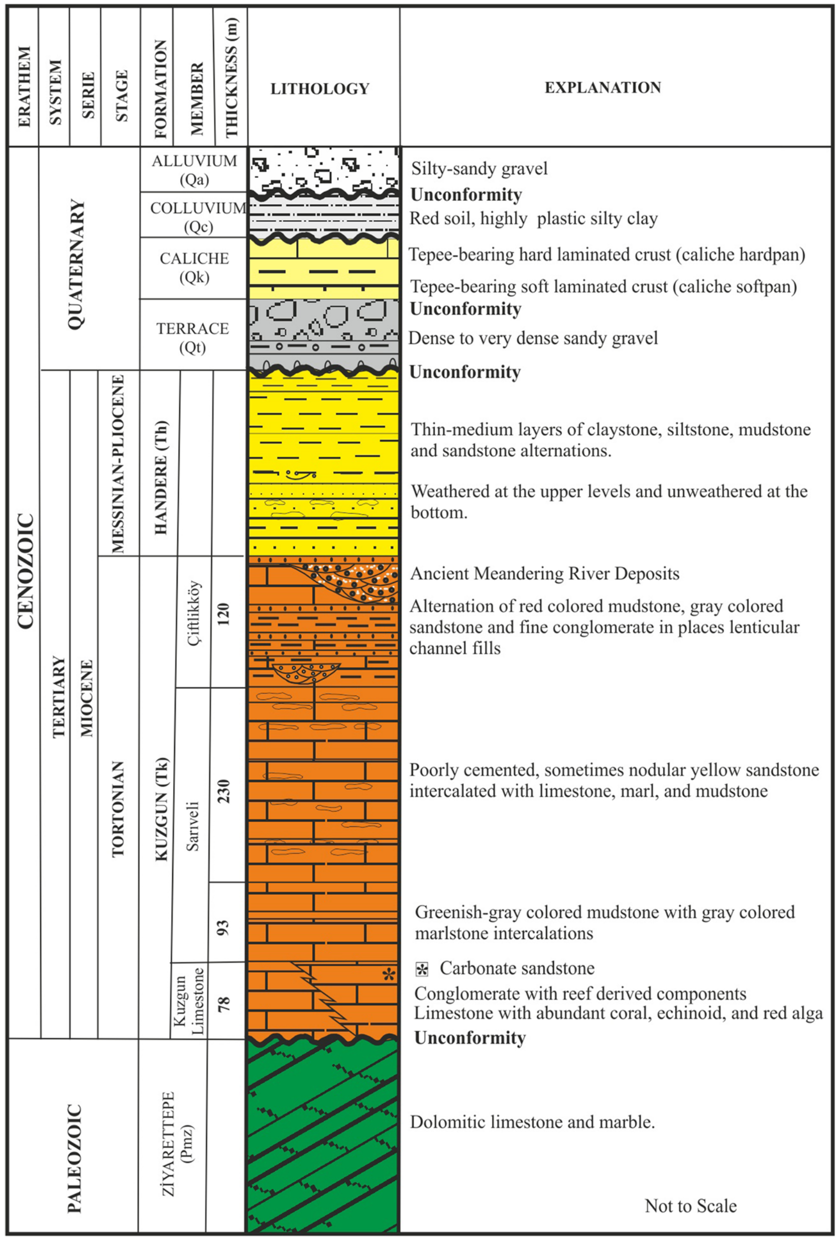
In the study area Paleozoic, Tertiary, and Quaternary units are outcropped (Figs. 2, 3). The Paleozoic unit Ziyarettepe formation (Pmz) is represented by very strong and good quality dolomitic limestone and marble, (Özgül 1973; Tutkun 1984). The Tertiary units are Kuzgun (Tk) and Handere Formations (Th). Kuzgun formation, named first by Schmidt (1961), mainly consists of alternating conglomerate, sandstone, mudstone, claystone and reef-cover deposits (İlker 1975; Senol et al. 1998). The claystone and mudstone levels are mainly reddish-brown colored and weathered at the upper levels (Eren et al. 2008). Handere formation, named also by Schmidt (1961), is composed mainly of dark yellow conglomerate, pebbly sandstone, sandstone, siltstone, and mudstone-marl alternations, and it also contains gypsum lenses. This lithological unit includes from thin to medium layers of claystone, siltstone, sandstone, and mudstone in the study area. Fine clastic units are recognized with parallel laminations while the conglomerate level is distinguished with cross beddings. These formations are overlain by Quaternary terrace, caliches, colluviums, and recent alluvium sediments. Terrace (Qt) is irregularly exposed along the small creeks and rivers. The lithological composition starts with conglomerate and pebbly sandstone at the base and continues to the top with gray colored, cross bedded, pebbly coarse sandstone and blocky conglomerate. Caliche (Qk) is formed by evaporation and subsequent carbonate precipitation from the groundwater that rises to the surface through the unconsilated sediments and soils on the arid and semiarid climatical region. Caliche deposits are formed on hillsides in parallel to the topography and attain a thickness of 3–5 m. It occurs in a variety of forms, such as hardpan, laminar crust, powder, nodule, tube, and fracture-infill (Wright and Tucker 1991). The caliche formation can be divided into two layers in the study area. A hardpan caliche is located at the top of the hills, with a thickness ranging between 1 and 3 m. Softpan, weak and soft caliche, includes carbonate gravels under the hardpan level. Colluvium (Qc) is the name of the loose sediment bodies that have been deposited by gravity transport at the bottom of low grade slopes. This lithological unit consists mainly of high plastic and stiff to very stiff silty clays in the study area. Alluvium (Qa) deposits are developed along the river sides and are generally composed of loosely cemented, poorly sorted conglomerate, gravel, and silty sand. Granular alluvium could be classified as dense to very dense soil in the study area (Hoş 1995; Taga and Demirkol 1996; Senol et al. 1998; Eren et al. 2008) (Figs. 2, 3).

Seismicity and tectonics

The MTM is located in Çukurova Basin, historically known as Cilicia and is near the East Anatolian Fault zone This is an area known to be seismically active. The region is surrounded with The East Anatolian Fault Zone on the east and the Ecemiş Fault Zone on the west and northwest (Aktar et al. 2000). There have not been any reported cases of large earthquakes ($M > 7$) in the near history of the region. The database, however, refers to several earthquakes with $M < 7$ that have caused damage in the area. The most recent earthquake, Adana Earthquake, struck southern Turkey on June 27, 1998, which had a magnitude of 6.2 (Yalcinkaya 2005). The event killed 145 people and left 1,500 people wounded and many thousands homeless in Adana and the surrounding area.

The most important hazard for Mersin and its surroundings in terms of earthquakes is the active faults in the region. Faults that threaten Mersin-Tarsus are, Ecemiş Strike-Slip Fault between Çamardı and Gülek in the north; Karsantı-Karaisali Fault Zone between Gülek and Karsantı-Karaisalı; Namrun Strike-Slip Fault between Gülek and Anamur; Yumurtalık-Karataş Fault that caused the 1998 Ceyhan earthquake;a fault line passing through Mediterranean Sea and reaching to Cyprus; Mut Fault near Mut, and the Ovacık Fault between Ovacık-Silifke. According to data provided by Boğaziçi University, Kandilli Observatory and Earthquake Research Institute, a total of 55

Fig. 3 Generalized stratigraphic section of the investigated area (modified from Eren et al. 2008)



earthquakes were recorded since 1900 in Mersin and its surrounding area that included 36 earthquakes between 3 and 3.9 and 16 earthquakes between 4 and 4.9 and three earthquakes between 5 and 5.9 magnitude (Fig. 4).

Therefore, the maximum expected earthquake with a moment magnitude of 6.2 was considered in the long-term stability assessment in this study.

Meteorological, rainfall and groundwater conditions

The climate of the region is semiarid with a mean annual precipitation of 601 mm, and annual evaporation of 1321 mm (Fig. 5). Annual average, minimum, and maximum temperatures are 18.74, 6.6, and 10 °C, respectively (DMİ 2006).

Failures occurred immediately after a heavy rainstorm between 1 and 9 December 2001. The total rainfall during the storm was 540 mm (Fig. 6). According to Fig. 6, the rainfall precipitation occurred for more than nine days in December 2001. The maximum intensity and accumulated rainfall were greater than 180 mm/d and 677 mm.

Field observation and assessment of slope hydrology indicated a permanent groundwater table close to the surface of the cut slope. A significant amount of runoff water is held by absorption due to dominant clay (smectite group, Eren et al. 2008) components of the soils. Accordingly, the

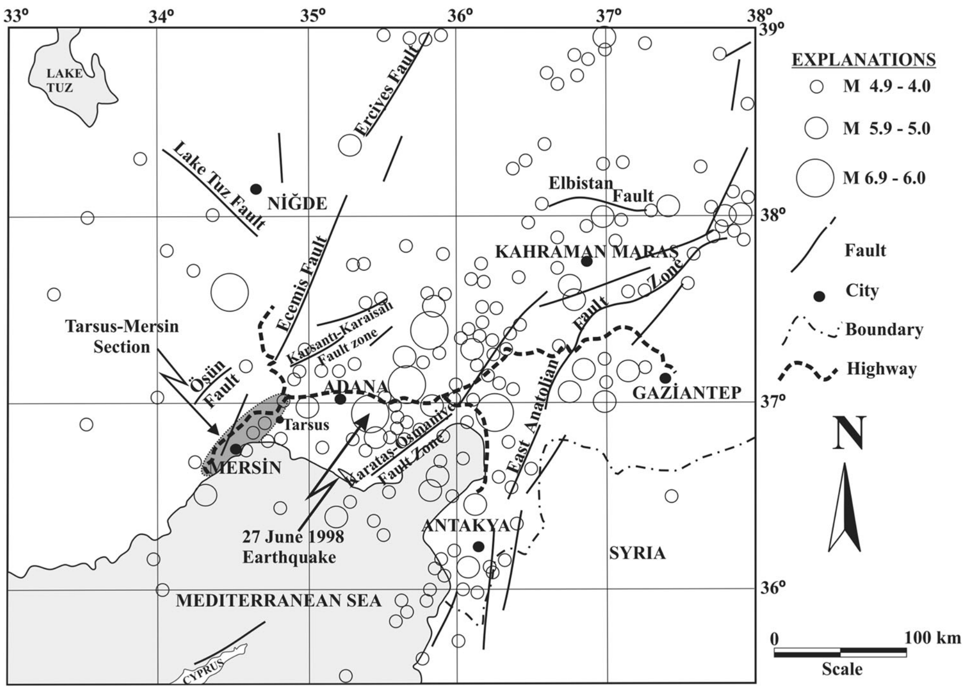


Fig. 4 Seismicity map of the study area and its vicinity for 1900–2004 (Kandilli Obsevatory Earthquake Research Institute 2004) (http://www.sayisalgrafik.com)

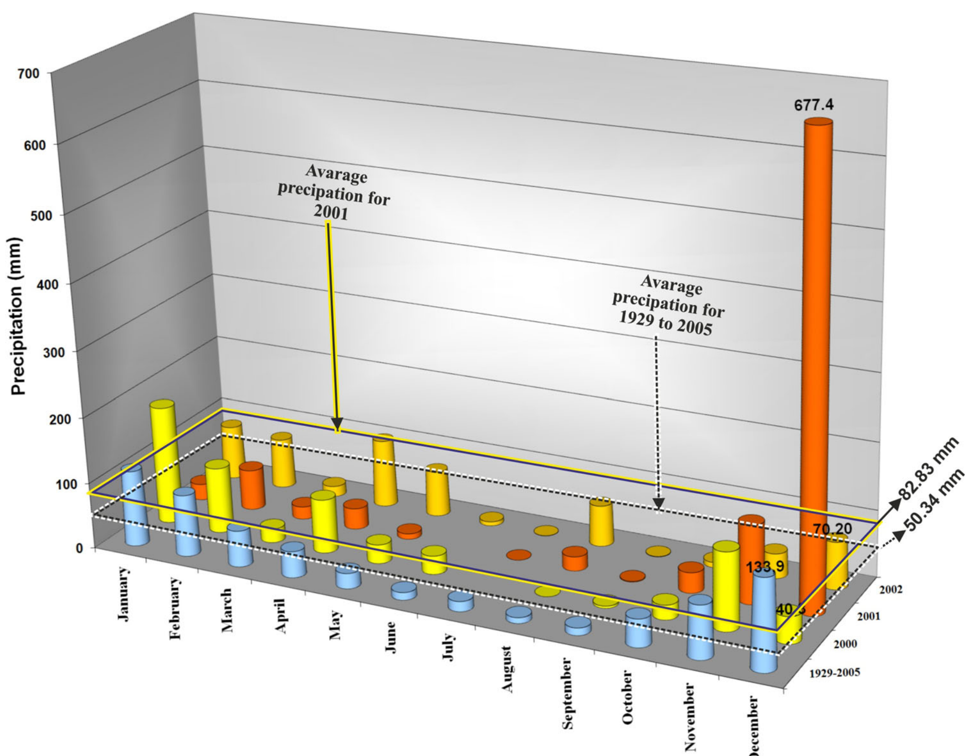


Fig. 5 Histogram showing the long-term precipitation for 1929–2005 and for the year 2001

soil consistency is classified as soft, which causes loss of strength and an increase in favourable conditions for sliding. Consequently, heavy saturation of soil has resulted in stability problems for the MTM cut and embankment slopes.

Geotechnical properties of cut slopes

MTM extends in a east–west direction. The total volume of 3.620×10^6 m^3 soil material has slid in 60 different cut slope locations on Motorway since the start of the

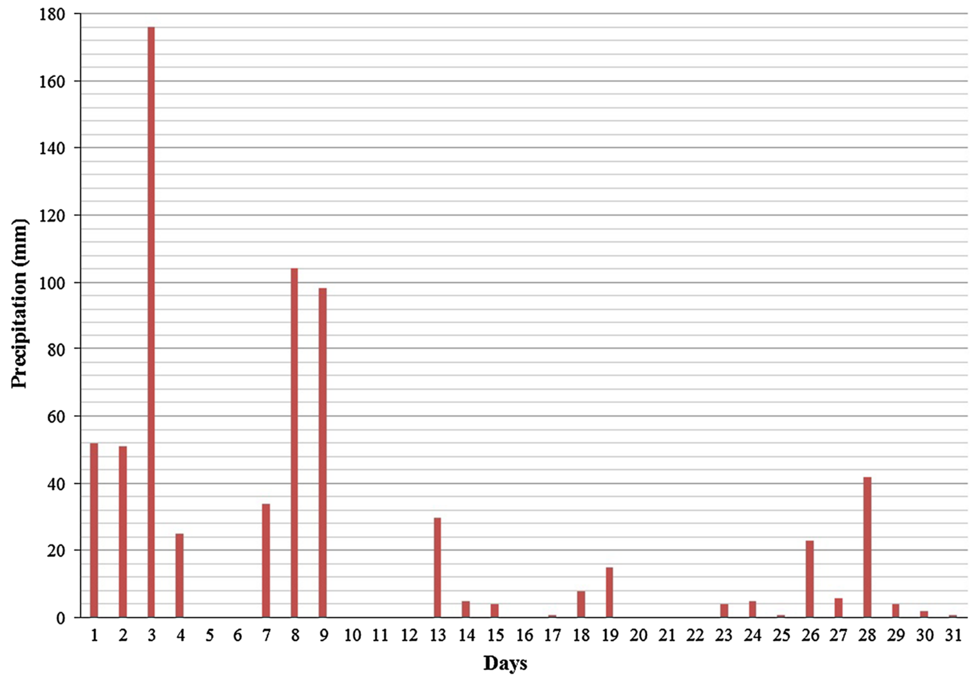


Fig. 6 Histogram showing the monthly precipitation in December 2001

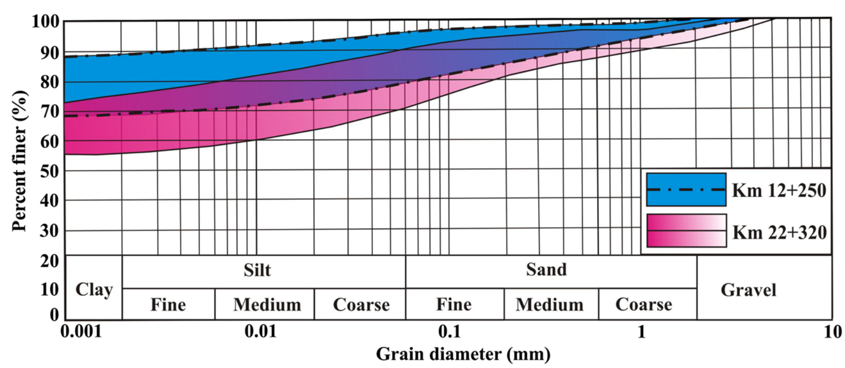


Fig. 7 Grain size distribution of the investigated cut slopes on the motorway

project (Fig. 2a). While cut slope in chainage km 12+250 and km 22+320 shows the same grain size distribution (Fig. 7) (Table 1), activity's and plasticity's are different (Fig. 8). Tertiary age sandstone–claystone alternations form the base rock throughout the motorway. Caliches are widespread and cover the base units in the study area and are also common around the Mediterranean Region. The most recent slope stability problem along the motorway was recorded in April 2009 in the embankment slope located at chainage km 10+800 of the motorway (Fig. 9). The embankment fell down about one meter and the landslide followed the formation of tension cracks. The cut materials obtained from the excavation slope at chainage km 12+250 were reused in the embankment fill (Table 1). The observations during ground improvement works indicated that compacting works were not performed as required.

The same cut slope design was applied in the 57 km long motorway without considering local soil and geotechnical properties (Fig. 10).

It was observed that slope stability problems generally concentrated along the zones where caliche structures are dominant. The landslides occurred from green and gray coloured sandstone-claystone and caliche structure that develop densely in this unit (Fig. 11). In the motorway project, the landslide in the slope at chainage km 12+250 having 2H:1 V slope starts with the scarp part at 4–5 m height (Fig. 11a, b). The main scarp is followed by minor scarp surface at approximately 90 cm height and divides into two separate parts (Fig. 11a). In the slope failure that occurred in December 2001, the slides were perpendicular to the movement direction and the upper part (surface of rupture) occurred as a result of a rotational slide in an almost vertical position. It was composed of swelling regions

Table 1 Geotechnical properties of the slope materials

	Km 12+250				Km 22+320				Caliche (Turkmen and Yilmazer 1998)
	Sample	Min.	Max.	Mean	Sample	Min.	Max.	Mean	–
Specific gravity, (G s)	18	2.41	2.73	2.51	18	2.44	2.71	2.65	–
Natural water content, wn	18	19	36	26	18	12	34	22	–
Natural unit weight, γ_n (kN/m^3)	18	16.11	19.60	18.62	18	12.29	20.21	17.64	21.1
Dry unit weight, γ_d (kN/m^3)	18	15.89	21.76	20.68	18	16.33	19.81	19.60	–
Saturated unit weight, γ_{sat} (kN/m^3)	18	16.29	21.07	20.1	18	17.13	20.04	19.02	–
Liquid limit (%)	6	54	69	61	6	38	48	44	–
Plastic limit (%)	6	20	29	26	6	21	26	22	–
Plasticity index (%)	6	35	45	38	6	27	22	24	–
Cohesion, c (kPa)	–	–	–	44	–	–	–	11	150
Friction angle, ϕ'(°)	–	–	–	19	–	–	–	27	18
Gravel (%)	5	0	0.5	0.25	5	1,3	7	3	–
Sand (%)	5	5	16	6	5	13	28	15	–
Silt (%)	5	15	21	17	5	54	76	71	–
Clay (%)	5	69	86	77	5	6	14	7	–

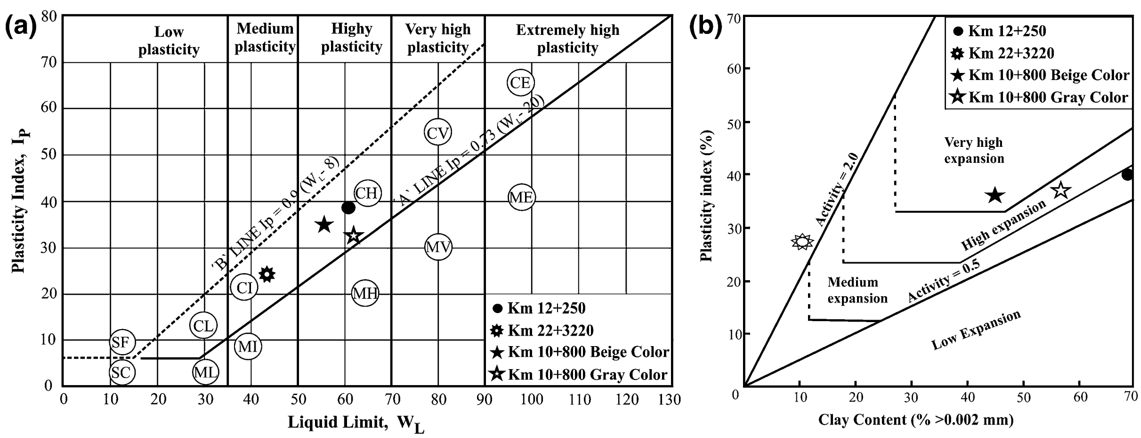


Fig. 8 Plasticity chart (**a**) and activity diagram (**b**) of the soils present at the study area

varying between 10 and 15 m. The movement generally started in the middle parts of the slopes and propagated towards the road platform, and the failed material was carried to the pavement. Then, the landslide continued progressively by reaching the upper level (Fig. 11a).

Several factors have been played a slippery role in the MTM. These factors are described as directions of general discontinuities, south directions of topographical slopes (Fig. 11c), and extremely thick caliche structure in the region (Fig. 11d). The site investigations uncovered a relatively permeable stratum, a caliche unit, overlying the upper part of the landslide. This unit has lots of horizontal and vertical discontinuities. In general, motorway slopes vary between 24–30 m, and remedial measures taken were not satisfactory although 5 m floats were built at every 10 m (Fig. 11).

In the slopes that the slips occurred, the type of movement, depth of the mass slipping, and activity situations were determined through field measurements. During the field studies, expansion cracks were observed between 18–49 cm and at a depth of 230 cm at the top parts of slopes (Fig. 12), and they were in bends in trees planted for development purposes and at water leakages in bottom parts. As there is a back-slope in this zone occurring as a circular fall and slips circularly, ground water accumulates in the upper parts and creates a continuously moving, expanding, and spreading structure (slip width 186 m).

Stability analysis of slopes

The main purpose of slope stability analysis is to contribute to safe and economic design of excavations and

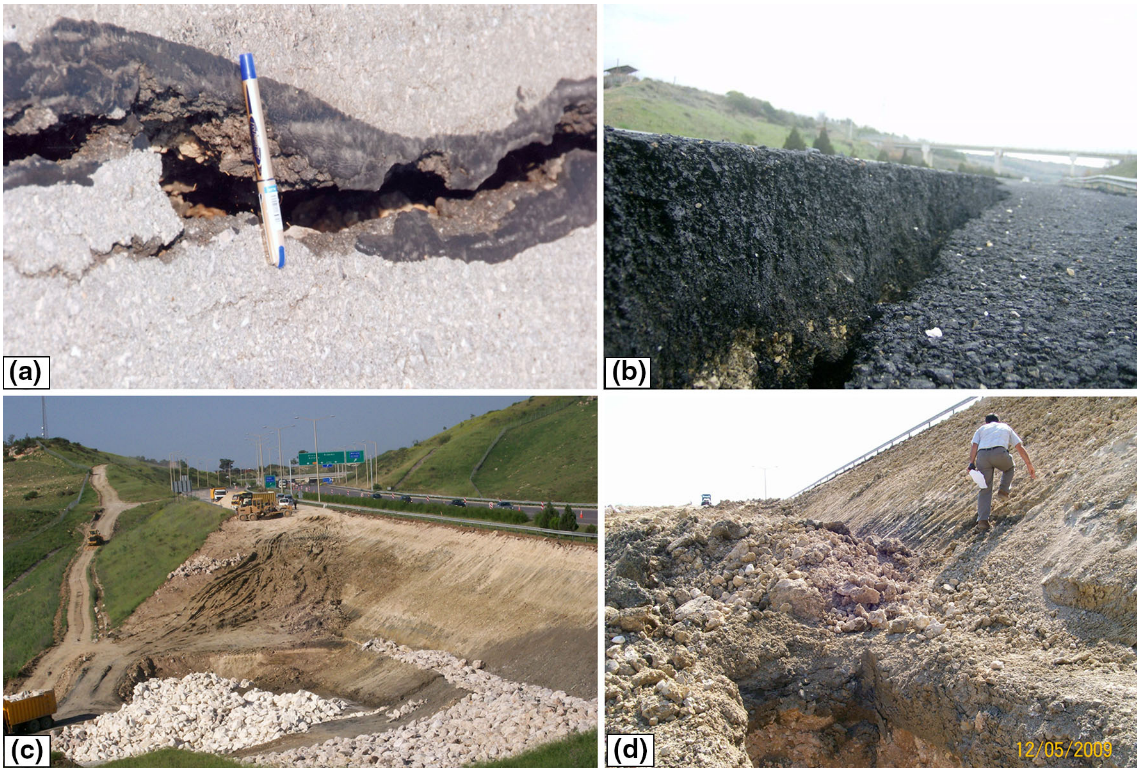


Fig. 9 Tension cracks in the pavement before failure (**a**), a picture of straight scarp on embankment slide (**b**), general view from embankment failure at chainage km 10+800 (**c**) and a close-up view of a failure surface (**d**)

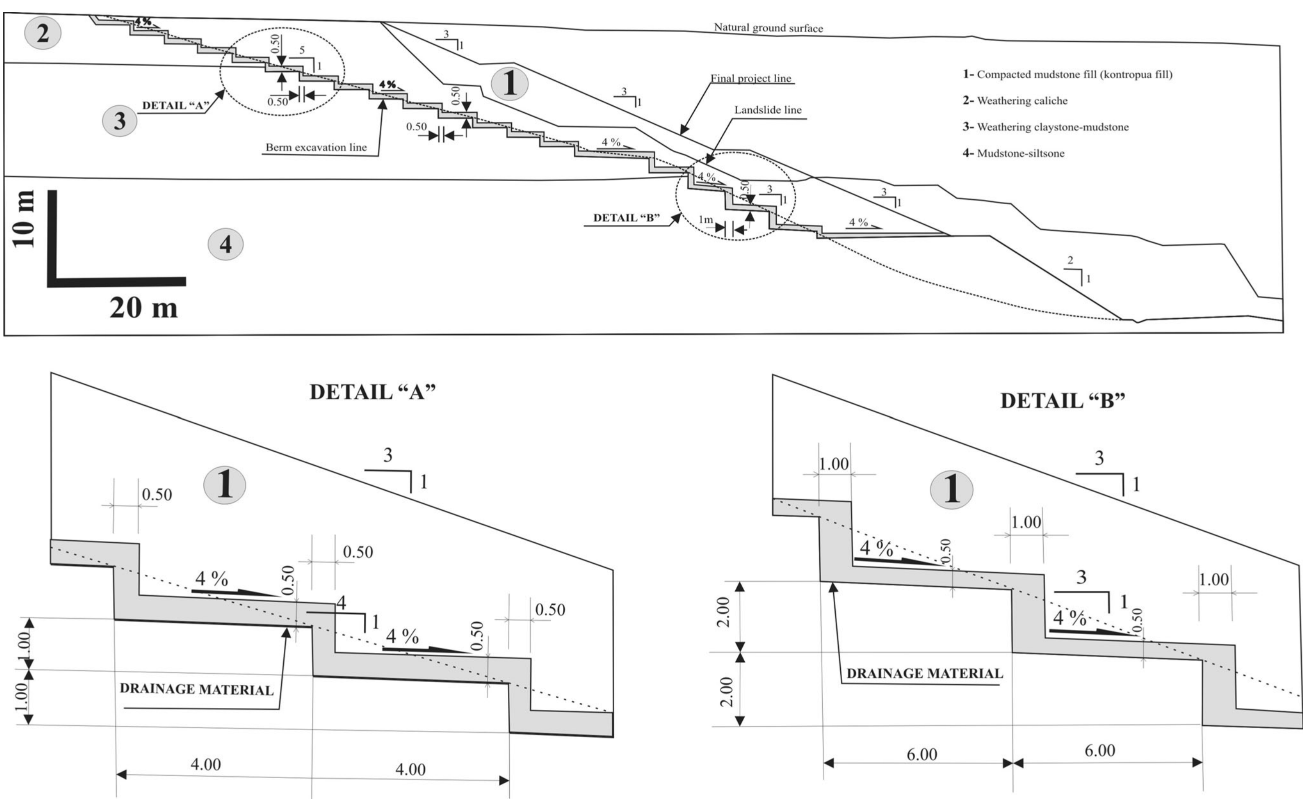


Fig. 10 Detail of identical project on cut slopes along the motorway during construction

Fig. 11 General view from cut slope sliding at chainage km 12+250 (**a**), rotational failure chainage km 22+320 (**b**), a close-up view from the northern slope failure (**c**) and tilted slump blocks in the thick caliche at of the northern slopes that slid (**d**)

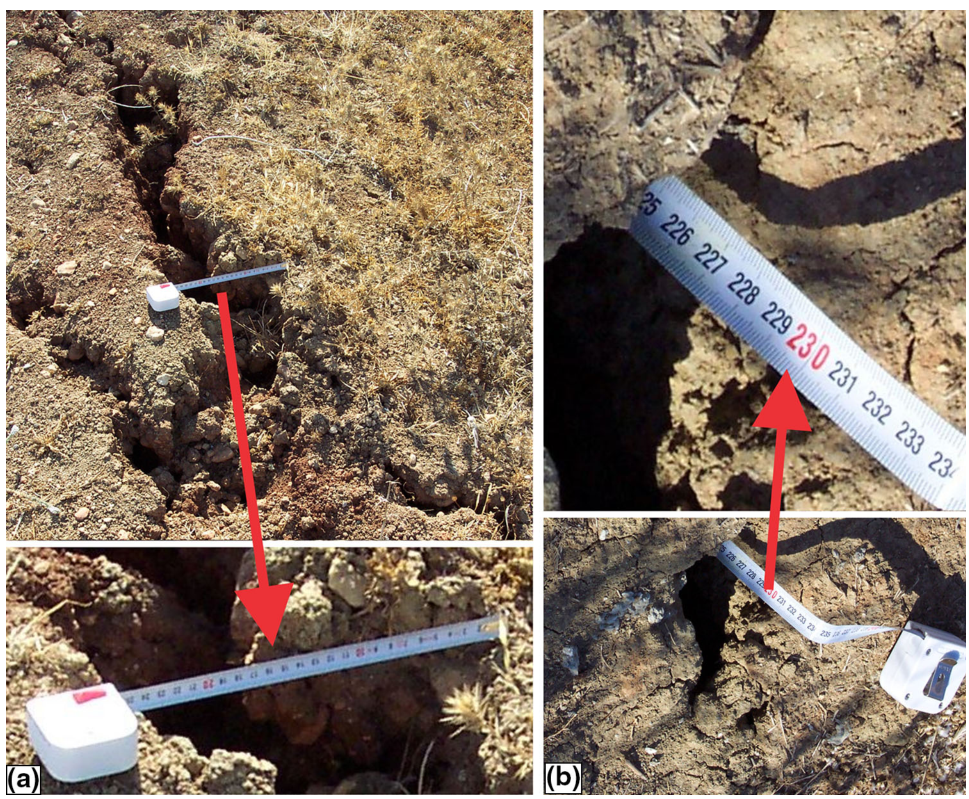


Fig. 12 A view from expansion cracks (**a**) and depth (**b**) at chainage km 12+250

embankments in the geotechnical project. In this study, the cut slopes on chainage km 12+250 and km 22+320 are evaluated by using the limit equilibrium method of dry and saturated as the static and dynamic conditions. Shear strength parameters of cut slope soil were obtained from consolidated undrained triaxial (CU) tests from the distressed zone of the slope. The soil samples were retrieved from depths of 0–3 m below the cutting surface. Barkin

(2004) reported that the average cohesion and friction angle were 44 kPa and 19° for chainage km 12+250 and 11 kPa and 27° for chainage km 22+320.

The peak ground acceleration (PGA) in the MTM was evaluated by Ulusay et al. (2004). The maximum horizontal PGA is expected to be 120 cm/s^2. Seismic acceleration coefficient is taken into consideration as 60 cm/s^2, which is in the range of 1/3–1/2 PGA of the region as suggested by (Marcuson and Franklin 1983) in this study.

Stability analyses were carried out by using two-dimensional limit equilibrium slope stability methods incorporated in the computer program Geoslope SLOPE/W 5.15 commercial computer program. In order to do stability analysis, the shear strength parameters acquired from the CU test and back analysis were compared, and suitable shear shear strength values were selected.

Back analysis of failure slopes

The dependability of the back analysis stems primarily on the exactness with which the main slip surface is decided on and the pore water pressure distribution along the slip surface (Chowdhury 2010). So far, equilibrium conditions have been used to find the strength parameters at failure. Back analysis techniques, suggested by Leonards (1982), were applied to failure slopes in order to get residual strength parameters at the sliding time.

In this study, when back analysis was applied, the soil was considered fully saturated because instability occurred immediately after heavy rains between the 1st and 9th of December 2001. The critical sliding failure surfaces were found to be the ones that connected the crest and toe observed in the site and identified as the primary failure plane in Figs. 11, 13a, c. For the analysis, variations of the residual shear strength parameters (c' and ϕ') of the dense silty clay satisfying a factor of safety (FS) of 1 corresponding to the limit equilibrium condition were determined for different shear strength pairs by using Slide (6.0) software of Rocscience (2012) for the circular slide (Table 2). While the residual shear strengths of the materials were obtained by Slide (6.0), the probabilistic analysis option was used to carry out back analysis of two variables simultaneously (Fig. 13b, d).

Remedial measures

The rerouting, unloading, flattening, buttressing, surface and subsurface drainage, reinforcement, retaining walls, vegetation, thermal treatment, soil hardening, etc., are common remedial measures in the literature (Turner and Schuster 1996; Abramson et al. 2001; Cevik and Topal 2004; Bromhead 2005).

There are many cut and fill slopes along the 57 km motorway. Since the construction of the motorway, stability problems were encountered at 60 different excavation slopes and one embankment slope. Stability problems could not be solved by simply changing slope angle of thenorth slopes, recompressing materials obtained from excavations, and putting rock blocks on slopes (Fig. 14). The long-term stability of the supported slope design was inspected using shear strength parameters determined by back analysis. The SLOPE/W 5.15 software Geoslope 2003) was engaged during analysis. It should be noted that the linear failure criterion was taken into consideration. Because the geotechnical and index properties of the chainage km 12+250 and chainage km 22+320 are similar, the stability analyses were only conducted on chainage km 12+250 (Table 3).

Stability analyses performed showed that rock blocks of 0.5–1 m thickness negatively affected stability. Slope stability analyses have been performed for several cases so as to simulate supporting action by putting boulders to the toe and installing a retaining wall under static and dynamic conditions for dry and saturated states (Fig. 14a–d). It is determined that the improvement structures formed by putting rock blocks at the bottom will lose their stability in an earthquake causing horizontal ground acceleration of 0.12 g (Fig. 14b). After the improvement to be made with a retaining wall, it is foreseen that there will not be any failure in slope improvements both in wet and dry conditions (Fig. 14c). The factor of safety of the final slope design of the retaining wall, in static and fully saturated conditions, is 1.35. In seismic conditions, considering a maximum of 60 cm/s^2 horizontal seismic load, the factor of safety decreases to 1.15 (Fig. 14c, d). In this study, partial removal of landslide material, retaining wall, and surface drainage are judged as remedial measures.

Mechanism of landslides

The determination of the cause of a landslide and its mechanism requires the stage in soil formation and other effects to be investigated carefully. Field investigations and laboratory works were carried out after the landslides. The derived information was integrated to identify the failure mechanisms of the heavy rainfall-triggered landslides. The integration of extreme rainfall characteristics in the evaluation of slope stability through matric suction distribution in soil is demonstrated by Lee et al. (2009). The slope failure appears to be the Miocene aged Kuzgun formation, which mainly consists of gray to light gray, fine grained, medium-bedded to thin-bedded muddy sandy siltstone-claystone. The overall pictures of these failed slopes are shown in Fig. 11. The failure height and width of landslide were about 25 and 150 m separately at the chainage km 12+250.

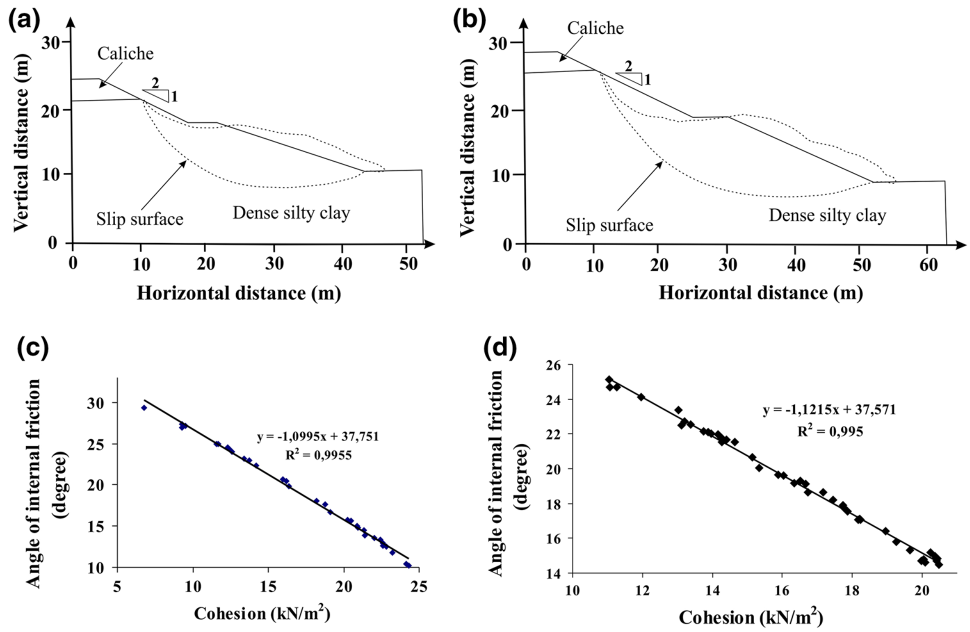


Fig. 13 Slide surface and results of two-dimensional back analysis of the sliding block of chainage km 12+250 (**a**, **b**) and km 22+320 (**c**, **d**)

Table 2 Data used in the stability analysis

	Km 12+250	Km 22+320
$\gamma_{natural}$ (kN/m^3)	18.62	17.64
$\gamma_{saturated}$ (kN/m^3)	20.1	19.02
Shear strerngth parameter		
c (kPa)[a]	44	11
ϕ (°)[a]	19	27
c' (kPa)[b]	16.14	15.55
ϕ' (°)[b]	21.29	20.61

[a] From CU tests

[b] From back analysis

The sliding thickness was more than 10 m. The second failure took place at the chainage km 22+320. The height of the slope was more than 20 m while its width was about 200 m. The lithology exposed on the landslide scarps are medium to thick gray brownish sandy siltstone occasionally interbedded with claystone. The claystone sequence contains the weathered silt interbedded clay lens. An important feature of these landslides is the geological sequence including a cap shaped caliche unit over a sandy siltstone-claystone at the underground surface. The caliche unit is involved in a lot of vertical discontinuity. Observed from the scarp and looking down from the top, the exposed strata are clay lens interbedded with sandy claystone and siltstone.

The following two factors might cause landslides after heavy rainfall: (1) Pore water pressure built up in the nearly vertical joints and fissures of claystone on the slope surface (Fig. 12) and (2) the low friction angle on the weathered claystone. In addition, the caliche unit has a negative effect due to the weight on the slope.

The mechanism of slope failure is thought to be the infiltration of rainwater causing a reduction of matric suction in the soil that results in a decrease in the effective stress. The rainfall is characterized by short and intense rainfall throughout the first ten days in December 2001. The high rainfall intensity and accumulated rainfall triggered these landslides located on the chainage km 12+250 and chainage km 22+320. The sliding debris was then pushed down by concentrated runoff along the MTM axis until it buried the road.

Results and conclusions

A caliche unit occurring in the region is quite thick and decreased slip resistance parameters were observed due to the water's reach to sandstone-claystone under the thick caliche layer. With the effect of these factors, slope stability problems have occurred in the north slopes starting from the construction stage.

Slips in the south slope occurred just after the excessive rainfall of 677 mm/m^2 on December 2001. Under that excessive precipitation, a decrease in shear resistance parameter was observed in parallel to an increase in pore water pressures in the clayey unit and stabile south slopes lost their stability.

Identical projects were applied in the 57 km motorway without considering local geological and geotechnical attributes in cut and embankment slopes. By the performed limit equilibrium analyses, it was determined that the slopes are stable under static and dry conditions, but they lose their stability under dynamic and saturated conditions.

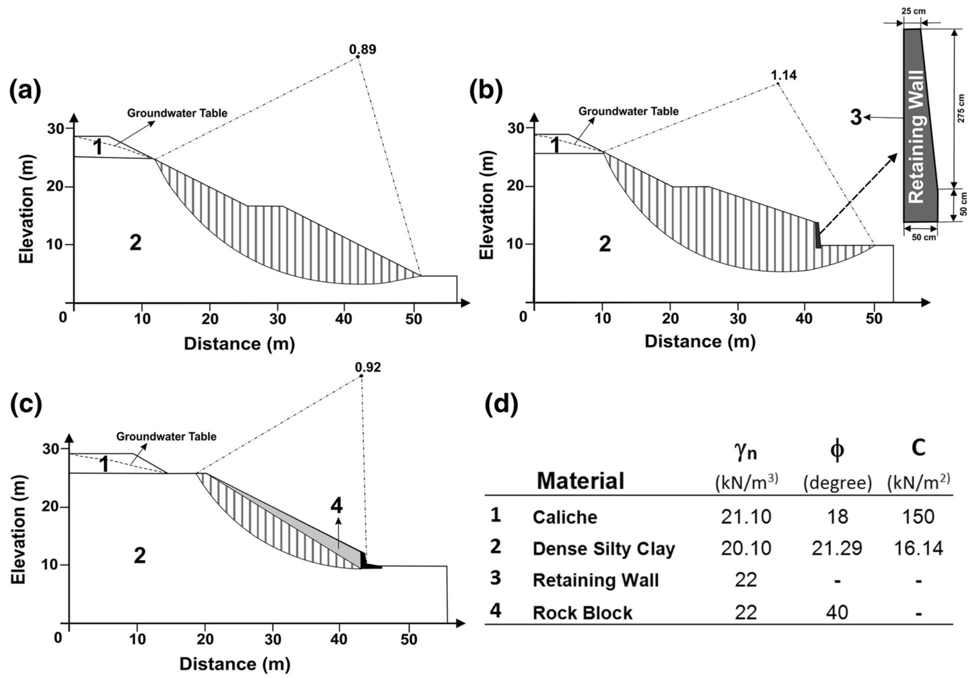


Fig. 14 Remedial slope stability analysis result. **a** Fully saturated and no quake, **b** supporting by putting rock block to the toe, **c** installing retaining wall and **d** used data in stability analysis on chainage km 12+250

Table 3 Stability analysis results for chainage Km 12+250

Remedials	Conditions			
	Dry		Saturated	
	Static	Dynamic	Static	Dynamic
No remedials	1.66	1.42	1.04	0.89
Rock block	1.16	1.02	0.65	0.56
Retaining wall	2.09	1.81	1.35	1.15

Earth material extracted from excavation slope at chainages km 12+250 were used as filling material at chainages km 10+800. Based on the observations during excavation works, it was clearly understood that required compression conditions had not been applied during filling.

It was observed that stability problems continue at 2:1 slopes that are formed by controlled compression of extracted ground materials. Geological, meteorologic, and hydrogeological features for the sites in this study were determined to be the most influential factors dominating the failure.

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References

Abramson LW, Lee TS, Sharma S, Boyce GM (2001) Slope stability and stabilization methods, 2nd edn. Wiley, New York, pp 736

Aktar M, Ergin M, Özalaybey S, Tapırdamaz C, Yörük A, Biçmen F (2000) A lower-crustal event in northeastern Mediterranean: the1998 Adana earthquake (Mw = 6.3) and its aftershocks. Geophys Res Lett 27(16):2361–2364

Anderson SA, Sitar N (1995) Analysis of rainfall-induced debris flow. ASCE J Geotech Eng 121(7):544–552

ASTM D4254-00 (2006) Standard test methods for minimum index density and unit weight of soils and calculation of relative density. ASTM International West Conshohocken, doi:10.1520/D4254-00R06E01. http://www.astm.org

ASTM D422-63 (2007) Standard test method for particle-size analysis of soils. ASTM International West Conshohocken, doi:10.1520/D0422-63R07. http://www.astm.org

ASTM D854-10 (2010) Standard specification for materials for soil-aggregate subbase, base, And Surface Courses. ASTM International West Conshohocken, doi:10.1520/D0854-10. http://www.astm.org

ASTM D4318-10 (2010) Standard test method for liquid limit, plastic limit, and plasticity index of soils. ASTM International West Conshohocken, doi:10.1520/D4318-10. http://www.astm.org

ASTM D4767-11 (2011) Standard test method for consolidated undrained triaxial compression test for cohesive soils. ASTM International West Conshohocken, doi:10.1520/D4767-11. http://www.astm.org

ASTM D2216-10 (2010) Standard test methods for laboratory determination of water (Moisture) content of soil and rock by Mass. ASTM International West Conshohocken, doi:10.1520/D2216-10. http://www.astm.org

Azzoni A, Chiesa S, Frassoni A, Govi M (1992) The valpola landslide. Eng Geol 33:59–70

Barkın N (2004) Mersin—Tarsus Otoyolu Güney Şevlerinde Meydana Gelen Duraysızlıkların İncelenmesi. M.Sc. Thesis, Mersin University, Mersin, (Turkish, unpublished)

Bishop AW (1955) The use of the slip circle in the stability analysis of slopes. Geotechnique 5:7–7

Brenner RP, Tam HK, Brand EW (1985) Field stress path simulation of rain-induced slope failure. In: Proceedings of 11th international conference on soil mechanics and foundation engineering, vol 2, pp 373–376

Bromhead EN (2005) The stability of slopes, 2nd edn. Taylor & Francis, London, p 411

Canuti P, Focardi P, Garzonio CA (1985) Correlation between rainfall and landslides. Bull Int Assoc Eng Geol 32:49–54

Cevik E, Topal T (2004) Relocation of a problematic segment of a natural gas pipeline using GIS-based landslide susceptibility mapping, Hendek (Turkey). In:Hack R, Azzam R, and Charlier R. (eds) Proceedings of the 1st European Regional IAEG Conference on Engineering Geology for Infrastructure Planning in Europe: A European Perspective, (Springer), pp 265–274

Chowdhury R (2010) Geotechnical slope analysis. Taylor & Francis Group, London

DMİ (2006) Report of Mersin meteorology station in 2006. Mersin, Turkey

Eren M, Kadir S, Hatipoğlu Z, Gül M (2008) Quaternary calcrete development in the Mersin Area, Sothern Turkey. Turkish J Earth Sci 17(2008):763–784

Finlay PJ, Fell R, Maguire PK (1997) The relationship between the probability of landslide occurrence and rainfall. Can Geotech J 34:811–824

Geoslope SLOPE/W 5.15 (2003) Software tools for geotechnical solutions. http://www.geo-slope.com

Hoş T (1995) Tarsus Ayrımı-Mersin Otoyolundaki Yarma ve Dolguların Jeoteknik İncelemesi. M.Sc. Thesis, Çukurova University, Adana, Turkey (Turkish, unpublished)

İlker S (1975) Adana Baseni kuzeybatısının jeolojisi ve petrol olanakları. TPAO Arama Arşiv No: 973, 63 p (Turkish, Unpublished)

Kandilli Obsevatory Earthquake Research Institute (2004) Catalogue of earthquakes in Turkey. Kandilli Observatory İstanbul, Turkey (unpublished data)

Kayadelen C, Tekinsoy MA, Taskıran T (2007) Influence of matric suction on shear strength behavior of a residual clayey soil. Environ Geol. doi:10.1007/s00254-007-0701-2

Kenney TC, Lau KC (1984) Temporal changes of groundwater pressure in a natural slope of non fissured clay. Can Geotech J 21(1):138–146

Lee ML, Gofar N, Rahardjo H (2009) A simple model for preliminary evaluation of rainfall-induced slope instability. Eng Geol 108:272–285

Leonards GA (1982) Investigation of failures. J Geotech Engng Div Am Soc Civ Engrs 108(GT 2):185–246

Marcuson, WF and Franklin, AG (1983) Analysis and remedial measures to improve the stability of existing dams. Seismic Design of Embankments and Caverns, In: Howard TR (ed), ASCE, New York

Ocakoglu F, Gökçeoğlu C, Ercanoglu M (2002) Dynamics of a complex mass movement triggered by heavy rainfall: a case study from NW Turkey. Geomorphology 42(329–341):330

Özgül N (1973) Torosların bazı temel jeoloji özellikleri. Türkiye Jeol Kur Bült, 19-1, 65-78 (Turkish)

Paul SK, Bartarya SK, Rautela P, Mahajan AK (2000) Catastropic mass movement of 1998 monsoons at Malpa in Kali Valley Kumaun Himalaya (India). Geomorphology 35:169–180

Petrucci O, Polemio M (2003) The use of historical data for the characterisation of multiple damaging hydrogeological events. Nat Hazard Earth Sys 3:17–30

Polemio M, Sdao F (1999) The role of rainfall in the landslide hazard: the case of the Avigliano urban area (Southern Apennines, Italy). Eng Geol 53(3–4):297–309

Rocscience (2012) SLIDE 6.0-2D slope stability analysis for soil and rock slopes. Rocscience Canada

Schmidt GC (1961) Stratigrafic nomenclature for the Adana Region Petroleum District. VII Turkish Petroleum Administration Bull No 6, Ankara, pp 47–62

Senol M, Sahin S, Duman TY (1998) The geological investigation of Mersin Region. General Directorate of Mineral Research and Exploration of Turkey (unpublished report), p 46 Ankara (in Turkish)

Sidle RC, Swanston DN (1982) Analysis of a small debris slide in coastal Alaska. Can Geotech J 19:167–174

Sitar N, Anderson SA, Johnson KA (1992) Conditions leading to the initiation of rainfall-induced debris flows. Stability and Performence of Slopes and Embankments -II. ASCE, New York, Geotech Eng Div Specialty Conf, pp 834–839

Taga H, Demirkol C (1996) Geology of the Emirler-Çavuşlu (Mersin) area. Bulletin of the Geological Congress of Turkey, vol 11, pp 1–6

Turkmen S, Yılmazer O (1998) Engineering geology of a caliche unit which caused noticeable slope failures along the TAG Motorway, Turkey. Environ Eng Geosci IV(4):519–523

Turner AK, Schuster RL (1996) Landslides—investigation and mitigation. Ins: Transportation Research Board, National Research Council, Special Report 247, National Academy Press, Washington D.C. pp 673

Tutkun SZ (1984) Saimbeyli (Adana) yöresinin stratigrafisi. Cumhuriyet Üniversitesi, Mühendislik Fakültesi Dergisi, Seri A Yerbilimleri, 1-1, 31-40 (Turkish)

Ulusay R, Tuncay E, Sonmez H, Gokceoglu C (2004) An attenuation relationship based on Turkish strong motion data and isoacceleration map of Turkey. Eng Geol 74:265–291

Urciuoli G (1998) Pore pressures in unstable slopes constituted by fissured clay shales. In: 2nd Int Symp on Geotechnics of Hard Soils-Soft Rocks, vol 2, Napoli, pp 1177–1185

Wright VP, Tucker ME (1991) Calcretes. Blackwell Scientific, Oxford

http://www.sayisalgrafik.com

Yalcin MN, Görür N (1983) Sedimentological evolution of the Adana Basin. In: Tekeli O, Göncüoğlu MC (eds) Geology of the Taurus Belt. Mineral research and exploration institute (MTA) of Turkey Publications, Proceedings of International Tauride Symposium, pp 165–172

Yalcinkaya E (2005) Stochastic finite-fault modeling of ground motions from the June 27, 1998 Adana-Ceyhan earthquake. Earth Planets Space 57:107–115

Yetis C (1988) Reorganization of the tertiary stratigraphy in the Adana Basin, southern Turkey. Newsl Strat 20:42–58

Yetiş C, Kelling G, Gökçen SL, Baroz F (1995) A revised stratigraphic framework for later Cenozoic sequences in the northeastern Mediterranean region. Geologishe Rundschau 84:794–812

Zezere JL, Ferreira AB, Rodrigues ML (1999) Landslides in the North of Lisbon Region (Portugal): conditioning and triggering factors. Phys Chem Earth A 24(10):925–934