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ORIGINAL ARTICLE

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Failure and flow development of a collapse induced complex landslide: the 2005 Kuzulu (Koyulhisar, Turkey) landslide hazard

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Abstract Koyulhisar located in a slope of hilly region and constructed in the side of a mountain along the North Anatolian Fault Zone is frequently subject to landslides. A catastrophic landslide occurred on the morning of 17 March 2005 in the North of the Kuzulu district of Koyulhisar (Sivas, Turkey). This landslide caused widespread loss of life, and damage to buildings, and lifelines. Fifteen people were dead and five were injured, 21 houses and a minaret were covered and damaged severely. The case study presented in this paper describes and analyses the results of the detailed surveys of an interesting landslide in Kuzulu district of Koyulhisar (Sivas, Turkey), based on field and laboratory measurements and monitoring of the slide area. Landslide initiated as a collapse, and developed into debris avalanches in the valley. This phenomenon caused a disaster in the Kuzulu district. The importance of this landslide in particular has been recognized both in terms of its consequence for the people and structures and in terms of its role in allowing an understanding of process and properties of landslide triggered by a collapse in limestone karst. In view of the potential for such events to occur again in this area and environs, understanding of the failure mechanism is very crucial.

Keywords Karst · Koyulhisar (Turkey) · Landslide · Limestone · North Anatolian Fault · Weathering

Introduction

A catastrophic landslide occurred on the morning of 17 March 2005 in the North of the Kuzulu district of Koyulhisar (Sivas, Turkey) (Figs. 1, 2). This landslide caused widespread loss of life, and damage to buildings, and lifelines. Fifteen people were dead and five were injured, 21 houses and minaret were covered and damaged severely (Fig. 3).

There are three main regions affected by landslide, such as: "Landslide area", "Flow channel", and "Disaster area" (Fig. 4). Sorgun district, where the landslide occurred, is the source of the disaster in Kuzulu district. After the landslide occurrence, landslide debris materials saturated with water were transported by the valley as a channel to the Kuzulu district. Materials having an approximate volume of 10×10^6 m^3 fully filled and covered the district within ˜15–20 min (Fig. 5). So, the settlement area in Kuzulu district was named as "Disaster area".

Landslide area is highly mountainous and wooded, and is located in the North Anatolian Fault Zone (NAFZ). It has been recognized that Koyulhisar is frequently subjected to landslides. The landslide initiated as a collapse, and developed into debris avalanches in the valley. This phenomenon caused a disaster in the Kuzulu district. In view of the potential for such events to occur again in this area and environs, understanding of the failure mechanism is very crucial.

Fig. 1 A view from landslide

The case study presented in this paper describes and analyses the results of the detailed surveys of an interesting landslide in Kuzulu district of Koyulhisar (Sivas, Turkey), based on field and laboratory measurements and monitoring of the slide area. The importance of this landslide in particular has been recognized both in terms of its consequence for the people and structures and in terms of its role in allowing an understanding of process and properties of landslide triggered by a collapse in limestone karst. To explain the mechanism of this landslide is also important because the environs of the landslide area having an approximate surface area of 500 km^2 is prone to landslide and affected by the lot of landslides.

Geography and morphology

Kuzulu district is located in a hillside of a hilly region. The stretch of the Kelkit River in this area extends E–W, passing south of Kuzulu. Topographic and morphological determinations were done by using 1:25,000 scaled digital elevation model (DEM) of the study area (Fig. 6). Topographic elevations change from 650 to 1,717 m. The highest hills are Çanakkaya, Tavşan, and Gerişüstü Hills, and their heights are 1,693, 1,717, and 1,708 m, respectively. However, the average value of slope angles is approximately 20°, those values reaches to 65–70° in some locations. The average value of slope angle in the landslide area is 21° (Fig. 7). The valley lying between the landslide area and disaster area have very steep slope (~50°). Direction of the slopes show differences, but the dominant slope directions are NW–SE and NE–SW (Fig. 8).

Geological framework and tectonic setting

The rocks out cropping (Fig. 9) in the study area consist of Campanien–Maestrihtien aged sedimentaries, limestone of Maestrihtien age, and Upper-Miocene volcanics (basalt).

Sedimentaries

Sedimentaries are especially observed in south of the study area, in the Kuzulu district. The Campanien–Maestrihtien aged sedimentary series consist of

Fig. 2 Location map of the study area

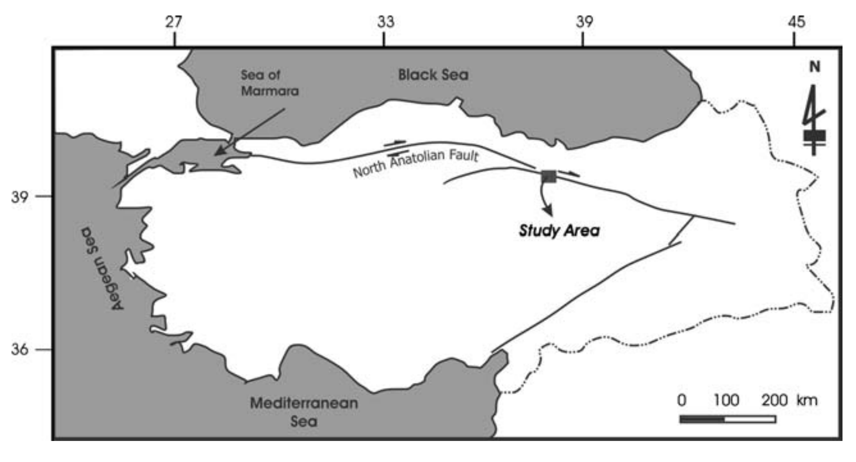
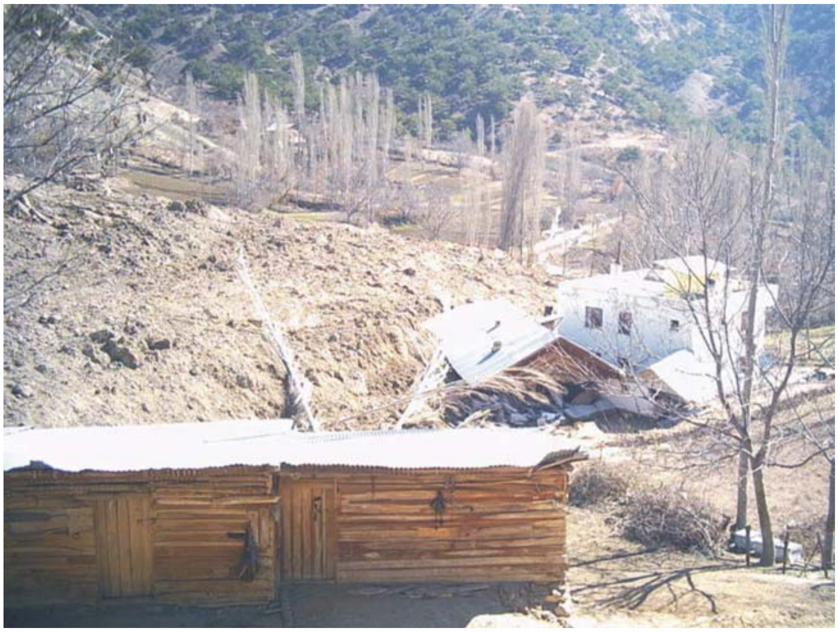


Fig. 3 Photo from disaster area



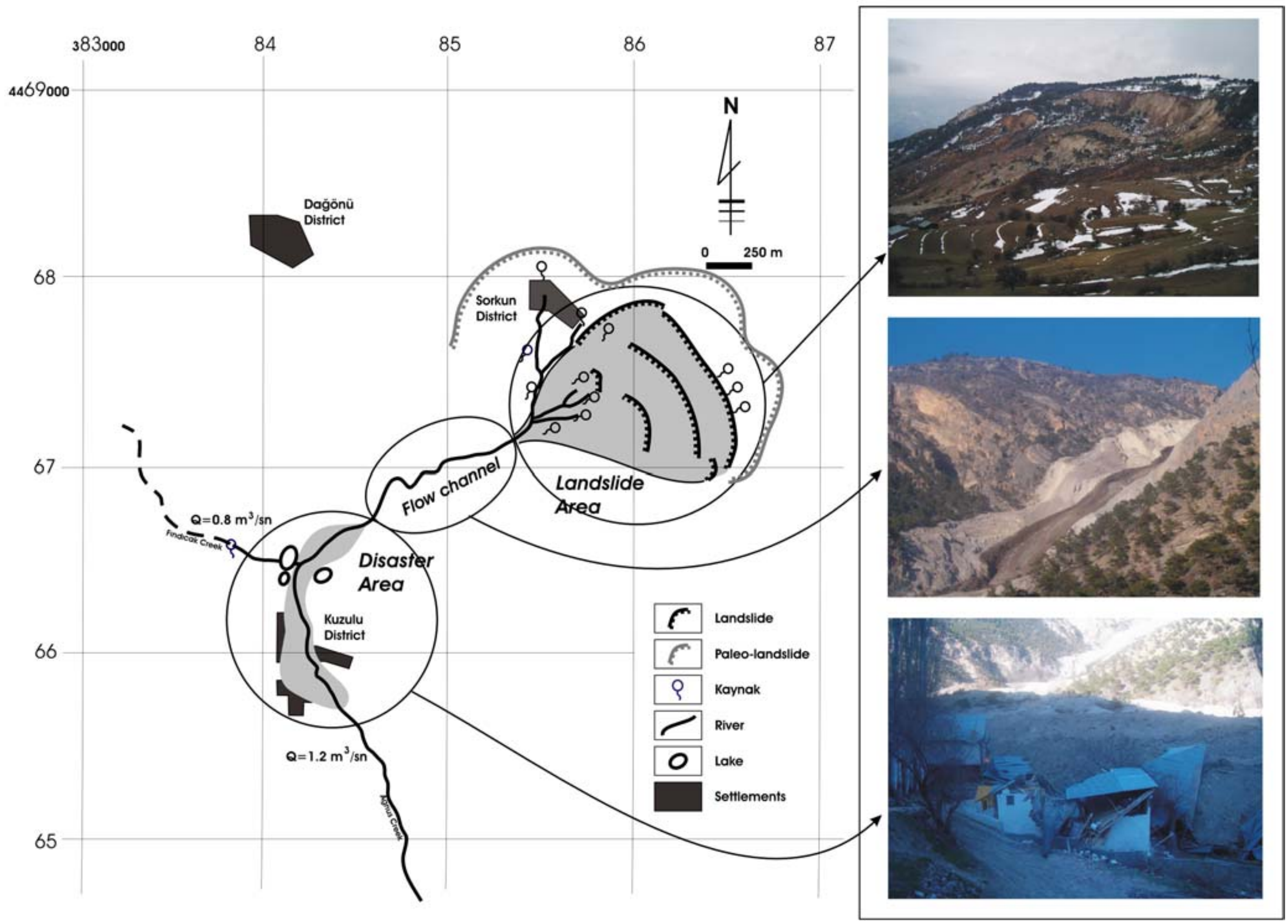


Fig. 4 Map of the "Landslide area", "Flow channel" and "Disaster area"

Fig. 5 Settlement area covered by debris material

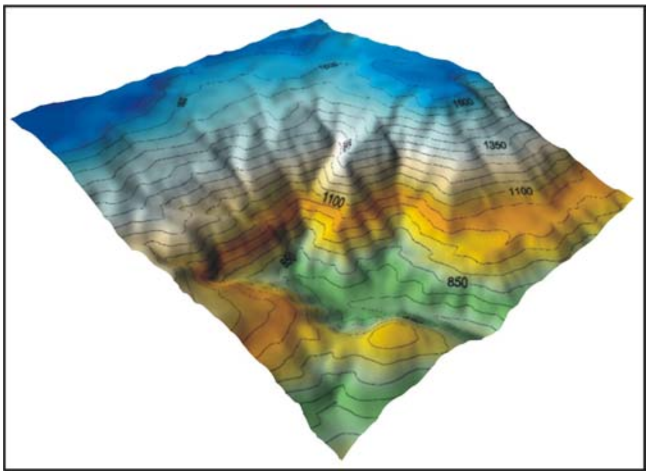


Fig. 6 Digital elevation model (*DEM*) of the study area

sandstones, shale, limestone, and volcanics. This serie is the oldest unit in the study area.

Limestone

Upper-Maestrihtien limestone is the oldest unit in the study area and was first described by Terlemez and Yılmaz (1980) who named it Igdir Limestone. Limestones in the study area are characterized as bedded, whitish yellow and pink, crushed and jointed. Karens (Fig. 10a) and dolines were observed in the study area (Fig. 10b). Bedding planes have the directions of 15/28, 10/25, and 288/20.

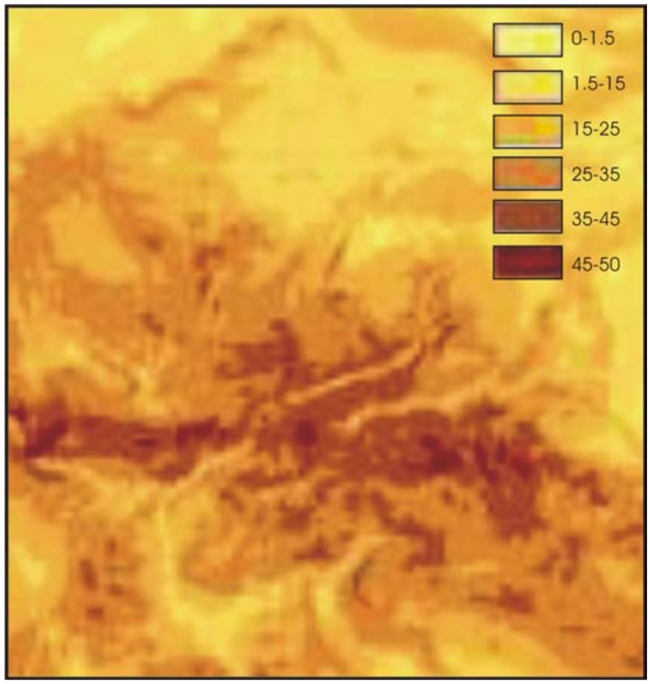


Fig. 7 Slope map of the study area

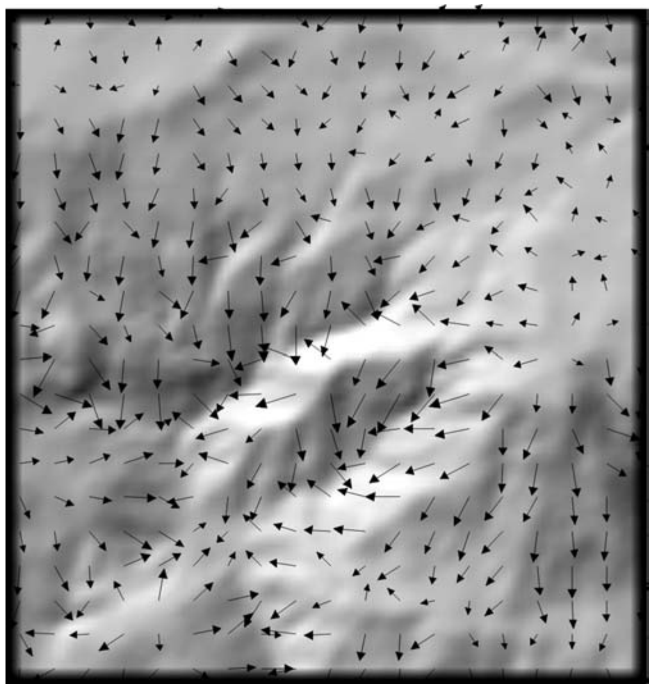


Fig. 8 Vector map of the study area

Volcanics (basalt)

Overlying the limestone, weathered basalts were observed in the north part of the Kuzulu district. Basalts in the

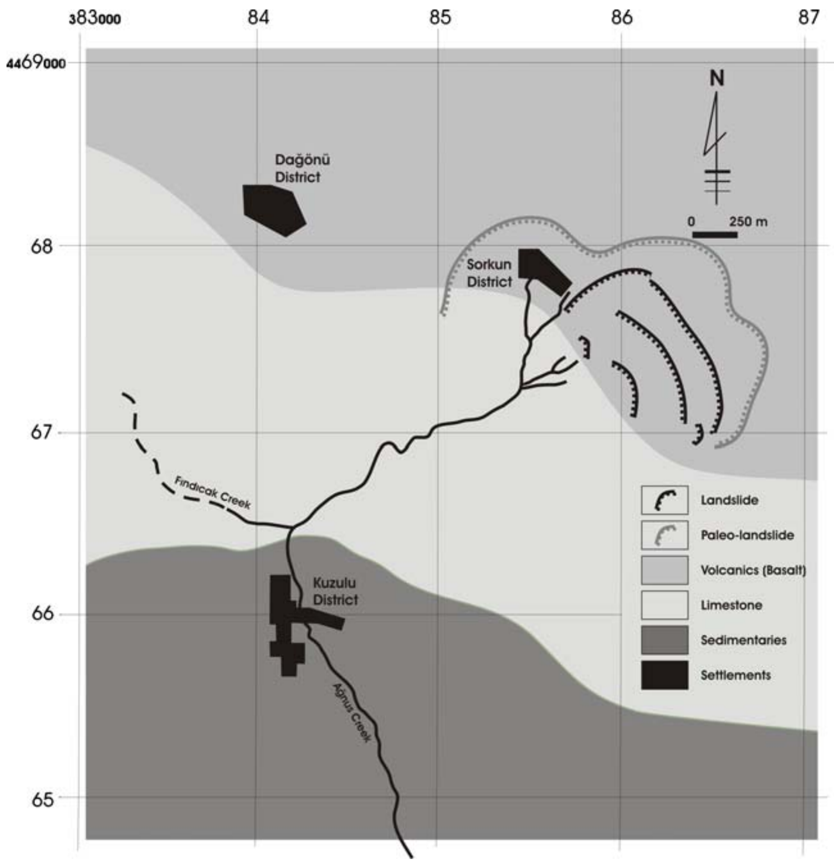


Fig. 9 Geological map of the study area

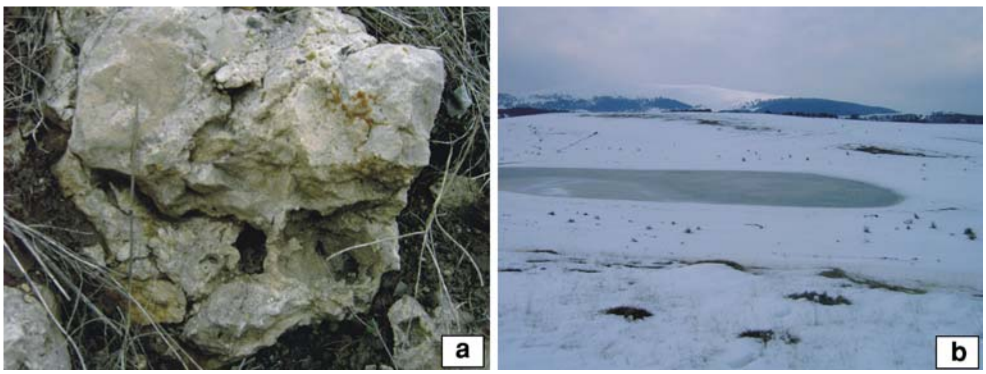


Fig. 10 A photo showing "-Karen" and "Doline" in limestone

landslide area are discolored and are changed to soil, but the original fabric and mineral content is mainly preserved. The properties of the soils are similar to the nature of the parent rock of basalt. Mineralogical determinations carried out as a whole rock powder diffraction determination by X-ray diffraction showed that the unit is composed of clay, quarts, and feldspar minerals. The respective average semi-quantitative quantity of clay, quarts, and feldspar minerals are 5, 25, and 70% (Fig. 11). This obtained mineralogical content largely supports the fact of the source rock of basalts. So this unit, where the landslide occurred, was classified as "completely weathered rock" in geotechnical point of view.

It is well known that weathering tends to progress more rapidly along faults and fault zones, where, due to cataclasis, the rocks have been crushed, so that in a sense, physical disintegration is complete even before any chemical weathering of rock mass begins. In the study area, abnormally deep weathering observed is associated with NAFZ, and with zones of closely spaced joints.

Landform is also effective on weathering due to the combination of hydrological and geomorphic characteristics of study area. Wooded characteristics of the study area controlled the rate of run-off and hence the rate of water in took to the rock mass. Especially, in the north of the landslide region, on the flat areas, the

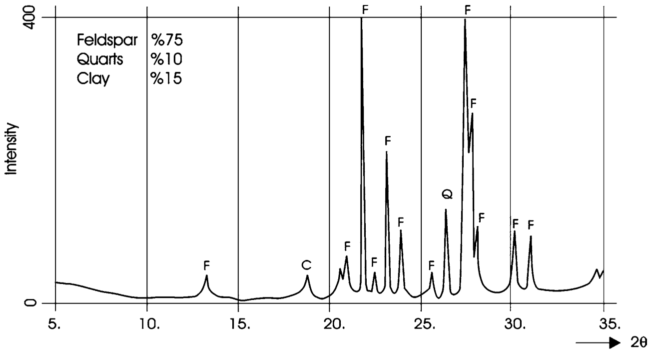


Fig. 11 Characterisic X-ray diffraction diagram of whole-rock powder

run-off coefficient is very low, and very much water could penetrate into the rock mass.

Tectonic setting

As is well-known, the neotectonic framework of Turkey is outlined and characterized by major intracontinental strike-slip faults, namely the dextral NAFZ and the sinistral East Anatolian fault zone, between which the Anatolian block moves westward relative to the Eurasian plate in the north and the Arabian plate in the south owing to the continued convergence of these plates since the middle Miocene (McKenzie 1972; Dewey and S engör 1979; Sengör 1980; Barka and Gülen 1988; Koçyiğit 1989). The study area is located in the near north of NAFZ (Fig. 12). This region has been mainly affected by the regional tectonic movements and faulting. The main fault in the study area is North Anatolian Fault, which extends in a direction of NW–SE. Koyulhisar is located in the seismically active NAFZ which has International interest.

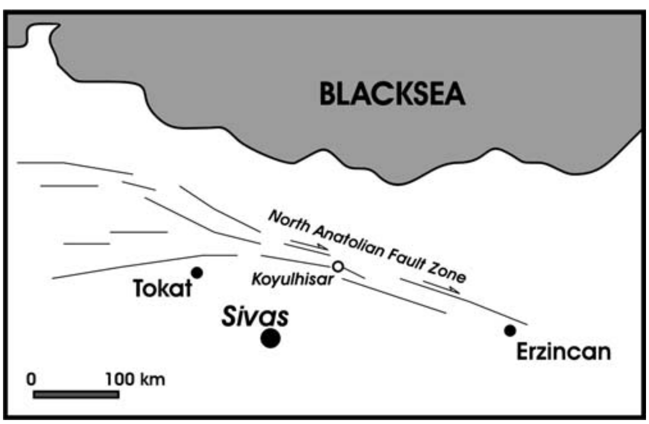


Fig. 12 Tectonic situation of the landslide area

Hydrogeological conditions

Rainfall is the main source of water in the study area, and it is the most important element in the hydrologic cycle. This area receives a mean annual rainfall of 619.1 mm. The minimum recorded value was 436.5 mm, measured in 1973, and the maximum measured value was 803.0 mm, recorded in 1968. Most rainfall occurs during April, with a mean value of 89.9 mm. Meteorological records for 20 years (1969–1995) show that the annual mean maximum temperature in August is 20.7°C; the annual mean minimum temperature is always recorded in January and is −1.5°C.

The main drainage system is dominated by the Agnus and Fındıcak creeks. The biggest river is Kelkit River, which extends parallely to NAFZ, and ~10 km far from landslide area. Hydrogeological investigations in the study area showed that the drainage areas of Fındıcak and Agnus creeks are 2.6 and 17.3 km^2, respectively (Fig. 13). And, respective discharge values of those creeks were obtained as 0.7 and 1.2 $m^3 s^{-1}$ by current meter measurements in the creeks. By using the surface drainage area of the Agnus creek and annual mean value of the precipitatition in the region, annual water input by precipitation (P) into the basin was computed by the following equation as 10.7×10^6 m^3:

$$P = AP_m \quad (1)$$

where A (17.3 km^2) is drainage area of Agnus creek and P_m is the annual mean value of precipitation in the catchment area (619 mm).

Annual discharge volume of the Agnus creek (Q_w) was computed as 37.8×10^6 m^3 $year^{-1}$ by the following equation:

$$Q_w = Q_d t \quad (2)$$

where Q_d is the total discharge (1.2 $m^3 s^{-1}$) and t is the time as a year (365 days).

If the annual water input by precipitation and discharge volume are compared, it could be seen that the annual discharge volume (Q_w) is 3.5 times greater than the annual water input by precipitation (P). This precipitation cannot suffice the discharge from Agnus creek, and it means a recharge from the neighbor basins. Investigations related to the limestones in the study area showed that the limestones have the jointed, bedded, and karstified characteristics. It is thought that the discharge of the Agnus creek is provided by infiltration from precipitation and karst area in the limestone. Discharge (Q) calculated from limestone was 22×10^6 m^3 $year^{-1}$, and infiltration coefficient (k) of limestone was computed as 0.41 by the following equation:

$$k = (AP_m)/Q \quad (3)$$

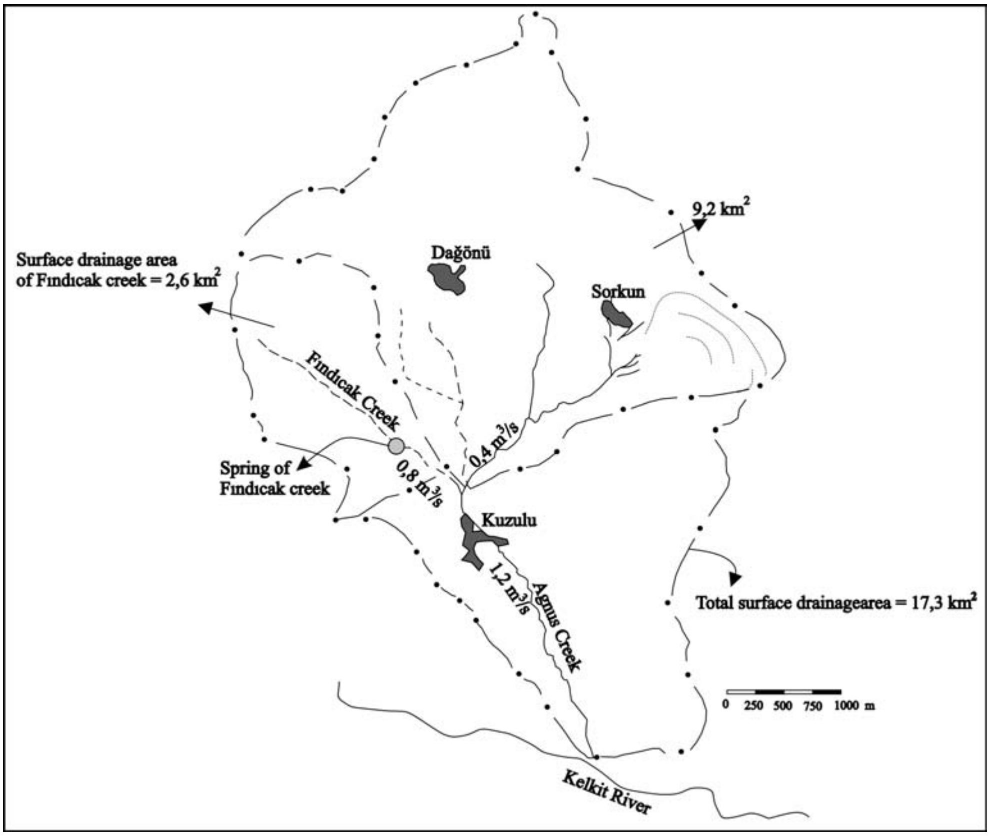


Fig. 13 Surface drainage areas of the Agnus and Fındıcak creek

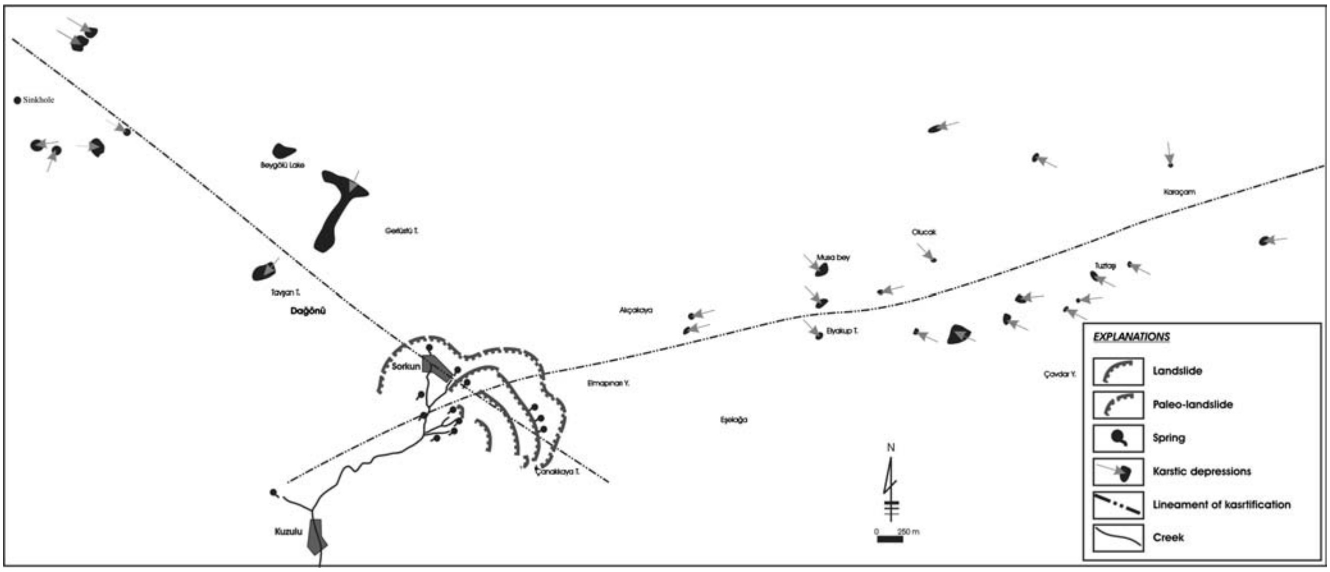


Fig. 14 Distribution of the karstic depressions in the landslide area and its environs

Günay and Yayan (1979) proposed a value of infiltration coefficient for karstified limestone in Antalya (Turkey) as 0.45. Ekemen and Kacaroglu (2001) calculated this coefficient as 0.55 in Tecer limestones in Sivas (Turkey). The infiltration coefficient obtained for limestone in the studied area also largely supports the karstification phenomena in the landslide area.

Especially the Fındıcak creek as a main source of Agnus creek, having a discharge value of 0.7 m^3 s^{-1} is needed a surface drainage area of 86.9 km^2 due to the annual mean precipitation (619 mm) and infiltration coefficient of limestone. But, real surface drainage area of Fındıcak creek observed was only 2.6 km^2. This is also an important evidence for karstification in the landslide area and its environs. It is thought that system of karstic fractures, fissures, bedding plains, and caverns plays a basic role in water flow through limestones.

Karst may be defined as the terrane characterized by the specific surface and underground landforms and features (karens, dolines, ponors, channels, caves, closed depressions, dry valleys, etc.) essentially developed in limestone and dolomite and also other soluble rocks (gypsum, salt rock, etc.), by a particular type of groundwater circulation and regime, and by occurrence of springs that usually have large capacity. Karst areas have some distinctive features which distinguish them from fissured and porous aquifers (Bakalowicz et al. 1995): (1) a general lack of permanent surface streams; (2) the existences of swallow holes (ponors) into which surface streams sink; (3) the presence of underground channels (conduits or drains) in which rapid water flow occurs; and (4) the occurrence of large springs (Kaçaroglu 1999).

Due to this concept surface investigations were carried out in the landslide area and its environs. As a result of the investigations, a lot of karst depressions, sinkhole, and dolines were observed along a lineament (Fig. 14).

Description and mechanism of the landslide

It has been recognized that the study area is frequently subjected to landslides. The landslide occurred in Sorgun district, in 17 March 2005 caused deaths of 15 people and Kuzulu district was seriously damaged. The landslide occurred was the source of the disaster in Kuzulu district. Landslide debris materials saturated with water were transported by the valley as a channel to the Kuzulu district, and settlement area was fully filled and covered by materials having an approximate volume of $10{\times}10^6$ m^3 within ~5–10 min (Fig. 1).

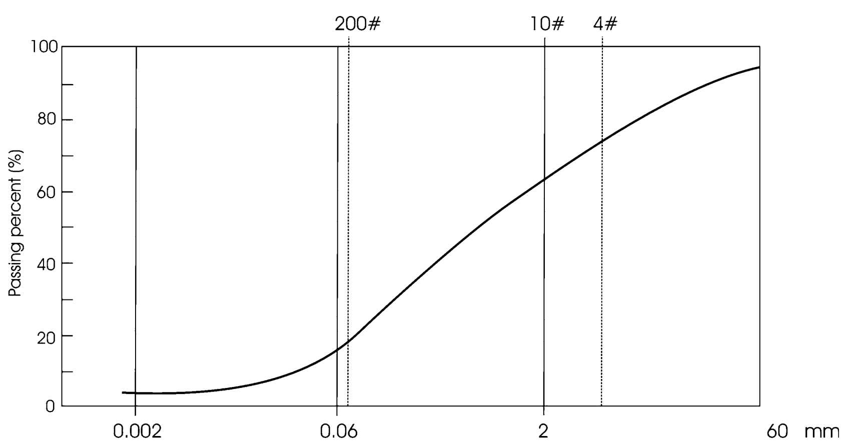
Soil mechanic tests, in accordance with American Standards Testing of Materials (ASTM) standards (Bowles 1992), were carried out on samples collected from the landslide material. Conventional coarse sieve, fine sieve, and hydrometer methods were used for grain size analyses. These analyses revealed that the soils weathered from basalts are composed of 3% block, 30% gravel, 42% sand, 10% silt, and 5% clay size material. The range of grain size is shown in Fig. 15.

Residual cohesion and internal friction angle of the weathered basalts having a natural water content of 1.61 g cm^{-3} were determined as $c_r = 0.35$ kg cm^{-2} and $\phi = 29°$, respectively.

If it is assumed that a circular failure was occurred, safety factor (F) of original slope is obtained as 1.34, by using the strength properties obtained and initial slope characteristics. This value of safety factor means that the original slope was stable in its initial conditions, and saturated condition was not a primary triggering factor.

Especially the north, northwest, and northeast of the landslide area is marked by occurrence of deformations induced primarily by karst. Displacement in the main scarp of the landslide was vertically measured as ~40 m; however, the initial height of the slope was ~80 m (Figs. 16, 17). Morphology of the main scarp gives a very steep (~90°) gradient. If we try to construct a sliding circle by using the observed slope angle of the main scarp, initial slope height, and angle, it could be seen that the toe of the landslide should be observed in the far of the landslide area. So it can be said that a displacement occurred vertically into a cave underlying the volcanics, and weathered basalts were dumped into the cave placed in karstified limestone. And this phenomenon triggered a translational slide. After the

Fig. 15 Grainsize distribution of the basalts weathered



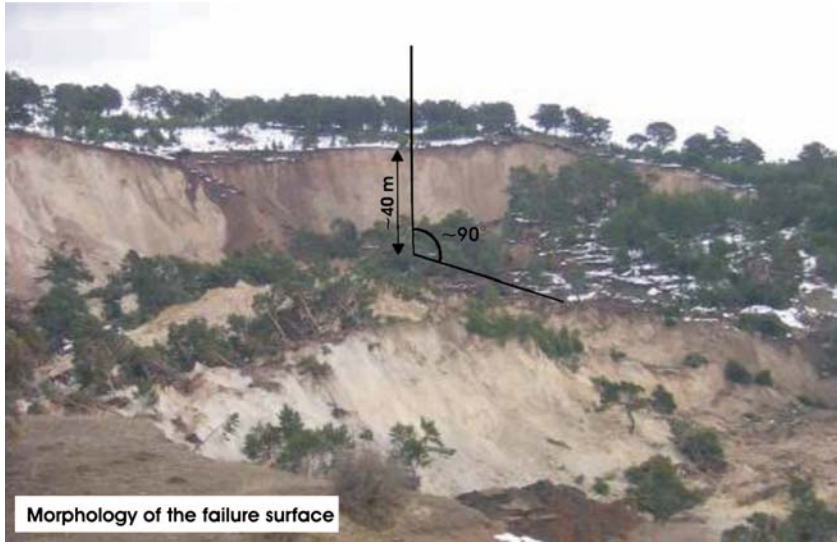


Fig. 16 Morphology of the main landslide scarp

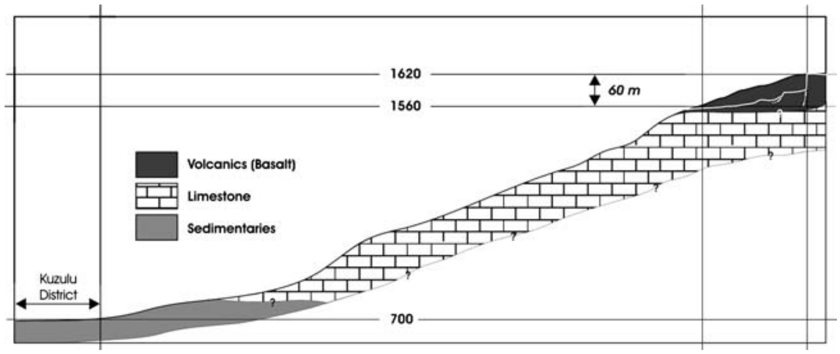


Fig. 17 Cross-section from south to north

displacement occurrence, weathered basalts saturated with water flowed over the limestone by acting like a fluid. Thus, sliding was to be easy and fast especially in the steep slopes of valley, because of the saturated conditions of the sliding material. And, debris avalanches transported by a steep valley, in the toe of the landslide, caused a disaster in the settlement area of Kuzulu district. Finally, this landslide was evaluated as a case of karst landslide development.

Discussion and conclusions

Landslide area is highly mountainous and wooded, and is located in the NAFZ. It has been recognized that Koyulhisar is frequently subjected to landslides (Sendir and Yılmaz 2002). The landslide initiated as a collapse, and developed into debris avalanches in the valley. This phenomenon caused a disaster in the Kuzulu district. In view of the potential for such events to occur again in this area and environs, understanding of the failure mechanism is very crucial.

Field investigations, analysis of geological data, and laboratory tests suggest that some factors have acted together on this slope to cause sliding.

Instability condition is especially connected to the joints or karst cavities in the limestone. Initial failure occurred by a vertical displacement in karstified limestone. And this phenomenon triggered a translational slide, and debris materials originated from weathered basalts saturated with water flowed over the limestone in the steep valley, and reached the settlement area. Landslide caused a disaster in the settlement area of Kuzulu district. The trees on the slopes had slowed down the surface flow of water, sourced from melted snow, and made the infiltration into the earth material of the slopes easy. Thus, adding the weight to the slope and increasing of the water pressure contributed to the collapse of the basalts into the karstic structure in limestone. During heavy rainfall, water flowed into the cavities and joints, inducing the development of concentrated water flow and, if the fractures are filled, high pore water pressures. Both the surficial water and groundwater circulation also played an important role in initiating the movements. Finally, this landslide was evaluated as a case of karst landslide development.

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