Geotechnical assessment of the 2005 Kuzulu landslide (Turkey)

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Abstract

In this study, a complex landslide, which occurred on 17 March 2005 near Koyulhisar town of Sivas Province of Turkey, is presented. The landslide resulted in 15 deaths and the destruction of about thirty houses at Kuzulu village. The main aims of this study are to assess the landslide in terms of engineering geology and geotechnics, to back-analyze the landslide in the source area, and to estimate its motion and destructive forces on structures. Furthermore, the effect of a future earthquake on stability condition of the mobilized but not completely failed mass adjacent to the right flank of the landslide is also investigated. Field observations, eyewitnesses, geomechanical laboratory tests, interpretations on pre-event aerial photographs and analyses using different approaches have been fundamentals of this study. Site observations indicate that the initial landslide in the source area occurred in highly weathered volcanics along a failure surface passing through the volcanics and along the interface between the volcanics and underlying limestone. Then the movement transformed into an earth flow and moved down through a V-shaped channel in the underlying limestone about 2 km until it stopped at a small settlement, which is called Kuzulu. Site observations and back-analysis of the initial slide suggest that the most likely cause should be water pressure increase as it is the season of snow melting and thawing of the groundwater. Interpretations on pre-event aerial photographs and the information obtained from eyewitnesses indicated that slope movements in the study area, where old landslide topography is evident, were continuing for many years. The simulation of the landslide with consideration of Bingham type yielding criterion together with water pressure variation suggested that the maximum velocity of the earth flow was 14.4 m/s and 13.6 m/s when it reached Kuzulu. Furthermore, this evaluation showed that the earth flow reached Kuzulu after 300 s, which is consistent with the information obtained from local people. The impact of the earth flow on the structures could be about 170 kPa against which only reinforced concrete structures may resist. Dynamic analyses suggested that a future earthquake, which may occur in the region, may result in a complete failure of the unstable mass remaining at the source area.

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1. Introduction

Large landslides are often characterized by a complex style of activity (Cruden and Varnes, 1996) due to their capability to suddenly change behavior. Such landslides can pass from a slump to a flow characterized by relatively high mobility in terms of both velocity and run out (i.e. Hungr, 1995; Crosta, 2001) But the modeling of these failures is generally difficult because they prevent direct observation of the phenomenon during its evaluation. The most recent, large and catastrophic
complex landslide occurred in Turkey on 17 March 2005 near the Sugözü village of Koyulhisar town (Sivas, Central Anadolu) and destroyed Kuzulu village. The landslide initiated within highly weathered volcanics in the mode of sliding and then transformed to an earth flow. It killed 15 people, and more than 30 houses and a mosque were buried and damaged by the earth flow material. A second but smaller landslide originated from the same source areas after 4 days and caused additional damages. Just after the main event, the governor of the province established an investigation committee consisting of members from two universities and the General Directorates of Mineral Research and Exploration (MTA), State Hydraulic Works (DSI), and Highways (TCK) on the scale and effects of the landslide (http://www.sivas.gov.tr/koyulhisar/bilim.htm). Then Gokceoglu et al. (2005) paid attention to the factors conditioning this landslide and its environmental impacts, and produced a landslide-susceptibility map of the landslide area and its close vicinity using the conditional...
probability approach and GIS technique. Tatar et al. (2005) briefly described the characteristics of the landslide.

The aim of this study is to assess the landslide in terms of engineering geology and geotechnics, to back-analyze the initial slide occurred in the source area, to estimate the motion of the landslide mass and its destructive force on structures by impact pressure through the use of the Bingham type yielding function. Furthermore, the effect of a future earthquake on stability condition of a mobilized but not completely failed unstable mass near the right flank of the Kuzulu landslide was also investigated by a dynamic model suggested by Aydan et al. (2005). The authors visited the landslide area about two months after the event. Field observations, eyewitnesses, geomechanical laboratory tests, interpretations on pre-event aerial photographs and stability analyses using different approaches have been fundamentals to this study.

2. General settings

The study area is located in Sivas Province of the northeastern part of Central Anadolu, Turkey, and about
10 km to the west of the town of Koyulhisar (Fig. 1). One of the well-known active faults of Turkey, called the North Anadolu Fault Zone (NAFZ), runs approximately E–W direction at the south of the landslide area (Fig. 2). Due to this, topography of the area is considerably steep and highly elevated. The NAFZ follows the stream bed of Kelkit River at the southern part of the landslide area. Between this river and the hills behind the landslide source area, the elevation ranges from 580 to 1850 m. In the study area, a number of secondary creeks joining to Kelkit River generally flow in NE–SW and NW–SE directions, and form deep valleys. Among these, Agnus and Findicak creeks are the main secondary creeks (Fig. 2).

Between the Kelkit River and the landslide area, some small settlements are founded. Sugözü village is the main settlement and located on the north bank of the Kelkit River (Fig. 2). The others are Kuzulu, Sorkun and Dagönü villages which officially belong to Sugözü village. The gently sloping small areas near these settlements are being used as farmland and grassland.

The majority of Sivas Province including the study area shares the climate of the Central Anadolu Region in which the summer seasons are hot and dry, while winter seasons are cold and considerably snowy. High elevations, particularly Kuzulu village and its northern parts receive heavy snow. The landslide occurred at an elevation between 1800 and 2000 m levels in mountainous area. The nearby meteorological stations are located in the Kelkit Valley, which are Koyulhisar and Susehri 1500 m below the elevation of the landslide zone. The authors have obtained the available meteorological data from Meteorological Agency of Turkey. Since the meteorological data (only rainfall) for Koyulhisar exist only for 1993, the data of Susehri with that of Koyulhisar are compared in Fig. 3a. Comparison of precipitation data of 1993 from both stations indicates (Fig. 3a) that variation in rainfall with time at both stations is considerably similar. Therefore, the rainfall data from Susehri is used. Based on the histograms of rainfall between September 2004 and August 2005 of Susehri station, highest rainfall occurred in November 2004 and there is an increasing trend in rainfall from January to May in 2005 (Fig. 3b). But it should also be remembered that elevation at the landslide source area is considerably higher than those at Koyulhisar and Susehri, and the land was covered by snow during the 2005 Kuzulu event (Fig. 3c). Although there is no information on the thickness of the snow cover in the landslide source area before the event, the period between March and May generally corresponds to snow melting period. Therefore, snow melting seems to be more important than rainfall for the landslide event.

The study area geologically consists of sedimentary and volcanic rock units. The Quaternary alluvial deposits covering a narrow zone through the valley of the Kelkit River are the youngest units (Fig. 2). Due to strike–slip nature of the NAFZ, different rock types...
confront one another at both sides of the fault. At the southern part of the NAFZ, an Upper Lutetian and Upper or Lower Eocene, and place to place Middle and Upper Eocene sedimentary sequence composed of sandstones, shales and conglomerates crop out (Herece and Akay, 2003). The limestones of Maastrichtian and Paleocene appearing at the northern block of the NAFZ, exhibit a large extent approximately along E–W direction. These yellowish-beige limestones forming steep slopes are highly tectonized due to their close proximity to the NAFZ. The Campanian and Maastrichtian aged sandstone, shale, limestone and volcanic rocks underlie this limestone (Fig. 2). Herece and Akay (2003) indicate that these units are associated with the development of a basin by overlapping transgression. At north, a volcanic cover overlying the Maastrichtian–Paleocene limestone is composed of basaltic lava flows and tuffs of Upper Miocene. These highly weathering-prone rocks posses soil-like behavior and the initial part of the Kuzulu landslide in the source area (sliding part) occurred in these weak materials (Fig. 2) forming gentle slopes compared to those of the limestone section. It is also noted that hummocky topography and old failure scarps indicating old landslide morphology are the typical features observed in the volcanics at the Sorkun village and its vicinity (Fig. 4). Sorkun and Dagöümı villages are located in a large old landslide zone.

The major structural feature at the study area is the NAFZ which extends WNW–ESE direction (Fig. 2). It is a 1200 km long dextral strike–slip fault zone. In a fracture zone, several fracture sets may exist. These are classified as T-fractures, R–R\textsuperscript{'} (Reidel)-fractures, S-fractures and P-fractures. Depending upon the stress state during shearing, some of these fractures may be suppressed. On the basis of the site observations and air-photo interpretations by the authors, lineaments coinciding with some of the NW–SE and NE–SW trending creeks, such as Agnus creek, through which the earth flow material accumulated and Findicak creek, are likely to be such features (faults) (Fig. 2). Due to the difficulties to access available outcrops, a limited number of dip and dip direction measurements could be taken from the bedding planes of the Campanian–Maastrichtian aged limestone. These measurements revealed that bedding planes in the limestone section dip towards SE and SW at different locations with inclinations of between 6 and 20 degrees.

The study area is located at a seismically very active region of Turkey where the NAFZ is the main earthquake source. The NAFZ is one of the world’s most important strike–slip faults due to not only to its significance for tectonics of the Mediterranean Region, but also to its remarkable seismic activity. It has produced eight gigantic earthquakes ($M>7$) in the period from 1939 through 1999. These earthquakes have ruptured the fault progressively from east to west. (Toksoz et al., 1979; Barka, 1996; Stein et al., 1997). Among these, two earthquakes occurred at the east and west of the study area in 1939 and 1942. The 26 December 1939 Erzincan earthquake ($M_s=7.9$) resulted in about 33000 loss of life and a surface rupture of 360 km. The segment of the NAFZ, which caused this earthquake, also passed from the southern edge of the study area. It is reported that many slope failures and huge rock falls occurred in the close vicinity and landslide lake observed nearby Sivas-Koyulhisar highway (Eyidogan et al., 1991). The second gigantic earthquake in the region occurred on 20 December 1942 ($M_s=7.1$) and was officially called as Erbaa earthquake. During this earthquake, a surface rupture of 50 km long developed and 3000 people lost their lives. In addition to these, the most recent earthquake with a magnitude of 6.8 ($M_s$), which hit the same region, is the 13 March 1992 Erzincan earthquake. Dead and injured people
during this earthquake were 590 and 1300, respectively. Its focal depth was 27 km and it caused the development of a 12–16 km long rupture zone, liquefaction and local landslides (Aydan and Hamada, 1992). All these earthquakes were felt and caused some degree of damage at Koyulhisar and its vicinity.

3. Description and mechanism of the Kuzulu landslide

The Kuzulu landslide occurred on 17 March 2005 at 10.30 (local time). The event initiated within highly weathered soil-like tuffs near Sorkun village located at an average elevation of 1600 m. Then a certain part of the displaced material transformed into an earth flow and moved through a V-type channel carved in the underlying limestone. This channel was highly steep and the steepest part of its slopes was about 40°–45° inclined. It widens at the sliding foot as seen in Fig. 2. Due to this steep topography and high water content of the displaced material, it flowed in SW direction and then turned to SE through Agnus creek (Fig. 2). Finally, the earth flow traveled within Kuzulu village for a distance of about 400 to 500 m and stopped after burying and/or destroying some houses and the mosque of the district. Plan view and longitudinal profile of the landslide, and typical views showing the main scarp, flow path and zone of accumulation at Kuzulu village are given in Figs. 5 and 6, respectively. Fig. 7 shows Kuzulu village before and after the landslide. According to eyewitnesses, the landslide body arrived to Kuzulu
within 5 min following a huge sound of impact. The earth flow accumulated at Kuzulu and formed a landslide dam on Findikak creek. As a result of this, a landslide lake occurred behind this dam (Figs. 2 and 8a). However, during the visit of the authors to the site, it was observed that the water from this lake was naturally flowing towards Kuzulu cutting through the landslide dam (Fig. 8b). Based on site observations performed by the authors, the thickness of the landslide dam is expected to be between 25 and 30 m (Fig. 8b). 15 of 79 people staying at Kuzulu district at the time of this event lost their lives and more than 30 houses were completely or partly buried by the earth flow material. Gokceoglu et al. (2005) estimated the amount of displaced earth material as $12.5 \times 10^6 \text{ m}^3$.

A second but smaller landslide initiated on 22 March 2005 at the source area near the main scarp of the 17 March 2005 event (Figs. 2 and 9). The displaced material also followed the same flow path and accumulated on the previous earth flow material. Due to this movement, toe of the accumulation zone was shifted about 50 m away and six houses at Kuzulu village were also buried and

Fig. 6. (a) Main scarp of the initial failure, (b) flow channel, and (c) accumulation zone of the earth flow at Kuzulu district.
one house suffered damage (Tatar et al., 2005). In addition, a small second landslide lake occurred at the eastern part of the valley (Fig. 2). On the other hand, mobilized but not completely failed huge potentially unstable mass still remains in the source area (Figs. 2 and 9). This mass is located near the right flank of the major slide at Sorkun and it developed in the same weathered volcanics. It is evident that this mass can easily be triggered by any factor such as an earthquake or heavy rainfall, and still threatens Kuzulu and Sorkun.

At the back of the major failure, there was a well-defined scarp feature where the failed material has dropped lower in elevation than the material at the front. Some back-tilted sections of the uppermost slope and trees were visible (Fig. 10a). The back-side of the landslide is steeply inclined and it has seemingly multiple parallel rotational slides. However, towards SW no tilting was observed in front of the failed and tilted blocks. This situation indicates that the toe of the failed slope underwent a translational movement probably parallel to the contact between the weathered volcanics and limestones. There is no evidence that the failure involved bedrock, but the failure surface coincident with weathered tuff–limestone contact, at least over the part of the landslide. This conclusion is confirmed by the observations carried out by the authors who found the contact between the underlying limestone and the unstable

Fig. 7. Views of the Kuzulu village before (a) and after (b) the landslide (from Koyulhisar Governorship).
mass near the right flank of the landslide (Fig. 10b). The inclination of the bedding in limestone at this location is 10° towards the sliding area. Striations on the surface of the main scarp measured at the western part of the landslide area (Fig. 10c) were evaluated by the method suggested by Aydan (2000). Fig. 10d showing a fault plane illustration of the sliding surface indicates that the direction of the sliding was towards SW. Without any boring logs, it is difficult to infer the position of the sliding surface. Nevertheless, based on the above mentioned findings it is very much likely that the failure surface consists of two parts. The upper part is a circular sliding surface passing through the highly weathered and soil-like volcanics and the second part consists of a planar surface along the contact (interface) between the volcanics and limestone. The geometry of the interface facilitated the movement towards the free face and it is possibly one of the contributing factors to the instability. By considering the location and inclination of the main scarp and the interface observed at a few locations, a cross-section of the initial failure zone at the source area.
was drawn (Fig. 5a and c). Fig. 5c suggests that depth of the failure zone near the main scarp is about 80–90 m.

The causes of the landslides are generally associated with gravity, earthquake and pore water pressure. If the gravity is the only force to act, the possible reason could be only creep failure, which will undoubtedly require the creep properties of the landslide material. The second cause may be earthquake. However, the catalogues of the national earthquake institutions such as Kandilli Observatory and Earthquake Research Institute (KOERI) of Bogazici University and the Earthquake Research Department (ERD) of the General Directorate of Disaster Affairs indicated that there was no earthquake felt in the close vicinity of the study area before and during the landslide event. Furthermore, Kalafat (2005) informed the authors upon their request that there are 5 stations of the KOERI seismic network, namely, Sivas-Karacayır, Gümüşhane, Tokat, Yozgat and Tunceli-Pertek, and none of these stations unfortunately recorded this event. The third cause may an increase in water pressure. The water pressure under static conditions will result from rainfall or thawing of frozen groundwater and seepage of melting snow. It is known that the landslide area was partly covered by snow at the time of failure and an important amount of thawing had occurred before the failure (Fig. 3c). In addition, it was reported that there are abundant springs at the landslide area (Fig. 2) and new springs also appeared along the flow path after the event (http://www.sivas.gov.tr/koyulhisar/bilim.htm). Some of these springs were also observed by the authors two months after the landslide. The springs flow from the contact between the volcanics and limestone, and from the scarp in the volcanics. In addition, some springs were evident in the V-channel at its lower elevations. Waters flowing from the springs could have also softened the mobilized material by reducing its strength. Therefore, it seems that the third cause mentioned above is the most likely one to trigger the landslide.

Various geomorphological evidences of previous slope instabilities in the source area of the 2005 Kuzulu landslide can be recognized from air-photo interpretations. The air-photos of the area taken in two different years (1973 and 2004) were available. Comparing these photos, significant changes can be recognized (Fig. 11). In 1973, a small part in the source area of the 2005 Kuzulu landslide (south of Sorkun) was swept away exposing a distinct white–gray zone free from trees. In addition, a disturbed zone at the northeastern tip of this area is recognizable (Fig. 11a). The photo taken in 2004 (Fig. 11b) suggests that (1) the boundaries of the unstable zone seen in the photo of 1973 extended to east and southeast, (2) trees appearing at south and east in the photo of 1973 disappeared probably due to slope movements, (3) the displaced material overtopped the terraces formed by the instability occurred in 1973 and began to fill the V-channel, and (4) evident depressions, which seem consistent with the scarp of the 2005 Kuzulu landslide, occurred at the east of the unstable zone indicating the retrogressive nature of the instabilities in the study site. In addition, an interview with Selim Piroglu, who is a member of the local council of Sugözü...
village, indicated that a large landslide has occurred two years ago (in 2003) at a location near the tip of the initial part (sliding part of the landslide at the source area) of the 2005 Kuzulu landslide body. This information also confirms the above given interpretations on the air photo taken in 2004. These evaluations, information obtained from eyewitnesses and the hummocky topography (see Fig. 4) observed in the vicinity of the source area suggest that slope instability at Sorkun was a phenomenon continuing for many years. In other words, the landslide occurred in 2005 is a result of the continuation of a retrogressive failure and near future landslide activities in the area should be certainly expected. However, because the landslide area is not densely populated and the people from Sugözü village do not live throughout the year in these areas located at very high elevations; the fore-running signs of the landslides could not be probably well recognized in time.

4. Sampling and landslide material properties

Landslide material properties were determined on samples taken from the landslide area by laboratory tests. Due to the presence of a mobilized unstable mass adjacent to the sliding zone (Fig. 9) and ongoing slow movements of the local detached blocks, the access into the landslide area and collecting samples from different locations in the failed zone was extremely dangerous. Therefore, a limited amount of samples could be collected for laboratory geomechanical testing. For the purpose, an undisturbed block sample from the upper sliding surface (western part of the main scarp) in the highly weathered tuff (Fig. 10c) and a undisturbed sample from the toe of the accumulation zone of the earth flow at Kuzulu (Fig. 6c) were extracted. Grain-size analyses, Atterberg limits and direct shear strength tests were carried out on both samples with measurements of
unit weight only on the undisturbed samples from the weathered tuff according to ASTM standards (ASTM, 1994). Because the amount of fines in the earth flow material was low, the hydrometer test was not carried out on the sample from this material. In addition, X-ray diffraction analysis was also performed on a sample recovered from the weathered tuff block to determine its mineralogical composition.

The XRD diffractogram of the sample extracted from the main scarp was obtained at Hacettepe University X-Ray Micro Analysis Laboratory using a Philips PW-1140 model diffractometer. The results of the whole sample mineralogy indicated that of clay minerals were dominant (53%) in the sample. The other minerals with smaller and/or negligible amounts were feldspar (29%), calcite (9%), quartz (5%), mica (2%) and dolomite (2%). This mineralogical composition, particularly the presence of clay and feldspar minerals confirms that the failed material is the weathering product of tuffs at Sorkun. The bulk unit weights of the specimens trimmed from the block sample of tuff range between 17.5 and 19 kN/m³ with a mean value of 18.2 kN/m³.

Grain-size analyses on the sample from the weathered tuff revealed that the clay and silt fractions dominate this
material, while the earth flow material sampled from the landslide tip generally comprised of sand and gravel with small amount of fines (Fig. 12). The liquid limit (LL) and plastic limit (PL) of the weathered tuff are 75% and 30%, respectively. According to the Unified Soil Classification System, this material falls into CH group representing high plasticity organic clay. The values of LL (36%) and PL (17%) of the fines content of the earth flow material are considerably lower than those from the material of the scarp. Based on its grain-size distribution and amount of fines content, the earth flow material is classified as GC group soil.

Finally, by taking into consideration soil classes and long term stability condition, consolidated-drained direct shear strength tests were carried out on undisturbed specimens extracted from the block of weathered tuff and on remolded specimens prepared from the earth flow material. Tests were run on 60 mm square samples with failure being investigated under different normal loads. Both peak and residual strength values were determined. The linear laws were well fitted to all data with very high correlation coefficients to obtain failure envelopes. The test results are given in Table 1. For the material representing the main scarp, internal friction angle was 20° for peak and 15° for residual conditions. This material generally behaves as a cohesive soil and its cohesion sharply decreases from 26.3 kPa to 13 kPa at residual state. For the earth flow material clearly a negligible cohesion was present, and peak and residual internal friction angles of 35° and 28.7° were measured in the tests. These results suggest that the earth flow material can be generally considered as cohesionless.

5. Landslide analyses

The collected data were used to study four main subjects. These are; back-analysis of the initial failure (sliding initiation stage), assessment of motion of the landslide mass and the impact pressure of the earth flow on structures, and investigation of the effect of a future earthquake on the potentially unstable zone, which is still in the source area and threatens both Kuzulu and Sorkun villages.

5.1. Back-analysis of the initial failure

In order to assess the failure mechanism and to estimate pore water conditions at the time of failure in the source area, a preliminary back-analysis of the initial failure occurred in weathered tuffs was performed using two-dimensional limit equilibrium techniques and Discrete Finite Element Method (DFEM). Pre-failure geometry was estimated from the topographical map produced in 1965. Limit equilibrium back-analyses were performed on the section shown in Fig. 5c using the slice methods of Janbu (1973), Spencer (1967), Morgenstern and Price (1965) and Aydan (Aydan et al., 1997). It is unnecessary to assume that the landslide mobilized the peak strength of the slope forming material. Palmer and Rice (1973) also suggest that progressive failure of slopes results in mobilization of residual strength parameters at the time of failure. Considering these, the residual shear strength parameters of the weathered soil-like tuff \((c_\tau = 13 \text{ kPa and } \phi_r = 15^\circ)\) were employed for the circular part of the failure surface. Same parameters were also used for the interface between the tuff and limestone. Because any borehole has not been drilled in the landslide area, no data to evaluate groundwater conditions at the time of failure was available. Therefore, it is considerably difficult to estimate a particular groundwater level.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Shear box test results</th>
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<tbody>
<tr>
<td>Material</td>
<td>Shear strength</td>
</tr>
<tr>
<td></td>
<td>Peak</td>
</tr>
<tr>
<td></td>
<td>(c_p) (kPa)</td>
</tr>
<tr>
<td>Sliding surface</td>
<td>26.3</td>
</tr>
<tr>
<td>Earth flow material</td>
<td>6.6</td>
</tr>
</tbody>
</table>

Fig. 12. Grain-size curves of the weathered tuff (a) and earth flow material (b).
However, because an abundant water discharge and melting snow were observed in the landslide zone, instead of defining a groundwater table, the pore pressure ratio ($r_u$) was employed in the analysis to assess the sensitivity of slope stability to variations in pore water pressure. A series of back-analysis were performed considering values of $r_u$ ranging between 0 (dry state) and 0.5. In the analyses, the failure geometry shown in Fig. 5c and a slope stability program called Slope 8 (GeoStru Enterprise, 1999) and the program called SLICE, which was developed by Aydan et al. (1997), were utilized. Then $r_u$–safety factor (SF) plot was constructed (Fig. 13) to determine the $r_u$ value satisfying the limit equilibrium condition. Depending upon the method used, the computed safety factors differ from each other, which are directly related how the interslice forces are modeled. The safety factor ranges between 1.22 and 1.45 for dry conditions ($r_u=0$). As for SF=1 condition, $r_u$ value should range between 0.15 and 0.35 depending upon the chosen method of stability analysis. These values imply that the saturation of slope material would be equivalent to 30% and 65%. Infiltration of melting snow into the soft slope forming material would likely have led to increase in pore water pressure prior to failure. In addition, the sliding surface promoted water flow towards free face, reducing the shear strength of the interface between the weathered tuff and limestone. Both these effects would contribute to instability.

As shown by Aydan et al. (1997), the slope does not become necessarily unstable when the safety factor becomes less than unity obtained from limiting equilibrium methods (LEM). Following a partial yielding and motion the slope may become stable again. In order to check this situation, DFEM method was employed to analyze the stability of the slope for the same geometry considered in limiting equilibrium analyses. In the computation, the saturation condition was varied in the same way as done in LEM analyses. Fig. 14 shows the displacement response of scarp and foot of the sliding body as a function of computation step. For the considered geometry of the landslide body, the slope becomes to yield at the curved part and yielding extends from the curved side towards the tip along the planar part. Since stress concentrations are released by yielding, the slope becomes stable after a certain amount of yielding for $r_u$ values less than 0.35. When the slope is stable, the displacements become asymptotic as computation step increases. However, it starts to become divergent when the slope is unstable. The saturation condition obtained from DFEM analysis was remarkably similar to that obtained from Aydan’s method.

5.2. Motion of the landslide mass and its impact on structures

According to eyewitnesses, the landslide body arrived to Kuzulu within 5 min following a huge sound of impact which implies an average velocity of approximately 7.67 m/s if the traveling distance is taken as 2.3 km. Nevertheless, the actual flow velocity profile is different from this average value. Therefore, motion of the landslide mass was evaluated by a series of analysis based on the methods described in the previous publications of the first two authors (Aydan, 1999; Aydan and Ulusay, 2002; Aydan et al., 2005). The method computes the position of the center of mass with the consideration of the profile and yielding characteristics of the sliding surface with time. In the analyses, the Bingham type of yield criterion was employed, and

![Fig. 13. Variation of safety factor (F) with pore pressure ratio ($r_u$) for the initial slide.](image)

![Fig. 14. Displacement responses of the landslide mass for various saturation coefficients.](image)
water pressure resulting from thawing of the frozen groundwater and melting snow was considered. Since the drainage of water during rapid motions would be difficult, the pore-water pressure may increase. However, the pore pressure coefficient cannot be greater than 1.

If the viscous resistance is neglected and the resistance is purely frictional, the travel distance could be much larger than the actual travel distance. Therefore, a linear viscous resistance was considered and the computations were done using the travel path shown in Fig. 5b. Fig. 15 shows the responses of travel distance (displacement), velocity and acceleration of the center of the landslide mass as a function of time. The maximum velocity was 14.4 m/s and the velocity of the earth flow was 13.6 m/s when it reached Kuzulu. Furthermore, the flow reached Kuzulu after 300 s (5 min) which is consistent with the information obtained from eyewitnesses.

The impact pressure of the earth flow on structures can be estimated from the fluid mechanics approach, which is commonly used for estimating tsunami forces and impact forces on objects due to the motion of fluids (i.e. Prandtl and Tietjens, 1934). If the fluid mechanics approach is utilized, the impact pressure would be a function of the density and velocity of debris. The pressure exerted on a unit area of a rigid wall would be about 170 kPa. For this impact pressure, masonry and wooden buildings would be easily destroyed while reinforced concrete structures may resist such forces if they were founded in ground with a sufficient number of reinforced concrete columns. Fig. 16 shows some examples of damages to buildings in Kuzulu. It seems that the reinforced concrete structures resisted well against the impact pressure of the earth flow.

5.3. Effect of a future earthquake on the mobilized mass

As mentioned previously, 1939 Erzinçan earthquake was strongly felt in the vicinity of Koyulhisar and many slope failures occurred. MKS intensity of the 1939 Erzinçan earthquake was IX. The maximum ground acceleration would be in the order of 0.3G to 0.9 G depending upon the ground conditions. The maximum ground acceleration was measured to be about 0.5 G in Erzinçan city during the 1992 Erzinçan earthquake (Aydan and Hamada, 1992). Since there is a huge potentially unstable mass in the source area of Kuzulu landslide, it would be desirable to check the possibility of the earth flow of this potentially unstable mass under seismic excitations. Therefore, the acceleration records measured at Erzinçan station of the Turkish Strong
Motion Network operated by the Earthquake Research Department (ERD) of the General Directorate of Disaster Affairs (http://www.angora.deprem.gov.tr) were utilized for this purpose. The material properties and slide profile were assumed to be the same as those used in the previous analysis. Fig. 17 shows the responses of travel distance (displacement), velocity and acceleration of the center of the landslide mass as a function of time. Although the accelerations, velocities and displacements are similar to those of Figs. 15 and 17, in Fig. 17 the first 50 s shows the effect of earthquake shaking on the landslide motion. The computed maximum velocity is 14.4 m/s and the velocity of the earth flow is 13.6 m/s when it reaches the Kuzulu district. Furthermore, the flow reaches the district after 300 s (5 min). There is almost no difference in computed results in the previous case and this case. The earthquake excitation only acts as a triggering mechanism for the landslide.

6. Conclusions

Mountainous areas are often associated with problems of slope instability and landsliding. Large landslides are often characterized by complex activity resulting from their capability to suddenly change behavior. These landslides may pass from a slide to a flow with relatively high mobility. The Kuzulu landslide case history outlined in this study is a complex and large instability phenomenon. The possible causes of this landslide, its mechanism and back-analysis of the initial slide, motion of the sliding body with its impact on structures and effect of a future earthquake on the mobilized unstable mass still remaining at the source area as a possible future threat have been discussed in this study.

Site investigations and stability analyses suggested that the sliding surface was composed of a circular surface passing through the highly weathered soil-like volcanics and a planar surface along the interface between the volcanics and underlying limestone. Then, due to high water pressures developed in the soil and steep slopes in front of the failure zone, the displaced material transformed into an earth flow, and moved through a V-shaped channel carved in the underlying limestone until it stopped at Kuzulu located at considerably lower elevations. Since there was no earthquake nearby before and at the time of the landslide, the possible causes may be creep and/or increase in water pressure due to thawing of frozen groundwater and melting snow. However, the back-analysis results of the landslide on 17 March 2005 (initial sliding in the source area) indicated that the most likely cause should be pore water pressure increase due to snow melting and thawing of the groundwater. It is also noted that on the basis of the interpretations on pre-event air photos and information obtained from eyewitnesses, it is evident that the slope movements in the study area are continuously occurring for many years indicating their retrogressive character and the possibility of a future large landslide.

The simulation of the landslide with consideration of Bingham type yielding criterion together with water pressure increase yielded likely displacement, velocity and acceleration responses. The simulation indicated that the maximum velocity was 14.4 m/s and the velocity of the flow was 13.6 m/s when it reached Kuzulu. Furthermore, the earth flow reached this village after about 300 s which is consistent with the information obtained from eyewitnesses. Based on the fluid mechanics approach, the impact on the structures by the earth flow could be about 170 kPa against which only reinforced concrete structures can be resisted. Observations on the houses at Kuzulu village confirmed this conclusion.

A huge part of the mobilized unstable mass still remains in the source area. In addition, the source area and its vicinity is an old landslide zone. Particularly the rise of groundwater pressure can reactivate these masses. Since the mechanical properties of the landslide material are already in their residual state, small disturbances can easily cause catastrophic slides in the source region as well as in the dammed section of the landslide mass. There is no doubt that reactivated landslides and associated earth flows will occur during rainy seasons and next thawing seasons of snowfall. Since the area is also known to be seismically very active, earthquakes could trigger further slides and flow
of the already mobilized landslide mass. The consideration of seismic loading as observed in 1992 Erzincan earthquake indicated that the potentially unstable mass can cause further landslides of similar characteristics and earthquakes act as triggering mechanism.

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