ORIGINAL PAPER

Studying the Interaction Between Active Faults and Landslide Phenomenon: Case Study of Landslide in Latian, Northeast Tehran, Iran

A. Khorsandi · S. H. Ghoreishi

Abstract In this article, the interaction between active faults and landslide phenomenon is studied. The case study concerns the landslide in the east of Latian Dam to the northeast of Tehran, the Capital of Iran. The methodology was based on geological studies, geomorphologic studies, the study of landslide phenomenon including its characteristics and its parameters, hydrogeology, geological engineering and the geotechnical studies. The results show that landslide is located in the crush and mylonitized zone of the Roodehen active fault. The geological formation includes the landslides of the Eocene tuffs, which have been severely crushed and pulverized by the Roodehen Fault's actions, and for this reason, they show very weak geotechnical characteristics compared to the natural tuffs. The layering slope of the formation is according to the natural ground slope and facilitates their slips. According to the results, the main reason for landslide is the impact of the Roodehen active fault and the creation of crush and mylonitized zone in the Eocene tuffs, while the secondary parameters are the local geological structures, the unfavorable conditions of the groundwater and their inadequate drainage and the construction of a road along the ground layers. The existence of groundwater, the low impermeability of the landslide materials and the inadequate drainage are also under the influence of the fault. Moreover, based on the results of this research and the location of the considered landslide and a number of others along the Roodehen Fault, it became possible to study the fault's activity from a seismotectonic point of view and to estimate the magnitude of such an eventuality by methods other than the conventional ones.

Keywords Landslide phenomena · Faults impact · Latian · Iran

1 Introduction

Landslide is a problematic geological phenomenon caused by a number of parameters. The main factor considered in this study is the fault. The different faults, particularly the active and seismic ones, displace earth materials (soil and rock) at the time of renewed agitation. Moreover, the mentioned faults crush and pulverize rock that is creating a landslide potential in them. The pulverization of rocks reduced impermeability and causes a poor drainage in the rock. The fault sometimes acts as the agent for transferring groundwater to the crush zone. Therefore, the availability of groundwater and the lack of appropriate drainage are secondary factors of landslide.

There were many studies in the context of this research; some of them are listed below.

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The landslide specifications such as displacement, the velocity and depth are mentioned (Keefer 1984).The distance of landslides from faults is the first factor of ranking and also the most important of the factor predisposing to landslides (Donati and Turrini 2002). During the 7.9 Richter earthquake in the Denali Fault in Alaska, which occurred on November 3, 2002, unconventional landslides happened. These landslides are located on a narrow strip of 30 km in width and 300 km in length along the fault's rupture (Harp et al. 2003).The rainfall, runoff, the topography, structural geology and material properties could also be possible affecting factors on landslides mechanism(Yuan et al. 2005). The tectonics process creating high angle normal fault, the thickness and spread of weathering granitoid of mantel and the depth of valley lead in several landslides (Letto et al. 2007). The landslide of Mobarakabad in the northeast of Tehran is associated with the activity of the Mosha-Fasham Fault as predisposing factor (Farhodi and Derakhshani 1999). The landslides of the Taleghan region to the northwest of Tehran had good natural coordination land sliding and fault density as well as distance from faults (Ghayomian et al. 2003). The landslide of Emamzadeh Ali in the north of Iran occurred on the crush zone of the fault (Ghamgosar et al. 2006). There were 25 cases of landslides in the Birjand region in the east of Iran, which were mainly associated with the active faults as predisposing factor (Elahpour et al. 2006). The landslide of Kalinrood Village in the north of Iran occurred on the crush zone of the fault (Akbari et al. 2003). In some areas of Hoban, the existing faults and large fissures are preparing factor for landslide formation (Hancher 1987). The existence of faults in each region indicates weak places with high potential for landslides (Cote and Hia 1987). Water infiltration within the limits of faults is quite possible, increasing the risk of landslide by soaking the surface materials (Matsukuras and Mizuno 1986; Fan et al. 1996; Creseenti et al. 1994). The results of other studies show the fault zones with high landslide potentials (Li et al. 1998; Conte et al. 1991; Morisawa and Hack 1984; Menges 1993). In Iran, the existence of long fault in foot of heights and local faults is a main predisposing factor for landslides formation (Zomorrodian 2004). The topography, geomorphology, rock type and network faults condition the general landslides in the past and even those occurring today(Bhalai 2010).The majority of landslides were situated on faults (Hosseini et al. 2011). Marques et al. (2011) using a setoff predisposing factors for cliff failures which mainly related to lithology, structures geology, faults and geomorphology.

The research reviews the landslide phenomenon of Latian Dam in the northeast of Tehran, the Capital of Iran (Fig. 1).Within the scope of the study area in the southern coast of the Latian Dam's Lake, there are many signs of landslides along the Roodehen Fault and its branch as a predisposing factor, and the phenomenon considered in this study is located to the east of the Latin Dam (Fig. 2). The altitude of the case study is 1,660 m above the sea level, located at 35°47′ North and 51°41′ east of Meridian. It occurred in March 2006, but the displacement of ground materials continues still at various intensities (at velocities of between 1.5 m per month and 1.5 m per year). The dimension of the landslide phenomenon is 480 m in length, 210 m in width and approximately 35 m in depth (Fig. 1). The geological characteristics of the landslide include heavily crushed and altered green tuffs with intrusions of dike and sill, located on the crush zone of the Roodehen active fault. The existence of groundwater and precipitation infiltrates has reduced the resistance of ground material causing land movement.

The landslide phenomenon was studied from geological, geomorphologic, hydrogeology, geological engineering and geotechnical aspects to determine its characteristics. The results show the landslide to be located in the footwall of the fault as preparing factor, which includes the crushed zone of different tuff, volcanic and pyroclastics rocks of the Eocene era (Fig. 3). The groundwater is directed by the fault to this zone (Fig. 6). The slope of the rock layers is parallel to the ground slope, which intensifies the slide of ground materials (Fig. 3). The secondary parameters such as lack of drainage by ground materials, the unfavorable condition of groundwater and the construction of road perpendicular to the alignment of the layers and the direction of the ground materials, movement have assisted the landslide and the subsequent movements.

Based on the study's results, it is believed that given the location of landslides on the margin of the faults as predisposing factor, their active states from a seismologic aspect can be studied, and the results of this research in the context of the above theory can also be applied to similar cases in the world.
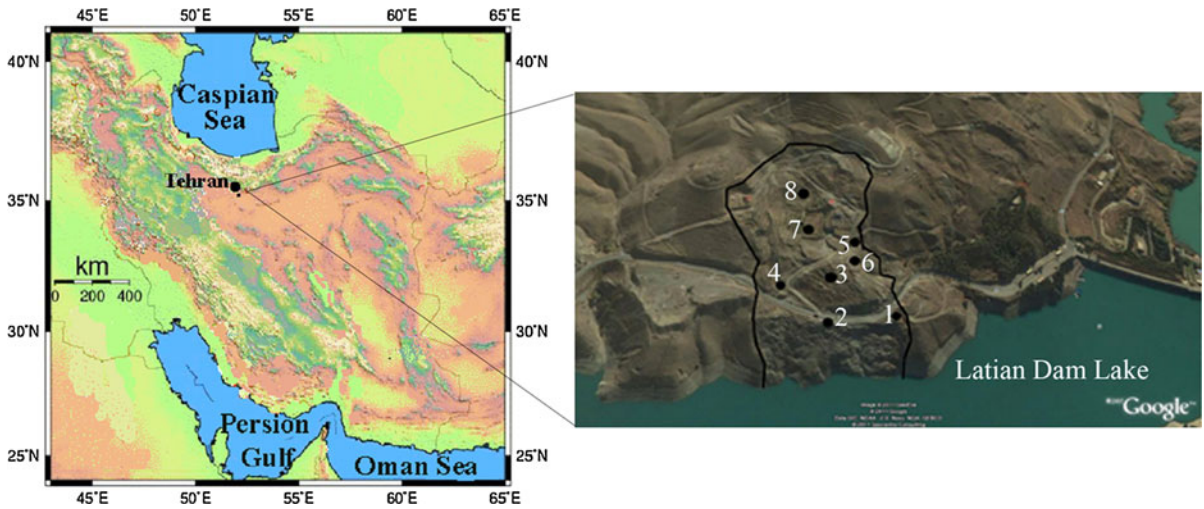
Fig. 1 The situation of Latin Dam landslide with boreholes (*1*, *2*, *3*, …) in northeast of Tehran in north of Iran. The landslide located in east bank of Latian Dam Lake, which their strike is southeast to northwest
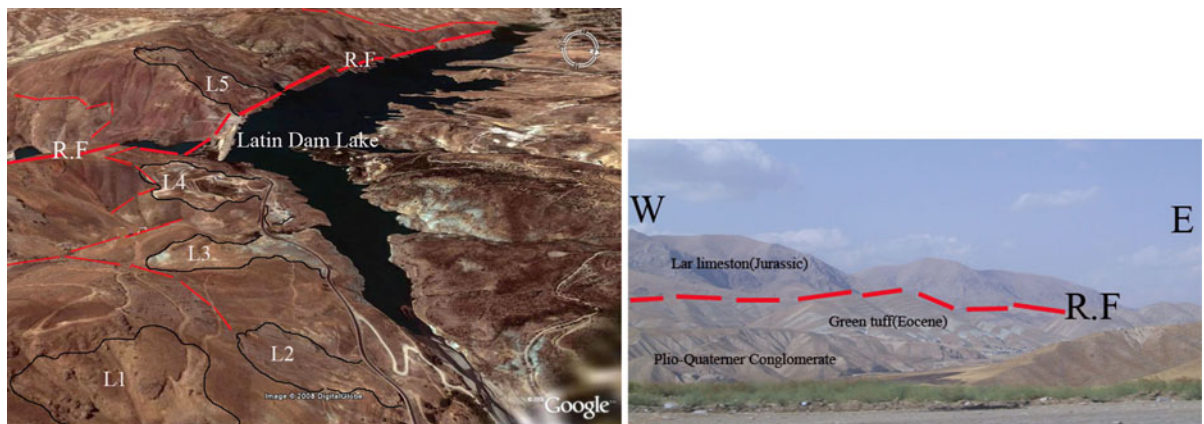

Fig. 2 The satellite image of Latian landslides (*L1*–*L5*) situation. The old landslides are *L1*, *L2*, *L3*, *L5*, and studied landslide is *L4*. The whole landslides situations are on active

Roodehen Fault and its branch. The *right* picture shows the Roodehen Fault in the north of study area

2 Geology, Structural Geology and Geomorphology

The geological map of the scope of the Latian landslide and its geological section is presented in Fig. 3. The existing geological formations within the study area are as follows:

Cambrian: The geological formations related to the Cambrian era consist of micaceous variegated and shale, cherty dolomite and siltstone (Barut Formation) ($\mathbb{C}_{bt}$), micaceous red siltstone, calcareous shale and sandstone (Zaygon Formation) ($\mathbb{C}_z$), red arkosic sandstone (Lalune Formation) ($\mathbb{C}$), which have probably been thrust upwards by two faults and placed in the proximity of newer formations (Fig. 3).

Jurassic: Lumped to thick-layered limestone and dolomite (Lar Formation) (Jl) is found in the Jurassic section.

Eocene: Thick-layered green tuff, tuffaceous shale, pyroclastics, tuff breccia, light green to gray calc limestone, shale, tuff and gypsum (Karaj

Fig. 3 The geological map of Latian Dam landslide and its geological cross section (**A**, B′). The R.F. is Roodehen thrust and active fault. The *R.F.* situation is between Eocene (*Ek*) and Jurassic limestone (*Jl*). The Jurassic limestone upthrusted on Eocene rock by Roodehen Fault mechanism
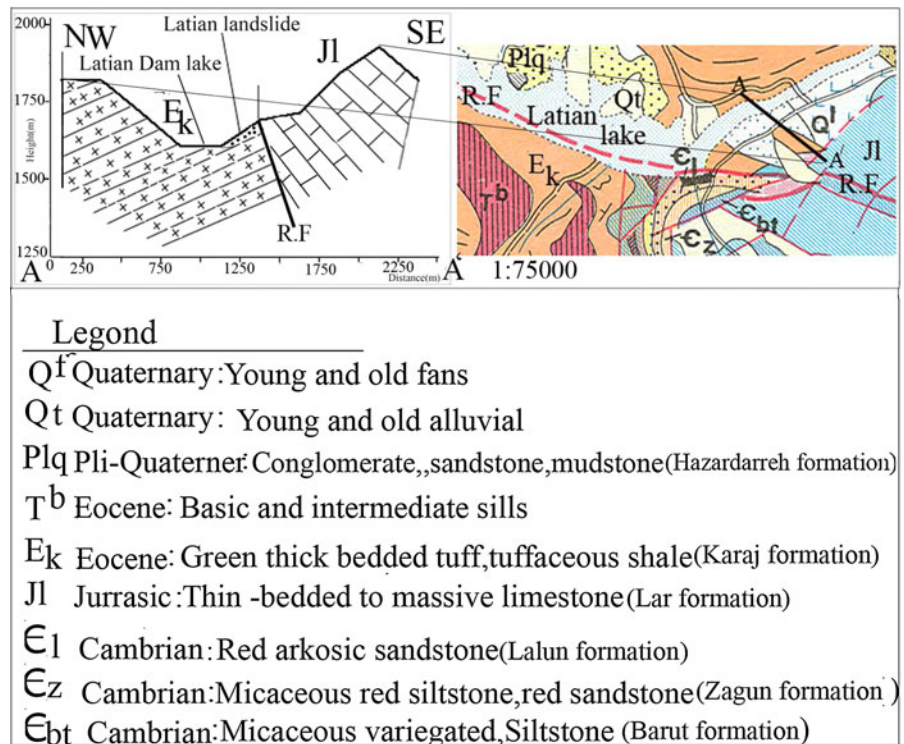
Formation) (E_k) have outcropped. The Latian landslide is located in the thick layered of green and gray tuff, volcano, marly tuff and altered calcareous tuff (E_k) (Figs. 3, 5).

Oligocene: Outcrops of basic sills (T^b) can be seen in the Oligocene section.

Pleistocene: Conglomerates, sandstone and mudstone (Hezardare Formation) (PL_q) form the Pleistocene.

Quaternary: Young and old conglomeratic alluvial (Q^t) and old and recent alluvial fans (Q^f) are observed in the Quaternary outcrops.

The structural geology of the study area includes Paleozoic and Cenozoic folds, which have been dissected and displaced by numerous faults. The main faults are the Mosha-Fasham overthrust faults, which have thrust the Eocene formation on the Quaternary sediments. The next fault is the North Tehran Fault which has placed the Eocene sediments next to the Quaternary sediments, and to the west in the north of Tehran, has caused the thrusting of Eocene sediments over the Quaternary ones. The Roodehen Fault (R.F.) is located on the top and west side of landslide, which has

caused the slip of Cambrian sediments over the Eocene formation and the Latian landslide and other landslides (Fig. 3) are located on its footwall. The last fault is located in the south, which has placed the Eocene sediments next to the Quaternary ones (Fig. 3).

The geomorphology of the study area includes anticline of Eocene (E_k) and Jurassic (Jl) formation (Fig. 3). The erosion process on anticline caused a big valley to be formed. The Latian landslide is located on southwest wall of valley (Fig. 3) where the Eocene layers slope is parallel to the ground slope which facilitates the ground material to slide. The ground slope in Latian landslide is different from top to down (Fig. 4). The landslide ground slope is 25–30 % in southeast and 5–10 % in middle to northwest of landslide (Fig. 4).

3 The Characteristics of Latian Landslide

Based on the results of field visits and measurements, the Latian landslide is a part of a larger and old landslide, which has occurred at a distance of 500 m to the east and upstream of the Latian Dam
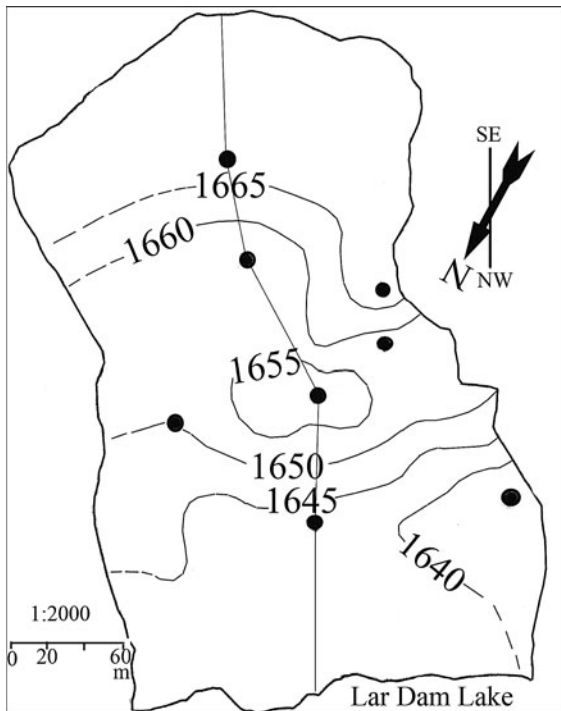
Fig. 4 The topographic map of Latian landslide with direct of engineering geology cross section. The topography map shows two ground surface slopes that are formed by landslide mechanism

(Fig. 1). The minimum and maximum heights of the old and large landslide are 1,600 and 1,725 m, respectively, while the new landslide is located at a level of 1,660 m above the sea (Fig. 4). The large and old landslide occurred in the green and gray tuffs of the Eocene (Karaj Formation), which are intensely crushed and pulverized, and have been completely distorted by infiltrates in form of dikes and sills. The crushed and pulverized rocks of the Karaj Formation are the results of the transmission of the Roodehen Fault and are considered as its secondary branch (Fig. 5). The movement of the landslide is in a northerly direction, and the displacement intensity of ground materials varies with the type of material involved. Based on measurements, the landslide is between 33 and 38 m deep, 470 m long and approximately 210 m wide. The landslide is a combination of transitional and rotational types, in which the direction of material displacement and velocity is not quite equal. The measured landslide velocity varies between 1.5 m per month and 1.5 m per year. The

southern boundary of the landslide is the Roodehen Fault branch, and it is limited to the north by the Latian Dam's lake, while waterways compose its auxiliary boundaries (Figs. 1, 3).

4 Hydrogeology

The groundwater level in the ground materials within the limits of Latian landslide is high reaching a maximum of between 30 and 32 m in the borehole no. 6 located in the northwest of the slip and a minimum of between 14 and 15 m from ground level at borehole no. 1 at the beginning of the slide (Figs. 5, 6). The study of the groundwater table in the boreholes drilled in the landslide shows the water flow to be in a south to northerly direction. Moreover, the existence of numerous springs to the south of the slide reveals the impact of the Roodehen Fault and its auxiliary branches on transmission of water from the Jurassic limestone formation (the Lar Formation) to the northwest of the landslide and the encounter of the groundwater with the crush and pulverized zone of the fault and the appearance of springs. Therefore, despite the southerly slopes of the geological layers of Cambrian and Jurassic formations, the groundwater in these formations is directed to the north by faults and fractures, and after encountering with the crushed and pulverized zones, which have a lower permeability, it is raised to the top to appear and numerous springs at ground level. Obviously, the availability of groundwater in the crushed rocks of the landslide zone is a factor contributing to the movement of ground materials and creation of landslide, which has been shaped under the influence of the overthrust Roodehen Fault.

5 Engineering Geology

Ten boreholes of a total depth of 630 m were drilled at different points on the landslide in the context of identifying the materials forming the Latian landslide and to determine the groundwater table, the permeability and the standard infiltration (Figs. 1, 5). The geological log of the deepest borehole (74 m) is presented in Fig. 5. According to the log, there is a mylonitized zone from ground level down to the depth of 32.2 m and a fault crush zone from the depth
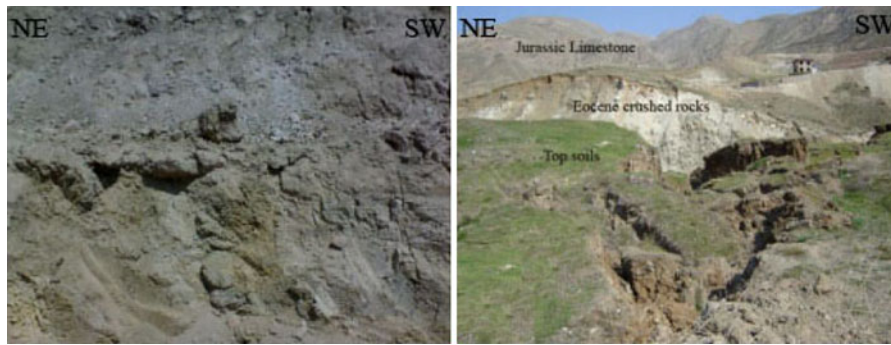
Fig. 5 The picture of Latian landslide and its crushed rocks. The *right* picture shows the landslide from northeast to center, and the *left* picture shows the crushed Eocene rocks
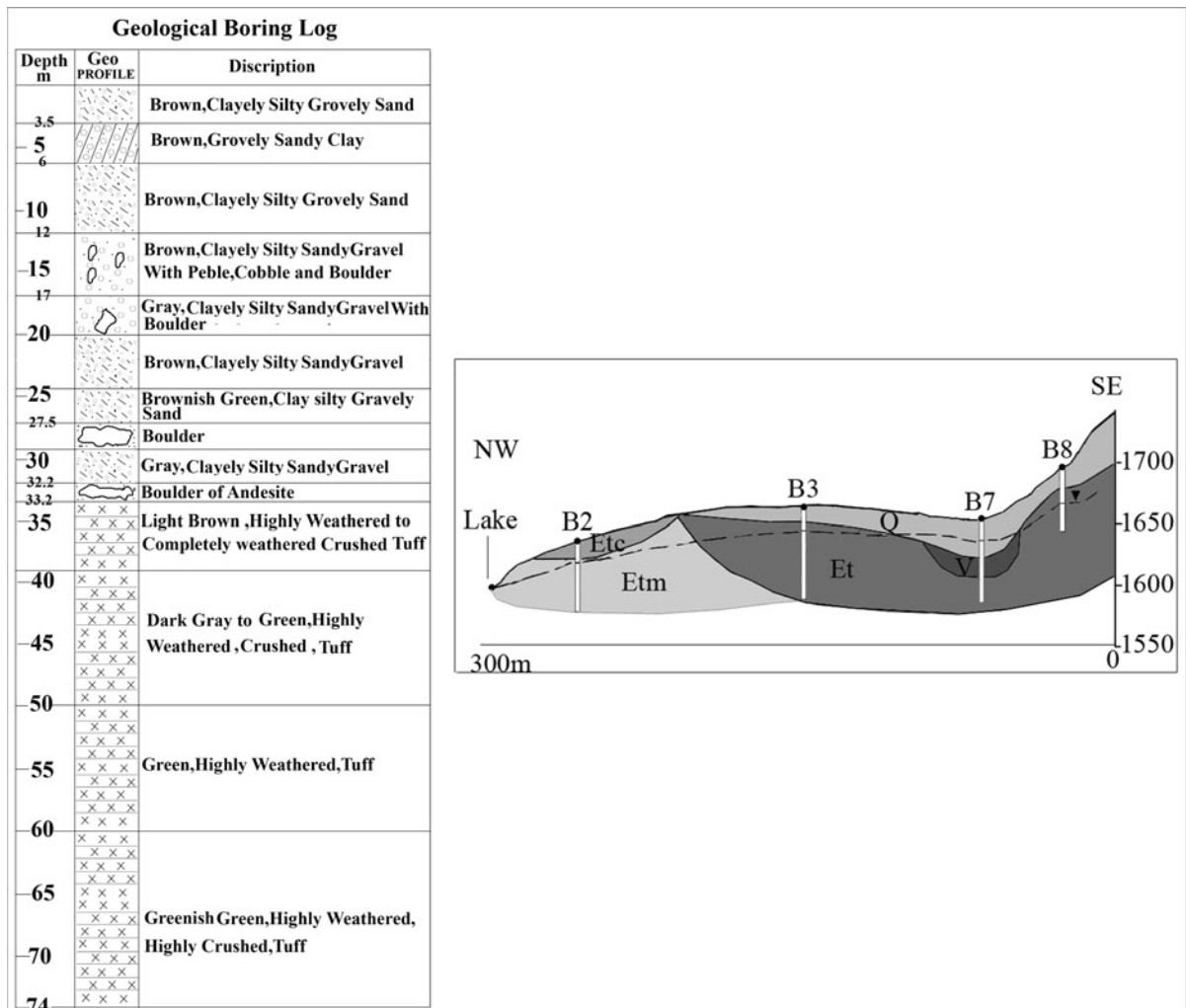

Fig. 6 The engineering geological cross section of Latian Dam landslide on base of borehole logs with the deepest borehole log (*B7*). In cross section, the *Q* is altered material, the *Et* is *green* and *gray* tuff, the *V* is Eocene volcanic rock, the Etm is marly tuff, and the Etc is altered calcareous tuff. The groundwater table is signed by *spaced line* and *filled inverted triangle*

Table 1 Geotechnical character's of Latian landslide boreholes

Borehole (no.)	Depth (m)	Altered material thickness (m)	Rock (m)	Lufran	Lugeon	C.P.T
1	60	23	37	4	2	20
2	54	25	29	1	0	13
3	75	19	56	8	7	9
4	45	25	20	8	7	13
5	70	12	58	2	3	16
6	80	9	71	3	6	15
7	74	25	39	7	0	25
8	64	9	55	0	4	10

Table 2 Comparison between intact and altered tuff geotechnical characters

Rock	Classification GSI	Cohesion (KPa)	Angle internal friction (Degree)	Tensile Strength (10^{-2} kPa)	Compressive Strength (KPa)	Deformation modulus (MPa)
Intact tuff	25–35	236–434	29.7–30	300–1,200	1,110–2,988	370–680
Altered tuff	10–20	37–79	10.7–14.9	3.9–18.7	28–95	0.30–0.46

of 32.2 m down to 74.5 m. The slip level was determined at the depth of 32.2 m. The permeability of ground materials in Latian landslide is very low and was measured at between 10^{-6} and 10^{-5} m/s. The low permeability of the landslide material is associated with the mylonitized and crushed zone of the Roodehen Fault and the existence of small aggregates such as silt and clay. The Fig. 5 shows the engineering geology cross section of Latian landslide on base of 4 borehole data.

The standard infiltration of the landslide materials varies from a minimum of 8 to a maximum of 25 impacts per 0.15 m of infiltration.

6 Geotechnical Parameters

The geotechnical parameters of Latian landslide based on 8 boreholes of total depth of 522 m are listed in Table 1. In table, the maximum depth of landslide is 25 m in boreholes number 7, 4 and 2. The comparison of geotechnical parameters of the Eocene rock of Latian landslide (tuff, E_k), which have been crushed and pulverized by the Roodehen Fault and its branch as predisposing factor with intact Eocene rock (tuff, E_k), reveals a sharp decrease in their geotechnical properties (Table 2). The weak geotechnical parameter of tuff is

one mine factor for Latian landslide formation and its displacement. The weak geotechnical parameter is created by Roodehen Fault and its branch as readying factor.

7 Discussion and Conclusion

The study of the Latian landslide located next to the active Roodehen Fault and on its crush zone reveals the impact of the fault on the landslide as the readying factor, main parameter and the controller of some auxiliary factors as shown in the flow chart of Fig. 7.

As shown in the chart, the two factors of geology and the active fault of Roodehen are the main actors in forming the Latian landslide. The geological parameters including the rock materials and the layering condition of the rock in relation to the ground slope are the main factors of landslide, while the active fault's parameters such as the crush and mylonitized zones, which have a very weak geo-mechanical properties and receive water from the active fault through the Jurassic limestone formation, have led to the landslide. The materials of the crush and mylonitized zone have a very low permeability, and their groundwaters are not drained properly, forming the secondary factors in
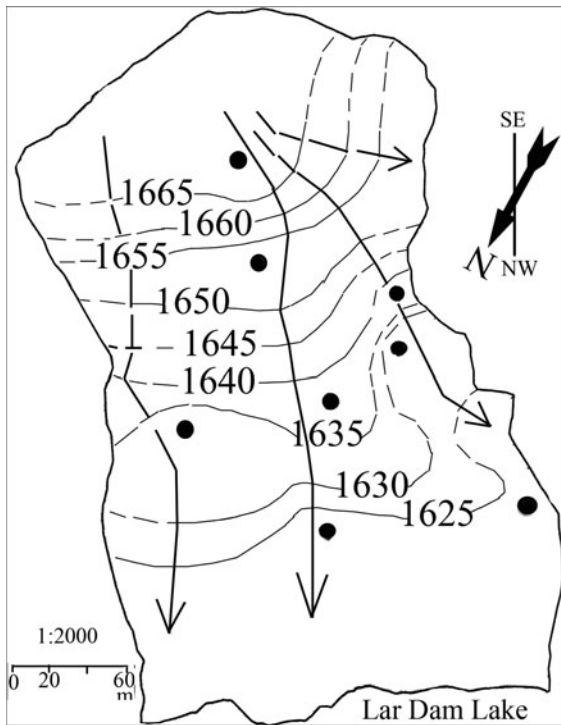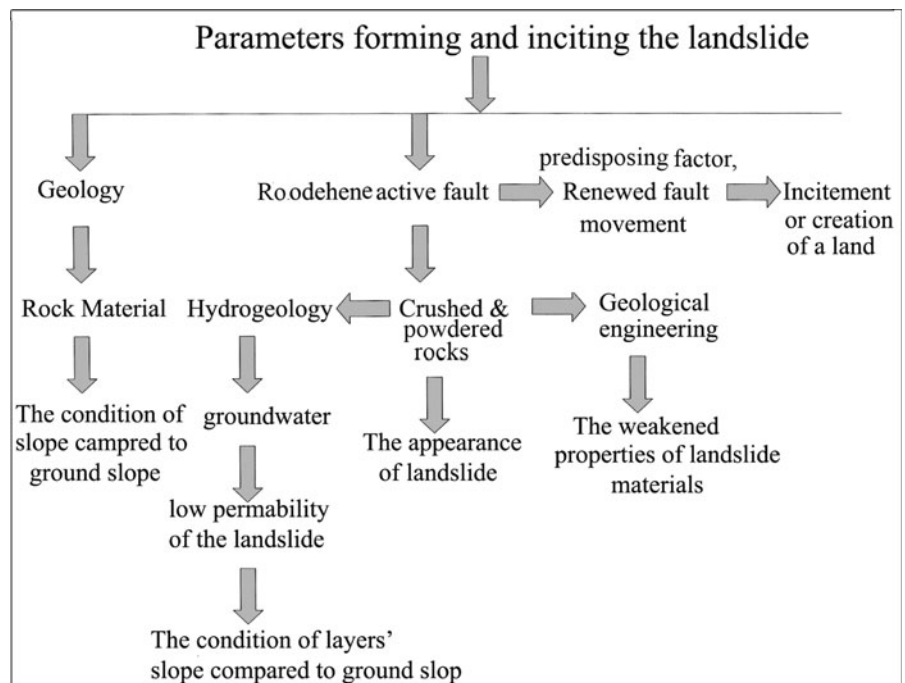
Fig. 7 Hydrogeological map of Latian landslide, which ground-water flow is from southeast (Lar Limestone) to northwest (Lar Dam Lake).The groundwater hydraulic gradient is different in landslide area. The minimum hydraulic gradient observes in southeast and maximum in northwest

inciting the landslide. They are under the influence of the main parameter, that is, the active Roodehen Fault and its branch. Moreover, the renewed fault movement would lead to seismogenic, which in turn would further incite or create the landslide. Therefore, based on the availability of landslide on the margin of the faults, their active state and their number, the magnitude of their probable earthquake can be estimated (Fig. 8).

The results of the studies show the followings:

1. There are a number of landslides, including the Latian landslide along the margins of the active Roodehen Fault.
2. The Latian landslide was formed in the Eocene tuffs located in the crushed and mylonitized zone of the fault.
3. The slope of the tuff layers follows the direction of the ground slope, which forces their slip.
4. The Eocene tuffs are crushed by the fault's activities and are of mylonitized type and have very weak geotechnical properties compared to natural tuffs.
5. Water is conveyed from the Jurassic limestone formation by the Roodehen Fault to the Eocene tuffs that have a very low impermeability and inadequate drainage.

Fig. 8 The flow chart on base of research idea shows impact of the fault on the Latin Dam landslide as the main factor and the controller factor of some auxiliary factors

6. The existence of a number of landslides along the margin of the Roodehen Fault proves the latter's active and seismic state.

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