

Mechanism of the giant Seimareh Landslide, Iran, and the longevity of its landslide dams

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Abstract Seimareh Landslide (SL) is globally recognized as one of the largest rock mass movements in the world. It is located along the border of Ilam and Lorestan provinces in southwest Iran, in the heart of the Zagros Mountain Range. There are controversial findings about the mechanism of the landslide formation. This field work study reviewed the possible mechanisms of failure and analyzed post-failure geomorphic features. Drainage pattern disturbance in the depositional region and consequent dammed lake formation are among the most significant characteristics of these features. Seimareh, Jaidar and Balmak are three large landslide-dammed lakes. The present study analyzed the processes responsible for the formation and erosion of the Jaidar and Seimareh Landslide dams using the available annual sedimentation and field measurements of the sediment deposited in these lakes. The results showed that the SL dam has been formed about 935 years after the landslide event. Detailed field investigations indicated a specific hydro-morphological condition in the landslide area. The results implied that the main causes of the failure were probably the particular hydro-morphological characteristic of the landslide source area together with the enormous eroding energy resulted from merging of two high-flow rivers which eroded the base of the southern flank of Kabir-kuh Mountain. However, the unusual size of the landslide suggests that an external factor, e.g., a huge earthquake, might have triggered the failure.

Keywords Seimareh Landslide · Mechanism · Landslide dam · Iran

Introduction

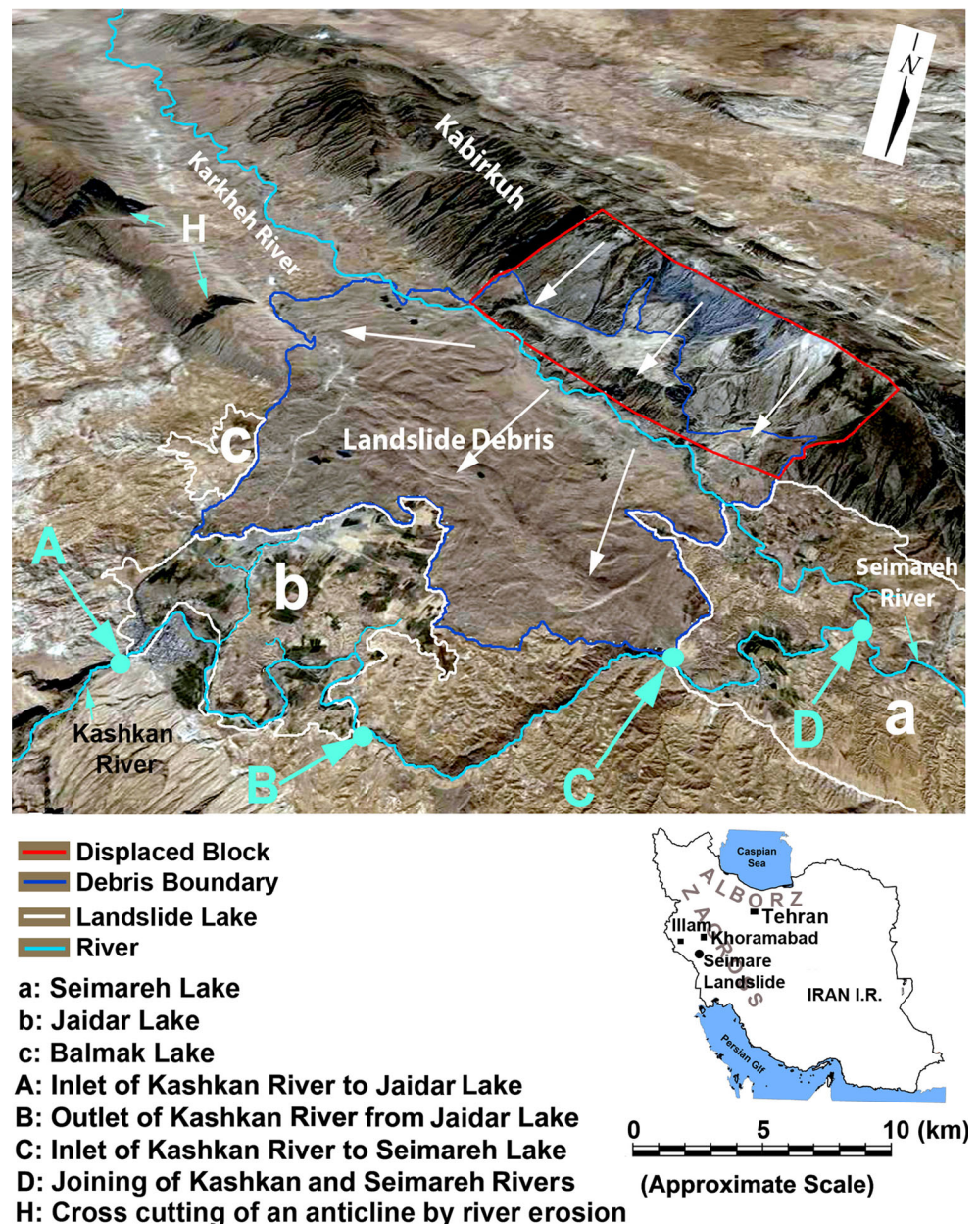
Mountains cover approximately 50 % of the Iran's total land. The Alborz and Zagros mountain ranges are the highest and longest mountain ranges in the north and west of the country, respectively (Fig. 1). High heights, geographic locations, and Mediterranean weather fronts increase the annual precipitation of these mountains over 450 mm that is significantly higher than the country's annual average of 250 mm. Furthermore, steep slopes, relatively high precipitation, and variations in geological contexts along with frequent earthquakes make them prone to slope instabilities.

Seimareh Landslide (SL) in southwest of Iran, and in the middle of Zagros Mountain Range, is one of the largest known landslides worldwide (Fig. 1). The SL was discovered and introduced for the first time by Harrison et al. (1935), and Harrison and Falcon (1937, 1938), during an oil exploration project. Their report included a 1:100,000 scale geological map and this slope movement was named Saidmarreh landslip. As the name of river basin and river in all geological documents of Iran is Seimareh, the first nomination to Saidmarreh landslip might be affected by the local dialog. Later, Oberlander (1965) and Watson and Wright (1969) conducted a geomorphic study on the landslide. The most recent study was published by Shoaie and Ghayoumian (1998, 2000) with a complete review of previous studies and some detailed field work. During the last few years, disasters caused by a similar failure have drawn the research interest of the local government and the regional development planner on this landslide.

It seems that SL was started by creeping of a giant block of hard rock overlaid the soft and low strength formation. The mechanism of this event has been described by the processes such as “mass rock creep” and “deep-seated creep” (Mahr 1977; Radbruch Hall 1978), “lateral

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Fig. 1 Front perspective view of the Seimareh Landslide (reproduced from Google)



spreading of ridges” (Radbruch Hall et al. 1976; Varnes 1978) and “sagging of mountain slopes” (Huchinson 1988). Deep-seated gravitational deformations and the relevant huge landslides are complex phenomena occurring through various mechanisms whose genesis and evolution are controlled by several factors. The most important factors are the structure, relief, tectonic, and seismic activity. However, the mechanism that produces “spreading” of mountain ridges with uphill-facing scarps and trenches on hillsides is still not completely understood. Consequent rock avalanche is characterized by sudden release of massive rock (Scheidegger 1973) reduced to minute grain size that moving as an avalanche that is very difficult to interpret because of their sudden evolution and scales.

Complexity of internal structure and type of involved deposits covering various materials ranging giant boulders to fine grains, interpretation of the mechanism and the use of failure models have not been successful. Banihabib and Shoaei (2000) presented a 2D model and showed a close correlation between the predicted travel distances (run-out) of the material and the field measurements. However, they had to use a hypothetical velocity reduction coefficient.

Methodology

Simulating the geomorphic conditions of the landslide area prior to the failure requires both extensive and

expensive geophysical explorations beyond the financial capacity of this study. Therefore, to analyze and interpret the failure mechanism and to achieve a relatively informative look-back at the paleo-geomorphology of the source area before the landslide event, information about the landslide features and characteristics were collected and compared with the present conditions of similar areas at the vicinity of the landslide (Shoaei et al. 2006). Then, possible effective factors in the initiation of this landslide were investigated and the differences in geomorphic features and scale were considered and analyzed. It was also assumed that an exceptional factor in the Seimareh sub-basin might have triggered such an unusual landslide.

In the first step, a 3D view was produced from satellite images of the landslide area, geomorphic features were recognized, and the limits were defined (Fig. 1). Then, the source area boundary, the detached rock mass, and the distribution and propagation of the displaced material in the Seimareh Valley were outlined. In addition, the lake sediments boundaries for the three main lakes formed by landslide dams were identified (Fig. 3). Afterwards, by measuring the altitude of the sliding block, deposited material, and selected benchmarks along the axis of the river, the profile along Seimareh River and Seimareh Lake was prepared (Fig. 3). In this work, a relatively precise geological map was prepared for the Seimareh area using available geological maps (NIOC 1970) and field survey data (Fig. 3). Finally, a profile of the pre-failure stage of the landslide area was generated based on the field investigation of the surrounding terrain (Fig. 4).

In this work, a hydro-geomorphologic study investigated the hydrology of natural rivers in the landslide area and in some of the adjacent basins. Moreover, longevity of landslide debris dam was studied as one of the most important post-failure events. By comparing the annual sedimentation rate in the lakes formed by the landslide debris with the total thickness of the deposited lake sediments, the standing period of these dams and the time of draining the lakes were calculated.

Study area

The study area covered entire landside including the affected post-failure areas as well as the surrounding region. This zone was located between 32°50'E and 33°15'E, and 47°30'N–48°00'N. These coordinates are part of the mid-Zagros Range tending NW–SE that forms the mountainous region of the Southwest Iran (Fig. 1).

Geological setting of the study region

Stratigraphy

The geological map of the study area was prepared by compiling four geological maps of Dal Pari, Dehloran, Kabir-kuh and Pol Dokhtar (NIOC 1970) and was controlled by some field surveys (Fig. 3). In general, the Zagros geology is a sequence of hard and soft layers exhibiting different levels of shear strength and erodibility. The less erodible sequences, which formed the scarps and cliffs in Zagros region, consists of mid-Cretaceous and Oligo–Miocene limestone beds; whereas, the soft and erodible sequences forming the valleys comprise Upper Cretaceous and Eocene marl, shale, Oligo–Miocene limestone, sandstone, and gypsum.

The geological succession of the study area starts with Upper Cretaceous formations (Aghanabati 2004). The lowest formation is the Sarvak that comprised shale and sandstone with high erodibility. The Ilam is superimposed on the Sarvak and is composed of a loose limestone (Fig. 4). The Gurpi formation overlays the Ilam formation and includes bluish-dark gray marl and some gray marl-limestone that are soft and prone to weathering and erosion. In some areas the lower part of the Gurpi formation changes laterally to white marl-limestone, is 110 m in thickness and is called the Imam Hasan member. Younger Paleocene–Eocene, Oligocene and Lower Miocene sequences include the Pabdeh and Asmari formations. The Pabdeh is 800 m thick and includes thin layers of shale and marl severely prone to weathering and erosion. The Pabdeh formation laterally changes to Amiran (fossiliferous, shale sand), Telezang (dark-gray limestone), Kashkan (shale and sand) and Asmari (thick limestone) formations (Fig. 4). The Asmari formation is 100–550 m of light to brownish limestone and dolomite. This formation forms most outcrops in the landslide area because of its high resistance to erosion, characterized by high-density jointing and fractures.

Overlying the Asmari, Miocene formations of Gachsaran consist of about 1,600 m of salt, anhydrite, colored marl, limestone and some bituminite shale that have been eroded mostly because of their solubility. They form the bedrock of plains and valleys in the area.

The Upper Miocene–Lower Pliocene in the study area consists of Aghajari (marl and red sandstone) and Bakhtiari (siltstone and conglomerate) formations. These formations are almost completely eroded and only a few small outcrops are occurred.

Quaternary sediments in the study area are mostly lake sediments from the SL dams, conglomerate, and alluvial deposits. The initial lake sediments spread over several tens

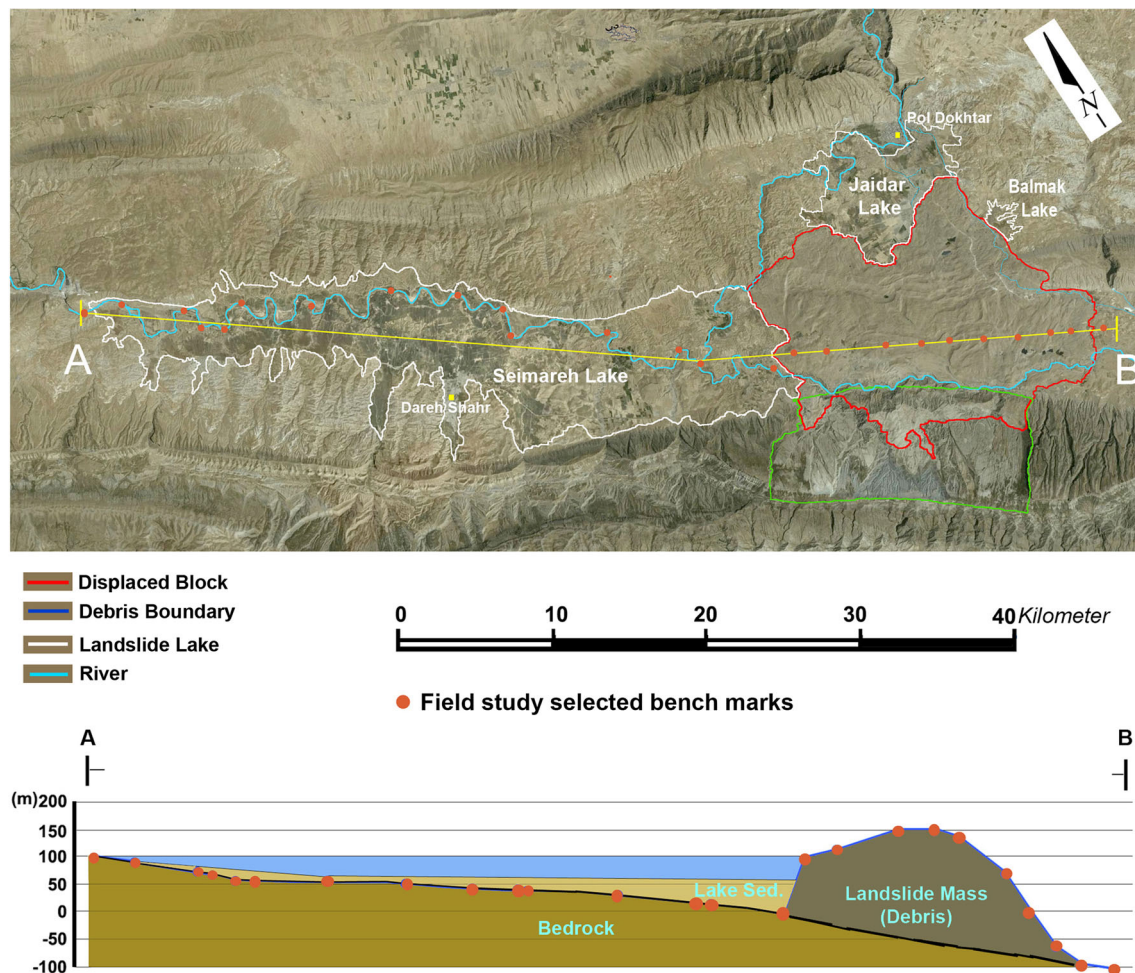


Fig. 2 Plan view of detached block, deposited debris, generated lakes (*top*) and cross section of the Seimareh Dam and Lake along the Seimareh River (*bottom*) (see Fig. 3 for geographic coordinators)

of square kilometers and were deposited in Seimareh, Jaïdar, and Balmak Lakes and several small ponds formed by the SL (Figs. 1, 2). Alluvial sediments resulting from the erosion of different formations have been deposited in the basin by surface flows and floods.

Structural geology and geomorphology

As depicted in the geological map of SL (Fig. 3), the area studied here is a part of the Zagros Range including a series of smooth and gentle folding (NW–SE trending) parallel to the fault system of the area (Aghanabati 2004). Figure 3 shows the studied area, which includes the Sarkan, Sultan, Maleh, Malush, Chenareh and Kabir-kuh anticlines appearing as a whale back morphology because of its plunged structure. Gachsaran formation consists of Miocene gypsum and gypsum lime with severe erodibility, and often severely washed away the valleys formed in the area. Therefore, a relatively wide valley is formed between northern and southern anticlines that include the Sarkan,

Sultan, Maleh, and Kabir-kuh anticlines. This valley is, in turn, divided into two derivative valleys by the Chenareh anticline around its middle parts (Fig. 3). Kabir-kuh Mt. is emerged as limestone ridge anticline of Mid-Cretaceous in the southern part of the area. At the edge of this anticline, there is a zone of Upper Cretaceous section that has been weathered and eroded.

Landslides in Zagros Range

The landslide database of Iran (FRWMOI 2002) indicates that about 98 % of the known, active, inactive, and historical landslides in Iran are located in the Zagros Range in the west and the Alborz Range in the northern part of Iran (Fig. 1). The Zagros Range is affected by humid mediterranean weather fronts and receives a rather high annual precipitation of 440 mm. The stratigraphy conditions of the Zagros, i.e., the alternation of weak low as well as hard fractured permeable layers, its active tectonic structure, and relatively steep slopes make the region susceptible to

landslide. Many landslides occur in the Zagros during intensive rainy seasons every year. Frequent rock falls and landslides have disturbed the natural drainage and morphological conditions of the region and resulted in numerous lakes and ponds in Zagros.

In a regional study (Souri et al. 2009), satellite images were used to identify the landslides with a length or width larger than a kilometer in the mid-Zagros Range. The study revealed 20 landslides, the majority of which was reported as structurally controlled slides. Among the studied landslides, the SL is one of the structurally controlled landslides that has some unique characteristics that are not found in other landslides in Zagros, such as gigantic size, involved geologic formations, velocity and widespread deposited debris.

Seimareh Landslide

Seimareh Landslide is identified as the largest landslide observed on aerial photos and satellite images in the Zagros Range. The complex and gigantic SL is one of the largest instability events among all continental landslides worldwide. It is located at the boundary of Ilam and Lorestan provinces (33°03'N and 47°41'E), south of Pol Dokhtar City (photo 1 in Fig. 5). The SL occurred from the northern hillslope of Kabir-kuh Mt. (Figs. 1, 2). This landslide is a complex type initiated by a block sliding of Asmari limestone and its underlying sediment. The failed rock mass was 16 km length, 6 km width, with an average thickness of 400 m, and detached from the edge of Kabir-kuh Mt. (2,640 m a.s.l.). Subsequently, 38 km³ of debris flowed over two valleys in north of Kabir-kuh and Chenareh anticlines to a distance of approximately 20 km on an average slope angle of about 5° (Figs. 1, 3). Along the way, the debris ran over topographic obstacles to generate local negative slopes in the travel profile.

At present, the lateral edges of the main detached block are visible as near vertical cliffs formed from Asmari limestone (photos 1, 4 in Fig. 5). Assuming that the average density of the hard limestone, shale, and sandstone is 2.1 ton/m³, the weight of the displaced material is estimated at over 79×10^9 tons, qualifying the SL as one of the few mega-landslides on the earth (Shoaei and Ghayoumian 1998, 2000). The detached and displaced material covers an area of approximately 200 km² with a mixture of mainly Asmari limestone and its underlying formation such as the Pabdeh marl and limestone with a wide grain size from fine grains to massive blocks. Blocks of 50×10^3 m³ in volume and 75×10^3 tons in weight were transported for over 10 km from the source indicating the very high velocity and enormous energy of the rock avalanche. One of the morphological characteristics of the SL is the severe disturbance of debris material in the northern plain of

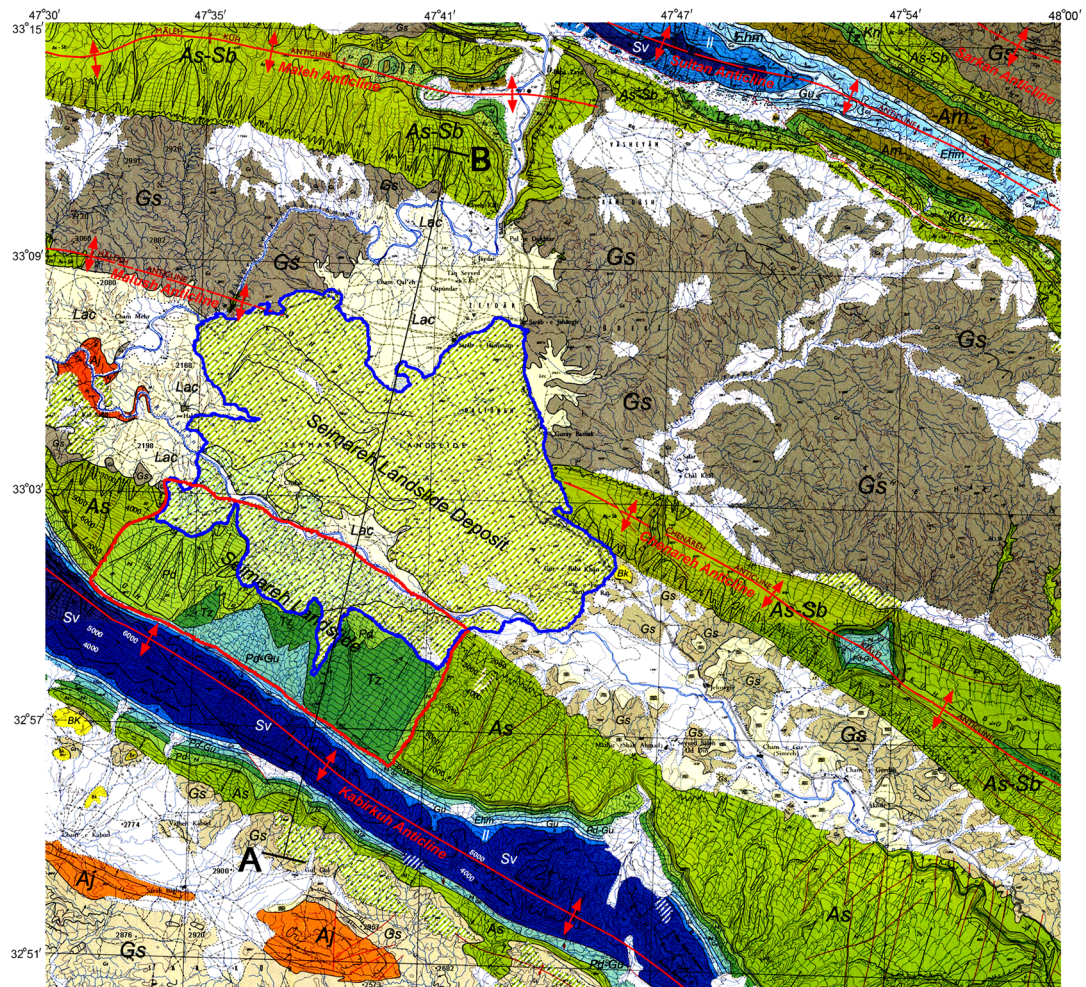
Kabir-kuh Mt. (photo 2 in Fig. 5). According to the legends told by local people, such disturbance is the result of a tribal combat in which giant slings were utilized. Extremely uneven topography and undeveloped drainage network in the area have formed various ponds with variable areas in the debris of the landslide (Fig. 1, photo 5 in Fig. 5).

Velocity and type of transported materials are the two main parameters in classifying this landslide. The rapid initial collapse of the detached block from Kabir-kuh Mt. provided enough energy to convert it into various size particles ranging from fine grains to massive blocks. This debris should also reach a high velocity to move for approximately 20 km distance.

Therefore, according to the Cruden and Varnes (1996) study, the SL should be classified as an extremely rapid landslide. Progression of the debris movement should also be with high velocity; otherwise, such a long movement is highly improbable. The velocity of debris has gradually declined toward the distal limit of the depositional area. The current geomorphology of the landslide site confirms that the transported material moved in an unsaturated debris flow and deposited suddenly. Such a landslide is classified as a “sturzstorm” (Hsu 1975) in which the landslide occurs suddenly and the resulting debris moves with ultra-high speed affecting a relatively large area. Regarding the run-out mechanism, the gigantic SL can be compared with the large historic landslides such as Rossberg (1806) and Elm (1881) in Switzerland (Schuster 1991). As the SL began with a huge rock slide followed by debris ultra-high-speed downward shifting, it could be classified as “complex rock slide-debris avalanche” according to the new classification (Cruden and Varnes 1996).

The mechanism of Seimareh Landslide occurrence

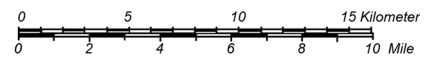
Studying the mechanism of ancient landslides is difficult since there is not enough data available from the pre-landslide event period. Geographic information system (GIS) and field-based studies have proposed new reconstruction methods the Paleo-morphology of landslide area (e.g., Nicoletti et al. 1993; Nicoletti and Parise 1996; Parise and Guzzi 1992). The methodology applied in the present research involves the reconstruction of the morphology of the landslide area based on the morphometric characteristics of similar nearby valleys that are not affected by landslide deposits. Therefore, a detailed geomorphology study was conducted based on aerial photo interpretation and field investigation. The procedures applied in this study can be adapted to the reconstruction of any type of geological body, assuming that the geometrical characters and cinematic evolution are known (Parise and Guzzi 1992).



Geological Legend

		Alluvium and Recent Deposits
		Sub-Recent Conglomerates
Quaternary		Sub-Recent Lake Deposit
		Bkhtyari Formation (siltstone and conglomerate)
u. Pliocene		Aghajari Formation (marl and red sandstone)
Pliocene		Gachsaran Formation (salt, anhydrite, marl, limestone and shale)
Miocene		Asmari Formation (thick limestone)
Oligocene		Asmari-Shahbazan Formation (thick limestone)
		Kashkan Formation (shale and sand)
Eocene-		Talezang Formation (dark-gray limestone)
Paleocene		Amiran Formation (fishoid, shale and sand)
		Pabdeh Formation (thin layers of shale and marl)
		Pabdeh-Gurpi Formation (shale and marly limestone)
		Gurpi Formation (marl and marly limestone)
		Emam Hasan Member (white marl-limestone)
u. Cretaceous		Ilam Formation (loose limestone)
		Sarvak Formation (shale and sand)

AB: Direction of Section on Figure 4

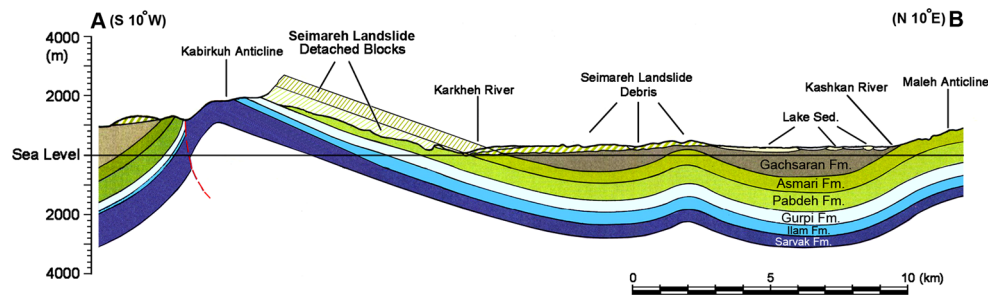


Conventional Symbols

	Road
	Topo contour in feet above SL
	Dip Slope
	Narrow scarp
	Vertical beds
	Anticlinal axis
	High angle fault
	Thrust fault
	Normal dip
	Overturned dip
	Landslide
	Displaced block in Seimareh Landslide
	Limit of Seimareh Landslide debris

Fig. 3 Quadrant geological map of the Seimareh Landslide [compilation of the geological quadrant map of Dal Pari, Dehloran, Kabir-kuh and Pol Dokhtar, NIOC (1970)]

Fig. 4 Geological cross section of the Seimareh Landslide with repositioned stratigraphy before landslide event; direction of section is shown in Fig. 3



The main sources of information used for this method were topographic data, geological maps, mesoscopic structural measurements including attitude of bedding, thrusts, strike–slip, normal faults, and gravitational failure surfaces. The reconstruction of the pre-landslide topography is used to compute the volume of material missed in the source area.

Figure 4 depicts a geological cross section of Kabir-kuh Mt. reconstructed through the analysis of surface geological data where the initial landslide took place. It was found that similar structures of Kabir-kuh are repeated in all northern and southern flanks of anticlines in the whole region. In the most slopes, the Asmari sequence is exposed above the Pabdeh and Gurpi formations. The bedding angle of 15°–20° in all anticlines is one of the main structural similarities throughout the Seimareh area. Such structural similarities are noted at the Maleh, Sultan, and Chenareh anticlines in the north of the Seimareh region. Instabilities of the flanks of the anticlines are common phenomena where harder materials slide over the soft beddings. Along Kabir-kuh, at least 20 landslides were recognized in the aerial photos (Souri et al. 2009). Therefore, as an initial conclusion, structural instability is the main predisposing factor of landslides in the region. Nevertheless, this factor could not be the single cause of a gigantic landslide such as Seimareh. Thus, the investigation was then focused on the triggering factors that could generate such a large landslide on the northern flank of Kabir-kuh anticline, particularly when very large distance of the material took place over a 5° plain. The involved factors must be big enough to detach a 38 km³ mass of rock and to transform it into a high-energy debris sheet spreading out over 200 km².

One of the possible scenarios is that the giant block of rock must have had enough space to slide and transform into a high-energy avalanche of debris. Such a wide and deep space might be formed by extensive erosion at the toe of the slope requiring considerable energy at the toe of the landslide. Based on this hypothesis, conducting hydrological study in addition to the geomorphological assessment is necessary.

Generally, in the Zagros region, both the seasonal and permanent rivers run along the axis of the anticlines.

However, tectonic discontinuities caused some rivers such as the Kashkan River (Fig. 2) to cut through the anticline and enter the adjacent valley to form spectacular geomorphic features (e.g., H in Fig. 2). The Kashkan River is one of the largest rivers in Lorestan Province that crosses the Maleh anticline entering the Seimareh plain to join the Seimareh River. The perspective view of these two rivers is illustrated in Fig. 1, where the Kashkan River joins Seimareh River to form the Karkheh River (point “D”).

Supposing the same climate and precipitation conditions in the region for the time of SL occurrence and the present time, is unlikely a true hypothesis. However, due to the lack of enough data this hypothesis can be acceptable for the analysis of the runoff and sediment loads. Table 1 presents the 30 years of data available in the study area (Saghafian et al. 2007).

The area of the Kashkan River watershed is 9.4 × 10³ km². At its entrance into the Seimareh plain at Pol Dokhtar gauging station (1.5 km north east of Pol Dokhtar City), the average discharge of the river exceeds 43.2 m³/s and its total annual sediment yield is approximately 1.344 × 10⁹ m³. Similarly, the average discharge of Seimareh River containing a basin area of 28.4 × 10³ km², is 125.4 m³/s. Its total annual sediment yield is approximately 3.9 × 10⁹ m³.

Comparing the Seimareh and adjacent basins showed that the joining of the Kashkan and Seimareh Rivers as the Karkheh River resulted in an unusual condition of high discharge and strong eroding force in the basin. Consequently, it changed its direction towards the northern flank of Kabir-kuh anticline and caused severe erosion at the toe of the detached giant slab.

Although the undercutting process is the main cause of the failure, there might be other triggering factors such as a high-magnitude earthquake to provide the acceleration and increase the driving force of the released block capped by Asmari.

Seismic studies in the Zagros region showed that the area experiences earthquakes on a daily basis. Studies of pre-historic earthquakes show that magnitude of 7 (on Richter scale) has been quite common in this region (Ambraseys and Melville 1982). Berberian (1994) claims

Table 1 Kashkan and Seimareh rivers' discharge and the corresponding sediment yield

River	Area of basins ($\times 10^9$ km ²)	Water		Sediment		
		Discharge (m ³ /s)	Total volume of water ($\times 10^9$ m ³ /year)	Discharge g/l	ton/m ³	Annual sediment yield ($\times 10^6$ ton/year)
Kashkan	9.4	43.2	1.344	8.064	0.006	6.0
Seimareh	28.4	125.4	3.9	6.245	0.0016	1.6
Total	38.8	168.6	5.244	14.309	0.0076	7.6

that frequent high-magnitude earthquake with long return periods hit Kabir-kuh area periodically. He reported a magnitude of 7.0 Richter earthquakes on a 200-km-long fault under Kabir-kuh anticline which took place about 11,000 years BP at around 33°N–47°E and probably triggered the SL.

Dating the Seimareh Landslide

Previous studies reported the date of the SL 1,000–1,200 years BP. These studies were mostly based on insufficient historical documents (Shayan 1994). Detailed field investigation of the landslide and surrounding regions showed that this landslide is undoubtedly much older than the previous reports.

The other line of evidence is the historical architecture dating back to the Sassanid dynasty (224–651 AD), such as the remaining foundations of bridges on the landslide-deposited material, or other geomorphologic figures formed from erosion of landslide debris. These constructions date back to approximately 2,230–2,660 years BP. Therefore, the SL must be at least 2,300 years old. Another evidence that can reinforce this statement is the lack of any historical report in 3,000 years of Persian Empire history, when recording such an important event was a common practice.

Remnants of the thick lake sediments in the area indicate the existence of a huge lake subsequently formed behind the landslide dam. The remaining buried vegetation at the bottom of the lake sediments can be used to date the landslide occurrence. In a ¹⁴C isotope-based study, Watson and Wright (1969) investigated the date of the landslide occurrence. They reported the approximate date of SL about 10,000 (± 120) years BP. This date is comparable with the date of Kabir-kuh anticline earthquake reported by Berberian (1994) that could be the main triggering factor of the Seimareh Landslide.

Post-failure events

Major drainage pattern disturbance and rivers shifting took place as well as the geomorphic changes in the landslide source and the depositional area. Many ponds formed on

the deposited landslide material since no developed drainage network existed. Some of these ponds are currently utilized as water supply sources for local peoples (photo 5 in Fig. 5). More important post-failure feature is represented by the landslide lakes that form behind river blocking landslide debris. In Seimareh area, enormous volume of displaced material extremely expanded. The SL dam on Seimareh River formed Seimareh Lake (“a” in Fig. 1). The western portion of the debris clogged Kashkan River to form Jaidar Lake on the south of Pol Dokhtar City (“b” in Fig. 1). At the eastern part of the debris, Balmak Lake was formed (“c” in Fig. 1) likely by blocking some temporary streams to the north of Chenareh anticline. Amongst these three lakes, Seimareh and Jaidar lakes were drained naturally and are now dry.

Jaidar Lake, as the second largest one, had an area of about 46 km². It was formed by debris blocking Kashkan River (Fig. 1). The maximum possible height of the Jaidar Dam (which is now eroded) was 50 m at the southern part; thus it could hold approximately 1.15×10^9 m³ of water. Assuming that climatic conditions of the landslide area at the time of failure remained unchanged from today and considering the present discharge of the Kashkan River as 1.344×10^9 m³/year (Table 1), it is expected that the dam was overflowed by the second year after the occurrence of landslide.

The largest post-failure feature in the region is the Seimareh Lake that is now completely drained and dried. The Seimareh debris dam was 100 m in height on the Karkkeh River resulting in a reservoir of 46.3 km in length and a total area of 259 km² following fill-up (Fig. 2). The measured altitude of the selected benchmarks (Fig. 2) and other field surveys data showed that the dam reservoir should have contained 11.84×10^9 m³ of water. The same assumption based on the last 30-year record of hydrometric data was employed for the Seimareh River. Considering the present discharge of the Seimareh River as 3.9×10^9 m³/year (Table 1), the Seimareh Lake must have overflowed about 4 years after the landslide occurrence.

However, thick lake bed sediment in these two lakes indicates that the debris dams had not been abruptly washed away and there was considerable time for sediment accumulation in the lakes after the formation of the

Fig. 5 Sample photos of the Seimareh Landslide site



Photo 1 Frontal view of the Seimareh Landslide (photo taken from a hill at the north side of Pol-Dokhtar City)



Photo 2 Disturbance of the displaced debris in the Seimareh Basin



Photo 3 Preserved profile of the sediment in the Seimareh Lake

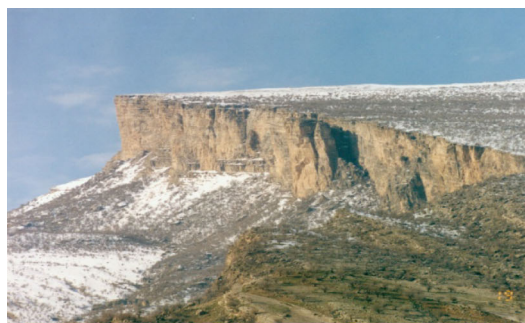


Photo 4 Cliff of Asmari limestone of detached block in Seimareh Landslide (Right side in Photo 1)



Photo 5 Remained ponds within deposited debris (See also Fig. 2)

landslide dam. The total thickness of sedimentation in Seimareh and Jaidar Lakes has been preserved at some locations (photo 3 in Fig. 5) that can be used as a reliable indicator for the longevity estimation of the landslide dams. Lake sediment structures such as cross-bedding, laminations, graded-bedding, convoluted structures, and nodules, and also biological structures including root-casts, plant remains, and freshwater gastropod shells appear in these sediments beds separating its boundary from the surrounding sediments. Because of high discharge of Kashkan River and the smaller reservoir of Jaidar Lake, it is possible that, after some time, the Jaidar Lake drained

into the Seimareh Lake. To find out the average thickness of the lake sediment, a thorough field survey was conducted. The rough bedrock surface makes the estimation of the sediment thickness difficult. Therefore, by dividing the area into several blocks and using sections of each block, the average sediment thickness of 60 and 30 m was estimated for Seimareh and Jaidar lakes, respectively. Because of local depressions or unclear boundary between the lake sediments as well as the weathered Gachsaran formation, the thickness of sediments exceeds the average at some points. Sediment beds became shallow upstream until they are only a few meters in thickness (Fig. 2).

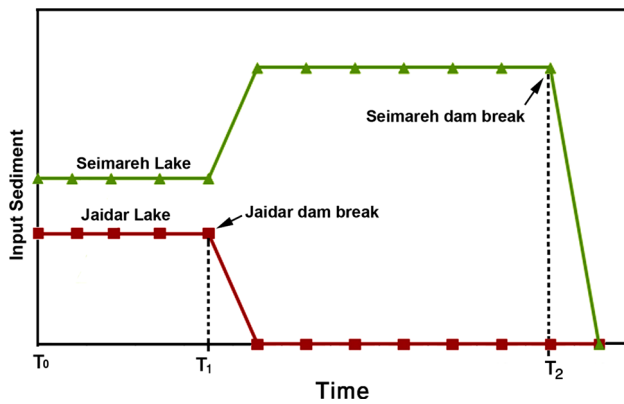


Fig. 6 A conceptual model for sedimentation process and dam stability

The basic concept of using the sediment thickness for dating is illustrated in Fig. 6. This model was suggested to estimate the stable period for Jaidar and Seimareh lakes. In this model, at the time of landslide occurrence (T_0), sedimentation began in both Jaidar and Seimareh lakes. This continued until T_1 , when Jaidar Dam broke and the total sedimentation in the Seimareh Lake was equal to sums of the Kashkan and Seimareh rivers sediments. Finally, at T_2 , the Seimareh Dam broke to bring the sedimentation process to its end. In this study, to estimate the longevity of the landslide dams (the time period between the landslide event and the break of the Seimareh Dam) the annual sediment yield rate over the total time period was applied. Based on the hydrographs of 30-year of sediment yield records at Pol Dokhtar and Karkheh River stations, the weight of the annual sediment carried by these rivers was estimated. Then, by applying the field density of the sediments, the weight was converted to volume and then to the thickness of sediment beds. The estimated thickness was compared with the measured field value to estimate the duration of the Seimareh Dam standing. As the Jaidar Dam was washed away earlier with a major impact on the Seimareh Dam sedimentation process, the longevity should be measured separately. Applying the data presented in Table 1, the following calculations were carried out:

$$d_{Jy} = \frac{(Q_K) \times (86,400 \times 360) \times (S_K)}{(\gamma_d) \times (A_J)}$$

$$d_{Jy} = \frac{(43.2) \times (86,400 \times 360) \times (0.006)}{(1.7) \times (46 \times 10^6)} \cong 0.093 \text{ m}$$

where d_{Jy} is the thickness of sediment for each year, Q_K discharge of Kashkan River per second, S_K sediment yield of Kashkan River (sediment per unit volume of water), γ_d density of sediments at Jaidar Lake, and A_J is the area covered by Jaidar Lake sediment.

In next step, by dividing the total thickness of the sediments measured in Jaidar Lake by the annual sediment thickness increment, the time required for sedimentation was calculated as the standing duration of Jaidar Dam as follows:

$$T_J = \frac{d_J}{d_{Jy}} = \frac{30}{0.093} \cong 325 \text{ years}$$

where T_J is the longevity of Jaidar Dam, d_J the sediment thickness measured in Jaidar Lake, and d_{Jy} the annual sediment thickness increment.

During Jaidar dam longevity, the Seimareh Lake received the sediment carried by the Seimareh River as following:

$$d_{S1} = \frac{(T_J) \times (S_S)}{(\gamma_d) \times (A_S)}$$

$$d_{S1} = \frac{(325) \times (6,245,000)}{(1.7) \times (259 \times 10^6)} \cong 5 \text{ m}$$

where d_{S1} is the sediment deposited in Seimareh Lake before the Jaidar Lake break down, S_S weight of total annual sedimentation of the Seimareh River, γ_d the density of sediments, and A_S is the area covered by the Seimareh Lake sediment.

Five meter of sediments in the Seimareh Lake was formed during the standing status of the Jaidar Dam, then:

$$(d_S) - (d_{S1}) = d_{S2}$$

$$(60) - (5) = 55 \text{ m}$$

where d_S is the total thickness of sediment beds in Seimareh Lake at present, d_{S1} the sediment deposited in Seimareh Lake before the Jaidar Lake break down, and d_{S2} the thickness of sediment deposited in the Seimareh Lake after the Jaidar Dam break.

To estimate the time required for 55 m of sedimentation in the Seimareh Lake, the same approach used for Jaidar, was applied as follows:

$$d_{K+S} = \frac{(Q_{K+S}) \times (86,400 \times 360) \times (S_{K+S})}{(\gamma_d) \times (A_S)}$$

$$d_{K+S} = \frac{(168.6) \times (86,400 \times 360) \times (0.0076)}{(1.7) \times (259 \times 10^6)} = 0.0905 \text{ m}$$

where d_{K+S} is the annual sedimentation in the Seimareh Lake from Kashkan and Seimareh rivers, Q_{K+S} total discharge of the two rivers, S_{K+S} sediment yield per unit volume of water of the two rivers, γ_d the density of lake sediments, and A_S is the area covered by the Seimareh Lake sediments

Finally, considering the sedimentation rate and thickness of the deposited sediment following the Jaidar Dam

break down, the time required for 55 m of sedimentation is calculated as follows:

$$T_S = \frac{d_{S2}}{d_{K+S}}$$

$$T_S = \frac{55}{0.0905} \cong 610$$

where T_S is the time required for 55 m of sedimentation, d_{S2} the thickness of sediment deposited in the Seimareh Lake before the break of Jaidar Dam, and d_{K+S} the annual sedimentation in the Seimareh Lake from Kashkan and Seimareh rivers' sediment.

The total time for the Seimareh Dam standing is the sum of the times spent for 30 m sedimentation in the Jaidar Lake and 55 m in the Seimareh Lake:

$$T = T_J + T_S$$

$$T = 325 + 610 = 935 \text{ years}$$

This analysis suggests the longevity of the Seimareh Debris Dam of 935 years. This long period after the landslide event might be because of a resistant damming structure formed by the composition and structure of debris.

Conclusions

The scale effect and the type of deposits involved in the SL cover various materials ranging fine grains to giant boulders. Therefore, previous interpretations of the mechanism of occurrence and the use of failure models have not been successful. This field work study reviewed the possible mechanisms of failure and analyzed post-failure geomorphic features. The results imply the possible main causes of the failure as the particular hydro-morphological characteristic of the landslide source area and the high-rate erosion at the base of the southern flank of Kabir-kuh Mt. by the river formed by the merging of two high-flow rivers. However, the unusual size of the landslide may indicate an external factor, e.g., a huge earthquake, as one of the most significant triggers of the failure process. The SL debris blocked surface drainage and formed massive landslide-dammed lakes. The processes responsible for the formation and draining of the Jaidar and Seimareh Landslide dams were analyzed, using the available annual sedimentation and field measurements of the sediment deposit in these lakes. It was concluded that the SL dam was in place for about 935 years after the landslide event.

More reliable and precise dating methods such as cosmogenic surface age and carbon dating should be conducted to more accurate dating of the landslide occurrence and breaking of the Seimareh Dam.

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