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ORIGINAL PAPER

Slope stability modelling and landslide hazard zonation at the Seymareh dam and power plant project, west of Iran

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Abstract The Zagros Mountains Range is an important structural unit in south western Iran and accommodates a significant portion of the 2.5 cm/year convergence between Arabia and Eurasia. This structural unit includes folds, thrusts, strike-slip faults and salt diapirs. There is evidence of past failures in the area, probably some 11,000 years ago. In the order of 30 million cubic metres of rock debris was moved from the Kabir Kuh Anticline as well as rock failures from the Ravandi Anticline. Investigations indicated 4.5 m of landslide/rock fall debris underlying about 28 m of lake deposits and 5.5 m of recent river alluvium upstream of the Seymareh Dam area. The direction of the Seymareh River bed was displaced by about 1,000 m to the northeast, forming a sharp river meander near the entrance to the gorge of the Ravandi Anticline where the Seymareh Dam is being constructed. The paper reports the rock slope instability modelling, kinematic analysis of slope faces and landslide hazard zoning undertaken.

Keywords Seymareh dam · Rock slope · Kinematic analysis · Instability modelling · Landslide hazard zonation

Résumé La chaîne du Zagros est une unité structurale importante du sud-ouest de l'Iran. Elle enregistre une partie importante des 2,5 cm/an de convergence entre l'Arabie et l'Eurasie. Cette unité structurale présente des plis, des chevauchements, des failles de décrochement et des diapirs de sel. Il existe des preuves de jeux de failles dans la région, il y a 11 000 ans probablement. Environ 30 millions de mètres cubes de matériaux rocheux se sont détachés de l'anticlinal de Kabir Kuh, de même que des glissements rocheux ont eu lieu à partir de l'anticlinal de Ravandi. Des reconnaissances de terrain ont montré que 4,5 m de débris issus de glissements de terrain et de chutes de blocs se trouvaient sous environ 28 m de dépôts lacustres et 5,5 m d'alluvions récentes en amont de la zone du barrage de Seymareh. Le lit de la rivière Seymareh a été déplacé d'environ 1000 m vers le nord-est, formant un méandre serré à l'entrée de la gorge de l'anticlinal de Ravandi où le barrage de Seymareh est en train d'être construit. L'article présente la modélisation des instabilités des pentes rocheuses, l'analyse des conditions de stabilité des versants et le zonage des risques de glissements de terrain.

Mots clés Barrage de Seymareh · Pente rocheuse · Analyse cinématique · Modélisation · Zonage des risques de glissement

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Introduction

The Seymareh dam and power plant project is being constructed on the Seymareh River at the entrance to a gorge in the Zagros Mountain Range in Iran. The dam site is accessible via the 40 km long Darreh Shahr—Ilam road, 106 km southeast of Ilam city (Fig. 1).

The river valley is U shaped with relatively steep slopes which overhang in some places. The slopes are nearly vertical up to 760 m, above which the angle decreases to 25° where weak marlstone interbeds are present. In the site area, the river is between 35 and 40 m wide. The main lithology at the dam foundation is the Asmari Formation (limestones). The limestones are typically strong, supporting the high near-vertical slopes.

Fig. 1 The location of the Seymareh Dam site in the Zagros Mountain Range of Iran (Lexicorient 2001)

The Seymareh Dam is a double curvature concrete dam with a 180 m high gated spillway and a 3,215 million cubic meter capacity (Fig. 2). Associated structures include upstream and downstream cofferdams of earth and rock fill and two diversion tunnels in the right bank. The diversion tunnels are about 473 and 397 m long with diameters of 10.5 and 8.3 m, respectively. The powerhouse contains three units with a total capacity of 480 MW generating 843 GWh/year electricity. The annual income from electricity generated by the project will be 42.5 million dollars and income due to the regulation of 3,215 million cubic metres of water will be 550 million dollars, making this one of the most important economic infrastructure projects in the area.

Some very large mass movements in the Seymareh area have been reported, which are believed to have occurred during the Quaternary (e.g. Kabir Kuuh reported by Harison and Falcon 1936). Shoaei and Ghayoumian (1997) suggested that many of the lakes within the mountainous area of western Iran could be due to the occurrence of landslides. Shoaei and Ghayoumian (1997) considered some 30 million cubic meters of debris was moved during one such event, which transported huge fragments of up to 54,000 cubic metres in possibly the largest mass movement in the Eastern Hemisphere. Smaller rock slides associated with the Kabir Kuh mass movement occurred on the northern flank of the Ravandi Anticline, where the Seymareh Dam is being constructed. Banihabib and Shoaei (2006) presented a model for sizing of debris deposition in the Seymareh area; a satellite image of the area is shown in Fig. 3.

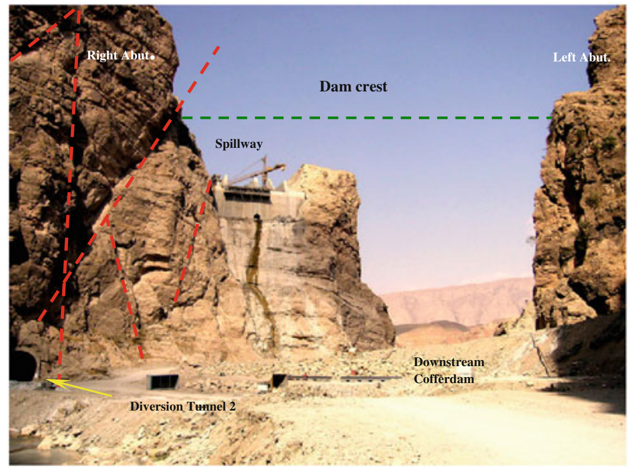

Fig. 2 Seymareh Dam foundation rocks and associated structures such as diversion tunnels, spillway and downstream cofferdam (2007)

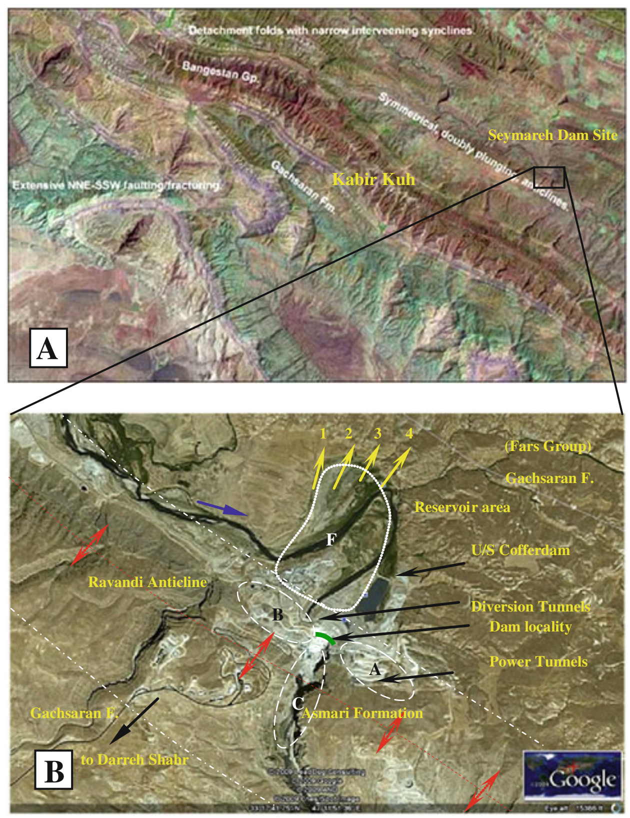

Fig. 3 Satellite image of the Kabir Kuh anticline in the Seymareh area (**a**) and Seymareh Dam site locality (**b**) that is being constructed on the northern flank of the Ravandi Anticline with a northwest-southeast trend. Zones A, B and C are indicating unstable rock slopes and zone F refers to the area that was covered with mass debris from a landslide in zone B. The *yellow arrows* indicate the changing of the river bed at four stages due to erosional process episodes since the landslide event (Google Earth, European technology 2009)

Due to this localised mass movement, the direction of the Seymareh River was changed locally from northwest–southeast to northeast–southwest adjacent to the entrance

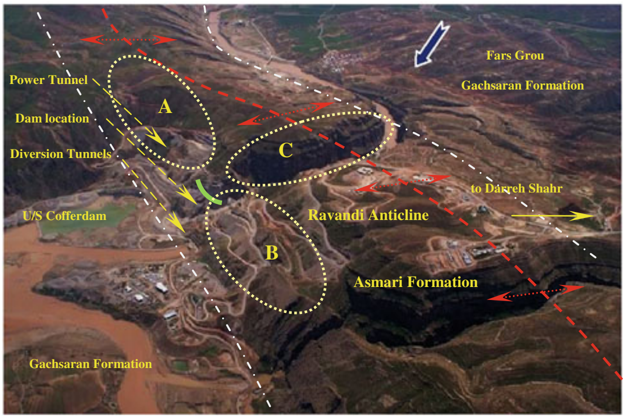

Fig. 4 Aerial view of Seymareh Dam site. The main unstable zones (A, B and C) and some accessory parts of the dam can be observed (photography by Khoshboresh 2007)

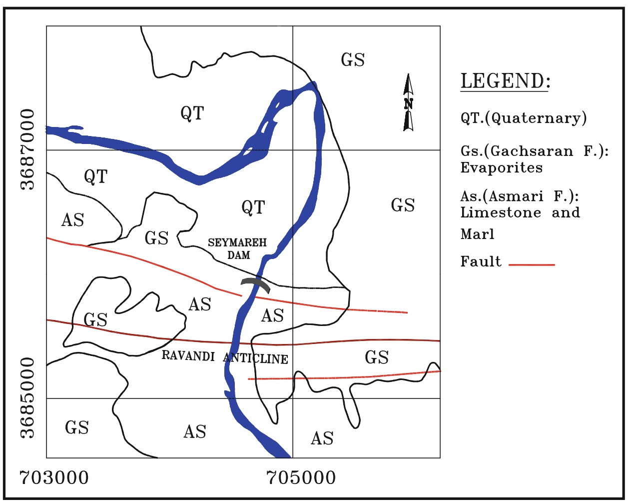

Fig. 5 Engineering geological map of the Seymareh Dam and power plant project

gorge of the Ravandi Anticline (Fig. 3b, zone B). Stratigraphic evidence from the exploratory boreholes indicates that this event most probably occurred contemporaneously with the Kabir Kuh anticline about 10 km south west of the Seymareh Dam. In addition field investigations indicate some slope instabilities on the left bank towards the future reservoir area (zone A) and also at two abutments in the downstream area (zone C).

Geology

The Seymareh Dam is located on the northeastern limb of the Ravandi Anticline. The foundation rocks are Asmari Formation limestones which have a 25°–35° dip at the entrance of the gorge (dam axis) gradually decreasing to 10°–15° downstream, near the anticline axis (Fig. 4).

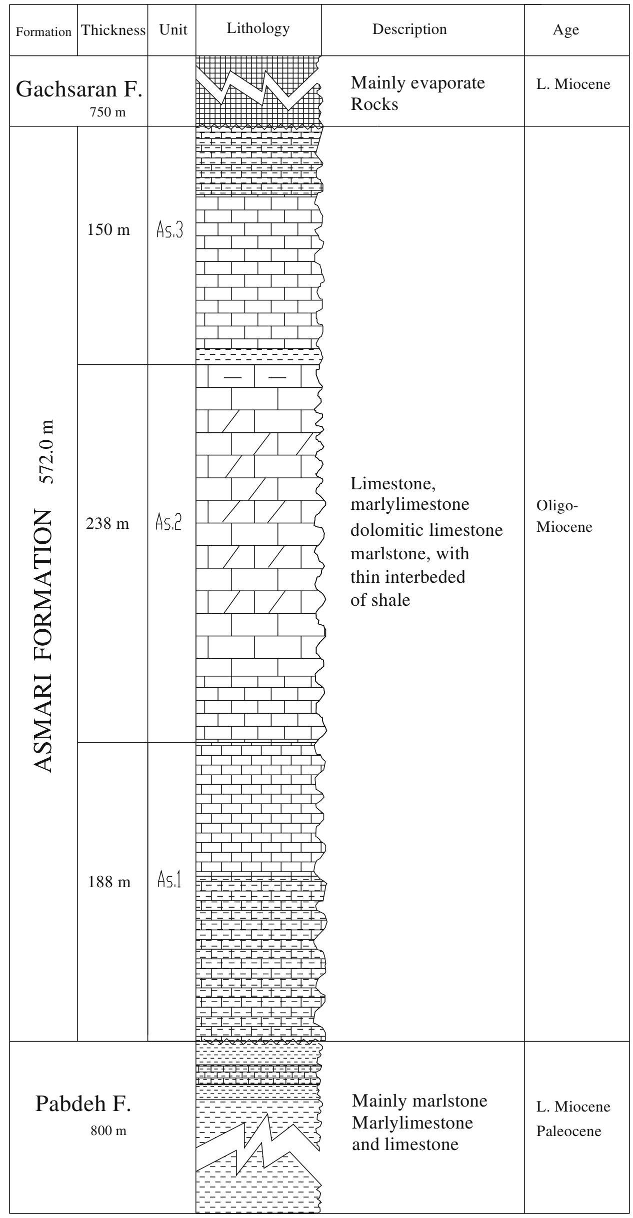

Fig. 6 Stratigraphic column of rock sequences at the Seymareh Dam and power plant project (Koleini 2012)

The geology of the project area is summarised in Figs. 5, 6 and 7. Of particular note is the Asmari Formation which constitutes the main foundation rock at the Seymareh Dam and comprises 572 m of alternating massive to thinly bedded grey to light brown fossiliferous limestone, microcrystalline limestone, dolomitic limestone, marly limestone and marlstone. It is unconformably overlain by Gachsaran evaporites. The Asmari Formation is divided into three rock units according to the engineering characteristics of the rock mass (Fig. 6).

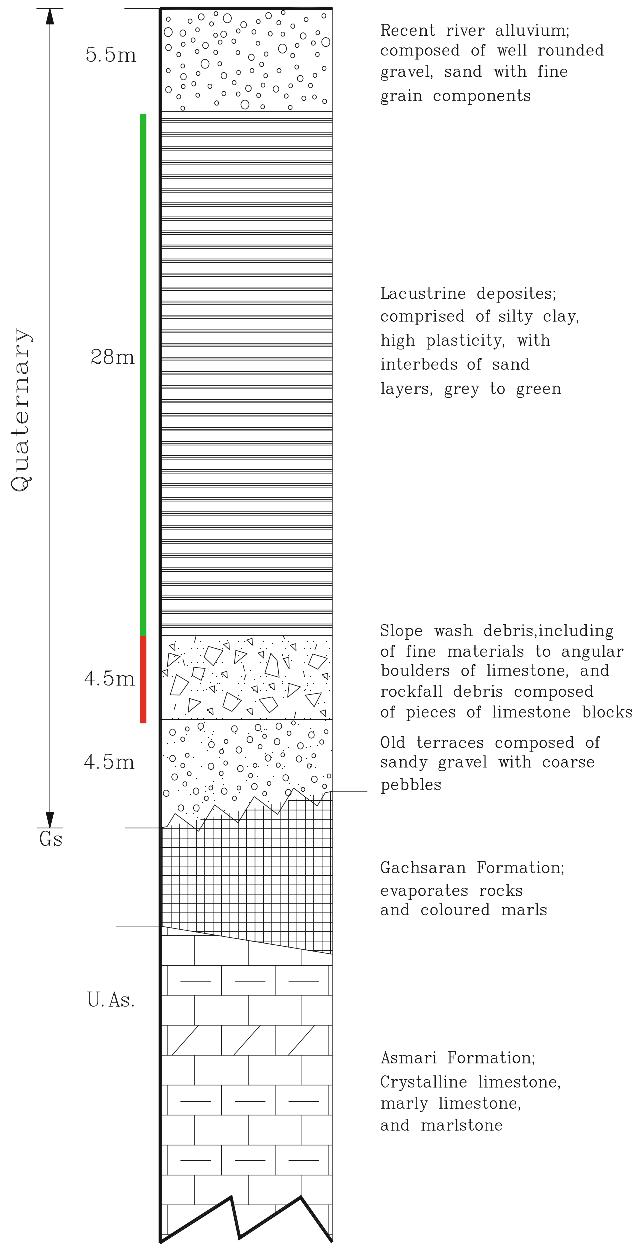

Fig. 7 Stratigraphic column of Oligocene to Quaternary sediments upstream of the cofferdam

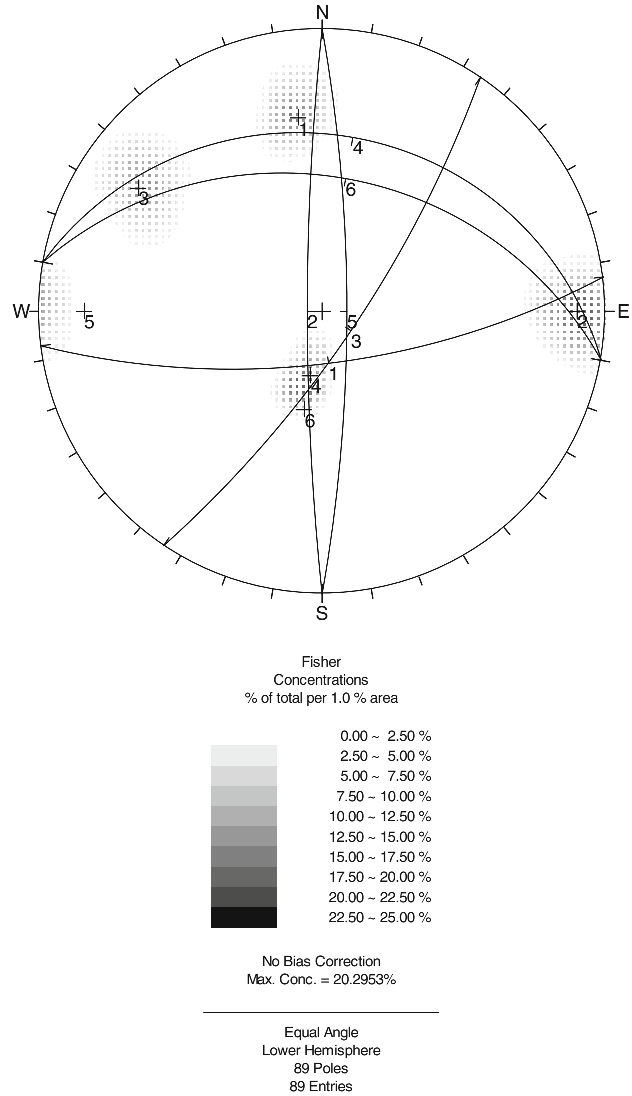

Fig. 8 Stereographic projection (counter plot) of main discontinuity sets

- Upper Asmari (As.3): 150 m, medium to thinly bedded, crystalline, bioclastic limestone and marly limestone.
- Middle Asmari (As.2): 238 m, massive to thickly bedded and karstified microcrystalline, dolomitic limestone and marly limestone.
- Lower Asmari (As.1): 188 m, medium to thickly bedded fossiliferous marly limestone and microcrystalline limestone.

Most rock instabilities are related to the middle and upper parts of the Asmari Formation.

Joint study and rock slope kinematic analysis

For the kinematic analysis, the lower hemisphere stereographical projection method, described by Hoek and Bray (1981), Goodman (1989) and Maurenbrecher and Hack (2007) was used. Planar and wedge failure modes were kinematically studied. Planar failure occurs if the discontinuity plane daylights into the slope face and the difference between the strike of the discontinuity plane and that of the slope face is 20° or less. Wedge failure occurs if the intersection of the main discontinuities is located in the area between the slope face and the great circles representing the angle of internal friction (Φ). The toppling failure is based on a two dimensional relationship (90-$\delta + \Phi < \alpha$ where $\delta =$ dip of discontinuity, $\Phi =$ friction angle of the discontinuity and $\alpha =$ slope angle.

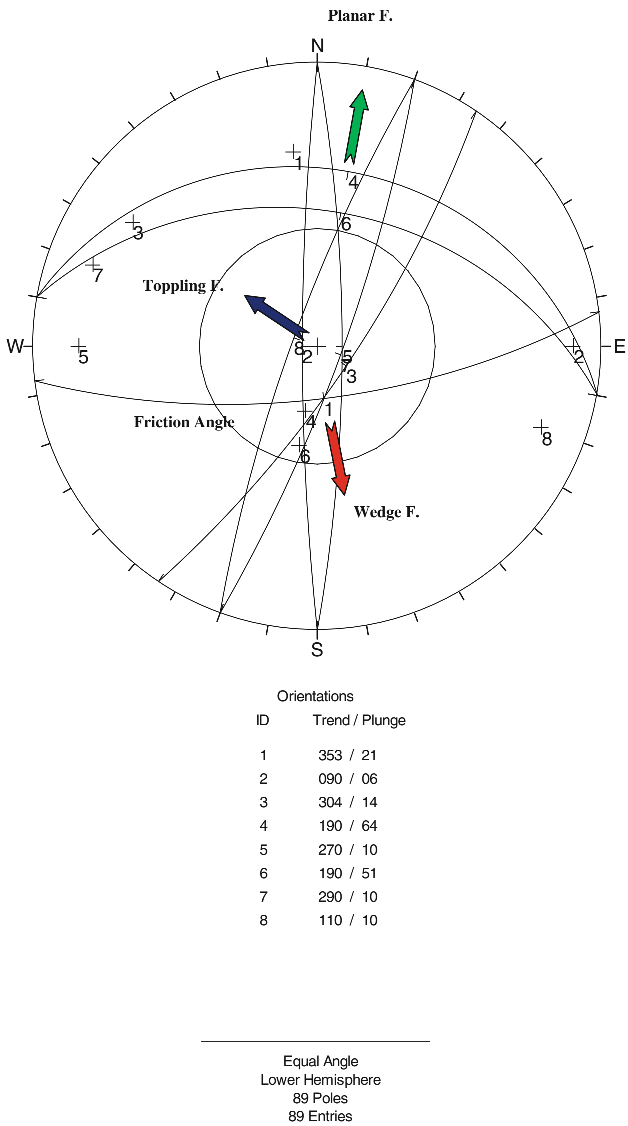

Fig. 9 Stereographic projection of main joint sets; wedge generated by the joint system Js.1, Js.3 and toppling failure by Js.3. The great *circles* 7 and 8 represent the rock slope faces on the downstream right and left banks, respectively (zone C) and great circle 6 represents the rock slope face at the northern flank of the anticline (zones A, B). Planar, wedge and toppling failure directions are indicated by green, red and blue arrows, respectively

A joint survey was undertaken, including 89 joints from two abutments at the dam location. Dips V5.1© (Diederiches and Hoek 2004) was used to created a stereographic projection of these joints into a contour plot with the main discontinuity sets (Fig. 8). Based on the stereographic projection of the joints, excluding the bedding planes, three major joint sets (Js.1, Js.2 and Js.3) can be distinguished.

Considering the anticline axis (azimuth 281) in addition to the field stress directions (derived from all axial planar orientation) joint sets Js.1 and Js.2, with azimuths parallel and perpendicular to the anticline axis, respectively, can be assumed to be extensional joints while Js.3 may be classified as a shear joint.

Great circle 6 (Fig. 9) is the rock slope face (40°) at the northern flank of the Ravandi Anticline and 7 and 8 represent the slope faces (80°) at the two flanks in the downstream area. In addition a rock mass internal friction angle of 45° was considered in this analysis.

The discontinuity surfaces are rough and wavy with apertures of <20 mm. The fillings are mostly calcite, clay minerals and rarely detrital materials, although in some places the joints have no infilling but have an iron oxide coating. The spacings of Js.1, Js.2 and Js.3 are 55, 65 and 140 cm, respectively. The characteristics of the major discontinuity sets are summarized in Table 1.

Figure 9 shows the kinematic analysis and geometrical characteristics of slope instabilities at the northern flank of the Ravandi Anticline, just upstream and downstream of the dam. The arrows represent the direction of rock failures.

According to the stereographic projection of joint sets it can be concluded that:

- the northern flank of the Ravandi Anticline is potentially unstable, particularly for planar failure through the bedding planes (Js.4) toward the northeast (green arrow),
- the downstream area of the right bank has the potential for wedge failure due to the intersection of Js.1 and Js.3 toward the southeast (red arrow),
- the downstream left bank is most likely to experience toppling instability due to Js.3, toward the northwest (blue arrow).

Slope stability analysis

Zone A (left bank, upstream area)

One of the important geotechnical problems is related to the stability of detached blocks from the Upper Asmari unit

Table 1 Major discontinuity sets

Discontinuity set	Dip direction	Dip	Spacing (m)	Discon. surface	Opening (mm)	Filling	Length (m)
Set 1	170–175	65–75	0.55	Rough-wavy	2–20	Clay, calcite	3–10
Set 2	270–275	80–90	0.65	Rough-wavy	2–20	Clay, calcite	3–10
Set 3	120–130	70–80	1.4	Rough-wavy	2–20	Clay, calcite	3–10
Bedding plane	010–020	25–35	0.35–3	Rough-wavy	<2	None, clay	>10

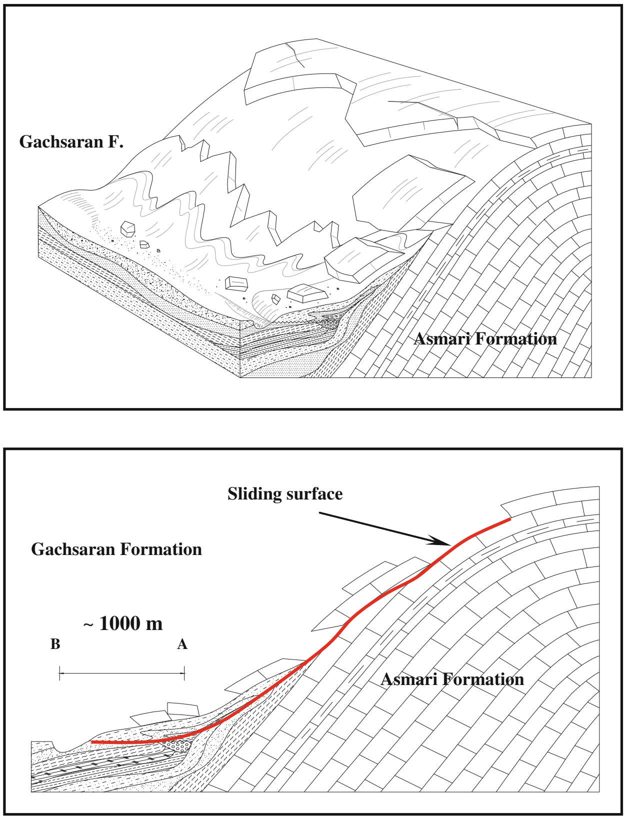

Fig. 10 Schematic block diagram (3D) and geological section (2D) of the Asmari and Gachsaran Formations at Zagros indicating folded belt and possible landslide hazard after impoundment of dam reservoir or heavy rainfall: planar sliding in Asmari limestone, rotational to planar sliding in Gachsaran evaporates

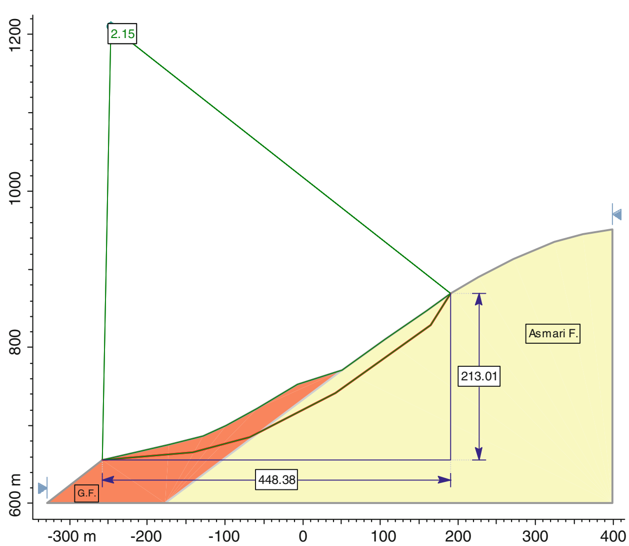

Fig. 11 Main critical slip surface model before impoundment of reservoir according to the field investigation. The slip surface is planar-rotational (composite surface) with a safety factor of 2.15 and 555 m radius

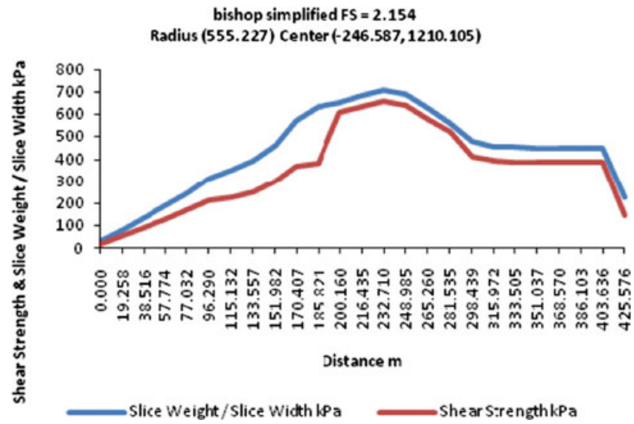

Fig. 12 Shear strength and slice weight/slice width ratio along slope before impoundment of reservoir

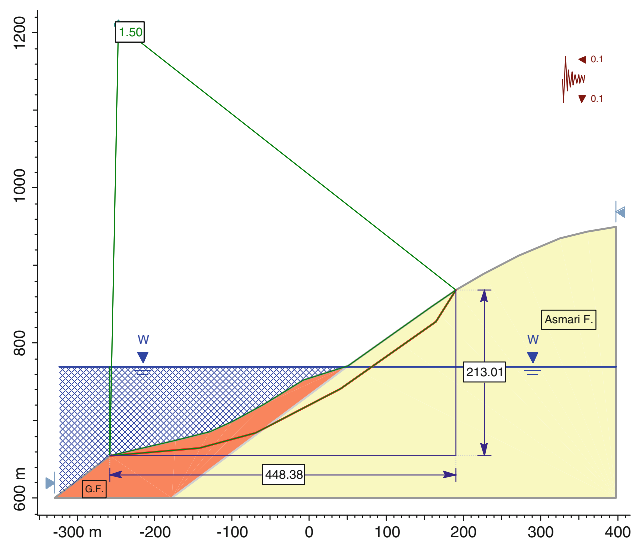

Fig. 13 Main critical slip surface after reservoir impounding with seismic load coefficient of 0.1. The slip surface is planar-rotational (composite surface) with a safety factor of 1.5

on the northern flank of the Ravandi Anticline. At an elevation of 620–800 m, there is a 250 m × 300 m area (Figs. 3, 4) which is covered by unstable blocks caused by the intersection of Js.1, Js.2 and the bedding planes on the left bank (about 200 m east of the dam axis). Based on stereographic projection of the joint sets (Fig. 8), the bedding planes will be the main rock sliding surface for most rock blocks, if instabilities occur (planar failure). The thickness of the unstable zone is estimated to be 20–25 m.

According to the above dimensions, the volume (**V**) of unstable rock in Zone A can be calculated as follow;

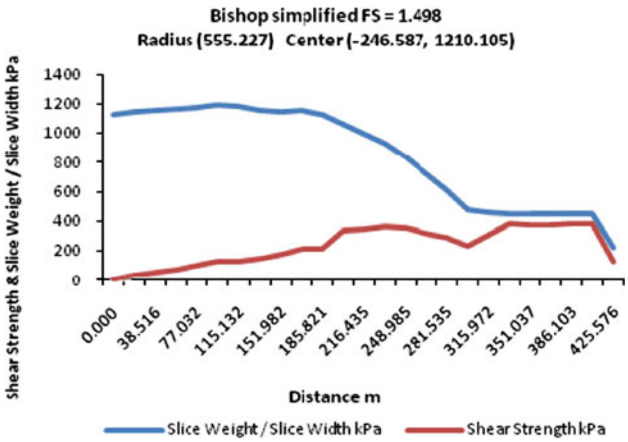

Fig. 14 Shear strength and slice weight/slice width ratio along slope after impounding of reservoir. Shear strength declined along slip surface after impounding

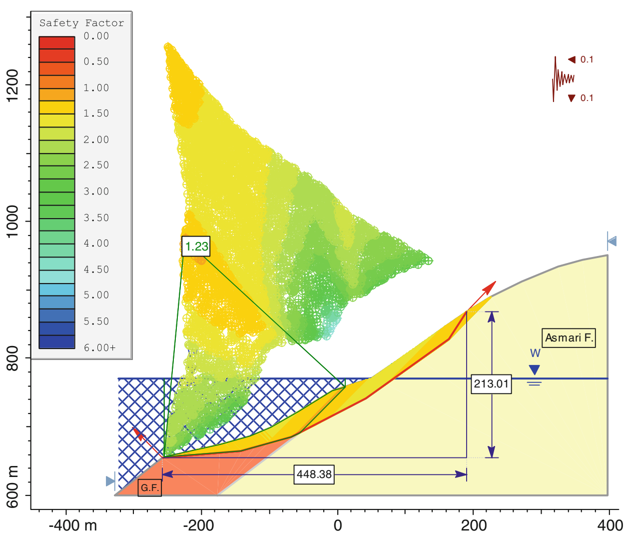

Fig. 15 All slip surfaces (cluster of points) with a safety factor <1.75 and critical slip surfaces with a safety factor of 1.2

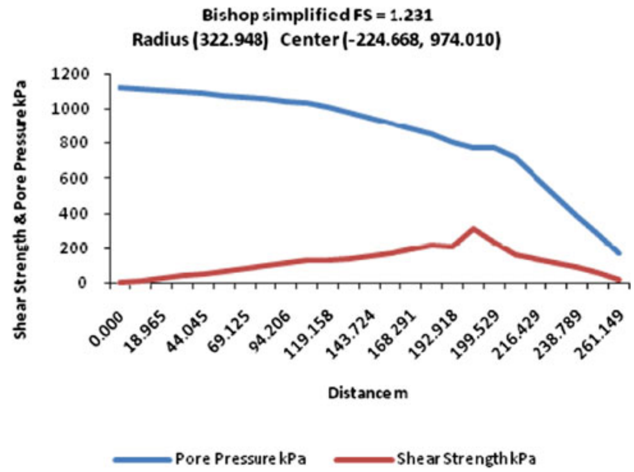

Fig. 16 Pore pressure and shear strength along the slip surface. Pressure calculated at the midpoint of the base of each slice by interpolation from the water pressure grid values

Fig. 17 U shaped valley downstream of Seymareh River with near vertical cliffs. Kinematic analysis indicates rock instabilities at *right* and *left* flank are mainly wedge and toppling, respectively

$$V = \text{Width} \times \text{Length} \times \text{Thickness}$$
$$V = 250 \times 300 \times (20 - 25)$$
$$V = 1{,}500{,}000\,\text{m}^3 \text{ to}$$
$$V = 1{,}875{,}000\,\text{m}^3$$

Zone B (right bank, upstream area (zone B)

Similar blocks can be observed on the right bank on the northern flank of the Ravandi Anticline. The slopes cut during access road construction induced rock mass instability (Fig. 4). Slope stabilization was carried out in some places, such as at diversion tunnels and hydropower tunnel headwalls, but according to the field investigations most of the road cuts are either not supported or insufficiently supported. In addition, the increase of water pore pressure after impounding of the reservoir or heavy rainfall may reduce the shear strength of discontinuities, especially on bedding planes, and hence facilitate rock sliding.

The satellite image of the dam site (Fig. 3b, zone B) shows an obvious sudden or abnormal change of river flow direction from northwest–southeast (N120E), parallel with the anticline axis, to northeast–southwest (N56E). This sharp river meander is only about 500–600 m from the dam location and is probably related to a large landslide. It is considered this caused the displacement of the river bed by about 1,000 m to the northeast (Fig. 10). In addition, consideration should be given to the possibility of seismicity resulting in rock failure and overtopping of the dam in the event of a large landslide.

Exploratory boreholes in the upstream area confirmed the large historic mass movement with 4.5 m of thick

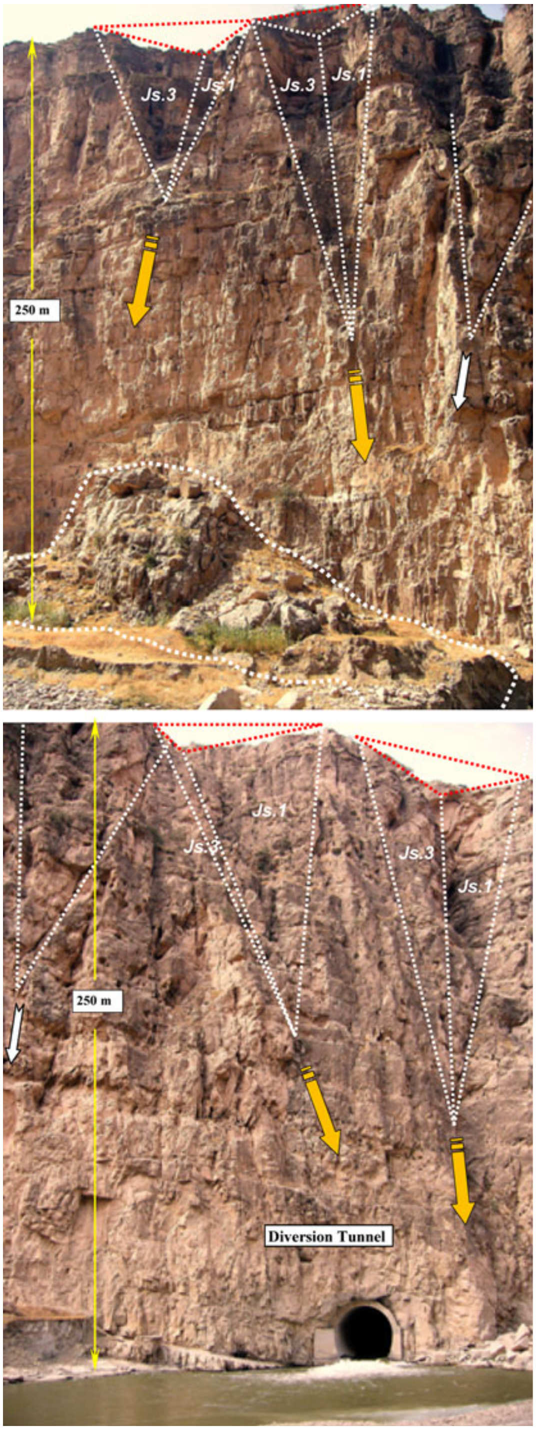

Fig. 18 Wedge failure along intersection of Js.1, Js.3 at right bank downstream of Seymareh River valley, some of which are historic. *Yellow arrows* show the direction of sliding toward the river valley; *white arrows* indicate probable wedge failures in the future

unsorted detrital and angular material grading from fine to big. These detrital deposits are situated at the base of about 28 m of thick grey to green lacustrine deposits (highly plastic silty clay with interbedded sand layers). These lacustrine deposits relate to a large lake formed some

Fig. 19 Toppling failure along joint set.3 on the *left* bank of the Seymareh River valley

11,000 years ago following the gigantic mass movement of the Kabir Kuh Anticline just 10 km south-west of the dam site. Assuming the thickness to be 4.5 m, the volume of the mass movement in zone F, resulting from rock failure at zone B, can be calculated as follows:

$$V = \text{Width} \times \text{Length} \times \text{Thickness}$$

$$V = 700 \times 1{,}000 \times 4.5$$

$$V = 3{,}150{,}000\,\text{m}^3$$

The evaporites of the Gachsaran Formation imply rotational sliding could take place, due to their high plasticity and flexibility (marl, gypsum and salt).

In this research Slide© (1989–2003 Rocscience Inc.) was used to identify the F.S or factor of safety (Figs. 11, 12, 13, 14, 15, 16). Slid© is a 2D slope stability program for evaluating the stability of circular or non-circular failure surfaces in soil or rock slopes. External loading, groundwater and support can all be modelled in a variety of ways (Rocscience). The stability of slip surfaces was analysed using vertical slice limit equilibrium methods. Individual slip surfaces can be analyzed, or search methods can be applied to locate the critical slip surface for a given slope (Rocscience).

The cluster of all possible axis points above the slope can be seen in Fig. 15. For a non-circular slip analysis, these points are automatically generated by SLIDE©, and are the axis points used for moment equilibrium

Table 2 Typical values of LHZ parameters (Gupta and Anbalagan 1995)

No.	Factor	Class	Rating
1.	Lithology:		
	(a) Kind of rock	Type I	
		Quartzite and Limestone	0.2
		Granite and Gabbro	0.3
		Gneiss	0.4
		Type II	
		Ferrous sedimentary rocks, well cemented, Sandstone with thin interbeds of clay stone	1.0
		Ferrous sedimentary rocks, weakly cemented, Sandstone with thin interbeds of shale and clay	1.3
		Type III	
		Slate and phyllite	1.2
		Schist	1.3
		Shale with interbeds of clay stone or non clay materials	1.8
		Shale, phyllite and schist, highly weathered	2.0
	(b) Kind of soil	Old alluvium deposits, well cemented	0.8
		Clayey soils with alluvium	1.0
		Sandy soils with alluvium	1.4
		Rock debris with sandy and clayey soils (slope wash);	
		Type I	
		Old and well cemented	1.2
		Type II	
		Young loose materials	2.0
2.	Structure:	I. >30°	0.2
	(a) Parallelism between joints and slope face	II. 21°–30°	0.25
		III. 11°–20°	0.3
	Planar (αj- αs)	IV. 6°–10°	0.4
	Wedge (αi- αs)	V. <5°	0.5
	(b) Joint dip in planar mode of	I. >10	0.3
	Failure (βj- βs)	II. 0–10	0.5
	Wedge (βi- βs)	III. 0.0	0.7
		IV. 0 to (−10)	0.8
		V. <−10	1.0
	(c) Discontinuity dip	I. <15	0.2
	Planar (βj)	II. 16–25	0.25
	Wedge (βi)	III. 26–35	0.3
		IV. 36–45	0.4
		V. >45	0.5
3.	Slope morphology:		
	(a) Escarpments, cliff	>45	2.0
	(b) High angle	36–45	1.7
	(c) Moderate angle	26–35	1.2
	(d) Low angle	16–25	0.8
	(e) Very low angle	<15	0.5
4.	Relative relief:		
	(a) Low	<100 m	0.3
	(b) Moderate	101–300 m	0.6
	(c) High	>300 m	1.0
5.	Land use and land cover:		
	(a) Agricultural		0.65
	(b) Residential		0.0
	(c) Thick vegetated land cover		0.9
	(d) Moderately vegetated		1.2
	(e) Sparsely vegetated		1.2
	(f) Barren land		2.0
	(g) Soil cover depth	<5 m	0.65
		6–10 m	0.85
		11–15 m	1.3
		16–20 m	2.0
		>20 m	1.2
6.	Groundwater condition	(a) Flow	1.0
		(b) Dripping	0.8
		(c) Wet	0.5
		(d) Damp	0.2
		(e) Dry	0.0

Correction factor: C1, highly weathered; C2, moderately weathered; C3, low weathered. Rock type I, C1 = 4, C2 = 3, C3 = 2; Rock type II, C1 = 1.5, C2 = 1.25, C3 = 1; αj, joint dip direction; αi, joint intersection dip direction; αs, slope dip direction; βj, joint dip; βi, joint intersection dip; βs, slope dip; I, very favourable; II, favourable; III, fair; IV, unfavourable; V, very unfavourable

Table 3 The maximum rating of LHEF landslides (Gupta and Anbalagan 1995)

Factor	Max. rate (LHEF)
Lithology	2
Structure	2
Slope morphology	2
Relative relief	1
Land use and cover	2
Groundwater condition	1
Total	10

Table 4 The classification of landslide hazard zonation (LHZ) according to Gupta and Anbalagan (1995)

Zone	TEHR rate	LHZ description	Concept
I	<3.5	Very low hazard	Reliable
II	3.5–5	Low hazard	
III	5.1–6	Moderate hazard	Local zones, susceptible to instability
IV	6.1–7.5	High hazard	Not reliable
V	>7.5	Very high hazard	

calculations. Block search is used to randomly generate the locations of the slip surface, such that the lower safety factor surface can be determined. As seen in Fig. 15, a F.S. of 1.2 was generated for the Gachsaran Formation evaporates after reservoir impoundment; the radius of the slip surface being 323 m. Figure 16 indicates an increase in pore pressure when the reservoir is impounded could reduce the shear strength along the slip surface.

Zone C (downstream area)

Downstream of the dam, the U-shaped Seymareh River valley has cliffs of about 250 m with gradients varying between 70° and 90°. The stereographic projection of joint sets (Figs. 8, 9) indicates wedge failure and toppling failure at the right and left bank, respectively. Figure 17 indicates the potential for wedge failures on the right bank and toppling on the left, such as has clearly occurred in the past (Fig. 18). Field investigations indicated up to 60,000 m^3 was moved, which now shows evidence of weathering and surface erosion. Figure 19 shows an example of slope instability on the left bank of the Seymareh River valley due to toppling failure.

Landslide hazard zonation (LHZ)

To evaluate the landslide hazard, five zones were identified based on six relevant factors (Tables 2, 3):

1. lithology,
2. structure,
3. slope morphology,
4. relief relative to the free face,
5. land use and land cover,
6. ground water condition.

The six parameters were summed to produce a total estimated hazard rating (Singh and Geol 1999—Table 4). According to the Anbalagan (1992) and Gupta and Anbalagan method (1995) the results indicate a low to moderate hazard for the Asmari Formation limestone cliffs and moderate to high hazard for the Gachsaran evaporites (Table 5).

Table 5 Total estimated hazard zoning at Seymareh dam site according to the Gupta and Anbalagan method

No.	Factor	Rate			
		Zone A, B (planar failure)		Zone C-right bank (wedge failure)	Zone C-left bank (toppling failure)
1.	Lithology	Limestone	Gypsum and Marl	Limestone	Limestone
		0.2 × 3	1.8	0.2 × 3	0.2 × 3
2.	Structure	0.5 × 0.7 × 0.3		0.2 × 0.7 × 0.5	0.3 × 0.8 × 0.5
3.	Slope morphology	High angle		Escarpment	Escarpment
		1.7		2	2
4.	Relative relief	Moderate		Moderate	Moderate
		0.6		0.6	0.6
5.	Land use and land cover	Sparsely vegetated		Sparsely vegetated	Sparsely vegetated
		1.2		1.2	1.2
6.	Groundwater	0–1		0–0.8	0–0.8
Total estimated hazard (TEHR)	Value (from 10)	4.2–5.2	5.4–6.4	4.5–5.3	4.5–5.3
	Percentage	42–52 %	54–64 %	45–53 %	45–53 %
Description of zone		Low to moderate hazard (LHZ–MHZ)	Moderate to high hazard (MHZ–HHZ)	Low to moderate hazard (LHZ–MHZ)	Low to moderate hazard (LHZ–MHZ)

Conclusion

The Asmari Formation limestones and Gachsaran Formation evaporites constitute the main rock foundations for the Seymareh Dam project. The Upper Asmari limestone with intercalations of marls and the Gachsaran Formation composed of gypsum, marl and salt, are susceptible to water absorption and dissolution which may result in a reduction in the shear strength of the rock mass when the reservoir is impounded and/or as a consequence of heavy rainfall.

The study has shown that the failure surface in the Asmari Formation limestone is likely to be planar towards the reservoir with wedge/toppling in the downstream area, while the flexibility of the Gachsaran evaporites implies failure will be rotational or along a composite surface.

The unstable areas adjacent to the dam site and through the reservoir area are composed of old mass failures, high angled rock slopes and crushed zones in the limestones. However, although the limestones with intercalations of marl and clay dip toward the reservoir, the Gachsaran Formation evaporites present the greatest risk of slope failure following impoundment of the reservoir.

In addition, the previous failures in zone B indicate the potential for landsliding at the northern flank of the Ravandi Anticline where the inlet of diversion and hydropower tunnel portals are situated and where access roads have been created, while more recently wedge and toppling failures downstream (zone C) also give cause for concern.

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