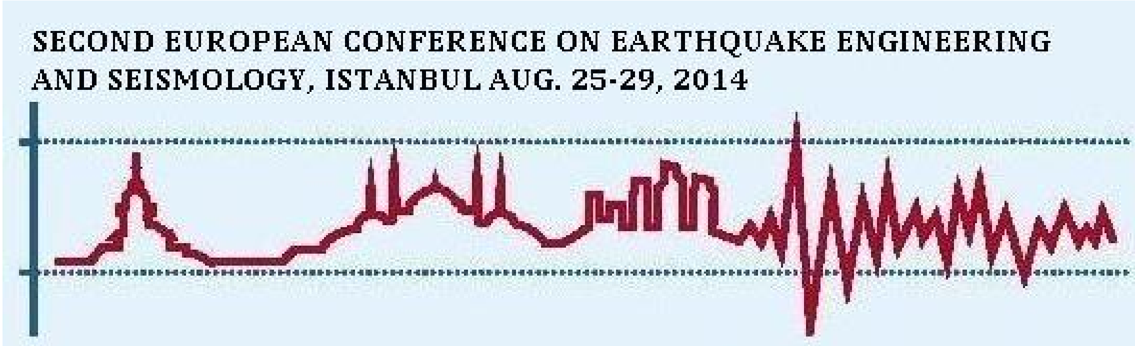

BEHAVIOR OF TWO EARTH-FILL DAMS DURING THE 11 AUGUST 2012 ARASBARAN, IRAN PAIR EARTHQUAKES

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ABSTRACT

In 11 August 2012 two earthquakes with magnitudes Ms 6.4 and Ms 6.3 with epicentral distance of about 14 kilometers and 9 minutes interval shook parts of northwest of Iran. These two earthquakes caused the destruction of about 350 villages and killed about 400 people in Arasbaran area in East Azarbaijan Province. Intensity was VIII in MMI scale in macro-seismic epicenter of the events. Focal mechanism of both earthquakes with tensor solution of earthquake moments was strike-slip with negligible normal component. Surface deformations on ground surface accompanied with these earthquakes were tension cracks with shallow depth and rarely with strike-slip displacements which includes variation trends from 60 to 150 degrees. Maximum measured displacement on these ruptures was about 0.5 meter.

Two earth-fill dams of Sattar-Khan and Nahand are constructed within the macro-seismic area which are 76 and 35 meters high, respectively. Accelerograph installed on the crest of the Sattar-Khan dam recorded the first earthquake's peak horizontal and vertical ground accelerations of 0.38 and 0.47g, respectively. Accelerographs installed on the Nahand dam were also triggered due to the first earthquake and measured peak horizontal and vertical accelerations of 0.21 and 0.07g, respectively.

Following the earthquakes, both dams were visited and the installed instrumentation in the gallery area, intake tower, and dam bodies were checked. Careful investigation showed that -in spite of very minor damages- both dams had continued their services without any disruption. This paper presents the seismotectonic conditions of the epicentral area and the results of investigation on the induced surface deformations due to the earthquakes. It also provides the result of post earthquake investigation of both dams.

INTRODUCTION

On Saturday, 11 August 2012 at 16:53 and 17:04 (within 11 minutes) two strong earthquakes occurred in northwest of Iran. The epicentral distance between both events was about 14 kilometers. Magnitudes of the pair earthquakes were Ms 6.4 and Ms 6.3, respectively. The focal depth of both events was 10 kilometers. Maximum intensity of both earthquakes was VII-VIII in MMI scale. Figure 1 shows the epicentral area and the intensity distribution of both earthquakes.

According to initial statistics, number of casualties was about 400 dead, 2600 injuries, and 50,000 homeless. Out of the 537 villages in the earthquake stricken area, 365 villages sustained 50 to 90% damage and 46 villages were completely destroyed. Two towns of Varzeghan and Ahar located within the macro-seismic epicenter of these two events respectively suffered the highest damages.

Study of the historical seismicity of Iran (Ambrasys and Melville, 1982) shows that the Azarbaijan Province has experienced destructive earthquakes many times. Berberian and Yeats (2001)

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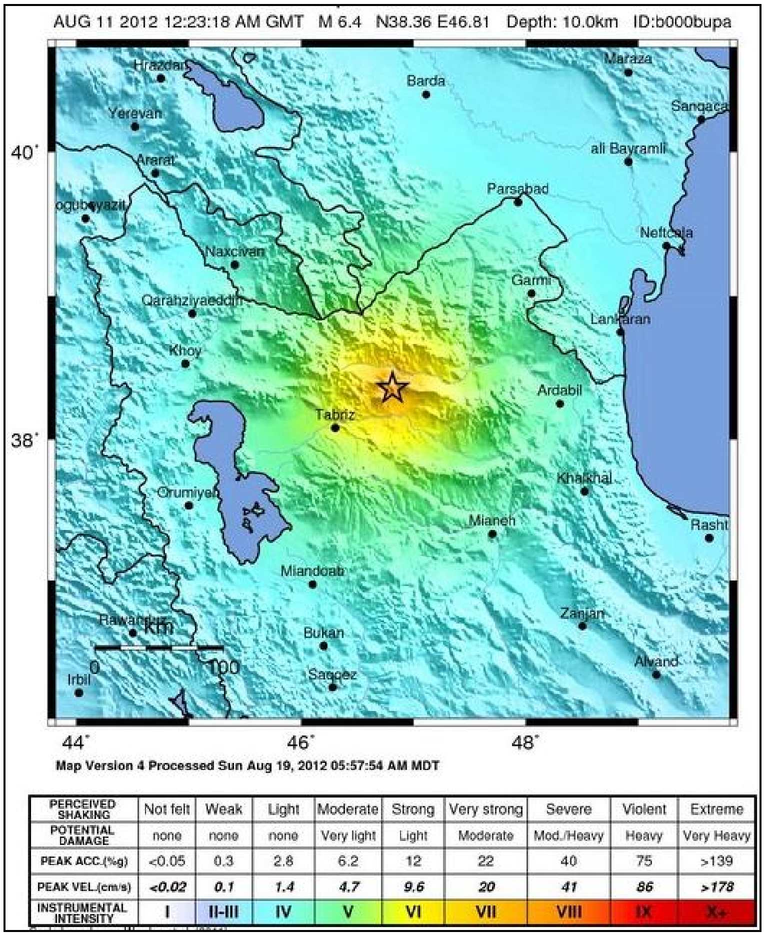
and Berberian (1997) through the study of these historical earthquakes have introduced the earthquake activities of the past earthquakes of the Tabriz area and its surroundings as cluster which does not have direct relationship between the magnitudes and the elapsed times on causative faults. The most important fault of the Azarbaijan region is the North Tabriz Fault whose recent activity has been proven by the shear on the Holocene alluvium, thrust of old rock units on young volcanic ashes and offset of young gullies. Presence of Sahand and Sabalan volcanoes with existence of many hot water springs on their skirts are evidences of the tectonic activities of the area.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.05	0.3	2.8	6.2	12	22	40	75	>139
PEAK VEL.(cm/s)	<0.02	0.1	1.4	4.7	9.6	20	41	86	>178
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 1. Location of epicenter and intensity distribution of pair earthquakes on MMI scale (USGS)

This paper presents the seismotectonic of the pair earthquakes affected area and describes behavior of the Sattar-Khan and Nahand earth-fill dams located at the macro-seismic area of the earthquakes.

SEISMOTECTONICS OF THE REGION

Present geomorphology of Iran is the result of convergence and oblique collision of the Arabian plate in southwest and Eurasian plate in northeast which has begun in Paleogene period. The collision zone extends from Bitlis (around Van) in east of Turkey to Minab transform fault near beginning of Makran subduction in southeast of Zagros in south of Iran. Central Iran zone as part of Eurasia, which both earthquakes have occurred on its northwest corner, played as a plastic plate of indentation tectonics model. Shortening direction (Maximum of principle stress axes) is strongly influenced by the rifting of the Red Sea and getting farther away of the Arabian plate from the African plate. In proximity of the suture in the collision area in Van, a tectonic indent is defined by Copley and Jackson (2006) and

Donner, et al (2013) which introduces the indentation tectonics as a governing tectonic process. In the plastic plate of the margin, corresponding to indentation tectonics pattern, slip lines are approximately perpendicular to each other are formed which change their direction by keeping distance from the indent. Noting to the direction of migration toward north of the Arabian plate with respect to the African plate, faults with northeast-southwest trend have all right lateral mechanism, and naturally faults with northwest-southeast trend have all left lateral mechanism. Therefore, it can be stated that the right lateral strike-slip faults of Pambak-Sevan, Agarak, Orduabad in Azerbaijan, and North Tabriz Fault in Iran play as slip lines of the plastic plate.

Amount of the slip rate due to this shortening is related to the amount of rifting of the Red Sea which is reported to be about 29 mm per year (Jackson and McKenzie, 1988). An important part of this shortening in the Arabian plate has resulted to creation of the Zagros fold and thrust belt and its under-thrusting under the central Iran zone. Convergence of the Arabian and Iranian plates is oblique with right lateral strike-slip component and its evidences reach to trans-Caucasus located between the Iranian Azarbaijan and small Caucasus block (Berberian, 1997).

Many researchers claim that the seismic deformation in northwest of Iran is the response of oblique convergence between Arabia and Eurasia. Deformation distribution between reverse faults (e.g., Spitak) and strike-slip faults like Chalderan-Khoy and Salmas are the result of oblique collision between the plates. Berberian and Yeats (2001) believe that many Iranian historical and twentieth century earthquakes are the result of interaction of reverse and strike-slip fault systems in Iran and state that the relocated epicenters of these earthquakes are very close to these areas. The pair earthquakes of 11 August are also located at the interaction of the strike-slip and reverse faults.

Due to location of these two earthquakes in a region with ancient history of Iran, Caucasus, Armenia, Turkey, and Azerbaijan several valid earthquake catalogues are published on historical earthquakes of northwest of Iran (Ambrasys and Melville, 1982; Pirousian, et al, 1997; Shebalin and Tateyossian, 1997; Berberian, 1997; …, but no important historical earthquake on these catalogues can be accurately selected to the recent pair earthquakes. Historical earthquakes appeared in the catalogues show that the seismic activity are concentrated to the southwestern regions in the proximity of North Tabriz Fault, in eastern areas around Heroabad fault and concentrates to the north of the region, but no historical earthquake is located exactly at the location of these two earthquakes.

Figure 2 shows a digital elevation model of the height of the pair earthquakes of 11 August 2012 area. This figure represents the important structural components of the area, epicenters of both earthquakes reported by IIEES and NEIC, and also the sites of both Sattar-Khan and Nahand Dams. Higher heights of the area have darker color in the image. The grey color ellipse in the middle of the image represents distribution of the aftershocks where longer diameter has an approximate east-west trend and to some extend corresponds to macro-seismic area of the events. Actually, the extension of the earthquakes felt area is much wider than this marked area. About 300 aftershocks greater than M_L 2.5 were recorded three days after the main shocks (IIEES). The magnitude M_L of two aftershocks were greater than 5, 15 between 4 to 5, and 114 were 3 to 4. The grey color ellipse also shows the aftershock distribution which was mapped by Donner, et al (2013). In some preliminary reports published immediately following the pair earthquakes, a fault was introduced as the causative fault of the earthquakes which is shown by a blue color line in Figure 2. The reason for this rapid announcement was mainly due to the fact that a fault is drawn by a dashed line in Ahar 1: 100,000 geological map which has cut the quaternary sediments and basically cannot be the causative fault of the recent fault earthquakes.

In this figure some important faults are also shown. Two right lateral strike-slip faults of Orduabad and Agarak with very clear surface features with approximately north-south trend are present in the northwest corner of the figure where southwestern ends change the direction to northeast-southwest trend. Since the southeastern end of Agarak fault in Iran is cut by the Eiry reverse fault, it does not have a significant extension in Iran and does not reach to the epicentral area of the recent earthquakes. Similar to Agarak fault, Orduabad fault is also cut by some small reverse faults and is not significantly extended in Iran. Both faults have played as the indentation tectonic slip lines and have large right lateral strike-slip component.

On the satellite images with good resolutions, there is another fault with an approximate length of 60 kilometers with east northeast- west southwest trend which caused a right lateral displacement in the Paleocene basal conglomerates unit and in some areas has resulted to the displacement in Eocene volcanic tuffs units. Right lateral surface rupture on this fault near the Sheran village has resulted to contact tuffs and Andesitic rocks belonging to upper Paleocene-lower Eocene and Basalts and Andesitic Basalts of upper Eocene. Portions of this fault are drawn on the Ahar 1: 100,000 geological map sheets. In Figure 2, this fault is drawn in the south of the aftershock concentrated area and is named Sheran fault in this study.

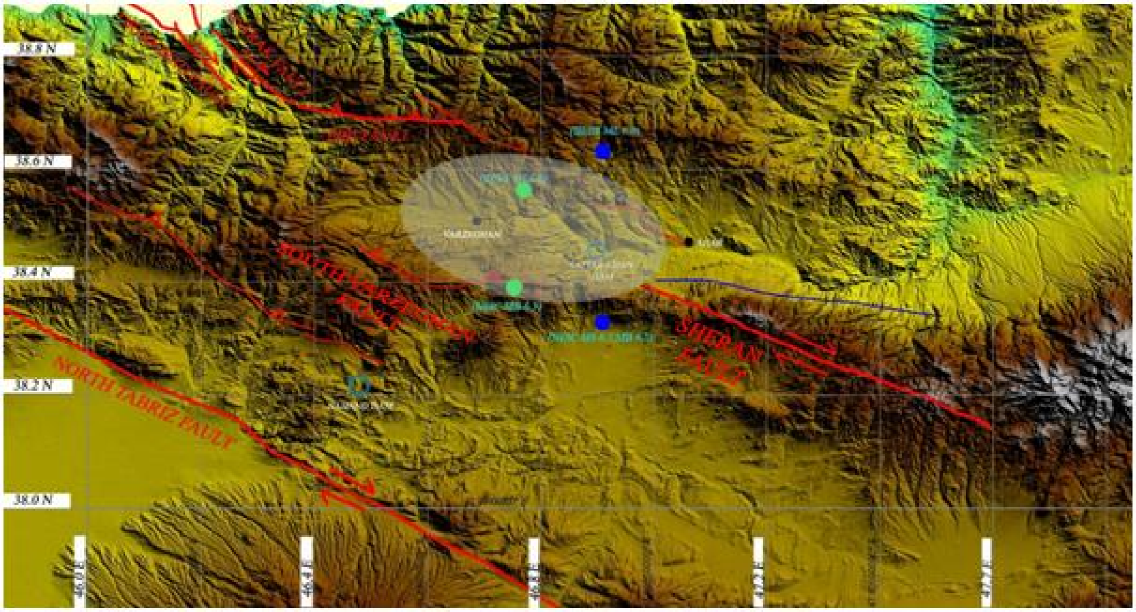


Figure 2. A digital elevation model of the height of the pair earthquakes of 11 August 2012 area showing the most important faults of the region. Black circle shows Varzeghan and Ahar cities, blue and green circles are epicenters reported by NEIC and IIEES, respectively. Light blue circles are the location of dams. Grey ellipse shows the concentration area of aftershocks.

Noting to distribution of the above faults along with their focal mechanisms, a transtension zone is recognized by the right stepping geometry of Agarak and the Sheran faults and their right lateral mechanism. This transtension zone has created the local depression in the Ahar area. Average height in the north Ahar and Varzeghan mountains has about 2300 m, in its southeast about 2200 m, and in west and southwest of Varzeghan about 2200 m from the free sea level. Regardless of the Ahar river, the Ahar city is the deepest part of the region and with an average height of 1330 m from the sea level is largely lower than the surrounding mountainous areas. Therefore, one probability is that the deformation transformation from right lateral faults of northwest of Iran like Agarak fault to the right lateral Sheran fault could be accompanied with a seismic barrier which aftershocks following the main shock brings the region to an inhomogeneous state of seismic strain.

Calculation of focal mechanism of 11 August pair earthquakes using 10 seismogram waveform along with aftershocks distribution were well studied by Donner, et al (2013) which are shown in Figure 3a. Fault plane solution obtained from focal mechanism of the first earthquake shows a strike-slip mechanism with very little normal component and the second earthquake has a strike-slip mechanism with very little reverse component. Nodal plates of focal mechanisms of both earthquakes have an average two north-south and east-west trends. Taking into consideration of strike-slip focal mechanism of both earthquakes with the assumptions of acceptance of the east-west nodal plate, as the earthquake causative plate, the two earthquakes had mechanisms of dextral strike-slip with small normal component and right lateral strike-slip with small reverse component. Fault dip was estimated to be 82 by Donner et al (2013) (Figure 3b) and most of the aftershocks had strike-slip mechanism. Their final seismo-tectonic model is shown in Figure 3d which shows that the causative fault is a part of the south Varzeghan reverse fault which itself is offset in a strike-slip manner. Acceptance of South Varzeghan northward dip reverse fault as a source scenario cannot be justified because of the presence of a 700 m subsidence in north of the fault in Varzeghan-Ahar. On the other hand, the epicenter of the first earthquake based on the NEIC report has at least 19 km distance from the fault that was reported by Donner, et al (2013).

According to available data, it seems that the developed transtension zone in the Ahar-Varzeghan pull apart which is due to the right step and right lateral strike-slip displacement has resulted to development of east-west strike-slip faults with minor normal component. The causative fault of the first earthquake can be of this fault category. Contour-Clockwise rotation and moving down of materials in northern block of South Varzeghan fault, lowered the threshold motion of the southern block and therefore, the second earthquake has most likely occurred on the South Varzeghan fault, as introduced by Donner, et al (2013).

In the field visit that took place following the occurrence of the pair earthquakes, the seismic source was recognized (Figures 4 and 5) and the Sattar-Khan and Nahand Dams responses to the quakes were investigated. The evidences showed that co-seismic surface deformation of the 11 August 2012 Arasbaran earthquakes consisted of surface tensional features with various, but an east-west dominant trends. With regard to their trend dispersions, they cannot definitely be related to a distinct seismic source. On the Tabriz-Varzeghan road, about 5 Km to Zaghan-Abad Village the maximum co-seismic horizontal and vertical displacements were measured 50 and 30 cm, respectively. Some of these types of failures were resulted on the ground lateral spreading near to gullies. Another surface deformation feature due to these earthquakes was planar landslides occurrence in foothills. Thus, it can be implied that the seismic surface deformation belongs to a secondary co-seismic surface rupture type rather than a primary type.

Although the South Varzeghan fault could be a seismic scenario for the second earthquake but no definite evidences were found exactly on the fault in the field visit. It seems that the actual rupture had slightly been migrated southward.

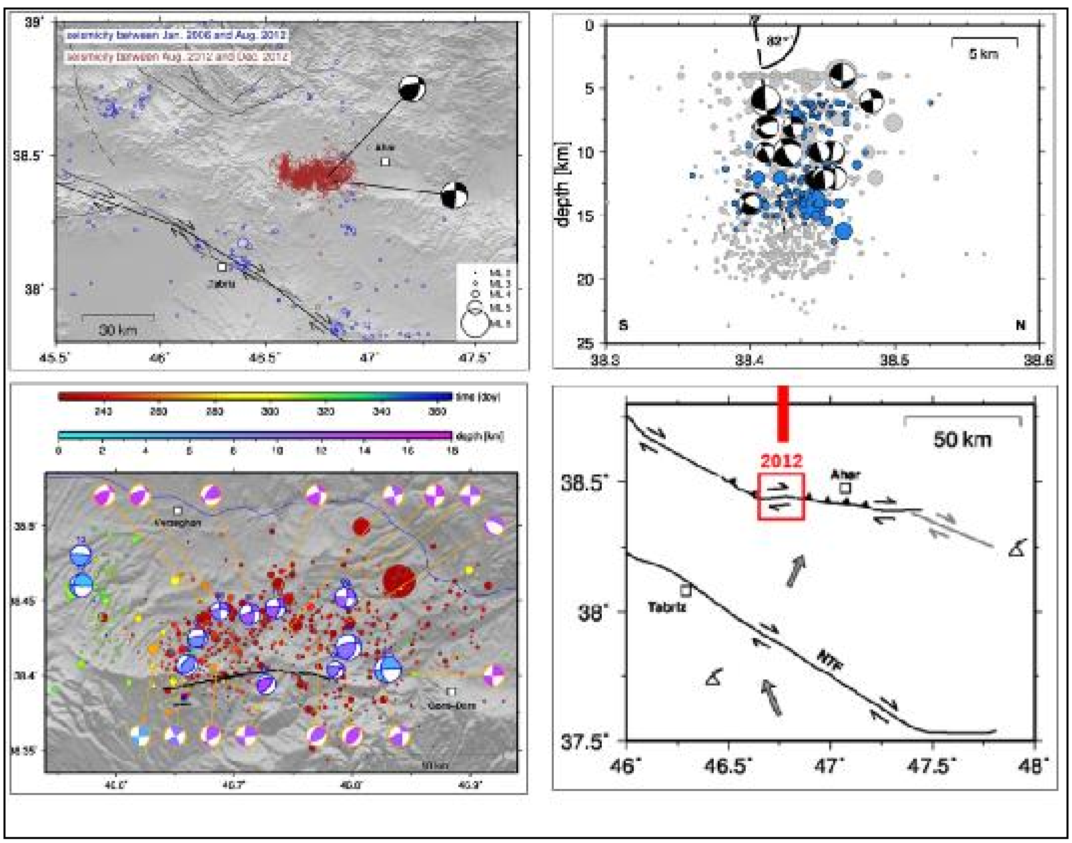


Figure 3. Focal mechanism of 11 August pair earthquakes using 10 seismogram waveform along with aftershocks distribution

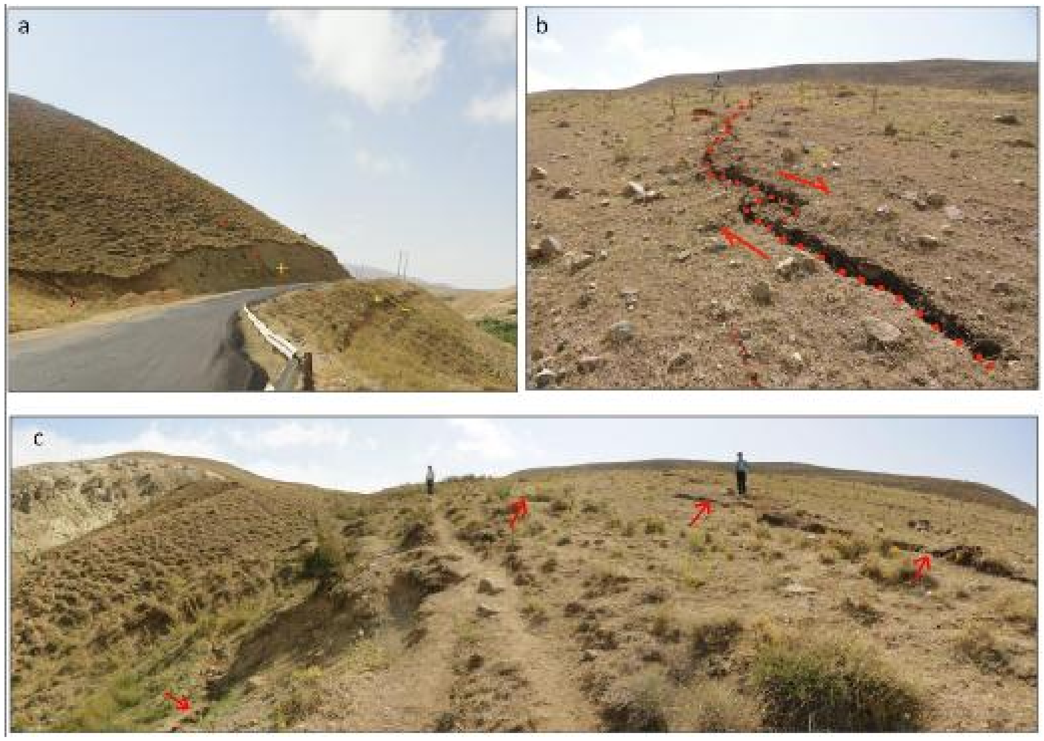


Figure 4. a) Southward dip E-W surface reverse faulting on the Tabriz-Varzeghan road, b) A dextral tension crack with a local pull apart, and c) Two tension cracks very near to south Varzeghan fault

Figure 5. A surface displacement due to lateral spreading near a gully close to the south Varzeghan fault (left) and the maximum measured displacement observed in the field (right).

EFFECT OF PAIR EARTHQUAKES ON SATTAR-KHAN DAM

The Sattar-Khan earth-fill dam with clayey core (Figure 6a) is built 15 km to the west of the Ahar city to supply the agricultural water of the downstream lands, drinking water of the Ahar city, and industrial water of Songun copper mine. Volume of the reservoir at normal water level is about 131 million cubic meters which regulates about 92 million cubic meters of water annually. The height of the dam is 76 m from the foundation but the height of water was 37 m at the time of the earthquakes. Length of the dam crest is 350 m and its width is about 11 m. Dam spillway is non-gated which was still under construction during the earthquake and taking into consideration of the river's annual intake, the reservoir has not yet reached to its normal water level. Cofferdam is a part of the body of the dam and the v/h ratio of both upstream and downstream faces is 1/2.4. The alluvial foundation which was found to have a potential to liquefaction was removed before the dam construction. During the study a tri-axial cyclic experiment was recommended but was not carried out. However, the consultant of the dam had proposed to increase the dam slopes which was confirmed by the dam owner. It should be noted that the study belonged to 15 years prior to the earthquakes and the Mazraeh fault had been introduced as the main earthquake scenario which is not related to the activated earthquake fault.

Three strong motion accelerographs were installed in different parts of the Sattar-Khan dam: Free field, drainage gallery, and the crest of the dam. Recorded Peak Ground Accelerations (PGA) values by these instruments are tabulated in Table 1.

Table 1. Recorded PGA's at different parts of Sattar-Khan dam

Location of accelerograph	Longitude (East)	Latitude (North)	PGA (cm/s/s) Longitudinal component	PGA (cm/s/s) Vertical component	PGA (cm/s/s) Transversal component
Crest	46.915°	38.457°	378	478	333
Gallery	46.915°	38.457°	268	247	248
Free field	46.915°	38.457°	192	196	249

Immediately after the earthquake, a special committee of the dam stability based at the East Azarbaijan Regional Water Organization observed the Sattar-Khan dam and did not report any special case of damage on the dam. However, some longitudinal cracks, sliding and siphon blocks was reported at the vicinity of the downstream irrigation network. During the visit, equipment operation buildings, drainage gallery under the dam body and the dam body were observed. No special sign of damage was observed on the dam body. Some transversal cracks (Figure 6b, 6c) on the asphalt on the crest near the left abutment were very shallow and because of growing of vegetations in them, were not related to the earthquakes.

Drainage gallery under the dam body was also visited. Other than hairy cracks (Figure 6d) in the gallery lining which was not clear whether or not were related to the earthquakes, no specific feature was observed. No water leakage was observed through the cracks. Debit of the drainage gallery at the grouting curtain had no change with the debit before the earthquakes

A doubt on a small creation of inclination in the middle column of the bridge between the dam intake tower and the dam body could be observed (Figure 7). The middle column of the intake tower connecting bridge toward the reservoir's right bank which has a higher height and narrower diameter has likely presented a different response to the earthquakes and seems that has inclined a little bit. Getting closer to the bridge, a continuous transversal crack on the access bridge to the intake tower was observed exactly on the middle column which a 4 cm right lateral displacement was observed along this crack (Figure 7). Taking into consideration that the dam intake tower has shown a different response to earthquake compared to the dam body, entrance control gates of the intake shaft needed to be controlled. The authorities of the East Azarbaijan regional water stability committee and the operator of the dam assured that this problem was controlled immediately after the earthquake and were sure of its safe operation. After impounding two steps micro-geodesy monitoring were performed. A strict proposal was made to the authorities of the dam operation to start a new monitoring process.

Figure 6. a) Downstream face of Sattar-Khan dam, b and c) Some old tension cracks on the crest of dam, growing the vegetation are seen in trace of cracks, d) Hairy cracks in the drainage gallery under the dam body.

Figure 7. Sattar-Khan dam intake tower. There is a doubt in development of a small inclination in the middle column of the bridge between the intake tower and the dam. The observed crack on the middle column is shown in the lower left corner.

EFFECT OF PAIR EARTHQUAKES ON NAHAND DAM

The Nahand earth-fill dam with clayey core (Figure 8) is located 43 km to the northeast of Tabriz City, the capital of the East Azarbaijan province. This dam was built to regulate about 32 million cubic meters of water annually to partially supply the drinking water mid-term supply of Tabriz City. The height of the dam from the river bed is 35 m, the length and the width of the crest are 730 m and 8 m, respectively, and the total reservoir volume is 24 million cubic meters. The length of the non-gated spillway is 30 m. The intake tower is reinforced concrete which two gates with maximum capacity of 5 cubic meters per second discharges the water.

Three strong motion accelerographs were installed in different parts of the Nahand dam: Free field, the entrance of the Tunnel beneath the dam body, and the crest of the dam. Recorded PGA values by these instruments are shown in Table 2.

Table 2. Recorded PGA's at different parts of Nahand Dam

Location of accelerograph	Longitude (East)	Latitude (North)	PGA (cm/s/s) Longitudinal component	PGA (cm/s/s) Vertical component	PGA (cm/s/s) Transversal component
Crest	46.479°	38.223°	212	67	132
Gallery	46.479°	38.223°	175	120	145
Free field	46.479°	38.223°	150	70	86

Figure 8. Nahand dam and its reservoir.

Several transversal cracks were observed on the crest of the Nahand Dam which did not seem that a long time had been passed since their development. However, we cannot exactly claim that all these cracks were necessarily developed due to the pair earthquakes. Growth of plants was seen in many of these cracks which were indicating that they were present before the occurrence of the earthquakes. In both directions of one of these cracks some signs of monitoring of the crack development were found which showed that some of those transversal cracks were old and might have possibly been due to natural settlement of the dam (Figure 9). The position of the water depth of peizometers of both sides of the grouting curtains is an appropriate response of the site and its components due to the pair earthquakes. Even if the development of some of the transversal cracks were due to the earthquakes, taking into consideration of the magnitude and duration of the pair earthquakes and their short distances to the site, no disruption became evident in the operation of the system. In spite of that, recreational villas constructed facing the right bank of the Nahand dam reservoir sustained serious damages due to the pair earthquakes. The main causes of the damage to the villas can be attributed to: Inappropriate materials used for their construction, unsymmetrical architectural plans of the buildings, effect of topography, and large thickness of soft bed rock which intensified the seismic waves and significantly contributed to their damage. Extension of damages has endangered the human settlement in this complex.

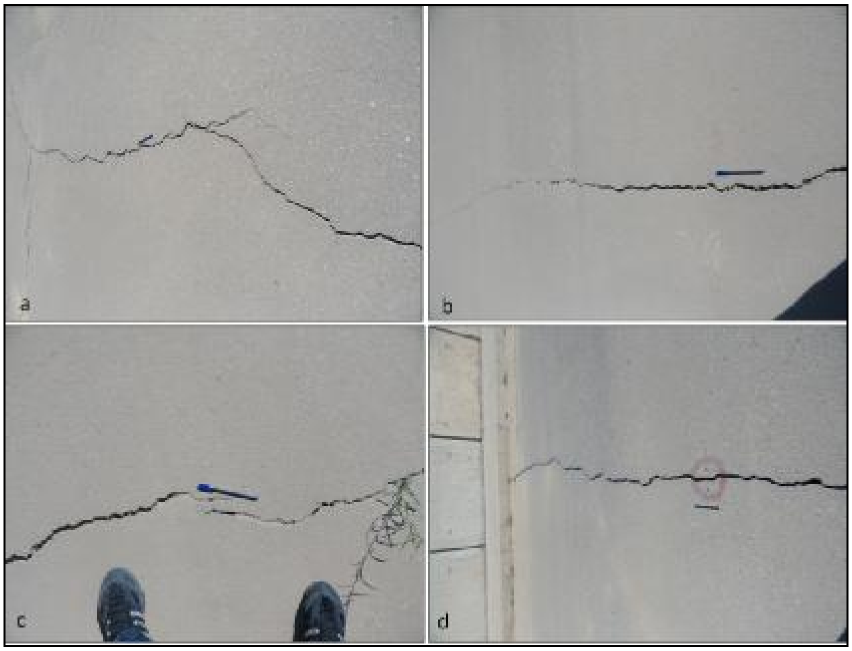


Figure 9. a) Transversal cracks on the Nahand Dam crest, b) With old filling, c) Observation of vegetation growth, and d) Under monitoring. Thus, it seems that most cracks existed before the earthquakes.

CONCLUSIONS

From the view point of seismotectonics, the causative distinct fault that can actually be attributed to the pair earthquakes was not found. All ruptures on the ground in the macro-seismic area including tension transversal or inclined cracks have various trends. However, seismic sources description was done by indirect morpho-seimotectonic evaluation. Similar to many other earthquakes in Iran, the origin of these earthquakes is a production of two reverse and strike-slip fault interaction.

The magnitude and distance conditions of the pair earthquakes with respect to both dam sites indicate that the occurred earthquakes were almost in the range of the Maximum Design Earthquake (MDL) or Safety Evaluating Earthquake (SEE) for both dams.

It seemed that no disruption was taken place to the operation of any of the dams, grouting curtain and other equipment. As a result, both systems' operation was evaluated to be in accordance with the codes. It should be noted that the design of both dam bodies were to a large extent conservative and the slope of 1/2.4 were constructed in both upstream and downstream faces of both dams; this could have contributed to a safe and continuous operation of the dams following the pair earthquakes.

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