Time-Predictable Earthquake Modeling on a Segment of Zagros Mountain Front Fault (Pol-e-Zahab Region) West of Iran

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SUMMARY
Extensive site-specific-study was carried out for Havasan earth dam site located on Darzanganeh River in northwest of Iran. The dam's left abutment lies on Eocene formations very near to Zagros Mountain Front Fault (ZMFF) and total measured dextral displacement along it is about 600 m. Dense distribution of large landslides parallel to ZMFF shows frequent landslides that were induced by earthquakes and have created artificial dams. Three thick layers of lake deposits were also recognized by mapping and drillings. Earthquakes which were detected following a thermo-luminescence dating on samples of the lake deposits as well as historical earthquake data represent that ZMFF ruptures may follow a time-predictable earthquake model. Considering the elapsed time of the last earthquake and the slip rate on ZMFF makes it possible to estimate the magnitude of the next earthquake, if any, in the dam useful life.

Keywords: Time-predictable earthquake model, Zagros Mountain front fault, Havasan earth dam

1. INTRODUCTION

Increase of knowledge on governing process in the Zagros crust (including basement and sedimentary cover) offers the impetus to evaluate the magnitudes of probable future earthquakes along the seismic sources. Due to insufficient subsurface data (e.g., deep seismic reflecting geophysical data) in the Zagros region, any progress in identifying the seismic sources rely mainly on morphotectonic and field investigation. Recent attention to the narrow valleys of Zagros as the sites of large hydraulic structures has raised the proper understanding of neotectonic and seismotectonic phenomena along the seismogenic faults. The Zagros Mountain Front Fault (ZMFF) is one of the most important seismic sources that pass very near from the Havasan Earth dam. Periodical nature of faults becomes an important factor for prediction trend of future earthquakes.

Reid (1910) presented a theory on earthquake cycle (periodicity) called elastic rebound theory. According to this theory, due to continuous loading stress on fractured rock, strain accumulates on one side of the fracture. When strain reaches to a critical value (elastic limit), the frictional resistance overcomes on a fault, and then the displacement takes place on both sides of the fault towards a position of minimum strain which results to occurrence of an earthquake.

Again, accumulation of strain begins for a future earthquake in the same fault following the release of the stored strain energy during an earthquake. This periodical nature of faults becomes an important factor for prediction of future earthquakes. Time-independent models assume that seismicity does not change with time but it does only with space. Most of the studies related to seismicity and seismic hazard assessment are based on the time-independent models (Papazachos et. al., 1994).

During the last three decades, some efforts have been made to assess time-dependent seismicity models. These efforts have revealed that repeated earthquake occurrences support time-predictable models in a single fault or plate boundaries. Two time-dependent seismicity models were proposed by

Shimazaki and Nakata (1980): 1) The slip-predictable model, and 2) The time-predictable model. Both models were then modified by some researchers like Sykes and Quittmeyer (1981), Anagnos and Kiremidjian (1984), and Papazachos (1989, 1992).

In general, only the size of a future earthquake can be predicted by the slip predictable model, while the time of its occurrence can be forecasted by the time predictable model. Many researchers have applied this model for earthquake prediction in different seismogenic regions of the world. Results of some studies have shown that the time-predictable model is more efficient for seismic hazard estimation and earthquake prediction compared to the slip-predictable model.

In this paper, validity of the time predictable model for earthquake generation is tested in an area in northwest of Iran. For this purpose, a paleo-seismological approach was carried out to forecast future earthquakes' sizes on the Salmaneh segment of the Zagros Mountain Front Fault (MFF). Evidences which were collected during the field investigations and aerial photograph analysis are presented. Stratigraphic and structural geology studies that lead to an estimation of slip rate of this segment are also explained. Magnitude recurrence model and the rate and return period of earthquakes are also discussed for this segment.

2. TECTONIC SETTING AND STRUCTURAL GEOLOGY COMPONENTS

During the seismic hazard assessment of an earth dam on Havasan River in northwest of Iran, it was found that the Zagros Mountain Front Fault with a long discontinuity is located at a very near distance from the left abutment of the dam. To follow the dam safety guidelines a detailed seismotectonic investigation was carried out which included a paleo-seismology study based on the thermo-luminescence dating on its secondary features.

Structural components around the effective radius of the study area are located in the Zagros Simply Folded Belt sub-unit on the western limb of the wide wavelength Gahvareh anticline (Fig. 1). The western limb of anticline consists of Eocene (Talezang formation) and Oligocene-Miocene limestone (Shahbazan formation) which have bedding with N-S trend. There is no formation in the eastern limb belonging to the Cenozoic era and has NW-SE trend similar to most of the Zagros mountain ranges. A 600 m dextral offset on the Zagros MFF is approved on Talezang limy formation in the western limb of Gahvareh anticline in foothills of Salmaneh and Bambu range (Fig. 1).

Other structural features in the vicinity of the study area are also demonstrated in a digital elevation map (Fig. 1). The main branch of the Zagros MFF reaches to the Ghasr-e Shirin segment fault southward and then seats beneath the southwestern limb of Bazideraz asymmetry and sometimes overturned anticline as a hidden fault. Since the Shahbazan formation in this anticline is becoming thinner, it seems that this fault could have affected the Eocene sedimentary basin and has been active in various times in the past. Its recent activity is also confirmed by southward tilting of alluvial and colluvial deposits in the southwest limb.

Another feature in the study area is the Krend Fault whose seismic activity is confirmed by historical and instrumental seismicity.

ZMFF in the Zagros belt has a NW-SE trend but as mentioned above, contrary to most parts of ZMFF, this section has an N-S trend. Alavi (2007) reported a Pan-African basement fault parallel to MFF called Khaneqin. With regard to both trends and the oblique convergence between the Arabian and Iranian plates, the possibility of MFF reactivation with dextral strike slip mechanism would be high, and therefore the sedimentary cover above the basement can be affected by this type of movement. Fig. 2 shows the sedimentary and structural components in a larger scale. One of the most geological features in the study area is the presence of a Lithologic unit that was named Dislocated Rock Mass (DRM) by Sayar (2011). The source of this unit can be the Talezang and Shahbazan formations and with the observed volume needs seismic loading.

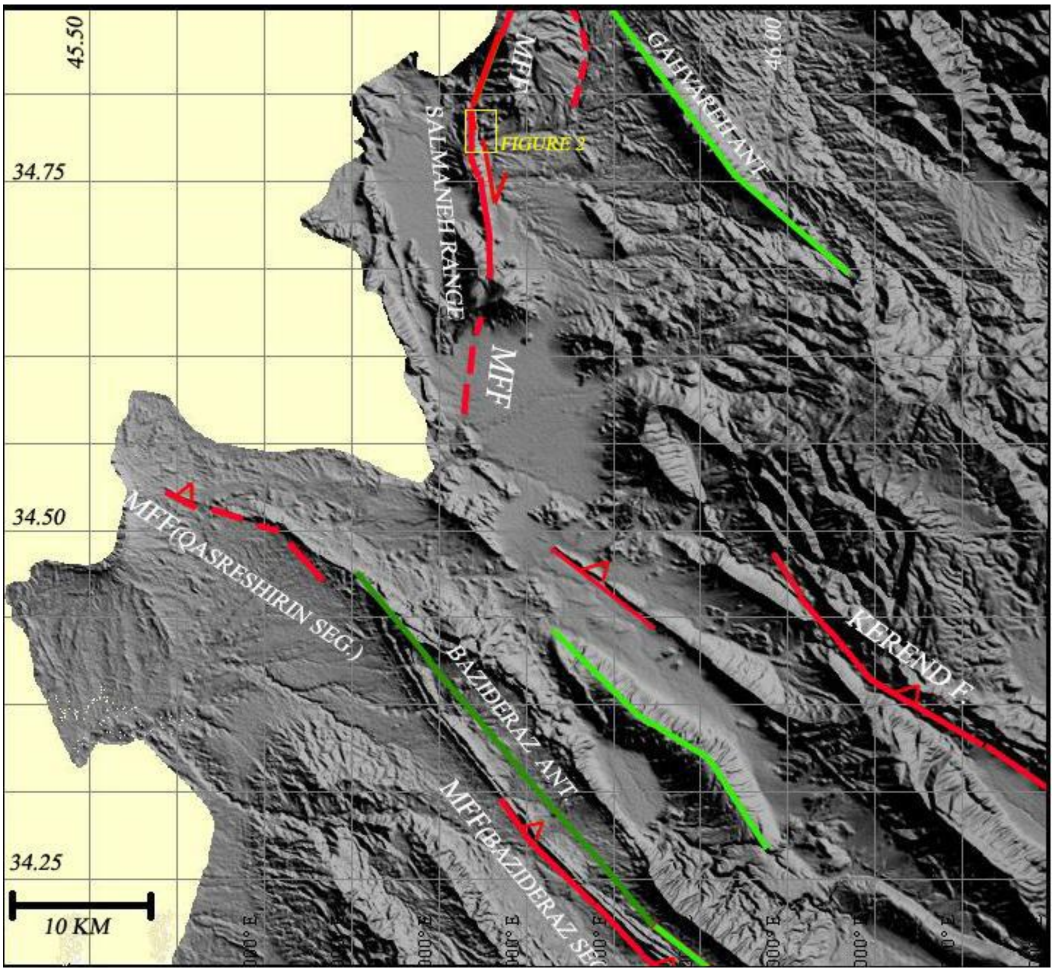

Figure 1. Structural components around the effective radius of the study area.
Yellow rectangle on top of the Figure is shown in a larger scale in Fig. 2.

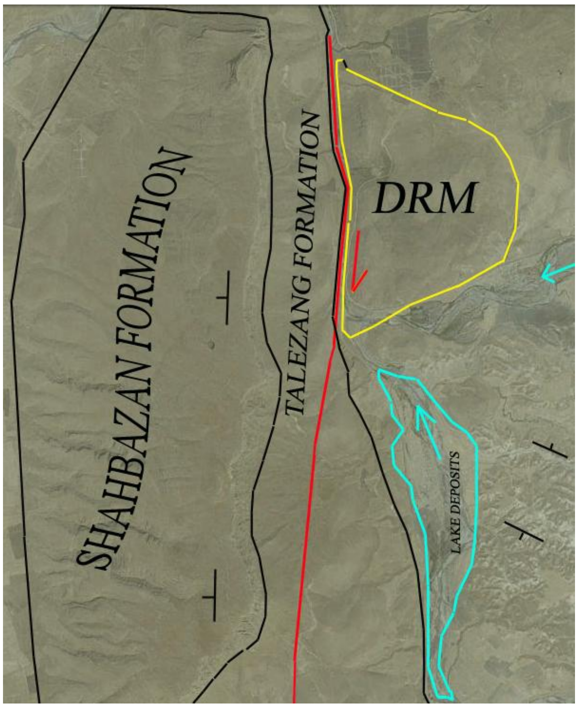

Figure 2. Sedimentary and structural components of the study area in a larger scale

Both above formations have bedding dip directions westward, inverse to the slope of topography, so their movement eastward could not occur by only gravity force. Barring of Havasan River by DRM unit is confirmed by the presence of many lake deposits' horizons. Two horizons were mapped in the field but in order to identify the right plurality of lake deposits' horizons, a 100 meter depth exploration borehole was drilled in the course of Havasan River. During the drilling another lake deposits' horizon could be logged right beneath the recent alluvial deposit. Drilling continued logging the basement rock.

Findings of the field investigation coupled with the borehole results indicate that there are three lake deposits' horizons in the study area which can imply that they were sedimented after three medium to large earthquakes.

3. ZAGROS MOUNTAIN FRONT FAULT MECHANISM

The Zagros Mountain Front Fault in the Zagros is considered as a high angle basement reverse fault with NW-SE trend. Before Berberian (1995) this fault had been introduced as Mountain Front Flexure (Falcon 1969, 1974). This fault is a production of inversion tectonic from initial normal faults. Therefore, the dip of this fault is very high, approximately 50-60 degrees (Jackson and Mc Kenzie, 1984; Ni and Barazang 1986). In the study area, due to the presence of both N-S Khaneqin basement Pan-African trend and oblique convergence between the Arabian and Iranian plates, the ZMFF plays as a strike slip fault role. Several transverse normal faults with respect to MFF have controlled DRM and rock falls. Along this fault, a 600 meter dextral offset in Talezang formation was measured. A right step over geometry can be observed in the foothill of Salmaneh range with regard to the Bambo range. The study area is transformed into a trans-tensional area due to this geometry (Fig. 3). Trans-tensional conditions are responsible for the transverse normal faults and the rotations of blocks.

The above evidences confirm that ZMFF has a dextral strike slip mechanism. In the western and eastern walls of ZMFF the Talezang and Asmari formations' outcrops have severely been deformed as primary faulting and secondary landslide ruptures. Due to the fault activity a 60 meter width crush zone is developed. Sub-vertical to sub-horizontal slickenside can be measured in the plane of fault or its branches. At least 3 lake deposit horizons' sediments are mapped (Figs. 4 and 5). Confirming the right lateral mechanism for MFF can refer to the overlapped boudinages which formed as in cherty interbeds in Talezang limestone. This type of deformation can be seen in simple shear deformation where final compression features overprinted on the tensional one (Fig. 5).

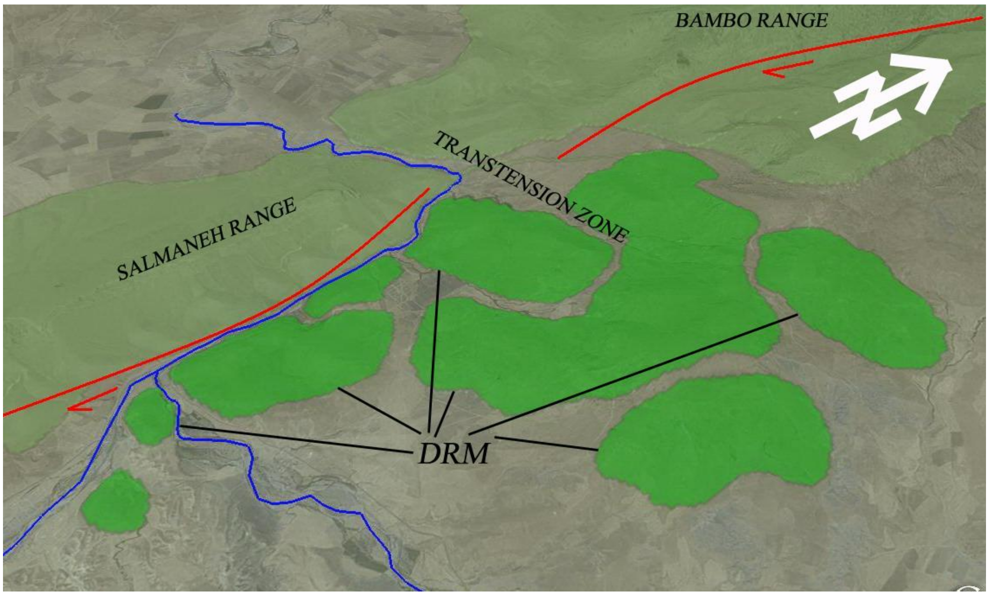

Figure 3. A right step over and trans-tension zone along ZMFF and DRM distribution

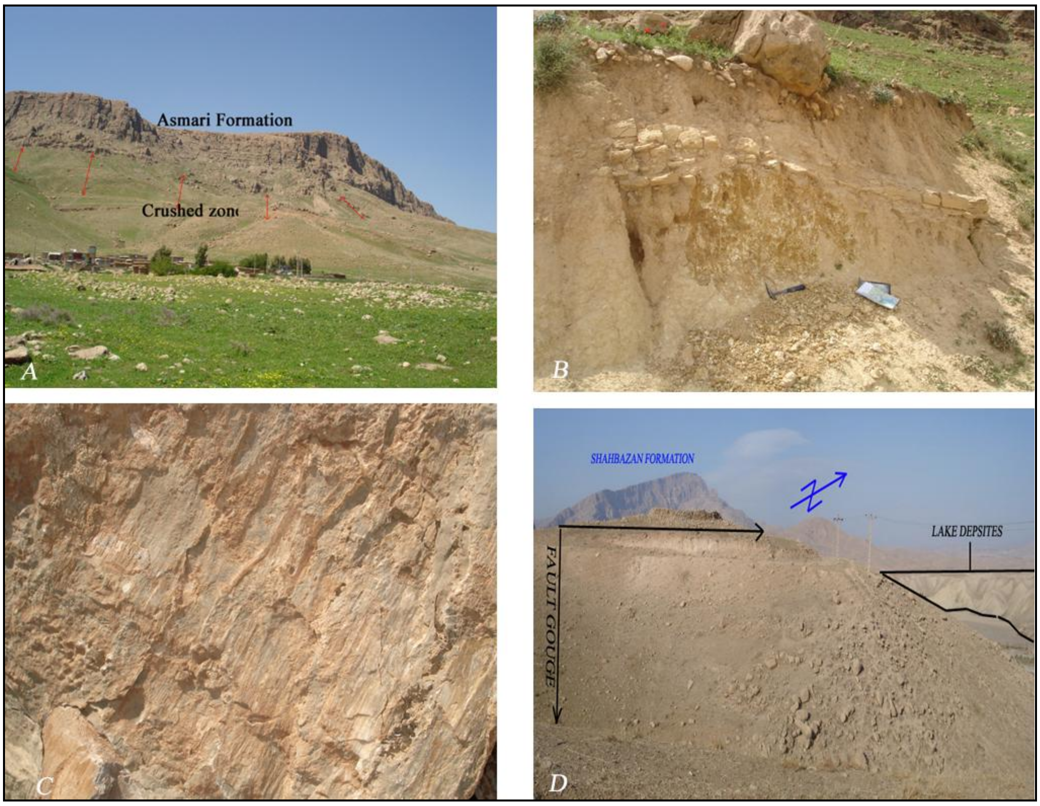

Figure 4. Field evidences collected in the study area: A) Crushed zone along the Salmaneh segment, B) Gouge zone along the Salmaneh segment fault, C) Sub-vertical slickenside in a plane of the fault, D) Fault gouge along the Salmaneh fault.

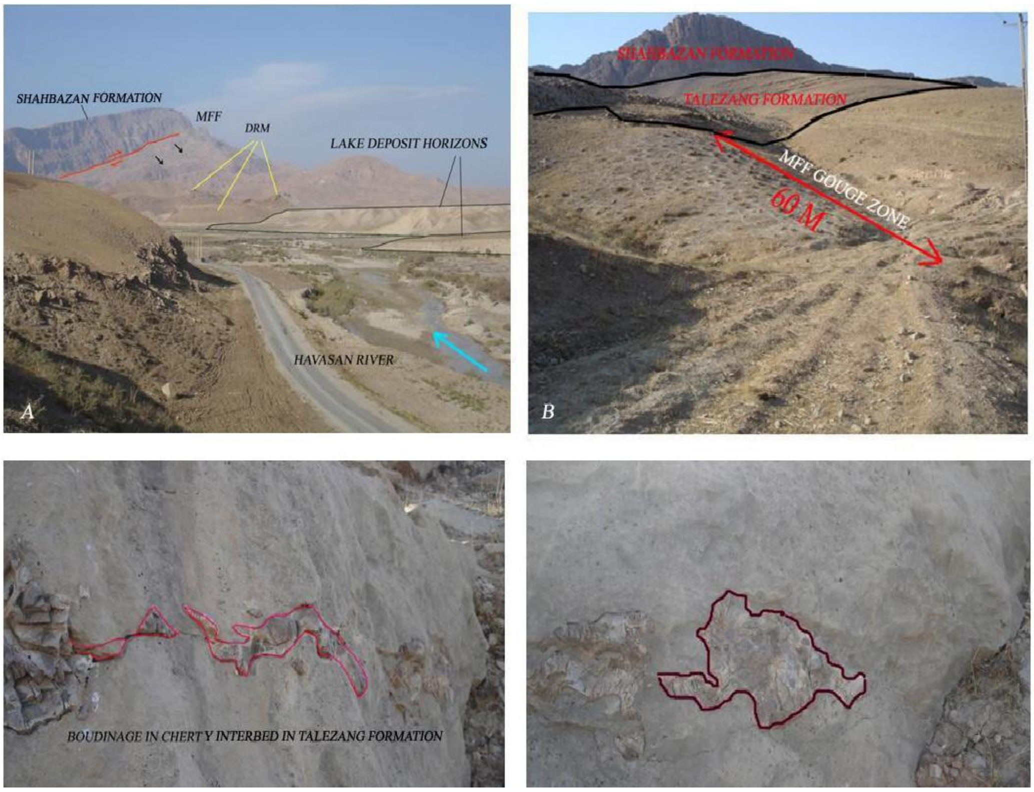

Figure 5. A) Two lake deposits besides the Havasan River, B) 60-meter width fault gouge along the Salmaneh fault, C) Overlapped boudinage in cherty inter-beds of Talezang formation, D) A rotated inclusion that confirms simple shear stress deformation.

4. SEISMICITY

Recorded history of seismic activities in the Pol-e-Zahab region goes back to 958 AC when an earthquake (Ms 6.4) occurred in that area. During this earthquake Sar-e Pol-e-Zahab, which then was famed as Helvan was damaged (Ambraseys and Melville, 1982). According to historical maps, Helvan was in a 10 Km distance from west of Khaneqin in the bank of Dialeh River in present Iraq. The distance between the old Helvan and ZMFF is too far than one can consider it as a causative fault for the 958 event. Similarly, 1118 and 1130 earthquakes can not be correlated to this fault either. The 1150.04.01 earthquake affected the Sar-e Pol-e-Zahab region and caused some deformations on mountains as rock falls. Historical data can imply that the epicenter of this event was in northwest of Iran near the 'Robat-e-Behroozi' region in the border between Iran and Iraq. In the Havasan dam site-specific-study it was evident that 'Robat-e-Behroozi' is located 5.5 Km to the west of ZMFF, Salmaneh segment, and the causative fault of this event was undoubtedly ZMFF. Berberian (1994b) also referred that the causative fault of this event was one of the ZMFF or Kerend faults.

Instrumental seismicity was also investigated in the study area. Epicenter of the 1946.10.12 event (Ms 4.2) is very near to the Ghasr-e-Shirin fault. Two events in 1966.04.01 (Ms 4.6 and 4.2) had a 23 Km distance to the fault segment. Similarly, the 1966.03.16 event located on the Krend fault was far from MFF. Causative fault of the 1979.07.01 and 1981.12.28 events was the High Zagros Master Fault. Based on the above reasoning, as a preliminary finding, one may admit that the Salmaneh segment of MFF has been experiencing a seismic dormancy for 850 years and energy is being accumulated on it.

5. PALEO-SEISMOLOGY APPROACH

The main appearance of the masses is along a limestone ridge on the right abutment of Havasan River in an area with a length of 6 Km and a width of 5 Km. The ridge, which is called Salmaneh Ridge, has a N-S trend consisting of two successive and conformable limestone to marly limestone formations on the left wall of the valley and the extension of the masses is on the opposite side of the ridge on the right wall of the valley. In this area, Dislocated Rock Masses (DRMs) are appeared as the masses that are very close to each other but are separated by erosion.

In addition to main emplacement of DRMs, several smaller dislocated masses were observed in a limited distribution up to 30 Km far from the main location. Their setting and other characteristics is like the main area.

The tremendous displaced masses are spread all over the area, especially at the confluence of two branches of the main river. The consequence of emplacement of the masses is the creation of a natural dam in the area. Another word, a closed sedimentary basin in the area in which considerable volume of fine grain materials alternated by coarse grain horizons are deposited. The present distribution of these deposits is on the upstream of the confluence point in an area about 25 km^2 whose distribution has been limited by DRMs emplacement. According to exploratory works, the maximum thickness of lacustrine deposits was evaluated to be about 90 to 100 meters.

Any given method should correspond to the fault characteristics and the nature of DRM. Evidently, not any method can be applied for every case. Movement of DRMs caused to close the river flow, leading to sedimentation of fine grain material over the limited basin whose total thickness reaches to about 100 meters. Using thermo-luminescence dating method on these deposits indicated three occurrences within the following times:

- 4900 years ago
- 6300 years ago
- 13000 years ago

These three times correspond to the sedimentation rate and in other word to thickness of the lake deposits. These three intervals and distinct times show, more or less, three stages of the river closure attributed to three tectonic occurrences.

Taking into consideration of the paleo-seismologic study, if the latest event on the Salmaneh segment of MFF was the 1150 earthquake, then the elapsed time would be 860 years. Knowing this parameter is very important for seismic hazard assessment because the size of future earthquakes can be predicted in a long term manner by combining the elapsed time and return period of the magnitude. From the published data on the tectonics of Zagros one can consider that the beginning of oblique shortening was in the Pliocene, about 1.64 million years ago. On the other hand, stratigraphic offset in the Talezang limestone was measured about 600 meters, and therefore, an approximate rate of 0.4 mm/year is reconstructed for slip on the MFF Salmaneh segment.

Taking into account of the 63 Km surface length and 75 Km subsurface length of the Salmaneh segment, and considering the Wells and Coppersmith (1994) empirical relationships, the maximum magnitude earthquake that can be expected to occur in the Salmaneh segment of ZMFF is Ms 7.2.

Figure 6 shows that the magnitude of event 1 can not be estimated and event 2 has experienced a displacement of about 270 cm. According to wells and Coppersmith (1994), either event 2 had a maximum magnitude of 7.2 on ZMFF or some small to moderate earthquakes occurred without noticeable records in the time interval between events 2 and 3. Thickness of the lake deposits supports the first assumption. Considering a small slip that had accompanied event 3, the magnitude of this event could not be greater than Ms 6.4. The magnitude of the 1150 historical earthquake which was reported by Ambraseys and Melville (1982) was equal to Ms 5.9. This confirms that small to moderate earthquakes could occur between events 3 and 4 which no evidence is remained from them. Considering the life time of the project (100 years), and noting to the elapsed time and a 45 cm accumulated slip, it may be concluded that the design earthquake which should be less than the maximum credible earthquake can be around Ms 6.5 for ZMFF as a strike slip fault.

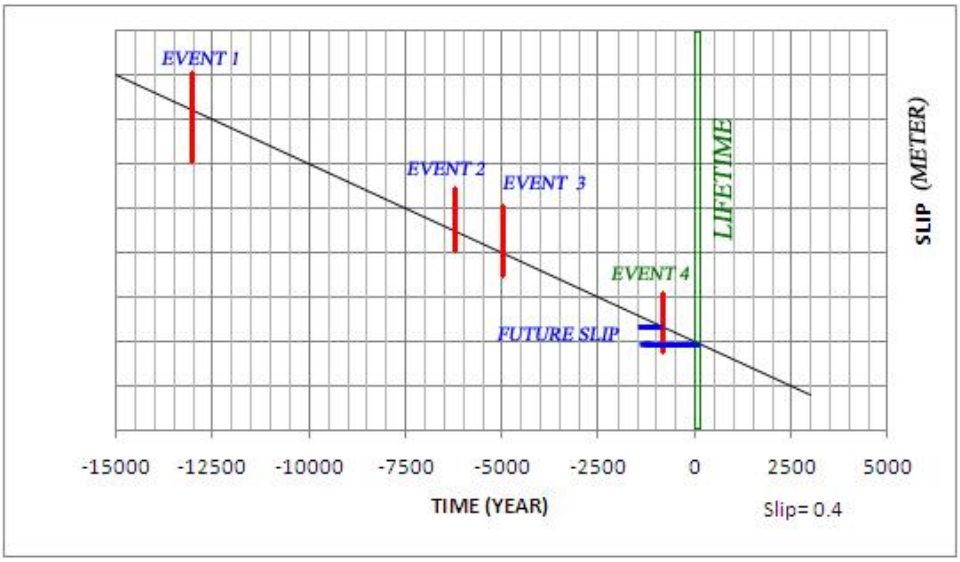

Figure 6. A diagram for prediction of the size of future earthquakes.

6. CONCLUSIONS

Fault slip rates are being used to constrain earthquake recurrence relationships for the site-specific probabilistic seismic hazard (ground motion) assessments. However, several assumptions are required to do it. It seems that for the Salmaneh segment from the Zagros Mountain Front Fault (ZMFF) all the measured slip across the fault is usually assumed to be a seismic slip, and the fault creep has not been recognized. Opposite directions of the Talezang and Shahbazan beddings and topographic slope indicate that the observed large landslides could only be occurred by seismic loading. It is assumed that the slip rate is an average and does not allow for the short-term fluctuations in the rate. An average slip rate of 0.4 mm/year is assumed to be applicable for a future time period (e.g., dam useful life).

Time-predictable earthquake modelling was performed for Havasan earth dam site area located on Darzanganeh River (Pol-e-Zahab region) which is a segment of (ZMFF) in northwest of Iran. Following a thermo-luminescence dating on samples of the lake deposits in the area which detected some earthquake occurrences in the past as well as historical earthquake data showed that ZMFF ruptures may have followed a time-predictable earthquake model. Taking into consideration of the elapsed time of the last earthquake and the slip rate on ZMFF made it possible to estimate the magnitude of the next earthquake in the dam useful life. According to this estimate the magnitude of the next earthquake during this period may be around Ms 6.5.

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