GEOMECHANICAL ASPECTS OF RESEVOIR TRIGGERED SEISMICITY OF THE UPPER GOTVAND DAM, IRAN

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Abstract

The Upper Gotvand Dam in southwestern Khuzestan Province is the highest core clay rock-fill dam of Iran with a height of 182m. Primary seismological study of the dam reservoir area based on a local network indicated an increase in seismic activity after impounding of a volume of about 2.1 billion m³ of its total 4.5 billion m³ storage capacity. The maximum recorded magnitude was 4.2 and most of the events had focal depths deeper that 8 km. The dam site and most of its reservoir area is underlain by Mio-Pliocene sandstones of Agha-Jari Formation. Based on the geotechnical data of the dam site and reservoir area and subsurface data form underlying oilfields, it is shown that the Agha-Jari sandstones beneath the reservoir area are highly fractured and permeable which facilitate downward diffusion of pore pressure. The Pir-Ahmad and Lahbari thrust faults are the two main active faults near the dam site. Further field survey showed that two E-W and SW-NE trending thrust faults with strike-slip components cut the reservoir area about 4 km upstream the dam site. The reservoir shape in this region is aligned with a SW-NE trending lineament and the main concentration of the recorded events after impoundment was within this area. The deepest part of the reservoir is underlain by Lali oilfield that is bounded by two NW-SE trending and opposite dipping faults creating a block faulted and uplifted zone beneath the dam reservoir. There is a strike-slip sense of motion almost parallel with the river course, as well. Although, the observed micro-earthquake activity is fairly coincident with the reservoir water level variation, the recorded triggered seismicity could not be accurately related to the existing active faults such as Lahbari and Pir-Ahmad faults since the mechanism of the micro-earthquakes is not known. The deep foci of these events which relate them to the underlying crust besides their prevailing NW-SE trend that is comparable to the general trend of reverse faulting in the region are most probably indications of triggering the pre-existing faults beneath the reservoir area rather than direct activation of seismicity in the region. According to the present study, the impounding of the Upper Gotvand dam most probably added some stresses on the pre-existing faults including Lahbari Active Fault to trigger larger initial stresses in the reservoir area.

Keywords: Gotvand dam; triggered seismicity; geomechanical properties; fault activity

1. Introduction

Reservoir Induced Seismicity (RIS) or recently noted [1] as Reservoir Triggered Seismicity (RTS) is defined as the failure of a pre-existing fault below an artificial lake due to dam reservoir impoundment after initial infill or by seasonal fluctuations water level. Accordingly Reservoir-Triggered Earthquake (RTE) introduced as the maximum level of ground motion capable of being triggered at the dam site by the filling, drawdown, or the presence of the reservoir [2]. During last decades, there have been about 130 RTS cases reported around the world. Investigation of case histories indicate a fairly strong correlation between the occurrence of triggered seismicity and reservoir size and filling history, hydrogeological conditions, faulting regime, and rock types [3,4]. Generally for dams higher than about 100 m or reservoirs with capacity greater than about 500 Mm^3 and also for new dams of smaller size located in tectonically sensitive areas, RTS should be taken into consideration. The Upper Gotvand (U.G) dam as the highest rock fill dam with clay core in Iran, is located in Khuzestan Province of southwest Iran. It was planned to produce electrical energy, flood control, water regulation and tourist attraction. The U.G. dam was constructed across the Karun River, in the north of Shushtar city (Fig. 1) with a height of 182 m. It belongs to a series of cascading dams constructed over the longest and biggest river of the country i.e., Karun river. The dam site foundation and abutments are underlain by sandstone and conglomerate rocks (Fig. 2) whereas, its reservoir area is mostly underlain by sandstones, marlstones and evaporitic rocks (Fig. 3).

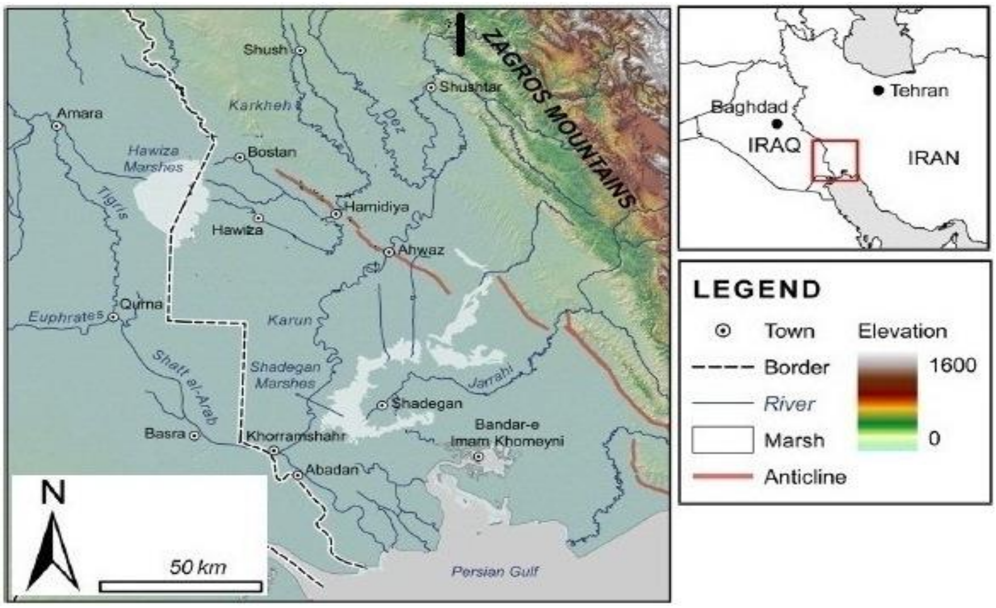

Fig. 1 – The location of the Upper Gotvand Dam (heavy black) site in Khuzestan Province

The dam site is located in the most seismotectonically active zone of the country resulting in instability of the abutments, seepage potential through the foundation and abutments [5,6,7,8,] and RTS phenomenon [9,10]. Impounding of the U.G. dam reservoir (Fig. 4) caused an increase in seismicity in the dam region, based on micro-seismicity studies. However, it is almost probable that it is partly related to oil extraction in the nearby hydrocarbon reservoirs regarding to the pre-impounding statistical data on the regional micro-seismicity and local state of stresses [11, 12]. The main concern of this study is to investigate the geomechanical properties of the U.G. dam site and reservoir rocks and possible relationship between the RTS, reservoir impounding and oil production.

Fig. 2 – An upstream (eastward) view of the Upper Gotvand dam reservoir and the outcropped formations; Bakhtyari (Bk) Conglomerates, Agha-Jari (Aj) Sandstones, Gachsaran (Gs) Evaporates

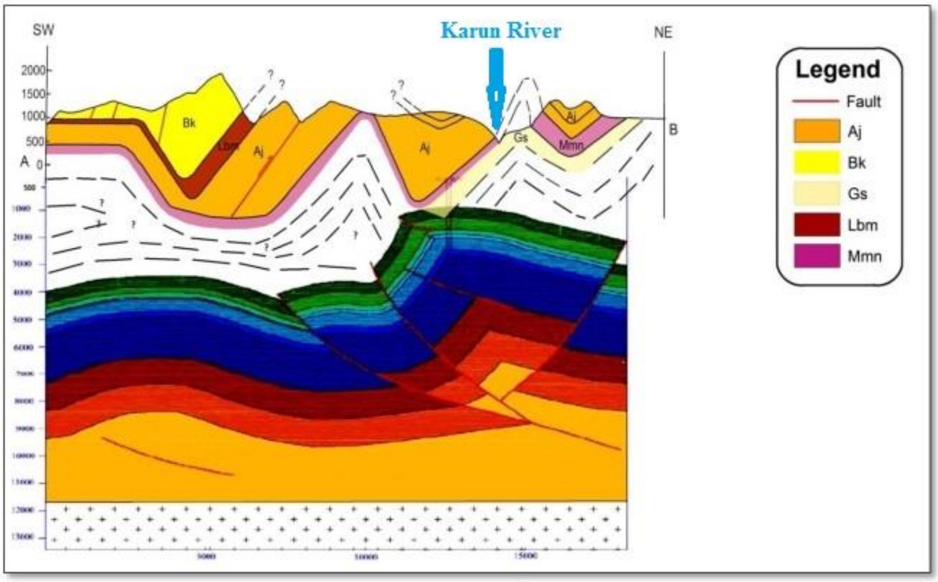

Fig. 3 – Simplified geological cross section across the Upper Gotvand dam reservoir about 3km upstream the dam axis; Bakhtyari (Bk) Conglomerates, Agha-Jari (Aj) Sandstones and Lahbari member (Lbm), Gachsaran (Gs) Evaporates, Mishan marlstones (Mnm)

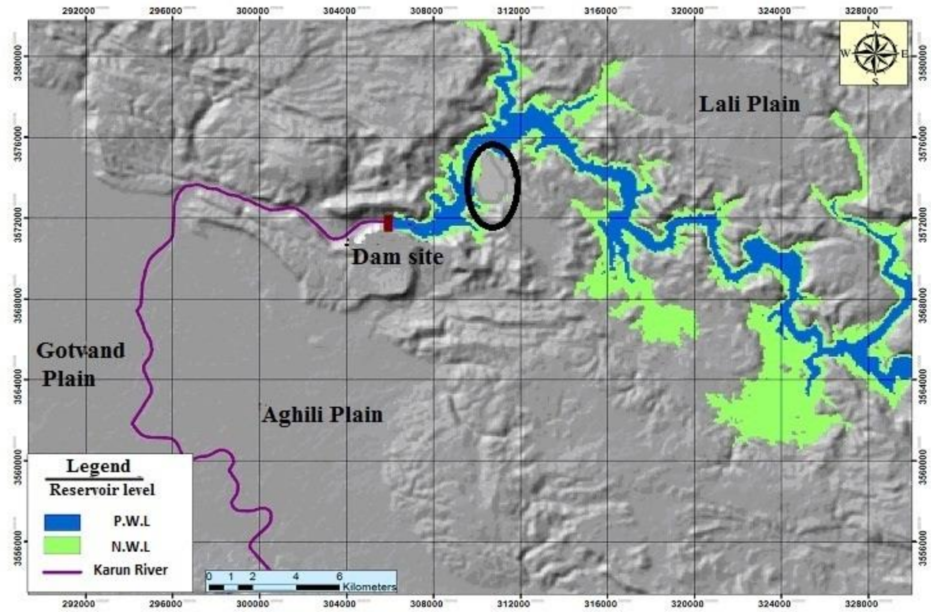

Fig. 4 – Digital Elevation Map (DEM) of the Upper Gotvand dam and reservoir region.
Reservoir water level (RWL) and normal water level (NWR) are shown.
Black ellipse indicates location of the geological section in figure 3

2. Seismicity, geological structure and tectonic setting

The U.G. dam is located in the Zagros Active Fold Belt from the seismotectonic point of view [13] in the northern part of Dezful Embayment structural unit. Fault plane solutions of the earthquakes in the region consistently show high-angle (40-50°) reverse faulting [14] with an estimated depth range from 8 to 13 km and 4 to 6 magnitudes (Figs. 5, 6, 7). As part of Zagros Simply Folded Belt [15], the study area is comprised of parallel, long anticlines and Karun River syncline [16]. The most important faults in the region are: Pir-Ahmad, Lahbari, Andeka, Lali and Shushtar thrust faults (Fig. 5) among which the first two are known as active faults [14, 5]. Subsurface structure of the region shows that the deepest part of the dam reservoir is underlain by Lali oilfield with a nearly 30 km length. This field is bounded by two NW-SE trending and opposite dipping faults creating a block faulted and uplifted zone beneath the dam reservoir [12]. The Lali structure is geologically a complex structure demonstrating a positive flower structure. The dam reservoir is bounded by a syncline in the south and an anticline on the north, respectively that created a rabbit ears structure. Interpretation of seismic profiles have revealed reverse faulting in the borders of this anticline that formed duplex and pop-up structures consisting of several fault blocks separated by thrust faults (Fig. 3).

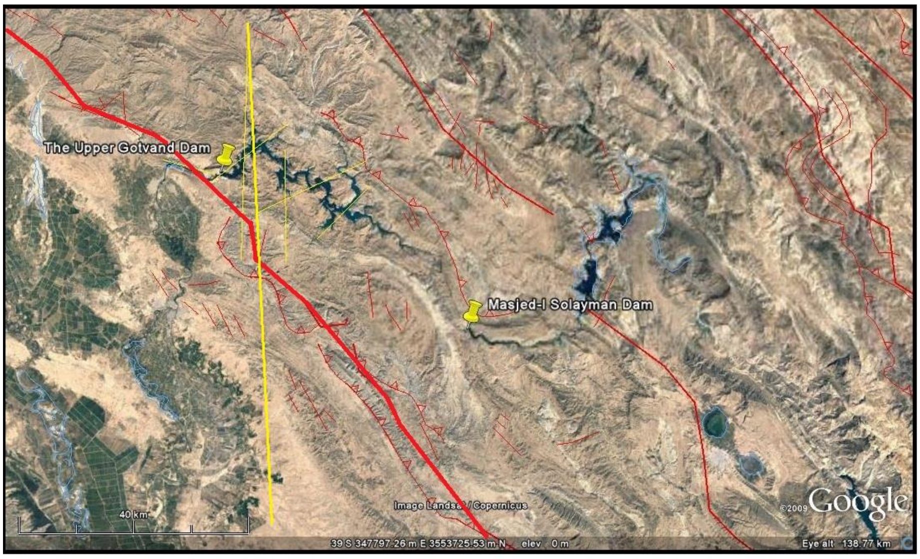

Fig. 5 – Google Earth view of the main morphotectonic lineaments in the area including Lahbari active fault (thick red) and Ahvaz-Lali (thick yellow) lineament

The local seismographic network for the M.I.S dam was established in June 2006, four years after reservoir impounding with 15 month period of recording. The data obtained from the U.G dam seismographic network was accessible from 2011 March 20 (Fig. 8) about 10 months before starting the impoundment. However, the impoundment of the U.G reservoirs was started on 2012 January 20 [10]. The observed micro-seismicity in the study region before [11] and after the impoundment indicated an average focal depth range between 12 km to 20 km.

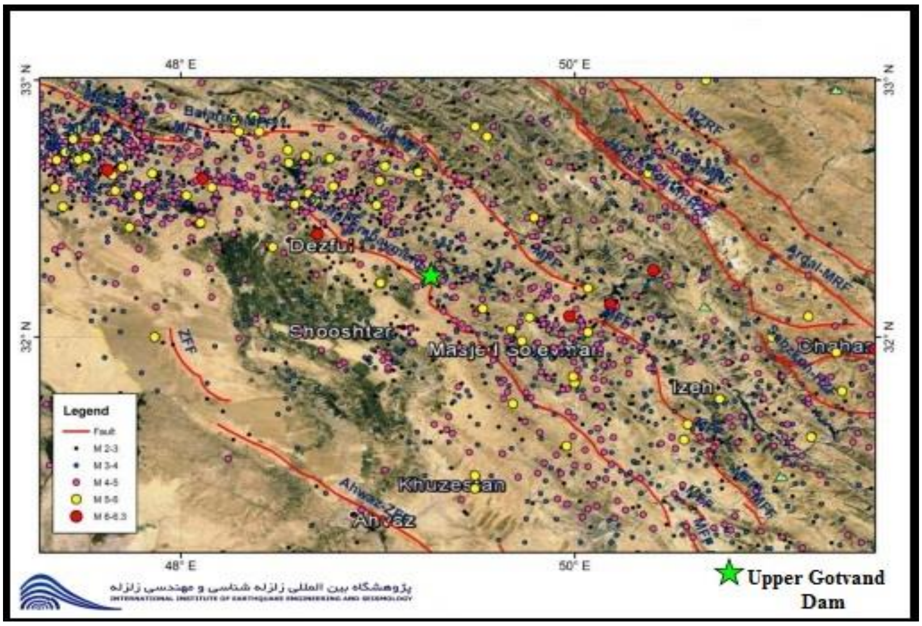

Fig. 6 – Seismicity map (1900-2016) of the region (after IIEES)

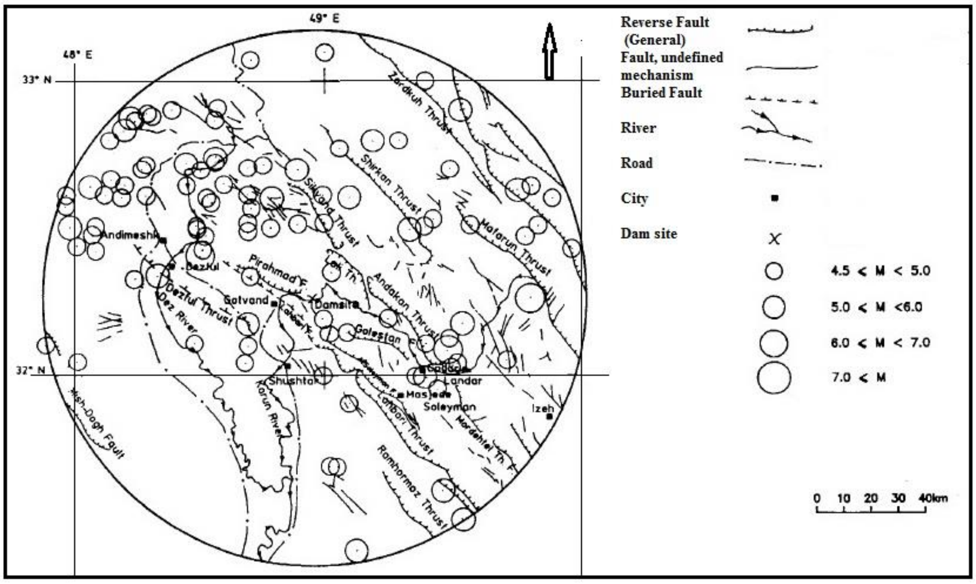

Fig. 7 – Regional seismotectonic features of the Upper Gotvand dam region (after Berberian, 1989)

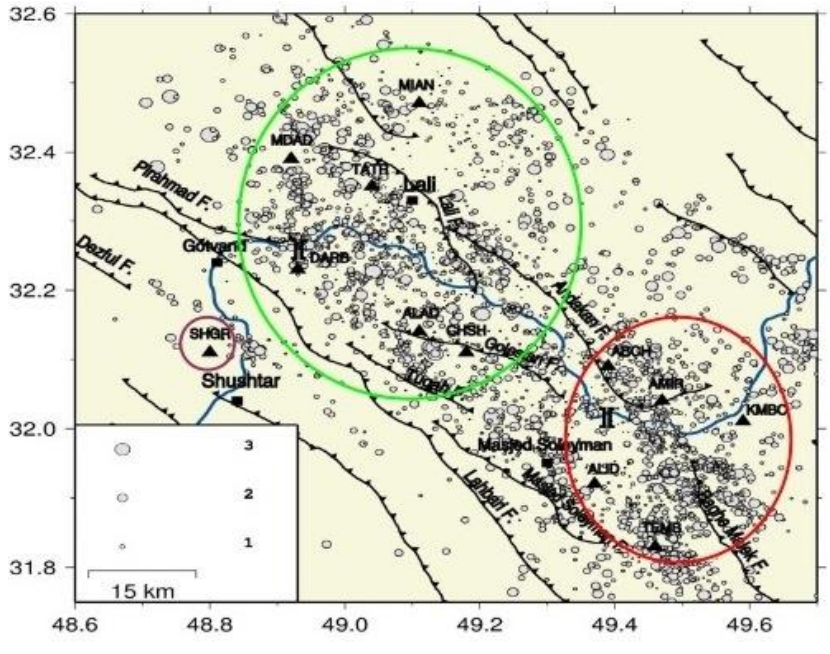

Fig. 8 – Distribution of local seismicity around the reservoir region between 2011 and 2013 (Ebrahimi and Tatar, 2018)

The calculated b value (usually higher than 1.2) for the region (Fig. 9) is similar to known b-values for the Zagros Belt [17] and is representative of the regional seismicity. The b-values estimated for the study region ranges from 0.6 to 0.98 and up to 1.3 [11, 18]. This value in regions with RTS is usually higher than 1-1.2.

3. Geomechanical features and triggered seismicity

As noted above, the U.G dam reservoir area is mostly underlain by sandstones, marlstones and evaporitic rocks [19]. The Agha-Jari Formation is folded and faulted, and its rocks contain veins of gypsum usually associated with clay stone beds. It is underlain by thick Gachsaran layers that sometimes thrust over the overlying formations including Agha-Jari layers [20, 21]. Most of the geological boundaries along Gachsaran-Bakhtiari contact show evidence of thrust faulting. The RQD values reported for Agha-Jari rocks are varying extensively and decrease significantly with depth [7] and ranges between 10 to 100 % and their geomechanical classification indicated them as week to very week nature (Table 1). The minimum and maximum values of Young Modulus in Agha-Jari layers vary between 2.28 and 11.2 GPa, respectively with a tensile strength value ranging between 1.9 and 3.2 MPa. The minimum and maximum values of shear strength for them were determined 0.33 and 0.16 MPa, respectively [22]. The corresponding values for Gachsaran layers vary between 0.0 and 5.9 MPa, respectively.

Table 1 – Geomechanical parameters of Agha-Jari rock samples

Name	**Formation (Agha Jari)**		
	Symbol	Unit	Value
Elastic modulus	E_i	GPa	37.25
Uniaxial Compressive Strength	UCS	MPa	82.72
Rock Quality Designation	RQD		47.25
Q System	NGI		1.42
Geological Strength Index	GSI	Pa	51.65
Density	ρ	gr/cm^2	2.54

Mechanical rock properties can influence the reactivation of a fault resulting in RTS. Permeability tests Agha-Jari layers indicated values up to 30 Lu [23] that corresponds to high permeable and groutable rock [24]. The average density of sediments in the overburden is between 1.8 and 2.2 g/cm3, so as a rough number, the vertical stress increases downwards with about 20 MPa/km. The pore fluid pressure values beneath the reservoir region indicated an increase from 21 MPa at a depth of 1944 m up to 35.3 MPa at a depth of 3577 m which is in the range of the expected value for oil reservoirs that is roughly 10 MPa/km [25]. However, this variation is about 0.05 MPa/km based on shear wave velocity changes [18]. The pore fluid pressure in the region does not clearly reflect redistribution of stress in the substratum. The maximum vertical stress [26] due to the dam reservoir impounding (maximum depth of 90m) is estimated about 1 MPa. The microseismicity of the area may not be due to any particular fault [18] regarding to distance of major known faults and the required stress regime and hydrotectonic circumstances [27] but may be connected to the stress generated by pore fluid pressure changes. Nearly constant high b-value in the studied region before and after the impoundment indicates heterogeneous stress distribution in the crust due to possible gradual increase in pore pressure. This is followed by faults weakening due to pore pressure diffusion [26, 28]. The effective vertical stress is then also increasing with approximately 10 MPa/km. It is noteworthy that only 21% of RTS sites are located in reverse faulting environments which are less susceptible to RTS than reservoirs in normal or strike-slip faulting regimes [29]. In reverse faulting regime, the minimum principal stress is in the vertical direction and is directly increased by reservoir impoundment, thus decreasing the diameter of Mohr circle and in turn, moving it further away from the failure envelope. For reverse faulting, the effective horizontal stress must be 3 times larger than the effective vertical stress. On the other hand, fractures in fault zones having permeability values within the seismogenic permeability range (0.5 – 50mD) can allow pore water to diffuse as Darcian flow, thus making it easier to induce seismicity. Otherwise, if fracture permeability is lower or higher than the seismogenic permeability, the flow through the fracture is negligible or too large, respectively and pore pressure diffusion is unlikely to occur [29].

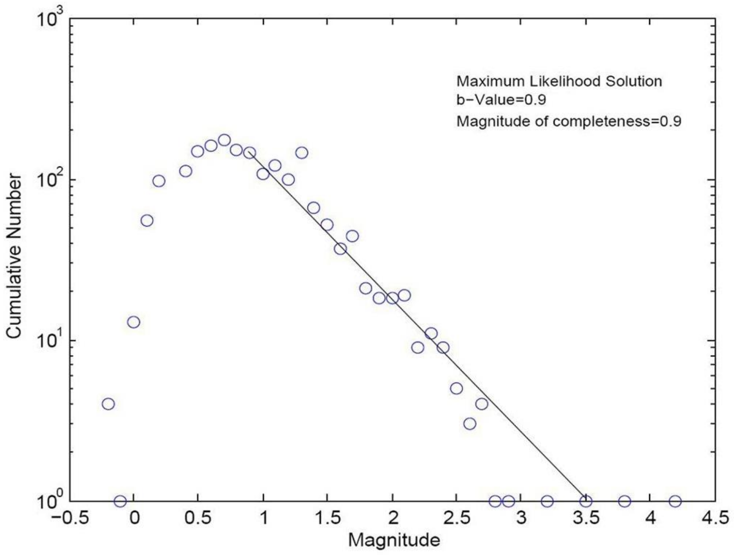

Fig. 9 – Estimated b-value for surrounding region of the dam and reservoir area [9]

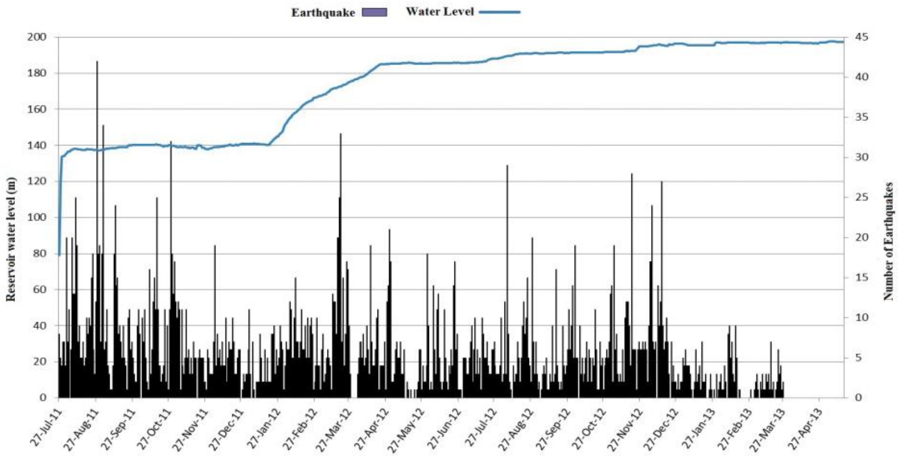

Fig. 10 – Temporal variation of initial seismicity and water level changes between 2011 and 2013 [10]

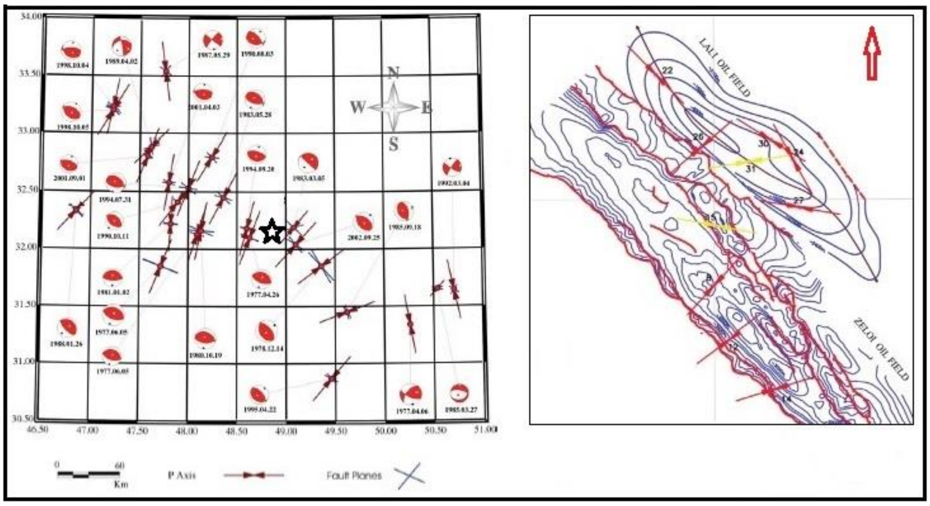

Fig. 11 –Regional stress directions and focal mechanism map of the Zagros Belt (left) compared to in-situ stress trends of Lali and Zilaie oilfields [12] beneath the reservoir region (right)

4. Discussion and Conclusions

The observed micro-seismicity around the Upper Gotvand Dam after impounding of a volume of about 2.1 billion m³ in 2012 indicated an increase in seismic activity of the region based on a local network. The calculated b-value is similar to known b-values for the Zagros Fold Belt. The maximum recorded magnitude was 4.2 and most of the events had focal depths deeper than 8 km with a concentration of events around the deepest part of the reservoir. This part of the reservoir with about 90 m depth is underlain by Lali oilfield that is bounded by two NW-SE trending and opposite dipping faults creating a block faulted and uplifted zone beneath the dam reservoir illustrating a rabbit ears structure. This area is the point at which few numbers of faults (known and inferred) interrupts each other. The dam site and most of its reservoir area is underlain by Mio-Pliocene sandstones of Agha-Jari Formation that are fractured but having moderate permeability due to marlstone and claystone interlayers. Although, the observed micro-seismicity is coincident with the reservoir water level variation, it could not be precisely related to neighboring active faults regarding to distance of them relative to the reservoir region. Besides, the mechanism of the micro-earthquakes is not well known. Although, interaction between the existing faults and reservoir-triggered forces could generate micro-earthquakes but this explanation could not be precisely proved since the extension of evaporitic Gachsaran Formation below the dam reservoir area as a highly impermeable and ductile layer. However, presence of thrust faults cutting the underneath formations in the Lali oilfield could increase fracture density of rocks and diffuse pore pressure diffusion beneath the reservoir. Pore fluid pressure increase in the region could resulted in redistribution of stress in the substratum. Hence, the observed micro-seismicity could indicate protracted induced seismicity resulting from fluid seepage in the crust that increases the pore pressure diffusion. Another possibility is fault creep phenomenon that remains to be investigated especially for operation period of the dam. As a final conclusion, although the impounding can cause diffused failures due to increase in both total stresses and fluid pressure however, it seems that the failures do not involve the known nearby active faults.

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6. References

References must be cited in the text in square brackets [1, 2], numbered according to the order in which they appear in the text, and listed at the end of the manuscript in a section called References, in the following format:

[1] ICOLD (2011): Reservoirs and seismicity – state of knowledge, bulletin 137, Committee on Seismic Aspects of Dam Design, International Commission on Large Dams, International Commission on Large Dams (ICOLD), Paris.

[2] ICOLD (2014): Selecting seismic parameters for large dams, guidelines, bulletin 148, Committee on Seismic Aspects of Dam Design, International Commission on Large Dams (ICOLD), Paris.

[3] Wieland M (2005): Review of seismic design criteria of large concrete and embankment dams. *Proc. 73rd ICOLD annual meeting.* Tehran, Iran, 10p.

[4] Wieland M (2009): Seismic Aspects of Bottom Outlets, Spillways, Intake Structures and Penstocks of Large Storage Dams. *Proc. 24th ICOLD congress.* Kyoto, Japan, 6p.

[5] Barjasteh A (2017): The impact of active faulting on the geotechnical properties of the Upper Gotvand dam, southwest Iran. Bull. Eng. Geol. Environment. DOI 10.1007/s10064-017-1163-8. pp. 1-14.

[6] Mahboubi A, Aminpour M, Noorzad A (2008): Conventional and advanced numerical methods of rock slope stability analysis, A comparison study, Gotvand Dam right abutment (Iran) Case Study. *Proc. 12th International Conference of International Association for Computer Methods and Advances in Geomechanics (IACMAG),* 1-6 October, 2008 . Goa, India. 9p.

[7] Nateghi R, Kiyani M (2008): Application of DEM technique in estimation of seepage and water tightening limit in dam sites (case study of the Upper Gotvand dam), (in Persian). *Proc. 2nd National. Conf. on Dam and Hydropower Plants,* IWPCO, Tehran, Iran, 8p.

[8] Mahmoodi Dovom Niasar H, Farough Hossieini M, Ahmadi M, Jalali M. E (2010): Investigation of the role of dam weight on time dependent behavior of the Upper Gotvand dam foundation (in Persian). *Omran Modarres Scientific and Research Journal.* **2,** 13 p.

[9] Tatar M (2012): Seismicity and seismotectonics in the Upper Gotvand dam region, (in Persian). *Proc. 1st Int. and 3rd National. Conf. on Dam and Hydropower Plants,* IWPCO, Tehran, Iran, 10p.

[10] Ebrahimi M, Tatar M (2018): Induced-stress modelling of the Gotvand-e Olya reservoir on the Golestan Fault. *Scientific Quarterly Journal, GEOSCIENCES,* **27**(107), 193-202.

[11] Jalali M, Memarian H, Zare M, Dusseault M.B (2008): Induced seismicity risk in Irani oil and gas fields. *42nd US Rock Mechanics Symposium and 2nd U.S.-Canada Rock Mechanics Symposium*, San Francisco, June 29-July 2, 2008.7p.

[12] Talebi H, Alavi S.A, Sherkati S, Ghassemi M.R, Golalzadeh A (2018): In-situ stress regime in the Asmari reservoir of the Zeloi and Lali oil fields, northwest of the Dezful embayment in Zagros fold-thrust belt, Iran. *Scientific Quarterly Journal, GEOSCIENCES,* **106,** 53-68.

[13] Berberian M (1995): Master "blind" thrust faults hidden under the Zagros folds: active basement tectonics and surface morphotectonics. *Tectonophysics,* **241,** 193-224.

[14] Berberian M (1989): Seismotectonic and earthquake fault hazard analysis at Gotvand Hydropower plant. *Ministry of Energy.* 176p.

[15] Falcon N.I (1974): Southern Iran, Zagros Mountains, In: Spencer A.M (ed), Mesozoic – Cenozoic Orogenic Belts. *Geol . Soc . London , Spec . Publ .* **4**, 199-211.

[16] N.I.O.C. (1977): Geological map of Lali, 1: 100000.

[17] Zamani G. B, Kianizadeh N, Parhizgari H (2015): Analysis of neo-tectonic stress state of Zagros orogeny and separation of stress regimes by earthquake data (in Persian). *Scientific Quarterly Journal, GEOSCIENCES,* **24**,219-230.

[18] Ebrahimi M, Tatar M, Aoudia A, Guidarelli M (2018): Loading effects beneath the Gotvand-e Olya Reservoir (south-west of Iran) deduced from ambient noise tomography. *Geophys. J. Int*., ***212***, 229–243.

[19] Dahrazma B, Hafezi Moghadas N, Hasanvand M, Karami R (2014): Investigation on the geochemistry of formations of Gotvand-Olya Dam reservoir and its influence on the quality of water in reservoir (in Persian). *Engineering Geology Journal*. **7** (1-1), 29-40.

[20] Barjasteh A (2012): Salt Tectonics and seepage phenomenon within the reservoir of the Upper Gotvand Dam in Khuzestan Province (in Persian). *Proc. 16th Symp. Geol .Soc. Iran, 4-6 Sept.* Shiraz University, Shiraz, Iran, 8p.

[21] Barjasteh A (2013): Geologic structure control on seepage potential of the Upper Gotvand Dam, Iran. *81st ICOLD annual meeting.* Seattle, USA, 9p.

[22] Khosravi F (2000): Dam site selection on problematic foundation with slickensides (in Persian). *Proc. 4th NIRCOLD Conf. On Dam Construction,* Ministry of Energy, Tehran, 636-644

[23] Ajalloeian R, Fatehi L, Ganjalipour K (2011): Evaluation of hydrojacking and hydrofracturing behavior in Aghajari formation (Gotvand dam site foundation), Iran. *Journal of Geology and Mining Research,* **3**(3), 46-53.

[24] Yazdinejad H.R, Hashemi S, Moradi M (2007): Evaluation of groutability and permeability relationship in Gotvand Dam. *Proc. 3rd Iranian Rock Mechanics Conference (in Persian).* Amirkabir University of Technology, Tehran, October 3-5, 2005, Iran, 6p.

[25] Fjaer E, Holt R.M, Raaen A, Risnes R, Horsrud P (2008): Petroleum Related Rock Mechanics. 2nd edition, **53**, Elsevier, Amsterdam, 514 pp.

[26] Vladut, T (1981): Geomechanics of Reservoir Induced Seismicity. *International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics.* 9.

[27] Kopf R.W (1982): Hydrotectonics: Principles and relevance. USGS, *Open-file report. Open-File Report 82-307*. doi.org/10.3133/ofr82307. 30p.

[28] Gough D.I, Gough W.I (1970): Stress and Deflection in the Lithosphere near Lake Kariba-I. *Geophys. J. R. astr. SOC.* **21***,* 65-78

[29] Talwani P, Chen L, Gahalaut K. (2007): Seismogenic permeability, ks, *J. geophys. Res.*, **112,** B07309, 1–18.