Sustainable and Safe Dams Around the World – Tournier, Bennett & Bibeau (Eds)

Safety measures for earth dams on basis of instrumentation data, dam site location and reservoir volume

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ABSTRACT: It is important to ensure long-term safety of dams constructed near populated cities and industrial areas. In this regard, in addition to the adoption of appropriate considerations during design and construction of a dam, the necessary controls should be made during operation periods to ensure its proper functionality and safety.

In this paper, by considering a collection of different instrumentation data a quantitative measure for the estimation and prediction of long-term dams' safety has been suggested. For this purpose, 5 large Earthfill or Rockfill dams in Iran have been selected and their corresponding instrumentation data studied. Studied dams are located near major cities in Iran and it is inevitable to ensure their desirable performance and safety. Among studied dams, Mahabad dam and Doroodzan dam have been operated for about 50 years, Masjed-Soleyman dam has been put to operation 18 years, Izadkhast dam have been operated for about 17 years and Silveh dam has been put to operation for about 1 year.

In accordance with the proposed method in this study and based on various studies and criteria like structural aspects, environmental impacts and dam break consequences; three levels of performance and safety for earth-dams, namely "Safe level", "Relatively safe level" and "Unsafe level", are introduced. It can be used to make management decisions about how the dams can be exploited during operational lifetime, safely.

RÉSUMÉ: Le projet d'approvisionnement en eau du barrage d'Itare est situé dans le comté de Nakuru au Kenya et comprendra notamment un barrage en enrochement à écran interne d'étanchéité en béton bitumineux de 63 m de haut avec un déversoir latéral sur la rive gauche. La géologie sous-jacente et les roches du barrage appartiennent à la suite volcanique du centre du Kenya datant du tertiaire, du pléistocène et du quaternaire, qui comprend une alternance de coulées de lave et de dépôts pyroclastiques. Les laves sont principalement des Phonolites se présentant sous forme de flux d'épaisseurs variant de quelques mètres à plusieurs dizaines de mètres. Les dépôts pyroclastiques inter-couches ont une composition, des degrés et une résistance aux intempéries variables, et vont de large tufs à lapilli à des couches de brèche tufacée et de Phonolite/ brèche tufacée. Ces paramètres variables, ainsi que les incertitudes, ont compliqué la conception de la fondation du barrage afin de répondre aux exigences de conception structurelle du socle du remblai du barrage en enrochement à écran interne d'étanchéité en béton bitumineux, du noyau étroit en asphalte et des enveloppes en enrochement. Cet article présente la méthodologie mise en œuvre pour quantifier l'interface entre la fondation et la structure rocheuse, y compris les aspects de conception tels que la stabilité, les tassements différentiels, l'optimisation de l'emplacement du socle et le contrôle des infiltrations.

1 INTRODUCTION

From the designing point of view and by considering construction and maintenance issues, efforts are always made to ensure that dams are susceptible to failure. However, number of dam failures have been reported due to the following reasons: earthquakes, landslides, severe flood, facilities failure, uncontrolled seepage, structural instability, military strike, vandalism and etc. (ICOLD, 1999). The International Commission on Large Dams (ICOLD) divides the failure reasons of dams into three general categories, as: Structural failure (due to piping or cracking in earth dams), overflow through the dam body (due to inadequate spillway capacity, improper operation or large landslides inside the dam reservoir), and sabotage (Intentional or unintentional) (ICOLD, 1999). According to the Washington state department of ecology and its dam safety policies, the main reason for the failure of the earth dams is reported due to overflow through dam body. Also, the comprehensive research was conducted by Middlebrooks on 220 earth dam disruptions between 1850 to 1950, which indicates that 50% of failures occur during the first five years of dam construction. Accordingly, 19% of failures had been occurred during the first impounding, 49% of failures was reported during the operational procedures among 5 to 50 years of dam operational period and only 1% of failures had been occurred after 50 years of the operational period (Middlebrooks, 1953). In addition, the most dangerous issue was reported as the overflow through the dam body. The statistics of the first impounding failures or fractures during dam operation confirms that the reliable system of instruments for monitoring in dam components is a very reliable method that can significantly reduce the failure risk in earth dams.

In this paper, five earth dams including: Silveh dam, Mahabad dam, Doroodzan dam, Masjed-Soleyman dam and Izadkhast dam in Iran are studied and instrument records have been analyzed. Moreover, observed problems in dam body during dam operation (such as cracking, uncontrolled seepage and undesirable deformations) are taken into account and a safety assessment has been performed. Also, reservoir volume and dam site location are considered in safety conditions.

2 STUDIED CASES

2.1 *Silveh dam*

Silveh dam is a recently constructed zoned earth dam located about 12 km Northwest of Piranshahr city with population 138,000 people in the Western Azerbaijan Province, Iran (Figure 1). The dam body encompasses different zones, including a clay core and an impervious upstream blanket, upstream and downstream shells of coarse-grained gravelly sand drain and filter. The capacity of the dam reservoir, at its normal water level is about 84 mcm. With

Figure 1. Arial view of Silveh dam and its reservoir on Apr. 2018

a crest level of 1579 m.a.s.l, the maximum height of the dam is approximately 89 m from foundation and its crest length is near 720 m (Jafarzadeh et al, 2018). The maximum cross section of this dam is shown in Figure 2.

2.1.1 *Instrumental records in Silveh dam*

Some Instruments are installed in the dam body and its foundation in order to monitor the behavior of the dam under different loadings, such as the dam body weight, embankment construction stages, dynamic and static pressures from the reservoir, effects of earthquake loading, and to determine the groundwater levels and the pore water pressure in the body and foundation of the dam. These instruments include electrical pore water pressure meters, inclinometers, earth pressure gauges, Casagrande piezometers, observation wells, earthquake accelerometer, V-notch, and surface settlement benchmarks (Abgeer, 2007).

During a time period of 15 months after first impounding of the reservoir, the maximum vertical and lateral movements of the crest in the maximum height section have been reported as 32mm and 10mm, respectively, in accordance with the inclinometer. Also, maximum vertical deformation in maximum height section by the geodetic measurements is 48 mm. In addition, the maximum pore water pressures amidst the dam body and its foundation in maximum height section of dam were 135kPa (recorded by electrical pore water pressure piezometer in clay core installed at 1515 m.a.s.l in N.W.L of 1573.5 m.a.s.l) and 315 kPa (recorded by electrical pore water pressure piezometer in dam foundation installed at 1485 m.a.s.l in downstream in N.W.L), respectively (Garakani et al, 2017).

The seepage through the dam body and its foundation has been continuously measured using a V-notch measuring weir (Figure 3). The maximum outflow recorded by the V-notch was

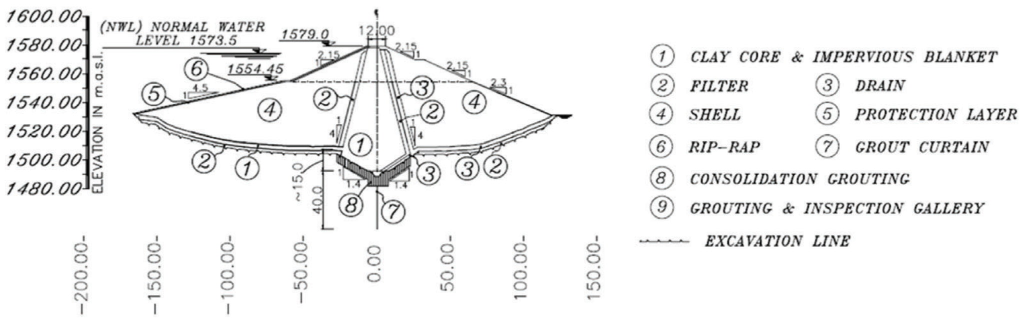


Figure 2. Maximum cross section of Silveh dam

Figure 3. A view of the V-notch seepage control in Silveh dam

reported as 83.5 lit/sec in Nov. 2018 at 1572.2 m.a.s.l. However, an unpredicted but controlled seepage was also reported at the right abutment of the dam with the maximum value of 9 lit/sec. This discharge value, for 6 months ago to now have remained constant (Abgeer, 2018).

2.1.2 *Significant warning cases*

1. Regarding instrumental recordings and visual inspections, no significant hazardous feature has been reported for Silveh dam, so far. Only, after 4 months from dam impounding, an unpredicted seepage was observed at the right abutment, near the spillway. To control and monitor the changes in the water level around right abutment seepage, nine observation wells were drilled and the water level changes in those wells were monitored, continuously.
2. Three electrical pore water pressure piezometers failure was reported at dam foundation and there are no data available right now.

2.2 *Mahabad dam*

Mahabad dam is a 50 years old constructed zoned earth dam located in vicinity of Mahabad city with population of 168,000 in the Western Azerbaijan Province, Iran. The dam body encompasses different zones, including inclined clay core, upstream and downstream shells of coarse-grained gravelly sand drain and filter. The capacity of the dam reservoir, at its normal water level (1358.5 m.a.s.l), is about 230 mcm. With a crest level of 1361.5 m.a.s.l, the maximum height of the dam is approximately 47.5m from foundation and its crest length is near 700 m (Jafarzadeh et al, 2014). The location of the Mahabad dam and city of Mahabad is shown on the Figure 4. Also, dam body in underlined by a liquefiable layer with about 30 m thickness (Abgeer, 2012a).

2.2.1 *Instrumental records in Mahabad dam*

For this dam also, typical instruments had been installed in the dam body and its foundation in order to monitor the behavior of the dam under different loadings (Abgeer, 2012b).

Based on the latest measurements data made in 2012, the maximum vertical movement of the crest between 2009 to 2012 was reported as 230mm, in accordance with the inclinometer. In addition, the maximum pore water pressures amidst the dam body and its foundation in maximum height section of dam were 70 kPa (recorded by electrical pore water pressure piezometer at clay core installed at1345 m.a.s.l in upstream in reservoir water level of 1357.5 m.a.s.l) and 308 kPa (recorded by electrical pore water pressure piezometer at dam foundation installed at1310 m.a.s.l in downstream in reservoir water level of 1357.5 m.a.s.l), respectively (Shahrabi et al, 2017& Abgeer, 2012b).

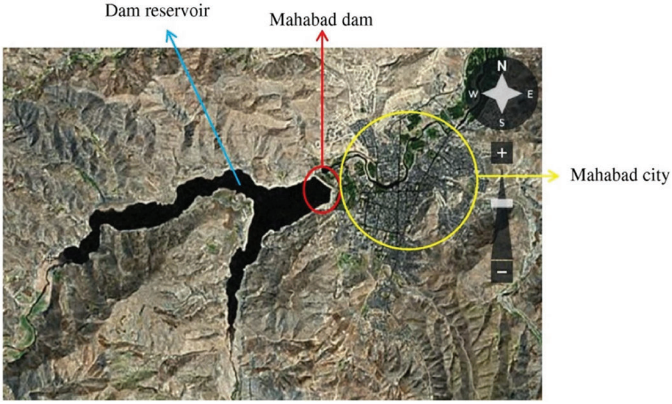


Figure 4. Mahabad dam site and Mahabad city

2.2.2 *Significant warning cases*

Regarding instrumental recordings and visual inspections, number of problems have been observed in the Mahabad dam. Among the aforementioned cases are:

1. The longitudinal and transverse cracks were reported atop the crest, in adjacent of the maximum height cross section. Monitoring of the cracks showed that the length and the aperture of them did not change significantly after a few months. In Figure 5 some observed cracks on the dam crest are shown.
2. The unpredicted seepage was reported at the bottom gallery in right side of the Mahabad dam with the maximum value of 10lit/sec in 2012 at 1358 m.a.s.l.
3. Based on the inspector's observations and recorded pore water pressures by the Casagrande piezometers on the left side of the dam, in long period time, it seems that the cutoff-wall in this area was not working properly and need repairs. The main reason of it's about the high pore water pressure in piezometers in dam foundation in left abutment of dam. In Figure 6 pore water pressure in left abutment side of Mahabad dam in 15 years period time is shown. From this figure, in L4 & L5 piezometers, pore water pressure level almost was in reservoir water level, that it shows cutoff-wall didn't have good performance in this area. This assumption was also partially confirmed by the results of geophysical investigations.
4. Liquefaction potential in dam foundation during sever strong ground motions, considering the dam site seismicity.

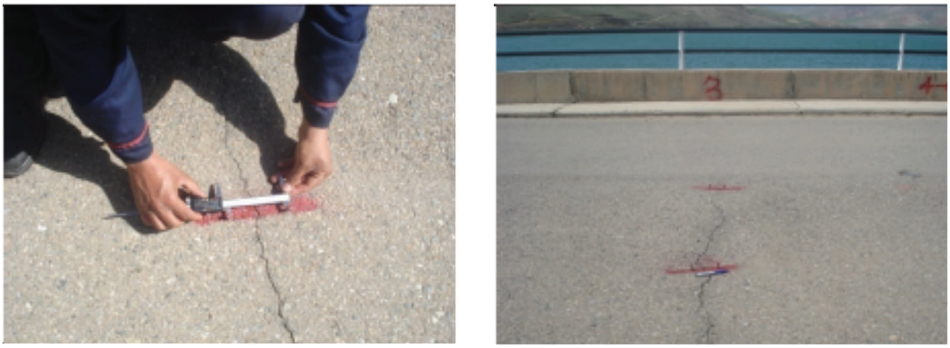


Figure 5. Numbering and monitoring of cracks in the crest of Mahabad dam

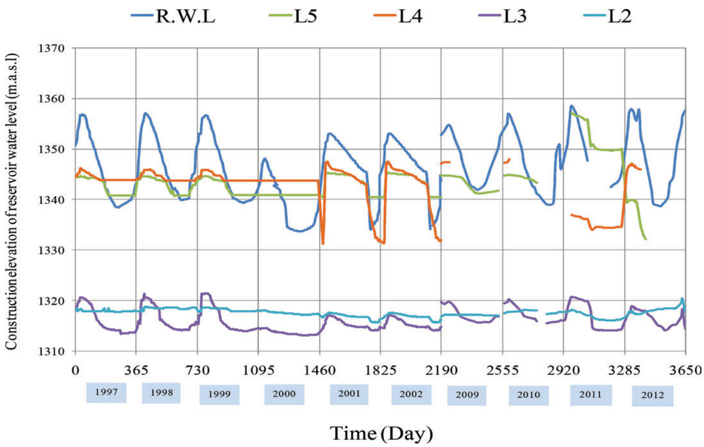


Figure 6. Pore water pressure in left abutment side of Mahabad dam vs. time

2.3 *Doroodzan dam*

Doroodzan dam is a 47 years old constructed zoned earth dam located in about 50 km Northwest of Marvdasht city with population 323,000 people in the Shiraz Province, Iran. The dam body encompasses different zones, including a clay core and an impervious upstream blanket, upstream and downstream shells of coarse-grained gravelly sand drain and filter. The capacity of the dam reservoir, at its normal water level (1676.5 m.a.s.l), is about 993mcm. With a crest level of 1683.5 m.a.s.l, the maximum height of the dam is approximately 55mfrom foundation and its crest length is near 710m. The reservoir surface in normal water level is 55 km^2 (Abgeer, 2014a). The Typical section is shown in Figure 7.

2.3.1 *Instrumental records in Doroodzan dam*

During construction some instruments were installed in the dam body and its foundation in order to monitor the behavior of the dam under different loadings, consisted mainly from piezometers and surficial benchmarks. Also, weir and seepage collection system at downstream of Doroodzan dam is shown in Figure 8.

During a time period of 4 years from 2011 to 2015, the maximum lateral movements of the dam crest have been reported as 16 mm, in accordance with the geodetic data. An unpredicted but controlled seepage was also reported at the left abutment of the dam with the maximum value of 120 lit/sec (Abgeer, 2014a).

2.3.2 *Significant warning cases*

Regarding instrumental recordings and visual inspections, number of problems has been observed in the Doroodzan dam. Among the aforementioned cases are:

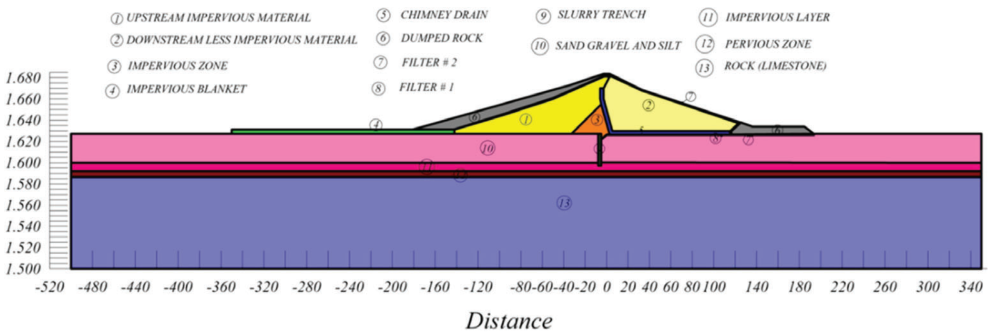


Figure 7. Typical cross section of Doroodzan dam

Figure 8. Measuring weir and seepage collection system at downstream of Doroodzan dam

1. The longitudinal and transverse cracks were reported atop the crest. All data shows that the cracks length changes with changing of water level in reservoir, especially the top of the reservoir water level. These cracks are generally seen across the crest, most of which lie down between the dam axis and dam downstream. The longitudinal cracks were reported atop the crest with the maximum length of 25 m, depth of 3 m and aperture of 70 mm. Some of the cracks in the crest of Doroodzan dam are shown in Figure 9.
2. The unpredicted seepage was reported at left abutment of dam with the maximum value of 120 lit/sec. The measurements indicate that seepage charge dependence on the reservoir water level. These changes are shown in Figure 10.
3. Casagrande piezometers failure was reported at seven parts of the dam and there are no data available right now.
4. Existence of liquefiable sandy layer in dam foundation.

2.4 *Masjed-Soleyman dam*

Masjed-Soleyman dam is an 18 years old constructed zoned rockfill dam located in about 25.5 km North east of Masjed-Soleyman city with population of 213,000 in the Khuzestan Province, in southeast of Iran on Karun river. The dam body encompasses different zones, including a clay core and an impervious upstream blanket, upstream and downstream shells of coarse-grained gravelly sand drain and filter. The capacity of the dam reservoir, at its normal

Figure 9. Cracks in crest of Doroodzan dam

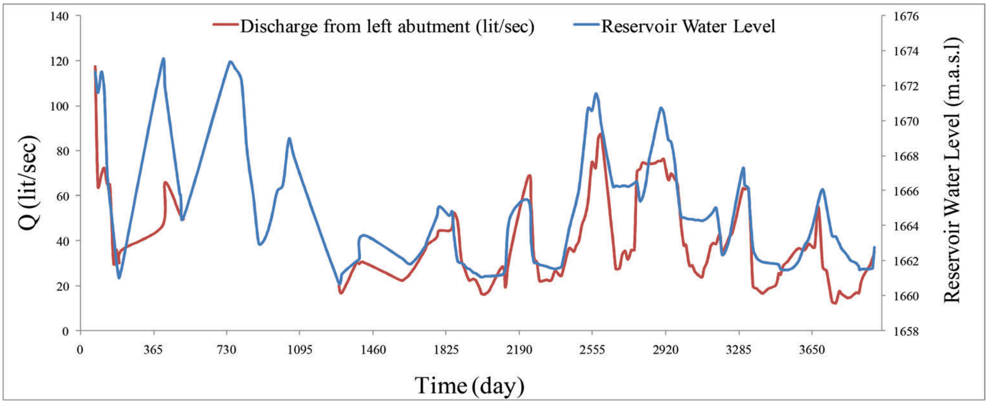


Figure 10. Variation of left abutment discharge and reservoir water level v.s time

water level is about 262 mcm. The maximum height of the dam is approximately 177m from foundation, its crest length is near 497m and crest width is 15 m. The reservoir surface in normal water level is 7.79 km^2 (Moshanir, 2007). The arial view of Masjed-Soleyman dam, one of the height embankment dams in Iran, is shown in Figure 11.

2.4.1 *Instrumental records in Masjed-Soleyman dam*

Due to importance and size of this high rockfill dam almost all types of instruments were deployed in dam body, foundation and abutments.

The seepage through the dam body and its foundation has been continuously measured using a V-notch instrument (Figure 12). The maximum outflow recorded by the V-notch 7 years after first impounding was reported as maximum 20 lit/sec (Jafarzadeh & Javaheri, 2003, Moshanir, 2007).

2.4.2 *Significant warning cases*

Regarding instrumental recordings and visual inspections, number of problems has been observed in the Masjed-Soleyman dam. Among the aforementioned cases are:

Figure 11. Top of view from Masjed-Soleyman dam

Figure 12. Measuring weir of Masjed-Soleyman dam

1. The longitudinal and transverse cracks were reported atop the crest. In Figure 13, a number of the cracks in dam crest is presented.
2. Due to the soft clay consolidation in the core of dam, vertical undesirable deformations on the Masjed-Soleyman dam crest is observed (Figure 14).
3. Some of Casagrande piezometers and electrical pore water pressure piezometers failure was reported at parts of the dam and there are no data available.

2.5 *Izadkhast dam*

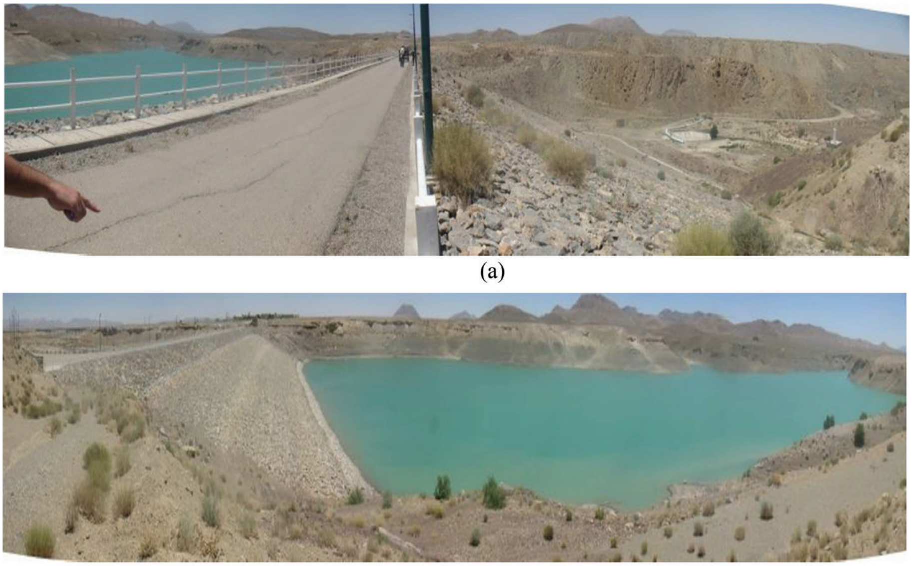
Izadkhast dam is a 17 years constructed zoned earth dam located in 65 km Abadeh city with 95,000 people in the North of Shiraz Province, Iran. The dam body encompasses different zones, including a clay core and an impervious upstream clay blanket, upstream and downstream shells of coarse-grained gravelly sand drain and filter. The capacity of the dam reservoir, at its normal water level (2209.8 m.a.s.l), is about 12 mcm. With a crest level of 2213.8 m.a.s.l, the maximum height of the dam is approximately 41.5 m from foundation and its crest length is near 296 m (Abgeer, 2014b). In Figure 15, Izadkhast dam crest and reservoir are shown.

2.5.1 *Instrumental records in Izadkhast dam*

For this dam also a variety of instruments were installed. Unfortunately, due to malfunctioning of reading and data acquisition system after a short period the reading of the instruments were not possible. Figure 16 shows this system at control room.

Figure 13. Cracks in the dam crest of Masjed-Soleyman dam

Figure 14. Bumpy crest of Masjed-Soleyman Dam due to non-homogeneous vertical deformations



(a)

(b)

Figure 15. Izadkhast dam, a) view of downstream, and b) dam reservoir

During a time period of 4 years from 2011 to 2015, the maximum lateral movements on the out of dam body, dam crest, out of spillway and spillway have been reported as 10.2, 9.2, 1.2 and 3.1 mm, respectively. Also, the maximum vertical movements on the dam crest have been reported 3 mm. These data obtained by the geodetic measurements.

As mentioned, the main problem in the instrumentation system of the Izadkhast dam is the inappropriate performance of the data logging system which causes no data to be recorded by the instruments from 7 years ago (Abgeer, 2014b). Also, operator of this dam did not took care about the installed instrumentation facilities (Figure 17).

Figure 16. Useless data acquisition system of instruments in control room of Izadkhast dam

Figure 17. Inappropriate maintenance of installed instruments in Izadkhast dam, Weir (left) and Piezometer (right)

2.5.2 *Significant warning cases*

Regarding visual inspections, number of problems has been observed in the Doroodzan dam. Among the aforementioned cases are:

1. The longitudinal and transverse cracks were reported atop the crest. All data shows that the cracks length changes with changing of water level in reservoir, especially the top of the reservoir water level.
2. For inappropriate performance of the data logging system in Izadkhast dam, no data to be recorded by the instruments from long time ago.

3 ANALYSIS AND DISCUSSION

In this section, based on the data obtained from the instrumentation of the studied dams and dam site location and reservoir volume, a quantitative-qualitative framework is proposed to detect the safety status of dams. Accordingly, at first, important parameters in the safety of these dams are considered as follows:

A) Instrumentation data, (I): Recorded data from the instrumentation can make a correct judgment on the safe operation of dams. In this regard, the following parameters are considered:
- Undesirable deformations, (Id)
- High pore pressures, (Ip)
- Crack detections, (Ic)
- Uncontrolled seepages, (Is)

B) Damaged instruments, (C): The failure of the instruments can be considered as a very important risk factor. Failing to observe the performance parameters of a dam is even more dangerous than the undesirable amount of those parameters.

C) Reservoir volume, (V): The reservoir volume is a main factor in determining of the risk of dam damage.

D) Dam site distance from a populated city, (D); Short distance between the dam's site and a populated city, definitely intensifies the risk of dam destruction.

E) Population and importance of the nearest town to the dam site, (P).

On basis of aforementioned factors, a "weighting parameter", W, ranging from zero to unity can be assigned to each of them that imply the importance level. This factor can be selected regarding previous experiments and engineering judgments.

Table 1. Ranges of Equation (1) parameters

Parameter		Suggested values	Weight factor
I	Id	0: small	$W_I = 70$
		0.15: moderate	
		0.30: large	
	Ip	0: low	
		0.10: moderate	
		0.20: high	
	Ic	0: small	
		0.15: moderate	
		0.30: large	
	Is	0: low	
		0.10: moderate	
		0.20: high	
C		0: All Instruments work properly.	$W_C = 30$
		0.50: At least half of instruments work properly.	
		1.0: Below 10% of instruments work properly.	
V		0: The reservoir volume is less than 10 million cubic meters.	$W_V = 30$
		0.30: The reservoir volume varies between 10 to 100 million cubic meters.	
		0.60: The reservoir volume varies between 100 to 500million cubic meters.	
		1.0: The reservoir volume is more than 500 million cubic meters (Ministry of Energy of Iran, 2011)	
D		0: The dam is located absolutely far from a large city.	$W_D = 10$
		0.50: The dam is located at least 10 times the reservoir length far from a large city.	
		1.0: The dam is located close to a large city.	
P		0: The nearest populated city to the dam site has less than 100,000 people.	$W_P = 10$
		0.50: The nearest populated city to the dam site has between 100,000 to 250,000 people.	
		1.0: The nearest populated city to the dam site has more than 250,000 people.	

Considering the risk function and the factors presented in Table 1, the following criteria can be taken into account to indicate the safety level of the dam: $R \leq 0.2$: Safe **(S)** $0.2 < R \leq 0.5$: Moderately safe **(M.S)** $0.5 < R \leq 0.8$: Unsafe **(U.S)** $R > 0.8$: Severely unsafe **(S.Us)**

Table 2. Safety status of studied dams

Dam	Id	Ip	Ic	Is	W_I	C	W_C	V	W_V	D	W_D	P	W_P	R	Status
Silveh	0	0	0	0.1	70	0.1	30	0.3	30	0.25	10	0.2	10	0.1	**S**
Mahabad	0	0.1	0.15	0.15	70	0.2	30	0.6	30	1	10	0.35	10	0.38	**M.S**
Doroodzan	0.15	0.1	0.3	0.2	70	0.2	30	1	30	0.1	10	1	10	0.43	**M.S**
Masjed-Soleyman	0.3	0.1	0.3	0	70	0.7	30	0.6	30	1	10	0.45	10	0.58	**U.S**
Izadkhast	0.1	0.1	0.2	0	70	1	30	0.3	30	0.1	10	0	10	0.29	**M.S**

By considering the risk factors and weighting parameters, following risk function, R, is presented as:

$$R = \frac{I \times W_I + C \times W_C + V \times W_V + (D \times W_D)(P \times W_P)}{W_I + W_C + W_V + (W_D)(W_P)} \tag{1}$$

In which:
I = the instrumentation data factor = Id + Ip + Ic + Is
W_I = the weight factor associated I
W_C = the weight factor associated with C
W_V = the weight factor associated with V
W_D = the weight factor associated with D
W_P = the weight factor associated with P
The suggested range of parameters in Eq.1 is presented in Table 1.

In accordance with the presented criteria, the safety assessment has been performed for the five studied dams and results are presented in Table 2.

4 CONCLUSION

In this paper, a qualitative-quantitative framework for safety assessment of large embankment dams is developed based on the instrumentation data and parameters regarding the reservoir volume, the distance from the dam to a populated city, the population of the nearest city to the dam and the workability of the instruments.

Accordingly, a weighted simple formula is presented by considering aforementioned parameters, namely risk function, and a range of outputs for this function has been introduced to show the safety index of the dams. In this regard, 5 large earth dams in Iran have been studied and their associated risk factors are presented. Based on the evaluations, one dam has been recognized as a “Safe” dam, one was found to be “Unsafe” and three were categorized as “Moderately safe”.

The presented framework can be modified by enriching the inputs and number of studied dams to reach to more precise results. Implementation of this method for damaged dams and their detail conditions, could increase the accuracy of this approach and proposed safety evaluation method.

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