Seismic and Geotechnical Aspects of the Large Earthfill Dam in a Seismicaly Active Region

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Abstract

The seismic and geotechnical aspects of 150M height Mixed-Clay core earthfill dam located in North of Iran in a severe seismic area near some main faults are discussed. As the dam is located in highly seismic area with some main faults, both ground shaking and fault movements in the dam foundation should be considered in the design. As a main fault is within a distance of about 1.5 km from the dam site, which can produce earthquakes with a magnitude up to 7.4, movements might be also anticipated along the minor faults or discontinuities in the bedrock. At least one minor fault (F1) cut the dam site. The design against multiple fault movements is considered so that after faulting and slip movements, adequate width of filter and transition zones are still available. The results of dynamic analysis are also presented to show the stability of the designed dam during earthquake loading. Sufficiency of designed filter and transition and considered freeboard is also concluded considering the results of dynamic analysis.

Keywords: seismic design, fault movement, dynamic analysis, permanent deformation.

1. INTRODUCTION

The earthquake hazard is a multiple hazard as besides ground shaking earthquakes can cause displacements along potentially active faults in the dam foundation or fault movements under the dam or in the reservoir. So the dam engineer should consider both shaking and movement effects for designing an embankment dam in a severe seismic area.

Haraz dam site is situated on the Haraz River on North Slope of Alborz Mountain Range in the North of Iran. It is located near to some major faults. So the dam should be designed considering existence of active faults. The dam site is located between North-dipping Chelav and Kelerd thrust Faults. The distance between hanging wall of Chelav Fault and the dam site is about 1 km. According to the seismotechtonic studies, a major rupture of Chelav fault could induce some sympathetic movements along secondary faults which probably located along the river bed under the dam. So the dam and internal zones should be designed so that after fault movement the core of the dam beside the filter and transition zones have enough thickness.

The dam should also be designed to tolerate the acceleration of maximum credible earthquake during ground shaking. It is generally believed that a dam which is conservatively designed against strong earthquake shaking would probably also safely withstand moderate movements of foundation faults (Sherard, 1974)[1]. The seismic hazard assessment identified that Khazar Blind Fault is the source controlling maximum credible earthquake (MCE) for the dam site based on Magnitude of 7.4. The peak horizontal and vertical ground acceleration (PGHA and PGVA) for MCE are 0.8g and 0.73g, respectively. The Finite element dynamic analysis is performed for safety evaluation of the dam during earthquake.

2. GEOLOGICAL AND SEISMOTECTONIC CONDITIONS OF THE DAM SITE

Haraz Dam site is located on North Slope of Alborz Mountain Range in the North of Iran. The Alborz is a stack of thrust sheets, produced by late Cenozoic compressional deformation. Deformation is due to the North–South Arabia–Eurasia convergence, and westward motion of the adjacent South Caspian relative to Iran. Major thrust or reverse faults within the study area are generally located parallel to dam axis. The dam site is located between North-dipping Chelav and Kelerd thrust Faults which were considered as branches of North Alborz fault. The dam site locates on hanging wall of Chelav Fault about 1km north of its surface trace. The F1 fault is approximately parallel to the major joint sets at the dam site, so it is likely that F1 be a major joint set. On the other hand, other unknown faults and discontinuities might be under river bed.

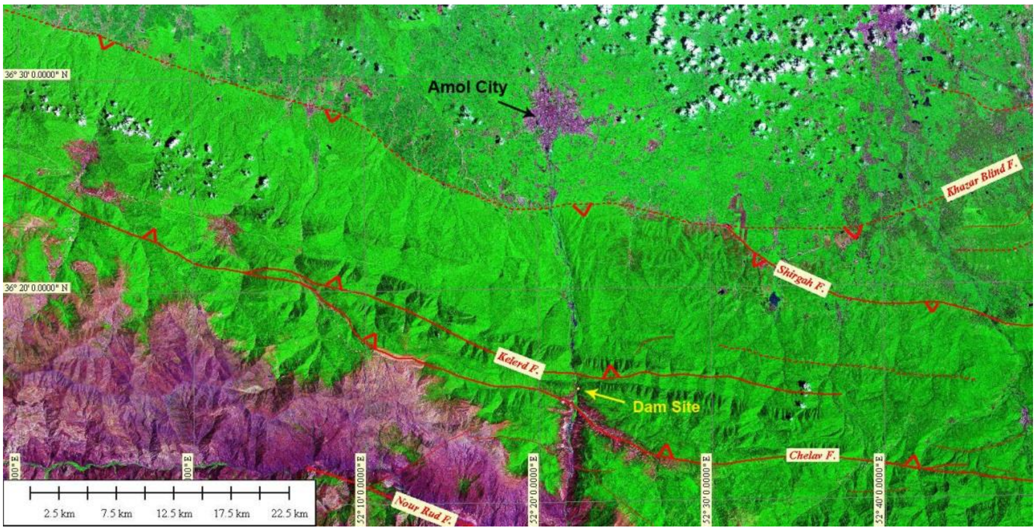

Figure 1. Illustration of Major Faults on LANDSAT Image

Generally, displacements on branch, Secondary or sympathetic faults are smaller than those on the generating fault. Potential displacement on a secondary fault decreases with increasing distance from the primary fault (McCalpin and Nelson, 2009) [2]. Based on engineering judgment and observations in other regions such as Bonilla 1967[3], displacement on secondary and sympathetic faults around the dam body can be up to 50% of displacement on the generating fault taking into account a distance of about 1km between the dam site and Chelav Fault. Therefore, in case the maximum co-seismic displacement along the Chelav Fault is assumed about 100 cm during an Ms 6.0 earthquake, the maximum displacement of 50 cm can be considered for secondary faults and discontinuity planes at the dam site.

As mentioned, Haraz earthfill dam is located in a severe seiamic area. According to seismotectonic studies, the peak ground acceleration (PGA) for different levels of ground motion at the dam site using deterministic and probabilistic procedures are as follow:

Table 1. PGHA and PGVA at the dam site for different design earthquakes

	Return Period	PGA(Average)	
		PGHA(g)	PGVA(g)
1	150(OBE)	0.21	0.15
2	500(DBE)	0.32	0.21
3	2000(MDL)	0.47	0.30
4	10000(SEE-Prob.)	0.65	0.44
5	SEE (MCE-84%)	0.80	0.73

The seismic hazard assessment identified that Khazar Blind Fault is the source controlling maximum credible earthquake (MCE) for the dam site based on Magnitude 7.4 earthquake. PGHA and PGVA for MCE are 0.8 g and 0.73 g, respectively. In addition to PGA, the time history and frequency content of the design earthquake affect the dam response. The acceleration response spectra for different design earthquakes are presented in Figure 2.

For the safety check of a dam at least three different earthquakes shall be considered for the SEE ground motion. (ICOLD, Bulletin 148) [4]. Accelerograms of three earthquakes of Tabas, Loma prieta and Manjil are scaled for the dam site according to the response spectra of the site. Tabas scaled acceleration time histories in the SEE level is the critical one which is imported as design earthquake in this paper and presented in Figure 3.

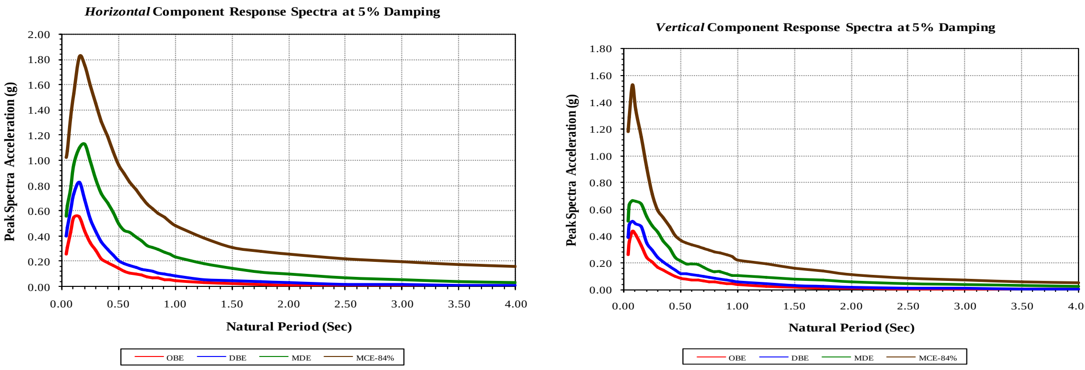

Figure 2. Acceleration Response Spectra for the dam site

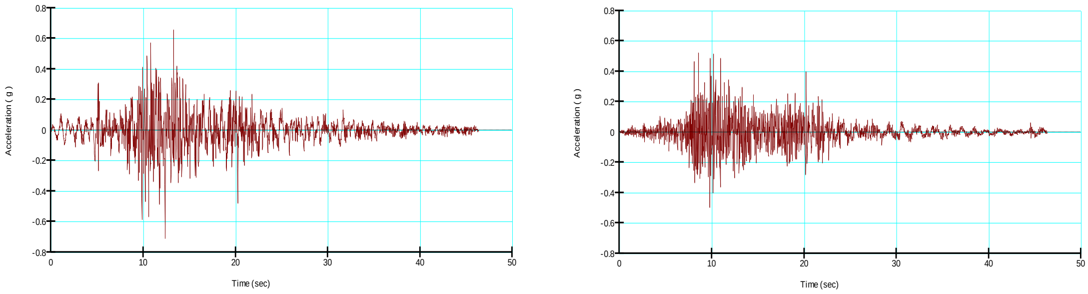

Figure 3. Horizontal (left) and vertical (right) acceleration time history (Tabas) in SEE level

3. GENERAL GUIDELINES FOR DESIGNING AN EMBANKMENT DAM NEAR AN ACTIVE FAULT

In 1998 the International Commission on Large Dams (ICOLD) published a guideline which addresses the issue of dams on active or potentially active faults (ICOLD, 1998, Bulletin 112) [5]. The basic statements relevant for the dam engineer given in the mentioned guideline can be summarized as follow:

1. When a major active fault is crossing the dam foundation the site should be abandoned and a more appropriate site should be looked for.

2. In highly seismic areas it may not be possible to find any site without fault slip hazard: In such a case, concrete dams should be avoided and preference be given to a conservatively designed embankment dam, designed with ample filter and transition zones, on both sides of a rather wide core, displaying ductile properties. There is a considerable confidence that such a structure can withstand, without failure, significant fault offsets.

3. If the seismotectonic conditions at a dam site are not clear, then the engineer should avoid concrete dams and select a conservatively designed embankment dam.

Sherard et al (1974) presented similar conclusions. Wieland et al (2008) [6] also state that concrete dams on active faults, or near some major active faults, are not advisable, and if a site with fault movements cannot be avoided then it is reasonable practice to construct a conservatively designed embankment dam.

According to the Wieland et al (2008) [6], the basic elements of an embankment dam, which can resist both differential ground movements and strong earthquake ground shaking, are the following:

1. Impervious core made of ductile material with a high failure strain to minimize the propagation of the rupture zone; prevention of internal erosion if core is cracked;
2. Thick filter and transition zones: about 50% shall still be available after faulting and slip movements;
3. Wide dam crest;
4. Flat slopes;
5. Generous freeboard: to prevent overtopping due to impulsive waves in reservoir and settlement of the dam crest;
6. Material selection and compaction of rockfill, etc.

The main concern of any embankment dam with impervious core is the erosion resistance of the core material. According to Sherard (1967) [7] 'the filter and transition zones provide the first line of defense against earthquake induced concentrated leaks through the dam. If thick, adequately graded, cohesionless transitions are provided, a leak can only get out of control in extreme cases of embankment distortion caused by foundation movement'. 'Where there is a choice between several types of materials for the core of a dam, which may be subject to an earthquake, it seems apparent that the resistance to concentrated leakage should be the main factor in the decision.'

An approximate classification of core materials on the basis of resistance to concentrated leaks was also made by Sherard as follow:

1. Very good materials: Very well-graded coarse mixtures of sand, gravel, and fines.
2. Good materials: Well-graded mixtures of sand, gravel, and clayey fines; highly plastic tough clay (CH) with plasticity index greater than 20.
3. Fair materials: Fairly well-graded gravelly, medium to coarse sand with cohesionless fines; clay of medium plasticity (CL) with plasticity index greater than 12, coarse mixtures of sand, gravel, and fines
4. Very poor materials are fine, uniform, Cohesionless silty sand; silt from medium plasticity to cohesionless (ML) (plasticity index less than 10) because these materials are highly erodible

4. DESIGN SPECIFICATIONS OF HARAZ DAM

The typical cross section of Haraz dam is shown in Figure 4. As seen a relative conservative design is adopted for Haraz dam in order to withstand ground shaking and tolerate fault movements during operation.

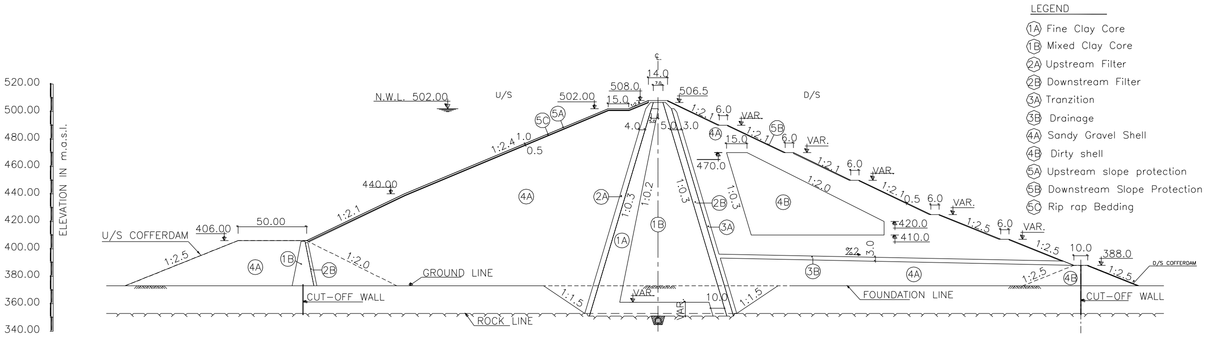

Figure4. Haraz dam typical section

The main features of Haraz dam are as follow:

A relative thick core is designed for Haraz Dam. The thickness of the core is 7 m at the crest elevation and the lateral slopes of the core is 1V:0.3H. The ratio of the core thickness (W) to the water height is about 65 percent. According to Sherard (1959) [8] cores with a width of 30 to 50 percent of the water head have proved satisfactory on many dams under different conditions. Probably a core with this width is adequate for any soil type and dam height. The core of the dam includes two main zones. A zone of fine clayey material (1A) in the upstream and lower elevations and a zone from well graded mixture of sand, gravel and clayey fines (1B) in the downstream and upper elevations of the core. These zones are designed considering the materials available in the site. The zone 1A includes medium to high plastic clay material in order to increase resistance of the core against concentrated leakage due to fault movements. The average of liquid limit and plasticity index of 1A zone is 42 and 18 respectively. The 1B zone on the other hand includes well graded mixture of sand, gravel and fines with average liquid limit and plasticity index of 32 and 12 respectively. The upstream and downstream filters are designed 5 and 4 m respectively. As the maximum displacement along secondary fault and discontinuity planes at the dam site is estimated about 50 Cm, considering a safety factor, minimum 2.5 to 3.0 m would be available after fault movement. A 15m berm is considered in the upstream at the Normal level elevation in order to decrease the permanent deformation near to the crest. The core is founded on groutable limestone and marly limestone sound rock. It means that all alluvial and weathered rock is excavated under the core of the dam. The upstream and downstream shell is founded on relative dense sandy gravelly alluvium. The 50m berm on the upstream is designed regarding limit equilibrium stability requirements.

5. NUMERICAL FINITE ELEMENT METHOD

Dynamic numerical methods utilize the time history of acceleration as direct input to the analysis. The dynamic analysis is carried out either in the time domain, or in the frequency domain using an equivalent linear or nonlinear method.

Over the years significant studies have been done in order to reach to more comprehensive understanding about the seismic behavior of earth and rockfill dams. Newmark (1965) and Seed (1966) were the first to propose methods of analysis to predict the permanent deformations of dams subjected to earthquake shaking. Various methods for predicting seismic deformation of earth structures have been developed based on Newmark's method and its modified versions by Sarma (1975) [9] and Makdisi-Seed (1978) [10]. The empirical relations developed by Jansen (1990) [11], Swiasgood (1995) [12] and Bureau (1997) [13] are generally based on statistical analyses of data from a limited number of failure case histories. With the advent of fast computers and significant progress in nonlinear material modelling and testing, the embankment dams are increasingly being studied by finite element and finite difference methods with advanced nonlinear material models [14]. In some cases, experts have even recommended three-dimensional analysis to include effects of canyon, and other site-specific geometric irregularities on the dynamic stability of a dam. [14-15]

The equivalent linear is one of the preferred methods which are advised in ICOLD Bulletin (ICOLD, B52). In this method, a linear analysis is performed, assuming initial values of damping ratio and shear modulus for different materials. The maximum cyclic shear strain is then recorded for each element and new values for damping and modulus are determined with defined Equations or Graphs (Figure 5). In order to perform dynamic equivalent linear analysis, finite element software QUAKE/W which is part of GeoStudio is utilized. QUAKE/W is a geotechnical finite element software product used for the dynamic analysis of earth structures subjected to earthquake shaking. The combination of dynamic analysis results together with the Newmark Sliding Block concepts can be used to estimate the permanent deformation. In GeoStudio, SLOPE/W uses the QUAKE/W results to perform these calculations.

In order to perform dynamic analysis, it is necessary first to perform static analysis by simulating stage construction and impounding of the dam. After completion static analysis, the equivalent linear dynamic analysis is performed by introducing acceleration time history and corresponding material model and boundary conditions. In the last step, the results of a QUAKE/W analysis are used in conjunction with SLOPE/W to estimate the permanent deformations that may occur during the earthquake. As real laboratory tests for dynamic properties of different materials of Haraz Dam are now been performing, these specifications are estimated here based on literature studies. There are functions in Quake/w in order to estimate the dynamic properties including maximum shear modulus, G-reduction and damping ratio functions based on work by different researchers [16-17-18]. The functions which are used for different materials of Haraz dam based on QUAKE/W formulation are illustrated in Figure 5.

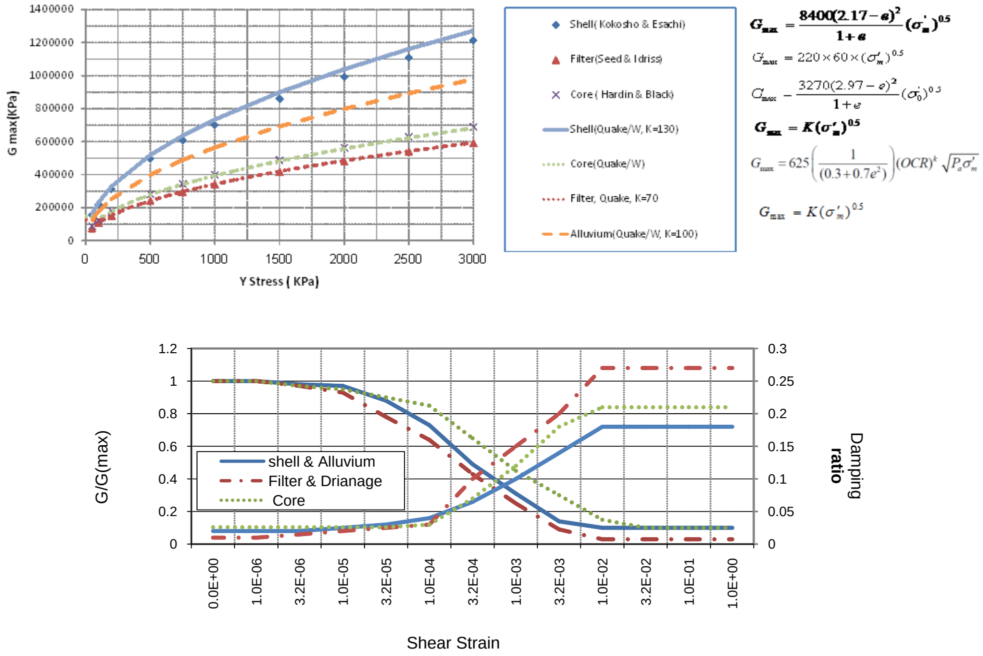

Figure5. G max, G/G max and damping ratio variation for different materials

6. PERMANENT DEFORMATION ESTIMATION

Permanent deformations are estimated according to the Newmark sliding blocks concept and presented in Figure 6. The maximum permanent displacement for near crest sliding block is about 155 cm for the design earthaquke.

As seen in Figure 4, a 15 m thick berm is considered on the Normal elevation of the upstream side of the dam, in order to decrease the permanent deformation near crest of the dam. To study effect of the considered berm on the calculated permanent deformation, equivalent linear analyses are performed on the typical section without a berm on the upstream slope. The results have shown that the Maximum permanent deformation near crest is increased from about 155 cm to about 273 cm, if the considered berm is omitted on the upstream slope of the dam.

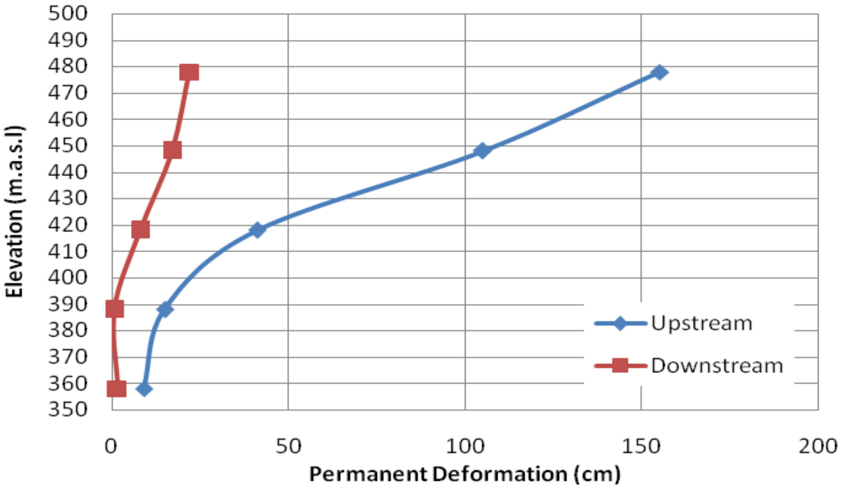

Figure6. Results of permanent deformation in different elevation- Haraz Dam

7. CONCLUSIONS

The seismic and geotechnical aspects of 150M height Mixed-Clay core earthfill dam located in North of Iran in a severe seismic area near some main faults are discussed. As the dam is located in highly seismic area with some main faults, both ground shaking and fault movements in the dam foundation should be considered in the design. The results of finite element dynamic analysis show that if the dam is designed to withstand permanent deformation imposed by design earthquake shaking, it would satisfy the criteria of designing the dam on the potentially active faults. The results also show that flattening the slopes near the crest of the dam or considering berm near the crest, has a significant effect in decreasing permanent deformation.

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