Experimental Study of Small Scale model of Sefid-rud Dam on Shaking Table

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ABSTRACT:

Due to the devastating M7.6 earthquake of June 20, 1990 which occurred in the northern province of Iran, Sefid-rud concrete buttress dam located near the epicenter was severely shaken. The crack penetrated throughout the dam thickness near slope discontinuity, causing severe leakage, but with no general failure. In this study, nonlinear seismic response of the highest monolith with empty reservoir is investigated experimentally through model testing. A geometric scaled model of 1:30 was tested on a shaking table with high-frequency capability to study dynamic cracking of the model and serve as data for nonlinear computer model calibration. Three construction joints are set up in the model to simulate effects of construction aspects. The experimental results are then compared with smeared cracked and damage mechanics finite-element simulations using nonlinear concrete constitutive models based on fracture mechanics. The crack patterns obtained from numerical models are in good agreement with those obtained from shaking table tests for the case of including construction joint effects and rigid foundation.

KEYWORDS: Sefid-rud dam, Buttress dam, Shaking table, Nonlinear fracture mechanics

1. INTRODUCTION

Sefir-rud concrete buttress dam was built during the period of 1958-1962 in the northern Iranian province of Gilan. It is 106m high in the middle section and 425m long at the crest. It consists of 26 monoliths, each 14m long. The slope of the dam on the downstream face is 1 in 0.6 and on the upstream side 1 in 0.4. This dam is constructed of plain concrete on a foundation material of Andesite and Basalt. Its reservoir is more than 1700 million cubic meters in volume and is vital for irrigating the vast rice fields in the downstream.

The dam was originally designed for static seismic coefficient of 0.25. An exceptional strong ground motion in the seismotectonic province of Gilan in northern Iran occurred on June 20, 1990. Its magnitude is estimated 7.6 in surface wave scale. Following the earthquake, the most serious observed damage to the dam was horizontal cracks that appeared in the upper parts of the monoliths, especially in the highest monolith. A major crack ran almost the whole length of the dam at about 14m below the crest. Site investigations following the earthquake indicate that the dam monoliths moved independently with permanent differential displacements of up to 50mm. these large relative displacements damaged the seals in the contraction joints and caused water leakage from the joints.

Due to the complex nature of the problem, the large size of the structure and difficulties in physical modeling, little experimental work has been pursued in small-scale modeling of concrete dams. A significant number of early experimental research programs were concentrated on the nonlinear seismic behavior of dam models. Donlon and Hall [1] tested a small-scale model of a dam monolith using a shaking table. Difficulties were encountered due to shrinkage cracking of the model in the process of drying. Ghobara and Ghaemian [2] conducted an experimental study of a small-scale model of Pine Flat gravity dam. Mir and Taylor [3, 4] conducted an experimental investigation of the nonlinear seismic response of a 30m high concrete gravity dam. They found that the hydrodynamic pressure using Westergaard's added mass was not reasonably representative, especially near the top of the model. Harris, Snorteland, Dolen and Travers [5] used a two-dimensional model of Koyna dam on shaking table to simulate effects and serve as data for nonlinear computer model calibration. Zhou, Lin, Jefferson and

Williams [6] performed a series of dynamic experiments for 20 models of high arch dams on shaking table, with the water ignored. Li, Meng and Tang [7] performed a seismic analysis of the powerhouse monolith of the Three Georges through model testing on a shaking table and numerical simulation using a three-dimensional finite element model of the structure. Tinawi, Leger, Leclerc and Cipolla [8] conducted shake table experiments on four 3.4m high plain concrete gravity dam models to study their dynamic cracking and sliding response. The experimental results were then compared with a smeared cracked numerical simulation. The difficulties in experimental modeling of concrete dams are mostly in material modeling and the availability of suitable equipment for testing. The objective of this study is to investigate nonlinear seismic behavior of sefid-rud dam through the use of a small-scale model of the highest monolith at a geometric scale of 1:30 on shaking table. Combined experimental and numerical analysis is performed to calibrate nonlinear finite element based models. Of primary interest is crack pattern, crack opening and closing and sliding along crack planes.

2. MODEL DEVELOPMENT

2.1. Similitude requirements

In order for the behavior of a small-scale model to accurately represent the corresponding behavior of its prototype, or full-scale structure, the model must follow certain laws of similitude. These laws which are determined by a dimensional analysis of the problem under investigation, are relationship among the dimensionless ratios formed by corresponding parameters of the prototype and model structure.

They establish requirements for the materials used to construct the model and the loading used to excite it. For the case of neglecting reservoir effects, three basic requirements that relate model and prototype are obtained. Equal gravity force (g) in the model and prototype gives the following three formulas:

$$T_r = \sqrt{L_r} \qquad 2.1$$

$$S_r = \rho_r L_r \qquad 2.2$$

$$A_r = 1 \qquad 2.3$$

Where T, L, S, A and ρ are time, length, stress, acceleration and mass density, respectively. Index r represents the ratio of these parameters in the prototype and model. The selection of a length scale L_r is typically based on the size of the prototype structure and the capabilities of the testing facility.

The scale chosen for this model is a 1:30 geometric scale and a concrete-based material with the same density is used for the material of the dam. According to similitude requirements, estimated properties of Sefid-rud dam small-scale model are summarized in table 2.1.

Table 2.1: Similitude requirements and model material properties

<table>
<tr><th colspan="2">Physical Parameter</th><th>Scale factor</th><th>Ratio</th><th>Prototype Estimate</th><th>Target Value</th></tr>
<tr><td colspan="2">Length</td><td>L_r</td><td>30</td><td>-</td><td>-</td></tr>
<tr><td colspan="2">Density</td><td>ρ_r</td><td>1</td><td>2250 kg/m^3</td><td>2250 kg/m^3</td></tr>
<tr><td colspan="2">Elastic modulus</td><td>$E_r = \rho_r L_r$</td><td>30</td><td>20GPa</td><td>0.667Gpa</td></tr>
<tr><td colspan="2">Time</td><td>$T_r = \sqrt{L_r}$</td><td>5.47</td><td>-</td><td>-</td></tr>
<tr><td colspan="2">Acceleration</td><td>$A_r = 1$</td><td>1</td><td>-</td><td>-</td></tr>
<tr><td colspan="2">Strain</td><td>$\varepsilon_r = 1$</td><td>1</td><td>-</td><td>-</td></tr>
<tr><td rowspan="2">Stress</td><td>f'_c</td><td rowspan="2">$\sigma_r = \rho_r L_r$</td><td rowspan="2">30</td><td>16.5MPa</td><td>0.55MPa</td></tr>
<tr><td>f'_t</td><td>3.20Mpa</td><td>0.107MPa</td></tr>
</table>

2.2. Material properties

In order to satisfy the requirements for spatial, physical, boundary, and moving condition similarities of the scaled model with those of prototype, bentonite was used in the cement mixtures as a component to reduce strength. Considerable work had been accomplished in reference [5] to produce an appropriate bentonite-based concrete mix. The use of bentonite in concrete mixes eliminates the problems in curing and associate shrinkage cracking when using concrete mixes having highly reduced properties. Ten trial mixes were made in the laboratory with the bentonite saturation prior to mixing. Standard 30cm×15cm cylinders were made form each batch. Compressive and tensile strengths of each mix were determined to select the best mix which meets the similitude requirements. Tensile strength was obtained from splitting tensile test. The physical properties of the final mix are shown in Table 2.2.

Table 2.2: Model mix physical properties

Water-Cement ratio	Bentonite-Cement ratio	Slump (cm)	Compressive strength (MPa)		Tensile strength (MPa)		Modulus of elasticity (GPa)	
			28 days	56 days	28 days	56 days	28 days	56 days
3	0.25	5.5	0.74	0.83	0.056	0.077	0.490	0.542

2.3. Model design, construction and instrumentation

According to the structural drawings of Sefid-rud dam and also considering the actual conditions of the shaking table, the model scale of 1:30 adopted in this research. The highest, non-overflow monolith was chosen because it was the most highly damaged monolith during Manjil earthquake. The cross section shown in figure (1) gives the dimensions of the monolith to be modeled.

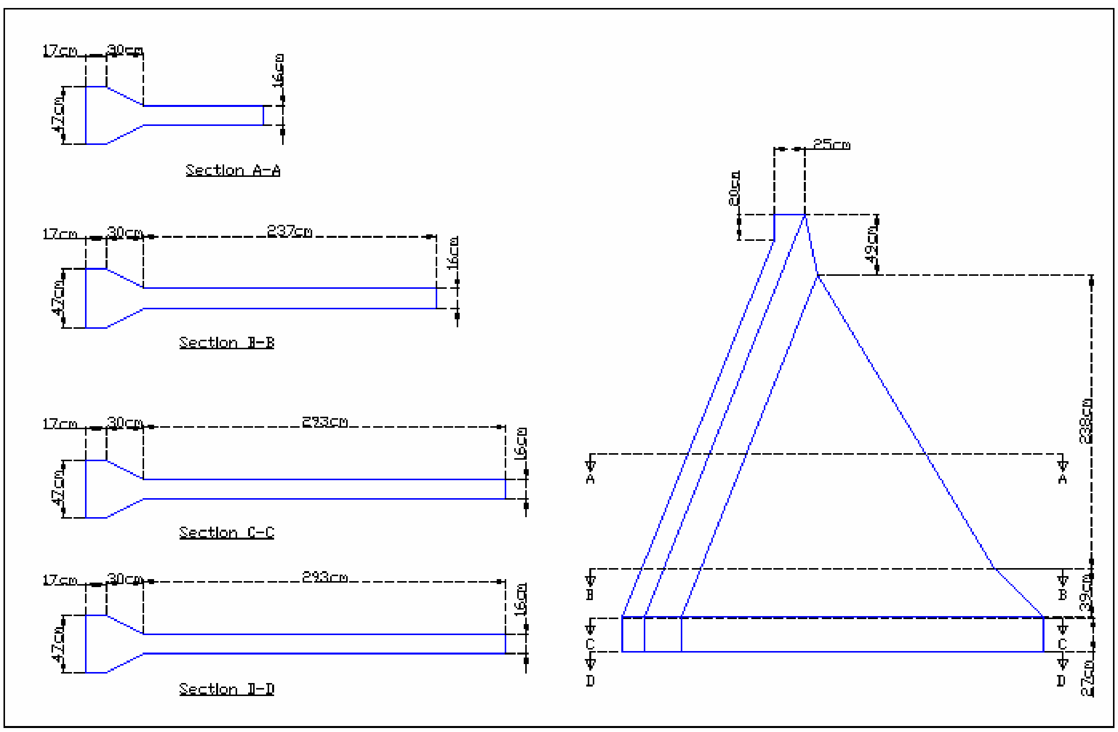


Figure 1: Model dimensions

After preparing bentonite-based concrete, the model was constructed on a shaking table in three stages to simulate horizontal construction joints effects as shown in figure (2). The model foundation was built from a high-strength concrete reinforced by steel bars to securely fasten the model to the shaking table and treat the foundation as rigid. Instrumentation included 16 accelerometers, 17 strain gauges and 11 displacement transducers. Accelerometers were mainly installed at the downstream, upstream and front face of the model as shown in figure (3). Strain gauges were mainly distributed on the top of the model where the most potential of cracking is expected. Displacement transducers were placed on a steel frame with a rigid foundation adjacent to the shaking table in such a way as to measure the total displacements of installation points of the accelerometers.

Figure 2: Layout of construction joints

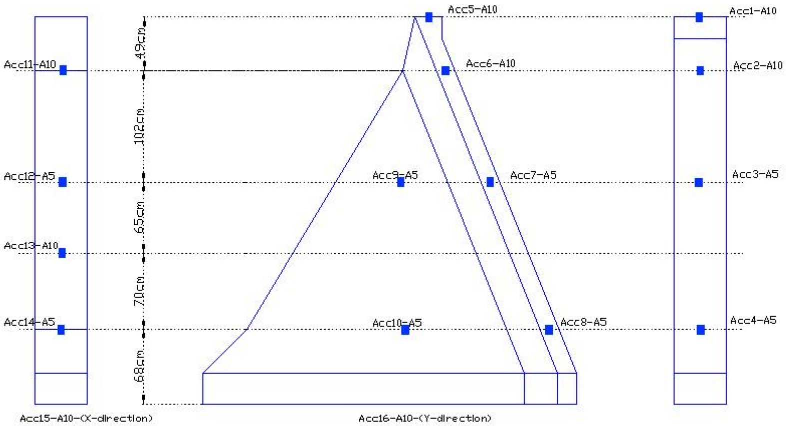


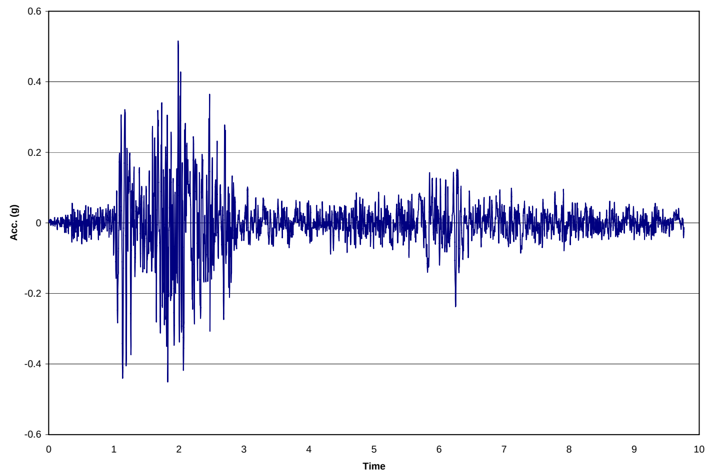
Figure 3: Layout of Accelerometers

2.4. Dynamic characteristics of the model

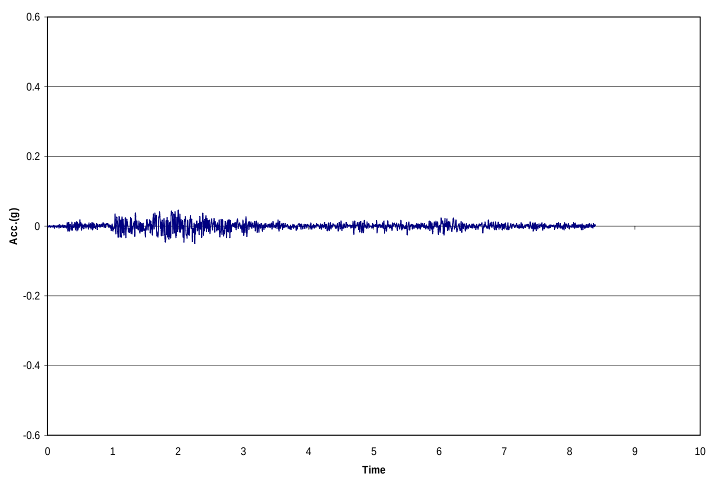
Using experimental sine-sweep tests on the model, the fundamental frequencies were obtained. Vibration frequencies for first five modes of the model are 4.1,11.6,17.4,23.2 and 27.1Hz, respectively. Mode no. 4 represents the motions along the stream. In this mode with the fundamental frequency of 23.2Hz, damping coefficient was measured around 2.9% of critical.

2.5. Test plan on the shaking table

The scaled model test on the shaking table adopted Manjil earthquake records in stream and cross-section directions as input. According to the scale factor, each seismic accelerogram duration is reduced to 1:5.477 of the original duration. Peak accelerations of longitudinal and transverse components are 0.51g and 0.49g, respectively. Applying cross-section earthquake component is only for obtaining a more detailed model response to serve as data in numerical model calibration. However, in concrete gravity dams due to the supporting action of adjacent monoliths, cross-section motions in the scaled model are not close to reality. As a result, the acceleration in the cross-section component is reduced to 1:10 to decrease the cross-section motion effects as shown in figure (4).



(a)



(b)

Figure 4: Model scaled base accelerations: (a) Longitudinal component (b) Transverse component

For more investigation, two linear numerical analyses with allowed and constrained cross-section motions were conducted to investigate the effects of cross-section motions on model behavior. Full scaled stream and cross-section records were used as seismic inputs. Numerical results with allowed cross-section motion are very close to those with constrained cross-section motion. As a result, preciseness of the experimental model can be reserved in the case of applying cross-section seismic record without any constraint at this direction.
Shaking table test is planed to begin at a level of 10 percent of the scaled Manjil record and will be gradually increased in equal intervals until the cracks develop in the model. This could lead to a gradual and controlled increase in damage.

3. TEST RESULTS

The model displayed developed failure characteristics when the longitudinal peak acceleration reached a value of 0.85g which is almost 1.67 times greater than the peak acceleration in Manjil record. The main structural damage in the model consists of an integrated crack in the upper part of the model. This crack runs the whole length of the model about 40cm and 61cm below the crest at upstream and downstream, respectively (Figure (5a)). The second structural damage was formed at the upstream face of construction joint no.2 almost 122cm below the crest as shown in figure (5b).

(a) **(b)**

Figure 5: Model cracking pattern: (a) Cracks at the top of the model (b) Cracks at the upstream face of the construction joint no.2

A comparison between crack patterns in model and Sefid-rud dam shows that the experimental cracks are in a satisfactory agreement with those occurred after Manji earthquake.
The results obtained from shaking table test include the responses of accelerometers, displacements transducers and strain gauges in both linear and nonlinear levels.
an abrupt change in the longitudinal displacement which would correspond with cracking initiation in the model was occurred in the model. Also, a permanent displacement about 2mm is observed after stopping the test. This behavior is a result of a sliding towards downstream which corresponds with failure characteristics of Sefid-rud dam.

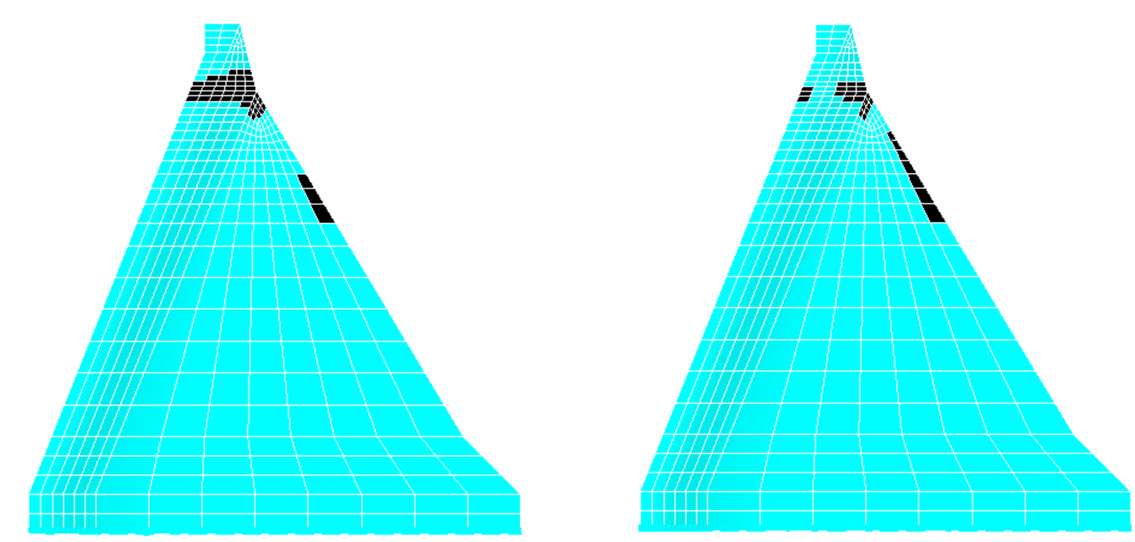
4. NUMERICAL MODEL CALIBRATION

Smeared crack and damage mechanics models based on nonlinear fracture mechanics principles are used to represent crack initiation and propagation. The development of the constitutive models relies on an energy-based softening initiation criterion, fracture energy conservation during cyclic excitation, shear deformations in the fracture process zone, and the subsequence rotation of the crack planes. The three dimensional constitutive laws and numerical procedures are presented in references [9-12] in detail and are beyond the scope of this paper.

Model finite-element meshing includes 780 20-node isoparametric solid elements. The modulus of elasticity, Poisson's ratio, unit weight, the true tensile strength and the ratio of the apparent to the true tensile strength, the specific fracture energy and the dynamic magnification factor applied on both of the tensile strength and the specific fracture energy are 0.542GPa, 0.2, 22072.5N/m^3, 0.077MPa, 1.25, 3.1N.m/m^2 and 1.30, respectively.

Figure (6) represents the crack patterns in a model with considering construction joint effects. It is obvious that the resulted crack profiles including a weak layer upon construction joints are in a satisfactory agreement those reported experimentally. However, it is observed that cracks are localized in downstream face of construction joint no.2 which is contrary to the experimental results.

The crack profiles resulting from the damage mechanics approach (shown in figure 6(a)) are more diffused than those resulted from the proposed smeared crack method at the upper part of the dam body. The more diffusion in the crack profile leads to excessive damage and therefore analysis termination. In smeared crack model, the analysis is terminated at the end of the record without any termination due to instability or excessive error in the energy balance.



(a) **(b)**

Figure 6: Crack patterns in a heterogeneous model with construction joint effects: (a) Damage mechanics (b) Smeared crack

5. CONCLUSIONS

1. An experimental study on the dynamic characteristics and seismic responses of the 1:30 scaled model of the highest monolith of Sefid-rud dam was conducted on shaking table. It was found that the nonlinear behavior of the model test were in satisfactory agreement with the prototype behavior during Manjil earthquake.
2. Sliding displacements about 2mm (equal to 6cm in prototype) due to the longitudinal record is approximately the same response in prototype.
3. Two approaches based on damage mechanics and smeared crack concept was proposed. The accuracy and the numerical stability of the proposed models and the developed software were established using the

available experimental results. The crack patterns obtained from numerical models are in good agreement with those obtained from shaking table tests for the case of including construction joint effects and rigid foundation. However, smeared crack model, shows more numerical stability than fracture mechanics model.

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