Investigation of Seismic Failure for High Arch Dam with model test on shaking table

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SUMMARY:
This paper presents the experimental investigations into the seismic failure for high arch dam with shaking table test. The similitude scale of high arch dam was studied firstly. Then we developed a like concrete material to simulate the mechanical behavior of the structural concrete in high arch dam. The shaking table tests have been performed on the scale model. A novel methodology based on Electro-mechanical Impedance Smart Aggregate (EMISA) was proposed to monitor the damage process in the model dam, which can overcome the limitations of the traditional techniques such as accelerometers and strain gauges. The experimental results reveal the failure process of high arch dam with respect to the different earthquake intensities.

Keywords: High arch dam, Seismic failure, Scale model, Shaking table test

1. INTORDUCTION

Several high arch dams are under construction or planning on the Yellow, Yangtze, and Red Water rivers to meet China's energy requirement. Some of them are 300-m high, making them the highest concrete arch dams in the world. Most of them are located in high seismic risk zones, with the design ground accelerations being over 0.3g, with a 10% probability of them being exceeded in 500 years. Real behaviours of high arch dams under strong earthquake are very important for an aseismic design, but few of them have experienced design or higher level of ground motions of earthquake. Although the numerical simulations are popular to study the earthquake responses of high dams, the absence of experience and field test data make it difficult to verify the numerical results. Small scale modelling has long been recognized as a valuable technique for experimental studies of seismic behaviour for the structures that cannot be directly tested (Ghobarah and Ghaemian, 1998; Harris et al., 2000). The major problems in applying this technique include: (1) similitude requirements for small scale modelling; (2) material modelling; and (3) suitable equipment for testing, especially for measuring the damage during the shaking process.

The seismic failure of high arch dam was experimentally investigated with the small scale model tests in this paper. The similitude modelling of high arch dam was presented firstly. The model material that is able to simulate the really structural concrete was developed for scale model test. A series of tests for a high arch dam were carried out on the shaking table. The seismic failure behaviours were monitored by two kinds of sensors: accelerometers and the Electro-mechanical Impedance Smart Aggregates (EMISAs). The major failure modes of high arch dam are reported by the experimental investigations.

2. SIMILITUDE MODELLING OF HIGH ARCH DAM

The elastic elasticity-gravity similitude law should be satisfied for scale modeling of arch dams because the hydrostatic pressure plays an important role of the dam failure. Also, the hydrodynamic pressure has the significant effects on the vibrations of dam, without considering the water compressibility, the hydrodynamic pressure on the dam should be similitude, i.e. the similitude factor of liquid density should be equal to that of the solid materials between prototype and model. For scale model test of arch dam, the previously-mentioned requirements for similitude modeling should be meted simultaneously. Thus the dynamic similitude law of the scale model for arch dam can be given by

$$\lambda = \lambda_E \lambda_\rho^{-1} \quad \lambda_t^2 = \lambda \tag{2.1}$$

where, λ is the geometric scale; λ_E is the elasticity scale; λ_ρ is the mass density scale scaled; and λ_t is the time scale.

Seismic model test conform to the similitude theory in the elastic phase. Taking considerations of the space limitation of the shaking table, the geometric scale should be determined firstly in this study.

$$\lambda = \frac{L_P}{L_m} = \frac{300}{0.77} = 390 \tag{2.2}$$

where L_p and L_m are the dam heights of prototype and model with unit of meter, respectively.

The similitude relationships between the prototype and scale model were represented by the following scales:
Elasticity:

$$\lambda_E = \lambda_\sigma = 302 \tag{2.3}$$

Density:

$$\lambda_\rho = 0.774 \tag{2.4}$$

Time:

$$\lambda_t = \lambda = 390 \tag{2.5}$$

where λ_σ is the scale of tensile strength between prototype and model.

3. MODELED HIGH ARCH DAM

One of the difficulties in physical modelling of concrete dams is mostly in material modeling (Zhou et al., 2000). To obtain the entire failure process in the model test, the model material is the key issue of the first importance. Mass concrete is known to be a linear and brittle material that contains micro cracks, which may develop to become visible under periodic loading. From the viewpoint of fracture mechanics, the cracks may expand rapidly and unsteadily once the stress intensity factors at their tips exceed the fracture toughness of the concrete. Unfortunately, it is still difficult to find relationships that relate stress intensity factors and fracture toughness from one material to another. Thus, the characteristics of the model material are very important for dynamic failure experiments, especially for high dams. Many reasons can be cited for the necessity to research into model materials. First, to simulate the final damage patterns of high arch dams, the model materials is required to be elastic and brittle, i.e. it must keep the primary tensile behaviour of mass concrete, by being elastic up to the proportional limit at which brittle fracture must occur. Second, Young’s modulus of the material must low enough to make the fundamental frequencies of the models lie in the frequency band of the shaking table to permit resonance tests to be performed. Third, the tensile strength of the model materials must be as small as possible to enable final failure of the models to occur within the nominal power of the shaking table. Additionally, it must be possible to mould and demould the models without causing any damage. The combination of all these requirements made the development of a suitable model material into a long and costly process.

After hundreds of trail mixes and subsequent modifications, a special material consisting of cement, rive sand, heavy quartz sand, heavy quartz powder, lead power, and water, in the ratios by mass of 1.00, 5.09, 29.41, 9.00, 0.05, and 385, respectively, was developed for the dam models. The elasticity and brittleness of the model material are similar to those of mass concrete. The experimental results show that the characteristics of the material agree well with those of mass concrete. Its tensile strength and modulus of elasticity are much lower than for mass concrete and are controlled by its age. The strengths of the model materials were tested by the standard procedure of indirect tension using a four-point beam test. The ideal strength ranges of the model material for seismic failure experiments were 0.30-0.70 MPa in compression and 0.03-0.06 MPa in tension. The dynamic Young’s modulus of elasticity and density were in the ranges of 600-1,000 MPa and 2,400-2,700 kg/m3, respectively.

The arch dam was built to scale 1:390. Steel forms were constructed to the scaled dimensions of the dam, with special attention to the accurate modelling of the curves of the arch dam. Normally, it takes 8 hours to mould a dam model and another 72 hours to cure it in a suitable laboratory environment, which consists of a temperature range of 15-18 ℃ and a humidity range of 50-70%. The photo of the arch dam model was shown in Fig. 3.1.

Figure 3.1. Photo of the scale model of high arch dam

4. TEST SETUP AND INSTRUMENTION

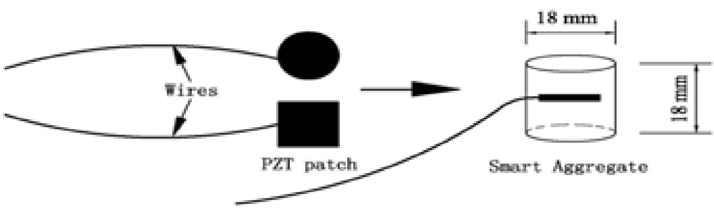
One of the difficulties in physical modeling of high arch dam is the availability of suitable equipment for measuring the dynamic responses and structural damage in the model. Two kinds of sensors were used in the experiments. One kind of sensor is the traditional sensors, such as accelerometers and strain gauges, which were mounted on the model dam to measure the dynamic responses during the shaking process. But rare sensors can investigate the damage development in model test. In the past, the visual observation is the commonly-used method to find the occurrence of the macro cracks in the surface of the model. The limitation of the visual observation is that it can only find the macro crack in the surface of the structure. However, the damage will occur and develop before the macro crack appears under the dynamic load such as seismic excitation. Therefore, it is motivated to study the damage monitoring technique for dynamic model test of high arch dam.

We proposed a novel methodology based on Electro-mechanical Impedance Smart Aggregate (EMISA) to monitor the damage process in the model dam, which overcome the limitations of the traditional techniques. Electro-mechanical impedance-based approach has provided an innovative approach for the structural damage detection with the advantages of structural simplicity, low cost, quick response and high reliability. The electrical impedance is measured at high frequencies, typically higher than 30 kHz, while the wavelength of the excitation is small and sensitive enough to detect minor changes in the structural integrity. According to the literature survey, it is found that the currently-used impedance approach mostly adopt surface-bonded PZT as sensor (Tseng and Wang, 2004; Bhalla and Soh, 2005; Park et al., 2006; Yang et al., 2008; Shin et al., 2008). For scale model of high arch dam, due to the small scale (e.g. 1:100 or smaller), the Young's modulus of model materials are much less than those of real concrete, which makes the difficulty in effectively actuating the host structure by the surface-bonded PZT. To remedy the limitations of the surface-bonded sensors, we presented a novel method based on the built-in EMISA to detect the seismic damage in the model experiments of high arch dam.

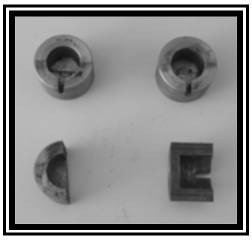
In order to prevent the PZT from crushing, the smart aggregates are formed by embedding a waterproof piezoelectric patch with lead wires into a small concrete block before casting them into a larger concrete structure. The ratios of the materials used for the fabrication of the smart aggregates are listed in Table 4.1. The fabrication process of the EMISAs is demonstrated in Fig. 4.1.

Table 4.1. Proportions of ingredients used for concrete mix (%)

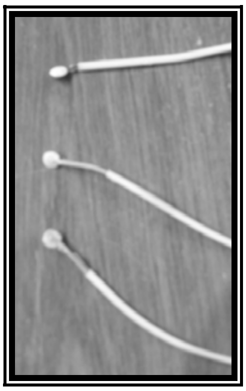
Cement	Water	Admixture	Sand	Fine aggregate
5.0	10.0	10.0	35.0	40.0



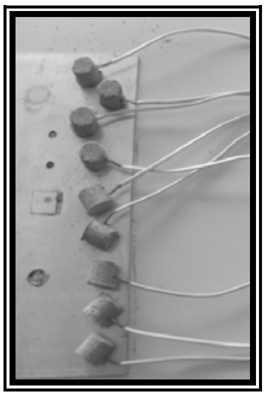
a) Schematic process of the smart aggregate



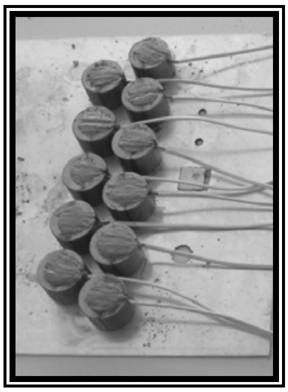
b) Steel Mold



c) Wires + PZT



d) Fabrication of the Smart aggregates



e) EMISAs

Figure 4.1. Fabrication process of EMISAs

During pouring the model material into the mold, the EMISAs were placed in the specific locations. After the model was finished, the EMISAs were inside the model dam. The lead wires were connected the EMISAs with the Agilent 4294A Impedance Analyzer. The impedance analyzer excites the built-in SAs with sinusoidal wave, with amplitude of 0.5 volt, then the PZT reflect the signals with vital information and all the information would be record by computer. After trial-error tests, 140 kHz-220 kHz was selected to detect the seismic damages for model dam in this study.

The sensor layout on the surface of the model dam was illustrated in Fig. 4.2. The sensors include 7 accelerometers, 12 strain gauges, and 16 Fiber Bragg Grating (FBG) sensors. Moreover, 9 EMISAs are placed inside the model dam.

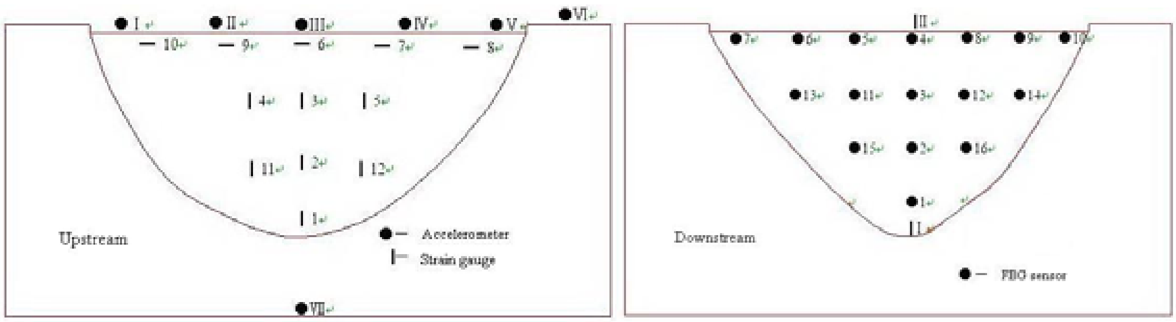


Figure 4.2. Sensor layout of arch dam model

5. EXPERIMENTAL RESULTS

Two scaled models, i.e. monoblock model as well as jointed monolith model, were built and tested on the shaking table. In this paper, only the results of monoblock model were presented. All of the experiments assumed the reservoir to be empty.

The monoblock model of high arch dam was tested on the shaking table in Dalian University of Technology, China. The upstream/downstream excitations were applied because additional, unreported tests showed that cross canyon excitation was less damaging. The seismic excitations are artificial earthquake generated by the response spectrum formulated in Specifications for Seismic Design of Hydraulic Structures (DL 5073-2000). The peak values of the acceleration history generated by shaking table are 0.17g, 0.46g, 0.68g, 0.89g, 1.04g, and 1.09g, respectively. The final failure of the model dam was illustrated in Fig. 5.1.

Figure 5.1. Final failure of arch dam model

After each load case, the principal frequency of the model dam was measured and shown in Fig. 5.2. From the figure, in the first 3 load cases, the principal frequencies are not changed, which indicates that the stiffness of the model dam is maintained. After load case 4, 5% reduction was happened on the principal frequency. In this phase, the incipient cracks were appeared close to the arch crown by visual observation. After load case 5, there is a sudden drop in principal frequency. After this stage, the principal frequency was reduced continuously. It is indicated that the severe damages were occurred in the model dam.

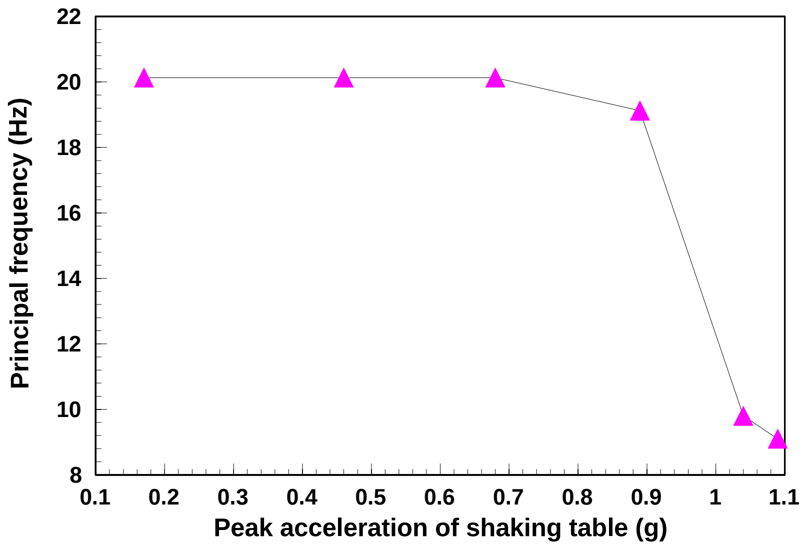


Figure 5.2. Principal frequencies of dam model under different seismic excitations

Meanwhile, the accelerations on the top of arch crown were measured in each load case. The peak accelerations on the top of arch crown were shown in Fig. 5.3. In the first three cases, the peak accelerations are not changed also. In load case 4, the peak acceleration is changed slightly. In load case 5 and 6, it is changed dramatically.

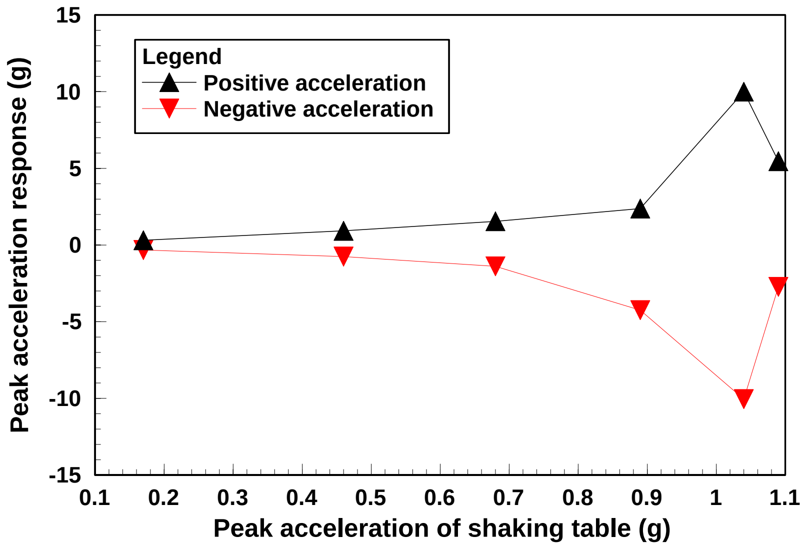


Figure 5.3. Peak acceleration responses on the top of the arch crown

To monitor the damage development during the tests, only first four load cases were measured with EMISAs. The measurements of the sensor close to the top of arch crown were plotted in Fig. 5.4. It is clearly shown that the impedance curves are changed even in the first four load case. It is demonstrated that the EMISAs is able to detect the incipient damages that the conventional sensor cannot detect.

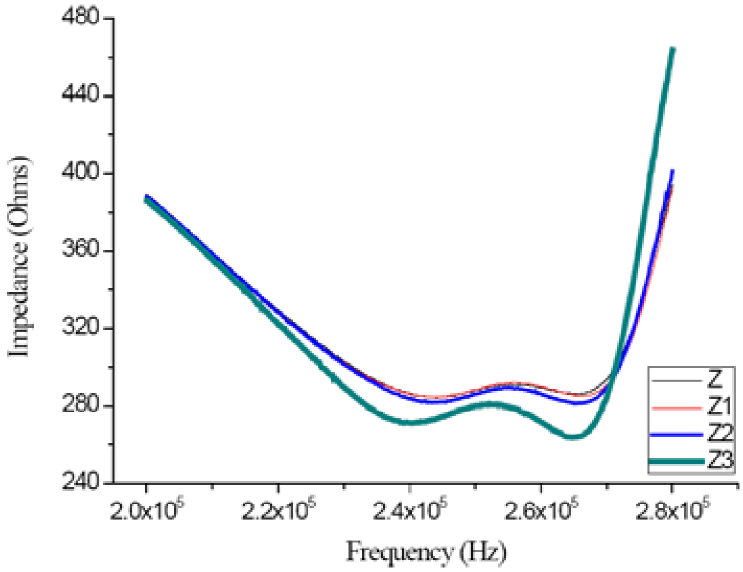


Figure 5.4. The impedance measurements of EMISA for first four load cases

6. CONCLUSIONS

The seismic failure for high arch dam with shaking table test was investigated in this paper. The similitude scale of high arch dam was built, and the model material was developed to simulate the mechanical behavior of the structural concrete in high arch dam. The shaking table tests have been performed on the scale model. The failure process of the model dam was monitored by two kinds of sensors. One is the accelerometer and another is the Electro-mechanical Impedance Smart Aggregate (EMISA). The measurements of the accelerometers can indicate the dynamic responses of the model dam, but it is unable to monitor the damage process under the seismic excitation. We proposed a novel methodology based on EMISAs to monitor the damage process in the model dam, which overcome the limitations of the traditional techniques such as accelerometers and strain gauges. The experimental results reveal that the EMISAs are sensitive enough to detect the incipient damages in the scale model.

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