IMPEDANCE-BASED SMART AGGREGATE FOR DAMAGE MONITORING IN A CONCRETE GRAVITY DAM MODEL

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The purpose of this study is to evaluate the damage of a scale model of a high concrete gravity dam during and after an earthquake. To detect the damage in the scale model, a built-in smart aggregates (SAs) were used in the scale model of a high concrete gravity dam. The electro-mechanical Impedances (EMIs) of SAs were measured for different experimental cases. The variations in the impedance spectral of the SAs were extracted as the damage-sensitive features. In this study, PZT were embedded in concrete to form a small cylinder, which is called smart aggregate. Then the smart aggregates were placed in the scale model, and the impedance/admittance signatures were measured by the impedance analyzer. The root mean square deviation (RMSD) of the impedance and admittance signatures was statistically calculated to detect the damage. The results demonstrate that the EMI-based SAs can effectively detect the seismic damage in the scale model, which shows the potential application to the structural health monitoring for high concrete gravity dam.

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ABSTRACT: The purpose of this study is to evaluate the damage of a scale model of a high concrete gravity dam during and after an earthquake. To detect the damage in the scale model, a built-in smart aggregates (SAs) were used in the scale model of a high concrete gravity dam. The electro-mechanical Impedances (EMIs) of SAs were measured for different experimental cases. The variations in the impedance spectral of the SAs were extracted as the damage-sensitive features. In this study, PZT were embedded in concrete to form a small cylinder, which is called smart aggregate. Then the smart aggregates were placed in the scale model, and the impedance/admittance signatures were measured by the impedance analyzer. The root mean square deviation (RMSD) of the impedance and admittance signatures was statistically calculated to detect the damage. The results demonstrate that the EMI-based SAs can effectively detect the seismic damage in the scale model, which shows the potential application to the structural health monitoring for high concrete gravity dam.

Keywords:High concrete gravity dam, Scale model, Seismic damage, Impedance-based smart aggregate (ISA)

1 INSTRUCTIONS

Several large-scale high concrete dams are under construction in the southwest of China. However, severe earthquakes are frequent in the area. Accordingly, seismic safety of high concrete dams has been a very important concern for the dam design. The experimental study of the scale model is an important way to investigate seismic safety and to predict seismic responses of high concrete dam. To author's knowledge, the visual inspection is the only way to detect the seismic damage or concrete cracking in scale model of high concrete dam. It is urgently motivated to develop the advanced sensing techniques to monitor the damage for the scale model test.

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 concrete dam, due to the small scale (e.g. 1:100 or smaller), the Young's modulus of model materials are far less than those of real concrete, which makes the difficulty to effectively actuate the host structure by the surface-bonded PZT. To remedy the limitations of the surface-bonded sensors, we present a novel method based on the built-in smart aggregate (SA) to detect the seismic damage in the model experiments of high concrete dam.

2 ELECTRO-MECHANICAL IMPEDANCE APPROACH

Based on the principle of electro-mechanical coupling effect, Liang et al. (1996) proposed an approach to model the interaction between PZT and bonded structure. The principle of EMI-based damage detection is schematically shown in Fig. 1.

The complex mechanical impedance Z can be expressed as

$$Z = R + iX \tag{1}$$

where R is the real part of the impedance, which called resistance; and X is the imaginary part, which called reactance.

The admittance Y is the inverse of the impedance, which can be expressed as

$$Y = G + jB \tag{2}$$

where G is the real part of the admittance and B the imaginary part. G and B are conductance and susceptance, respectively.

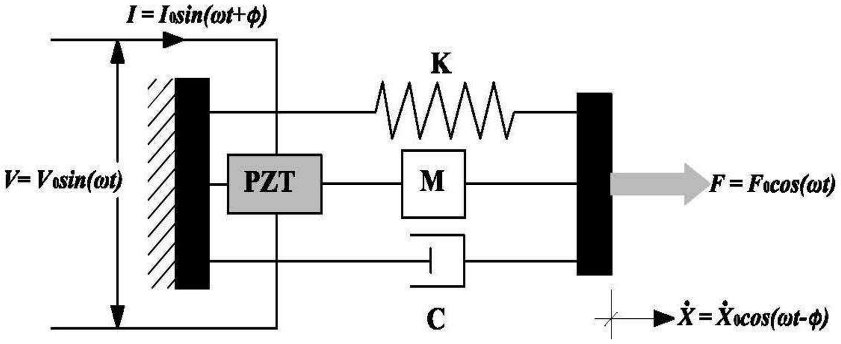


Figure 1. A SDOF system under dynamic excitation

The mechanical impedance, Zs of the host structure idealized as a SDOF system (in Figure 1), The apparent electro-mechanical impedance of the PZT as coupled to the host structure is given by

$$Z(\omega) = \left[i\omega C \left(1 - {k_{31}}^2 \times \frac{Z_s(\omega)}{Z_a(\omega) + Z_s(\omega)} \right) \right]^{-1} \tag{3}$$

Where C is the zero-load capacitance of the PZT, and   is the electromechanical coupling coefficient of the PZT. The changes of the mechanical properties of the host structure may be detected by monitoring the variations of the electro-mechanical impedance functions shown in Eq. (3).The admittance is the inverse of the impedance.

3 GENERAL DESCRIPTION OF THE EXPERIMENTS

The construction procedure of model dam was as followings: (1) Steel mould was built on the shaking table. (2) The model materials were casted into the mould. At the same time, the smart aggregates were placed inside the model dam at the specific locations. (3) The mould was removed after 48 hours. The dimensions of model dam were illustrated in Figure 2.

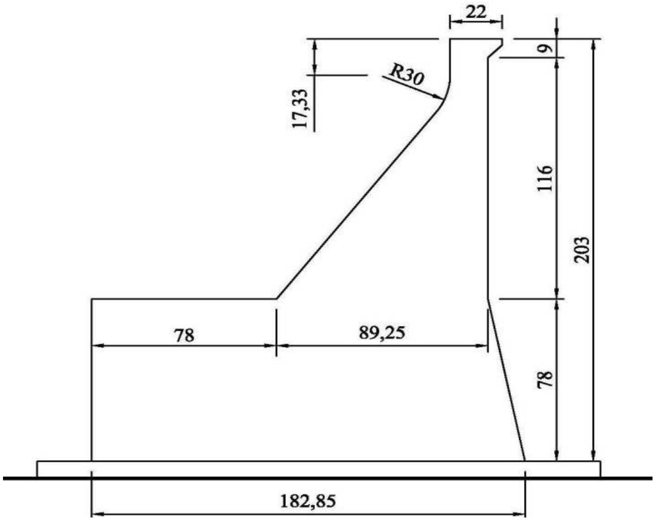


Figure 2. Scaled model dam

The experiment worked on the shaking table facility at the Earthquake Engineering Institute, Dalian University of Technology, Dalian, China. The shaking table, its maximum horizontal displacement, velocity and acceleration are respectively ±75mm, 50cm/s, 1.0g while the maximum vertical displacement, velocity and acceleration are ±50mm, 35cm/s, 0.7g, respectively. And its frequency ranges from 0.1 to 50Hz

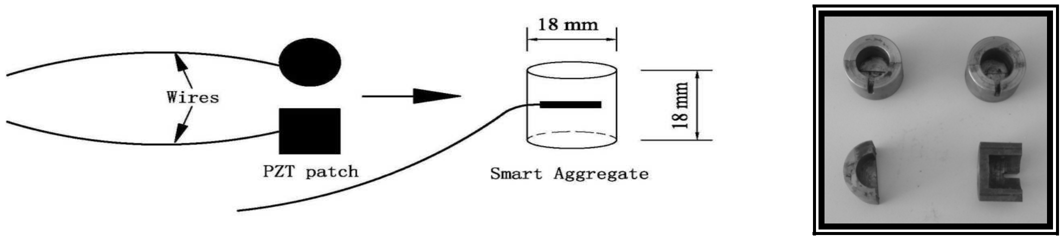
4 EXPERIMENTAL PROGRAMS INSTRUCTIONS

4.1 Smart Aggregates

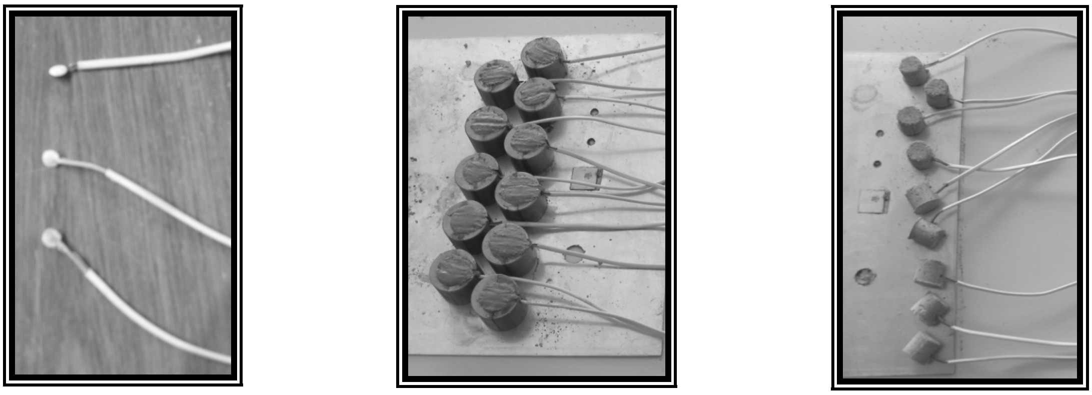
Recently, an embedded PZT approach, which is named as smart aggregate (SA), was proposed to detect the damages in concrete structures (Song et al., 2008). Nevertheless, the smart aggregates are only applied to the elastic wave-based approach for structural health monitoring. In this study, we adopted the concept of smart aggregate for EMI-based damage detection in scale model test of high concrete 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 1. The fabrication process of the SAs is demonstrated in Figure 3.

Table1. 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) Smart aggregates

Figure 3. Fabrication process of the smart aggregates

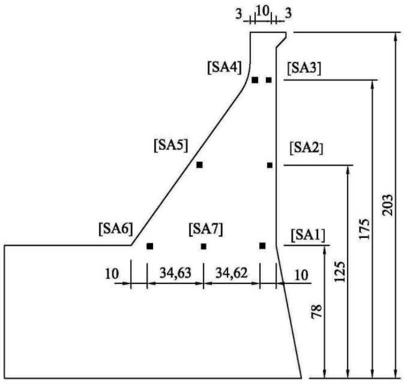


Figure 4. Locations of the smart aggregates in the model dam

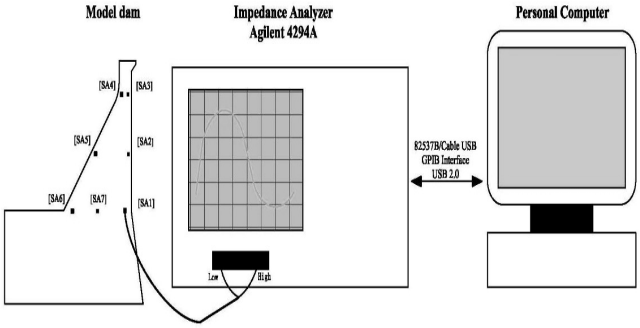


Figure 5. Experimental set-up for damage detection

4.2 Experimental set-up and test programs

To evaluate the aseismic performance of Concrete Gravity Dam, seven smart aggregates have been placed in the model dam respectively, whose locations were shown in Figure 4. And 3 load cases were carried out in the model experiments. The excitations generated by shaking table were artificially seismic waves with Peak Ground Acceleration (PGA) 0, 0.2g, 0.5g, and 0.7g, respectively. Before and after each load case, the damage detection was performed by using of the SAs in the model dam.

The experimental set-up for seismic damage detection was illustrated, in Figure 5. The built-in SAs were connected with Agilent 4294A Impedance Analyzer, which excite 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.

5 EXPERIMENTAL RESULTS AND DISCUSSIONS

To evaluate the damage, this paper prefer to Root mean square deviation (RMSD) that proposed as damage index by Giurgiutiu and Rogers (1997).The root mean square deviation (RMSD) of the impedance and admittance signatures is given by

$$RMSD(\%) = \sqrt{\frac{\sum_{i=1}^{n}(R_i^1 - R_i^0)^2}{\sum_{i=1}^{n}(R_i^0)^2}} \times 100 \qquad (4)$$

where the resistance of the PZT, R_i^0, is measured under healthy condition; R_i^1 is the corresponding post-damage value, and n is the number of sampling points.

In the damage index, the larger difference between the baseline reading and the subsequent reading, the greater the value of calculated RMSD is. In RMSD index, R can be replaced with X, G or B, respectively. The calculated values reveal the health state of the structure after each damage phase.

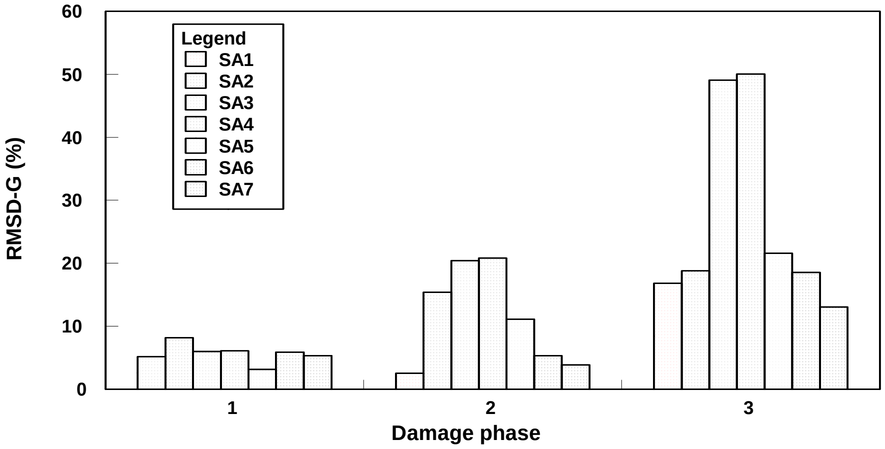


Figure 6. RMSD-Gs with respect to sensor locations

The calculated RMSD-Gs with respect to sensor locations were also plotted in Figure 6, with respect to different damage phases. For damage phase 1, all SAs can detect the occurrences of slight damages within the sensing area, but the amplitudes of RMSD-Gs are less than 9% and fluctuated. Since the seismic damages are slight and invisible, the damage severities, which presented by the amplitudes of calculated RMSD-Gs, cannot be verified by the model test. Nevertheless, the built-in SAs can definitely detect the occurrences of seismic damages in model dam. After load case 2, the cracks were appeared and they propagated with the increase of the seismic intensities. Overall, the damages close to SA3 and SA4 are the most severe, while those close to SA1 and SA7 are the slightest. From figure 10, it can be observed that the amplitudes of RMSD-Gs correspond to the cracking behavior and damage severities at different locations in model dam. Therefore, a sensor network of EMI-based SAs can effectively detect the seismic damage in a distributed fashion.

6 CONCLUSIONS

In this paper, we proposed a novel methodology of Impedance-based smart aggregate (ISA) to detect the seismic damages in a scale model of high concrete gravity dam. The SAs have been fabricated by embedding the waterproof PZT patches with lead wires into the small concrete blocks, which provide the protections for the PZT sensors. Based on the scale modeling, a small scale model was built for a high concrete gravity dam. And the SAs were embedded inside the model dam at the predetermined positions. The impedances and admittances of the built-in SAs were measured before and after each load cases of seismic excitations. Also, the damage indices based on the RMSDs of measured data were studied to quantitatively evaluate the damage in the model dam. The detecting performances of built-in SAs were investigated with respect to sensor locations. The results demonstrated that the amplitudes of RMSD-Gs correspond to the damage severities at different sensor locations. It is concluded that the proposed method of EMI-based SAs can effectively detect and quantify the seismic damage for a scale model of high concrete dam, which provides a potential means to monitor the damage in real dam.

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