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Experimental study on high gravity dam strengthened with reinforcement for seismic resistance on shaking table

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Abstract. In order to study the dynamic failure mechanism and aseismic measure for high concrete gravity dam under earthquake, the comparative models experiment on the shaking table was conducted to investigate the dynamic damage response of concrete gravity dam with and without the presence of reinforcement and evaluate the effectiveness of the strengthening measure. A new model concrete was proposed and applied for maintaining similitude with the prototype. A kind of extra fine wires as a substitute for rebar was embedded in four-points bending specimens of the model concrete to make of reinforced model concrete. The simulation of reinforcement concrete of the weak zones of high dam by the reinforced model concrete meets the similitude requirements. A tank filled with water is mounted at the upstream of the dam models to simulate the reservoir. The Peak Ground Acceleration (PGA) that induces the first tensile crack at the head of dam is applied as the basic index for estimating the overload capacity of high concrete dams. For the two model dams with and without strengthening tested, vulnerable parts of them are the necks near the crests. The results also indicate that the reinforcement is beneficial for improving the seismic-resistant capacity of the gravity dam.

Keywords: similitude relationship; seismic measure; model test; reinforced bar; shaking table

1. Introduction

In lifeline engineering, the performance of dam against strong earthquake is one of the issues of common concern to the engineers, because the disaster caused by flood is unimaginable once a dam breaks. Although the assessment of seismic safety for dams under strong earthquakes, especially high concrete dams, is always a focus of research in the field of seismic engineering, very few cases of existing concrete dams suffered serious damage from the earthquake are taken as reference. None of concrete dams, except Hsinfengkiang buttress dam in during 1962 earthquake in China, Koyna gravity dam during 1967 earthquake in India, Pacoima arch dam during 1971 and

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1994 California earthquakes, Rapel arch dam during 1985 Chile earthquake, Sefid Rud buttress dam during 1990 Iran earthquake, and Shih-Kang concrete diversion dam during 1999 Chi-Chi earthquake in Taiwan, have been shaken by a severe earthquake of duration long enough to induce significant damage (Wieland 2003).

Based upon the conditions described above, so far physical model test and numerical modeling are widely adopted to investigate responses of concrete dam under earthquake.

Although substantial progress has been achieved in the mathematical modeling, to date, due to unavoidable shortcomings such as simplification in numerical model and approximation in constitute relationship, it can not solve completely the problems as a single satisfactory method on safety assessment for concrete dams. However, the problems to be studied are so complex that they can not be easily handled by numerical method. So physical models, as an instrument for validation and calibration of numerical models (Müller *et al*. 1979, Alvarez 1979), are often necessary to identify the key mechanisms. Model test has the potential of being used for the analysis and the verification purposes.

In over decades, considerable experimental research programs had been accomplished in previous studies (Donlon *et al*. 1989, 1991, Mir and Taylor 1995, 1996, Zhou *et al*. 2000, Harris *et al*. 2000, Li *et al*. 2004, René *et al* 2000, Philippe *et al* 2002, Wang and Li 2006, 2007, Ghaemmaghami and Ghaemian 2008) to study the nonlinear seismic behavior of concrete dam models. Many kinds of model material were proposed to satisfy the laws of similitude between model and prototype (Donlon *et al*. 1989, 1991, Harris *et al*. 2000, Niwa and Clough 1980). Many test approaches were adopted to investigate the performance of concrete dams subjected to severe earthquakes, such as the shaking table test, the centrifuge test (Waggoner *et al*. 1993, 1995, Uchita *et al*. 2005) and the actuator modeling seismic load test (Ghobarah and Ghaemian 1998).

However, all the research works mentioned above are to investigate dynamic behaviors and earthquake responses of the concrete dams. Almost none of them proposed a measure to improve performance of concrete dam against intense earthquake. Seismic performance is a key problem in the design of dams. The effective measures are very useful in improving the safety and reliability of high concrete dams. However, Little research has been reported in this field.

Technology of reinforced contraction joints was applied relatively earlier in arch dam engineering to reduce the contraction joint openings, to prevent water stop damaged, and to improve the dam integrity. Some projects (Wieland 2003), such as Inguri arch dam in the former Soviet Union, Rapel arch dam in the Chile, Sir arch dam in the Turkey, adopted the technology. Zhang *et al*. (2000) developed a numerical model of contraction joint reinforcements to investigate non-linear seismic response of Xiaowan arch dams with contraction joint opening and joint reinforcement, and optimize control of the joint opening.

A limited number of research programs were conducted to investigate measures to improve performance and strengthen safety of concrete dam for seismic resistance. To evaluate the effectiveness of the reinforcement measure, Long and Zhang (2008) developed a modified embedded-steel model which combines the approach of stiffening reinforced steel (Gilbert and Warner 1978, 2007) with the zoning method of lightly reinforced concrete (An *et al*. 1997). The model can simulate the nonlinear seismic damage response of concrete dams with reinforcement, but ignores the influence of the slip between the reinforced steel and its surrounding concrete on the cracking response of the dams. Kwak and Filippou (1990, 1995) developed a reinforced steel model which is embedded into a concrete element and includes the bond-slip effect by incorporation of the equivalent steel stiffness. This model can be used to investigate the influence of the reinforcement slip on the dam responses by easily implemented into standard finite element procedures. Long *et al*. (2009) conducted comparative studies of the seismic response of gravity dam with and without reinforcement. The numerical analyses account for several nonlinearities such as concrete cracking, tensile plastic offset strain of concrete, stiffness recovery when a crack closes and the bond-slip effect.

In the model tests, Zhao (2007) performed experimental study of RCC gravity dams strengthened with reinforcement in monolith for seismic resistance. They adopted method of increasing elastic modulus of model material to simulate reinforcement concrete of earthquake damage parts of the concrete dams. Although the method has a certain effect, a logical similarity relation can never found between model and prototype, because the strength of the material changes with its elastic modulus. Ghaemmaghami and Ghaemian (2010) conducted a shaking table test on small-scale retrofitted model of Sefid-rud concrete buttress dam which was damaged during the devastating 1990 Manjil earthquake. The dam was repaired and strengthened using epoxy grouting of cracks and the installation of post-tensioned anchors. After completion of grouting and drying the grouted areas, 12 cables anchored at the top of the model and fixed at the model foundation were installed on both sides of the model following the same configurations as retrofitted Sefid-rud dam. Experimental results showed that the post-tensioning resulted in a significant decrease in dynamic responses in terms of crest displacement and measured strains of the retrofitted model in comparison with its corresponding responses at the faultless model test.

Huangdeng RCC gravity dam is built on the Lancang Jiang in Yunnan Province, Southwest of China, during 2009-2012. It’s about 14 km and 631 km away from Kunming city and Yingpan Town, respectively. The highest of the dam is 203 m, the length of the crest is 464m. It consists of 20 monoliths, each about 25m long. This dam is constructed of roller compacted concrete on a foundation which composes of granite porphyry, ivernite and tholeiite. Its reservoir is more than 14,180 million cubic meters. The hydroelectric power station is capable of an installed capacity of nearly 1,900 million kilowatts and an annual generation capacity of 8.629 billion kilowatt-hours. It is vital for irrigating the vast rice fields in the downstream.

In order to further study the dynamic destruction mechanism and aseismic measure for concrete gravity dam in intense earthquake, the dynamic model experiments of water retaining section of Huangdeng gravity dam with and without the presence of reinforcement were conducted to investigate their whole processes from damage to failure and effectiveness of the aseismic strengthening measure. The work studied the performance of the dam section, explored its weak links, and evaluated the effectiveness of the strengthening measure. Base on comparison between the experimental results of models with and without strengthening, it is found that although the strengthening measure can not improve the tensile properties and the first cracking acceleration, development of the major crack to inside of dam can be restricted; that maintains a integrity of dam head, prevents the crack penetrating rapidly throughout dam body and even threatened to topple down. The results offer important reference to engineering designers and aseismic design.

2. Model development

2.1 Numerical simulation procedure

The prototype dam was reduced at a proportional scale to conduct dynamic test on the shaking table. To make a small-scale model accurately represent the corresponding behaviors of its prototype, the model must satisfy a series of similitude requirements in terms of geometry, physical and mechanical properties, boundary conditions and initial states. The similitude requirements for model test have been summarized in previous study (Donlon 1989, Ghobarah and Ghaemian 1998, Ghaemmaghami and Ghaemian 2008, 2010). For the case of a dam-reservoir system, it is necessary to keep the similarity of earthquake inducted hydrodynamic pressure of the model and the prototype. That is, the ratio of density of the model and prototype reservoir liquid should be equal to the ratio of the mass density of the model and prototype material (Ghobarah and Ghaemian 1998). Besides the three well-known basic laws of similitude, the ratio of reservoir liquid density and the ratio of force are established from the scaling theory. According to dimensional analysis, dimensionless ratios that relate the behavior of model and prototype are given in following equations

$$T_r = \sqrt{L_r} \tag{1}$$

$$S_r = \rho_r^d L_r \tag{2}$$

$$A_r = 1 \tag{3}$$

$$\rho_r^w = \rho_r^d \tag{4}$$

$$F_r = \rho_r^d L_r^3 A_r \tag{5}$$

where T, L, S, A, F and ρ represent time, length, stress, acceleration, force and mass density, respectively. Subscript r is the ratio of these parameters in model and prototype structure. Superscript w and d represent respectively the reservoir water and dam in modeling system. The scale chosen first for this model is a 1:100 geometric scale based on the size of the prototype dam and the capabilities of the testing facilities as well as properties of model material. A concrete-like model material with almost the same density is used to construct the model of dam section. According to similitude requirements, estimated properties of the small-scale model are summarized in Table 1. The reservoir was only approximately modeled by a small tank at the upstream side of model in the test.

Table 1 Similarity requirements and model material properties

Physical parameter	Scale factor	Ratio	Prototype value	Model value
Length	L_r	100	——	——
Density	$\rho^d{}_r$	0.83	2400kg/m^3	2900kg/m^3
Dynamic elastic modulus	$E^d{}_r=\rho^d{}_r L_r$	83	33.15GPa	0.399GPa
Time	$T_r=\sqrt{L_r}$	10	——	——
Acceleration	$A_r=1$	1	——	——
Strain	ε_r	1	——	——
$f_c^{'}$ $f_t^{'}$	$\sigma_r=\rho^d{}_r L_r$	83	24.57MPa 2.34MPa	0.296MPa 0.0282MPa
Force	$F_r=\rho^d{}_r L^3{}_r A_r$	830000	——	——

Note: According to similar law of elasticity-gravity, $\rho_r^d = \frac{2400}{2900} \approx 0.83$, presume ε_r=1.

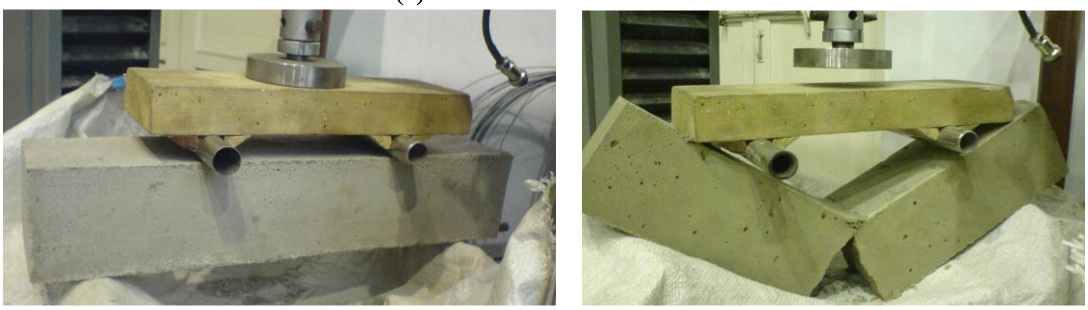
Table 2 Ingredients proportions used for the model concrete mixture (%)

Water	Cement	Ore powder	Barite	Barite powder
8.0%	2.0%	14.5%	30.5%	45.0%

(a) The knocking cantilever beam test for the dynamic elasticity modulus

(b) The uniaxial compression test

(c) The uniaxial tension test



(d) The four points bending test.

Fig. 1 The material tests for additional parameters of the model concrete

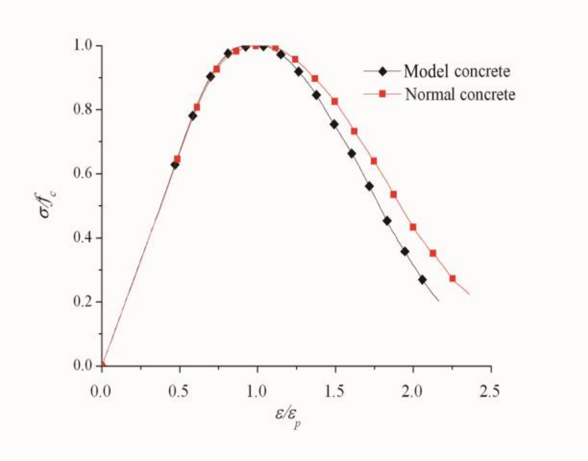


Fig. 2 Dimensionless compressive stress-strain curves of the model concrete and normal concrete

Fig. 3 Typical compressive fracture mode of the model concrete

To meet the similitude requirements of physical, spatial, boundary and loading conditions between the small scaled model and those of prototype, a kind of model concrete made of cement, barite, barite sand, ore powder, additive, etc. is manufactured by DUT. The ingredients proportions of the model concrete for the testing are shown in Table 2. The model concrete contains only small quantities of cement to reduce the strengths. Physical test of the material was done to measure some important parameters such as the compressive strength, tensile strength, static and dynamic elasticity modulus, etc. to support the models test. Dynamic elasticity modulus was primarily determined to select the best mix proportion of the model concrete which meets the requirements of the specified modulus for the test. The knocking cantilever beam test for the dynamic elasticity modulus was performed by the testing specimen (100×100×515 mm) for the study, and the value obtained was 386.6 MPa at 24h of curing age. The material tests for additional parameters of the model concrete are shown in Fig. 1. The material compressive and tensile strengths are respectively 0.285 MPa and 0.027 MPa.

The model mixture shows the same mechanical properties with prototype concrete in the laboratory testing. The compressive stress-strain relationship and the forms of damage are similar to those of normal concrete, shown in Fig. 2 and Fig. 3. In addition, the typical tensile stress-strain curve derived from uniaxial tensile test is basically a linear in ascending segment. Of particular significance, the normal concrete breaks for all compressive specimens tests failed in a classic shear plane of approximately 65° (Harris *et al*. 2000). Other trial mixtures were tested in the laboratory based on gypsum, rubber powder, bentonite, plaster, lead powder, etc. combinations and these materials created failure modes such as horizontal layer crushing different from normal concrete. The law-strength concrete modeled the kinematic failure mechanism better than the materials made from other combination, although not all parameters met simultaneously the similitude requirements.

2.2 Simulation method of reinforcement concrete

Model tests for reinforcement concrete structures began in the early 1960s (Along 1980, Kong *et al*.1983). After several decades' development, the researchers began to concentrate on the studies of model tests of large complex structures. They did a great deal of work and obtained many important results for constitutive relations of model materials. However, the selection of model materials still is the key issue. With the wide application of the micro-concrete as a model material, Maisel (1980), Patricio *et al*. (1999) imbedding galvanized wires instead of steel bars into specimens of micro-concrete to simulate slabs, beams and columns of reinforcement concrete.

Based on characteristics of the model concrete mentioned above, the method for simulating reinforcement concrete was explored to provide a basis for models test of Huangdeng RCC gravity dam which is strengthened with reinforcement in monolith for seismic resistance in the work.

The low-strength model concrete developed by DUT is mainly used to produce models of monolith hydraulic structures such as dams, piers and so on. Its elasticity modulus and strengths are very low. When the experiment of the concrete dam with reinforcement is conducted with the model concrete as model material, it is very hard to solve the problems caused by low adhesiveness, and elasticity modulus and strengths proportional relations between the galvanized wires and the model concrete, and so on. So it is difficult to simulate the reinforcement concrete of gravity dam with the concrete and galvanized wires.

Judging from the comprehensive effects of properties of reinforcement concrete, reinforcement for concrete can not markedly improve the concrete tensile strength, but can increase its ductility. The ductility of reinforcement concrete is much better than that of normal concrete. The ratio of reinforcement to concrete in gravity dam is extremely small for seismic resistance, mainly to improve the tensile properties, tensile ductility and integrity of earthquake damage areas. To simulate effects of reinforcement concrete with the model concrete, judging from the comprehensive effects, as long as the ductility of the concrete constitutive curve in descending segment can be improved, can areas of reinforcement concrete on the dam be simulated.

After material selection and test research, en extra fine wire used in wire mesh was adopted as model material of steel bar, the diameter, elastic modulus, and tensile strength are respectively 0.25 mm, 24 GPa, 300 MPa by measuring the geometric size and mechanical properties of the extra fine wire.

20 extra fine wires were made into a small mesh, as shown in Fig. 4. The mesh was embedded into bottom of specimen (100×100×515 mm) to carry out four-point bending test. The initiation and propagation of the cracks were recorded by CCD high speed video and replayed for analysis of macroscopic crack, as shown in Fig. 5. The cracking tensile strength, maximum load were calculated and shown in Table 3.

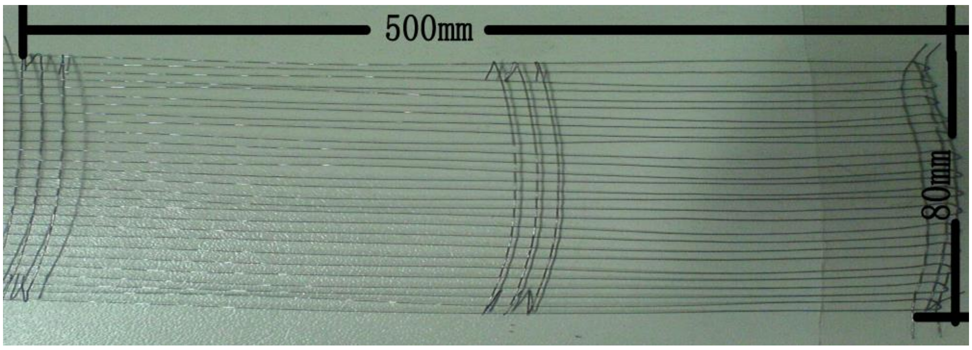


Fig. 4 The mesh of extra fine wires Embedded into the model concrete.

Fig. 5 The cracking process of simulated reinforcement concrete.

Table 3 The datasheet of tensile test for the model concrete with reinforcement

Numbers of the wires	Cracking load/KN	Cracking strength/MPa	Maximum load/KN	Maximum deflection/mm	The width of main crack /mm	Numbers of cracks
	0.296	0.101	0.608	3.21	1.3	5
20 wires	0.287	0.098	0.597	3.10	1.4	4
	0.302	0.103	0.632	3.29	1.5	4

Note: The table shows the crack width is manually determined by vernier caliper, so the values are approximation. applying Laser Rangefinder should be applied to get the width.

In the work, it was found that the cracking tensile strength of the model concrete strengthened with the extra fine wires was a little more than that of pure model concrete. That indicates that the improvement of tensile strength of the model concrete with “reinforcement” is limited. It is the same as that of reinforcement concrete.

The phenomena were observed in the four-point bending test of specimens in which the 20 longitudinal “reinforced bars” were embedded. It could be seen that when the specimens were loaded to approximately the cracking strength the first crack presented. Then the load suddenly dropped at the maximum value but rapidly rose up afterwards. The load continued to show an upward tendency with fluctuation, at the same time several small cracks presented on the surface of specimen, and a main crack went on extending upward in the process. It was shown that the load was mainly supported by the extra fine wires at this time. The specimens were not brittle, and they did not lose carrying capacity and stability immediately when they cracked. Finally the main crack reached a certain width, tensile “reinforced bars” into the necking stage; the load began to go down, the specimens were not pierced by the main crack.

The simplified pull-out test was adopted to validate the validity of adhesiveness between the model concrete and the wire. Three wires of different lengths were pre-embedded inside the specimens before the test, and either end of the wires left outside was pulled out with a speed of 2 mm/min by universal testing machine. The burial depths of the wires were 10 cm, 15 cm and 20 cm, respectively. The test showed no phenomena that the model concrete of specimen surface fell off, and the wires drawn out. But the wires were broken when the pulling force reached their ultimate loading capacity, 16~17 N. It indicated that the adhesiveness between the model concrete and the wire was adequate to meet the similitude requirements.

According to the discussion above, without regarding to bond stress-slip relationship between reinforced bars and concrete, the reinforcement concrete in weak zones of dam can be better modeled by the model concrete with extra fine wires.

To respective stresses of the model concrete and extra fine wires, the bond force between them can be considered as external force. In the scope of elasticity, according to similarity relationships of elasticity modulus and external force ($S_r=E_r\varepsilon_r$, $U_r=\varepsilon_r L_r$), the external force scale between the prototype steel bars and the model extra fine wires are obtained by the following equation

$$F_r = E_r^c L_r^c U_r^c = E_r^s L_r^s U_r^s \tag{6}$$

where E, U, F are elasticity modulus, displacement, external force, respectively. Superscript s and c represent the rebar and concrete, subscript P and M represent prototype and model, respectively. Since bond stress-slip relationship between steel bar and concrete is not taken into account, $U_r^S=U_r^c$ can be deduced. Assuming that elasticity modulus of steel bar is 200GPa, E_r^S=8.33 is obtained. Consequently, ratio of cross-section area of steel bars $L_r^{S2}\approx 8.1\times 10^5$ is calculated by $L_r^S\approx 900$ from formula Eq. (4) above.

In order to simulate the reinforcement concrete in the weak zones of the dam under strong earthquake, two groups of 12 extra fine wires of Φ0.25@2 distribution are placed near the upstream and down stream face of neck part of the dam model with reinforcement, respectively. It is equivalent to placing four layers of steel bars of Φ36@250 distribution in the corresponding positions of the prototype dam. The protective layer thickness is 20mm in the model.

2.3 Model design, construction and instrumentation

The experiment was completed Institute of Earthquake Engineering Laboratory at DUT in China. The models with and without the presence of reinforcement were constructed on shaking table and excited in a biaxial corresponding to the horizontal stream direction and vertical direction.

To eliminate the influence of external environments on the test results, the typical water retaining dam section models with and without the presence of reinforcement were exactly the identical in model material, loading, foundation and influence of reservoir except the seismic strengthening measure in the testing. Both of the models were 203cm in the total height, and 25cm in the thickness. The foundations of both models were constructed with material which was the same as the model concrete of dam body. Foam board was used between the two models to separate them. After demolding, the foam board was sawed through to make the models did not interfere with each other. The model of cured 24 hours is shown in Fig. 6. Some all-thread rods are imbedded in the foundations to fix the models on the shaking table.

A small tank is instilled on the water side of the models with a size of 6.0 m×0.8 m×2.1 m to simulate the effect of hydrodynamic pressure. In the test, the tank was filled to the designed height with water. To avoid water impulsive wave reflection from the back wall of the tank to the upstream face of the model, an energy dissipator which is a cage made of fiber nets and battens was installed at the other end in the tank away from the models. The dissipator consisted of 4 layers of fiber nets at intervals of 20 cm, and its size was 60×80×200 cm, as shown in Fig. 7 The water body vibrated together with the models to simulate the effect of hydrodynamic pressure in the testing. A complete suite of concrete material laboratory tests were performed immediately after the models test.

A detailed explanation was made including instrumentation types and installational positions. Instrumentation for test series was consisted of the measurements of, Fig. 8:

Accelerometers: 7 sensors were placed every 30cm along height of each model to record the accelerations in horizontal along the stream direction. Two were placed on the each crest and the supporting platform respectively, to record the accelerations in the horizontal stream and the vertical directions;

Fig. 6 Model of water retaining section, model with strengthened was printed in blue

Fig. 7 Water tank and dissipator

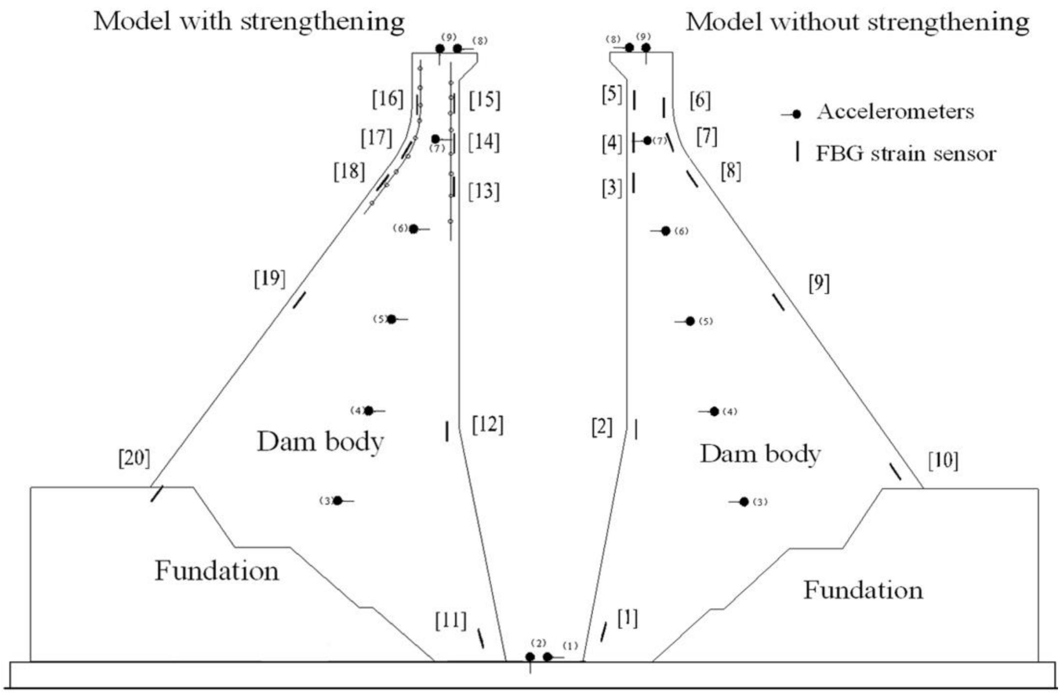


Fig. 8 Sensors placement.

The gauge fiber bragg grating (FBG) strain sensor: 8 were extensively used in the upstream and downstream face of each dam model, as shown in Fig. 8. The traditional resistance strain gauge is easily interfered by outside environment. In strong electro magnetic interference condition of the earthquake simulation system, resistance strain gauge has a great noise. It is difficult to accurately measure the response data among weak signal. FBG as a new type of intelligent sensor appeared in

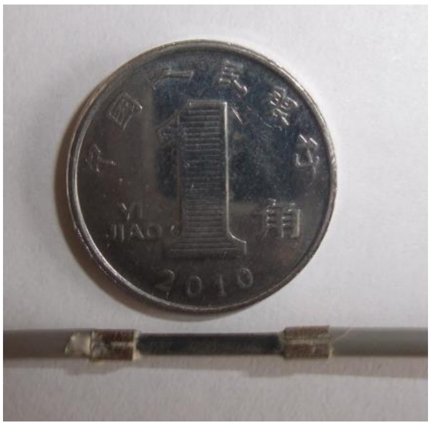


Fig. 9 Gripper packaged FBG strain sensor

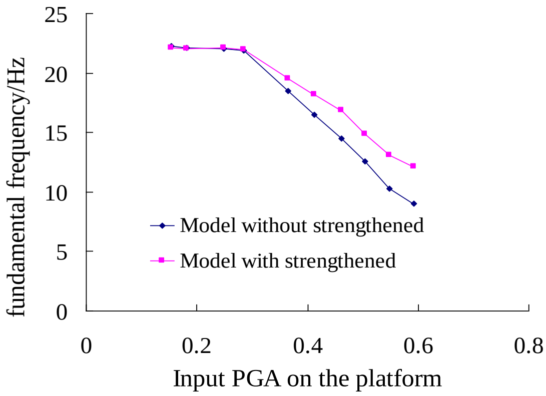


Fig. 10 Fundamental frequencies changes with the PGA on the platform

recent 10 years, as shown in Fig. 9. The small dimension sensor with holders in both sides is protected and packaged by stainless steel tube, and it is a newly developed strain measurement equipment. The FBG strain sensor can be embedded within the structure to measure the strain. It has the advantages of small size, high precision and flexible use demonstrating promising potentials.

2.4 Procedure of seismic failure models test

Based to the scale factor (Eq. (1)), each seismic accelerogram duration is reduced to 1:10 of the original duration. The artificial wave of Huangdeng dam site response spectrum was used as input for the models. Numerical analysis predicted that the fundamental frequencies of both models with and without the presence of reinforcement (not including reservoir) are approximately 23.25 Hz. The two types of model were conducted simultaneously on the shaking table. Using experimental white noise (sine-sweep) tests on the models, the fundamental frequencies of both were almost identical, namely 22.17 Hz. The models were then excited with the peak ground acceleration (PGA) of the shaking table gradually increasing until the failure occurred completely. The PGA was increased, but the frequencies of excitation were decreased to compensate for the reduction of the natural frequencies of the models caused by cracking.

Due to the limitation of testing procedure, the test is performed under increasingly intensive PGA. The increasing step-by-step loading method is the equal of period of vibration increased. It causes damage of models in a lesser degree before the first crack appearing. In this case, obtaining exciting acceleration which produces the first crack at the models in the test is a bit smaller than it really is, so the results of these examination show that these methods will give reasonable safe conclusion for assessing the safety of gravity dams subjected to earthquake ground motions. The excitation was planned to begin at 30% PGA (it is 0.251 g) of Huangdeng dam design earthquake. After testing for each level of earthquake, the models were tested and concluded by white noise excitations at 0.05 g to identify possible damage; within a limited time to check the obtained results, another set of testing was performed for the next level of PGA.

In actual dam structure, each monolith is laterally supported by the adjacent monolith. Modeling no support was provided laterally in the two models due to the experimental limitations.

Therefore, to remove lateral vibration effects, a biaxial shaking table was used to excite the models in horizontal stream and vertical directions. The PGA of vertical direction is 2/3 that of horizontal stream direction in biaxial input ground motion.

3. Test results

3.1 Fundamental frequency of model

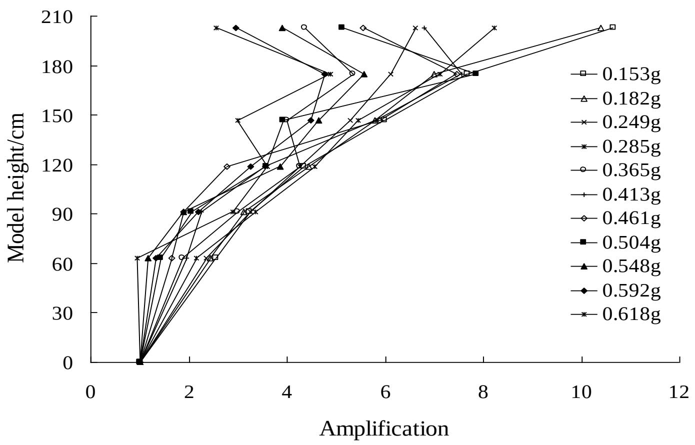
According to transfer function from the platform to the crest of the models, the fundamental frequencies of the models under the various levels of earthquake were obtained. The cracks configurations in the models were not easily detected by naked eyes, they could be determined only by the data and results measured in the testing. The crack had been formed soon after the fundamental frequencies of both models showed a sudden reduction together.

The changes of the fundamental frequencies under various levels of earthquake is shown in Fig. 10 With inputting PGA in the range of 0.153~0.285 g, the changes of the frequencies of both models with and without the presence of reinforcement were very small. After the PGA reached 0.365 g, the models fundamental frequencies were reduced, but the decrease rate of fundamental frequencies of the model with reinforcement was lower than that without strengthening. The results indicated that the models overall stiffness was hardly change at all before the PGA reached 0.285 g. After the PGA reached 0.365 g, the stiffness decreased rapidly. This phenomenon indicated that the exciting acceleration produced the first crack at the neck parts in the models. However, after the model with reinforcement cracked, further expansion of the crack was restricted for being strengthened. So the model with reinforcement maintained a certain degree of integrity, and its fundamental frequencies fell slower.

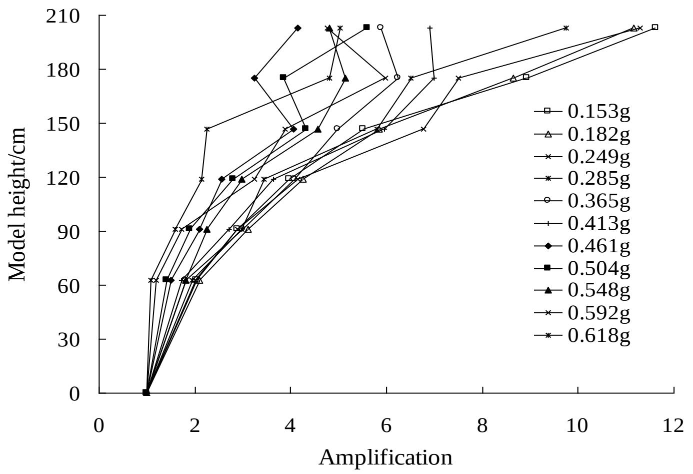
3.2 Acceleration distribution

The distributions of acceleration amplification factors along the height of the water retaining section models with and without reinforcement are shown in Fig. 11. With the increase of inputting seismic PGA, it could be seen that the responses of accelerometers on each model were both in linear and nonlinear levels. In the figure, it is obvious that the acceleration amplification factors of both models increase linearly along height of the models, and decrease with the increase of the PGA, before the PGA reaches 0.365 g. The maximum of the factors under the PGA of each level is at the crests of both. When the PGA reaches 0.413 g, at the height of 150~180 cm of each model, the amplification factors are suddenly changed. It can be seen that the neck and nape near the crest is weak zones of dam during the earthquake. A survey of real dams (Wieland 2003, Ghaemmaghami and Ghaemian 2009, 2010), dynamic model tests, and numerical analyses (Long *et al*. 2009) indicated that the upper area of the gravity dam was its weakest zone and that, in general, this is where crack occur first in earthquake.

Comparing Fig. 11(a) with Fig. 11(b), it is clear that they have the same change trend in linear level but differ from nonlinear level. In nonlinear behavior (the PGA is more than 0.365 g), the change of the acceleration amplification factors of the model with reinforcement is less intense, and more regular than that without strengthening. it indicates that the cracks in the dam model with reinforcement propagate relatively slowly, the model has a good integrality after the model concrete cracking.



(a) Model without strengthening



(b) Model with strengthening

Fig. 11 Amplification factor distribution along the model height

3.3 Damage analysis of dam models

The damage developing patterns of the models with and without the presence of reinforcement are listed in Table 4. For the both of models, the most vulnerable part of them is the head of dam.

Under the condition of full reservoir, when inputting seismic wave PGA reached 0.365 g, the first crack of both models appeared at downstream face of the neck. The level of the PGA plays a important index for assessing the safety of gravity dam subject to earthquake. However, the crack of model without strengthening propagated greater extent than that with reinforcement. The visible crack ran through the whole of the model without strengthening under the 0.504 g of the PGA. The design PGA of Huangdeng gravity dam is 0.251 g, its seismic overload coefficient of 1.454(0.365/0.251) was high enough for safety for the dam. When cracks ran through the model without strengthening, the overloaded acceleration multiples was 2.007(0.504/0.251). These

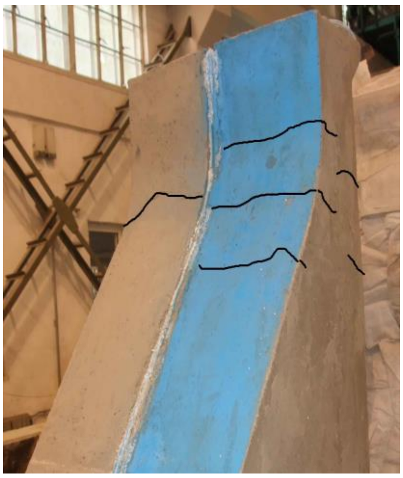
Table 4 Failure forms of models under various PGA on the platform in the test

No.	Failure locations		The PGA on the platform
	Model without strengthened	Model with strengthened	
1	Middle part of downstream arc face appeared crack, about 7cm long.	Bottom part of downstream arc face appeared crack, about 3cm long.	0.365g
2	25cm away blew crest of model upstream face cracked, and the crack was rapidly expanding into center of model.	The upstream face cracked, meantime the second crack was found above the first crack of downstream.	0.413g
3	The cracks of upstream and downstream face joined through the model body.	Two cracks gaped below the main cracks of up and down stream face.	0.504g
4	The dam head was rocked obviously more than dam body.	The main cracks of up and down stream face stretched each other forward, but don't joint through	0.592g

(a) Dam section failure of model without strengthening

(b) Dam section failure of model with reinforcement

(c) Upstream surface dam section failure



(d) Downstream surface dam section failure

Fig. 12 Dam section failure patterns under the earthquake results indicated the dam section had a good seismic performance, and enough safety storage under the design PGA. The major crack propagated relatively slowly because the extra fine wires embedded in upstream and downstream face of dam model neck played a key role in preventing development of crack, so it didn't develop throughout the thickness of model with reinforcement in the end of test. It indicates that the strengthening measure has little effect on the creaking acceleration, but there is a significant difference in the post-cracking development of the major crack. The measure is be prevents the major crack from running through upstream-downstream face of dam, and contributes to the integrality of the dam after concrete cracking.

The locations and patterns of both models cracking in the dynamic testing are shown in Fig. 12. In the figures, the cracks of neck and nape are sloping straight line and intersect at the interior of model without strengthening. The damage forms of the model with reinforcement consist of the major cracks of upstream and downstream face and secondary small cracks nearby. The locations of the major cracks of model with reinforcement are approximately 10cm lower than those without strengthening. Taking test facilities and reservoir water into account, the test was not proceeded to make the head part of the model without strengthening drop down. For the model material's waterproof performance limitation, the upstream surfaces of both models were mounted plastic film to isolate models from water in the testing. However, once dam concrete cracks, reservoir water will rapidly intrude into the cracks in the actual project. Water may fill inside the cracks on the dam upstream face and hence result in pressures in there, influencing crack propagation as well as the behavior of dam. Consequently, cracking is an important non-linear phenomenon to consider in the seismic response of concrete gravity dams. The effect of water pressures inside cracks is smaller than that of cracks only on the global modal properties and response of these dams (Tinawi and Guizani 1994). The test do not take influence infinite foundation into account, so no crack was discovered at the heels of dam models during the vibration.

3.4 Strain analysis

The maximum tensile strains at various locations of both models are listed in Table 5. It can be seen that the maximum dynamic tensile strains of dam models with and without presence of reinforcement have occurred respectively at FBG no.7 and no.18 where the cracks lines had passed through the locations near. The large strain with a value of 941$\mu\varepsilon$ indicates that a complete opening has occurred in cracked zones of the model without strengthening, as shown in Fig. 12(a). Some maximum strains of locations (FBG no. 13, 14, 16, 17, and 18) of model with reinforcement are also more than the value of cracking strain, that means the damage occurred at the corresponding locations, as shown Fig. 12(b). The locations of exceeding tensile strain threshold in the model are in conformity with the fact of being observed during the testing.

It can be seen from the Table 5 that the maximum opening of the major crack of dam model with reinforcement is much less than that without strengthening. That is because the reinforced bars have some effect on reducing the maximum opening and extension of the major crack. The maximum strain values of other locations of model with reinforcement are larger than those without strengthening, because the tensile stresses are significantly released when the propagation and opening of the cracks cause the stress redistribution in the dam model without strengthening. For the model with reinforcement, the reinforced bars bear mainly tensile stress after the model material cracking, so the reinforcements are helpful in preventing the upper part of the dam from destabilizing.

The larger strains at heel of models with and without the presence of reinforcement are shown in

Table 5 Maximum tensile dynamic strains at various locations of model

Model without strengthening		Model with reinforcement	
FGB no.	Max. dynamic tensile strain(με)	FGB no.	Max. dynamic tensile strain(με)
1	367	11	381
2	241	12	287
3	294	13	427
4	605	14	446
5	314	15	376
6	327	16	411
7	941	17	484
8	305	18	491
9	204	19	217
10	301	20	327

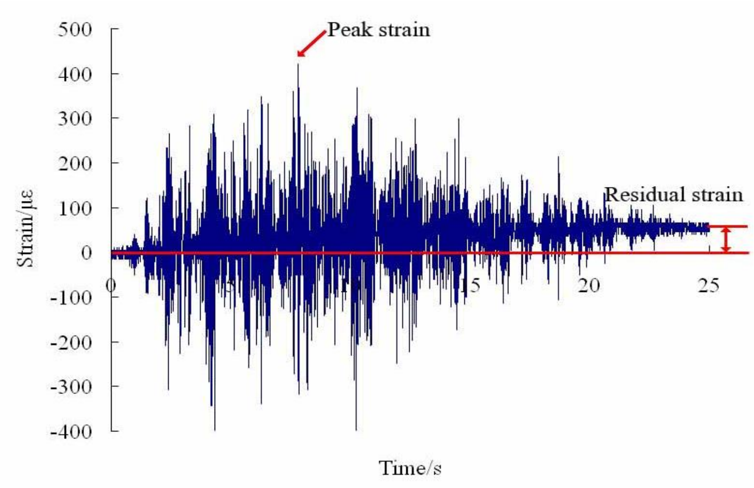


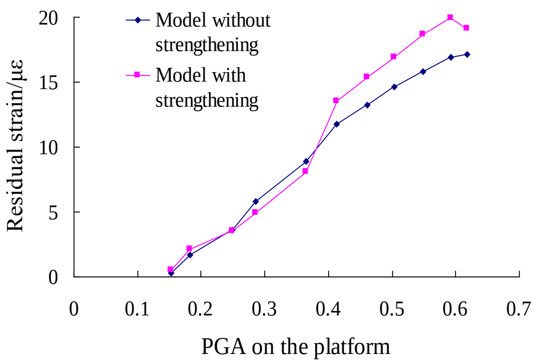
Fig. 13 The diagram of residual strain response with time history

Table 5. Although no visible crack is observed, the values of both FBG no.1, 11 approximate to the cracking tensile strain. It is proposed that the strengthening measure should be applied for seismic resistance in the heel zone for dam.

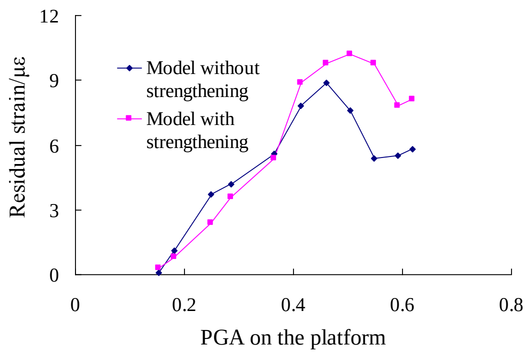
3.5 Residual strain

Concrete-like materials have characteristic of damage accumulation in earthquake loading, before the materials cracking. Yang *et al*. (2006) established the relationship between the ultimate residual strain and the fatigue accumulative damage of concrete under tensile load.

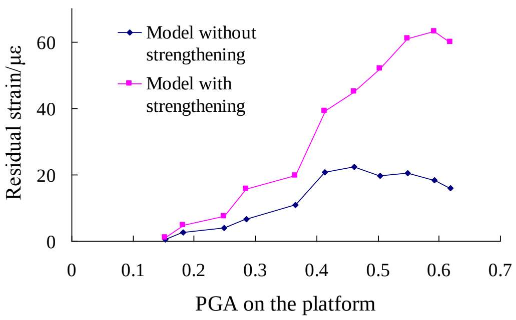
The damage accumulation of concrete of the dam is analysed by residual strain (Fig. 13) in the test. With the increase of inputting seismic PGA, the developing trends of residual strains of various locations are shown in Fig. 14. In the figure, the residual strains of heads, heels and toes of both models are larger than those of their waists, and the maximum values of both models appear at arc section near downstream face of them. These are consistent with the analyses on the damage and the strain above. All of the residual strains were less than 10 $\mu\varepsilon$ before the PGA=0.285 g, demonstrated the models were not damaged basically. The residual strain at arc section near downstream face of model without strengthening was approximately 80 $\mu\varepsilon$ at the PGA=0.365, showed that a certain damage accumulation had occurred at the location before the model concrete



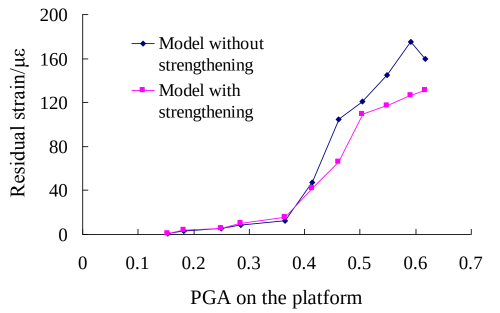
(a) Sensors [1] and [11] above the heel of dam



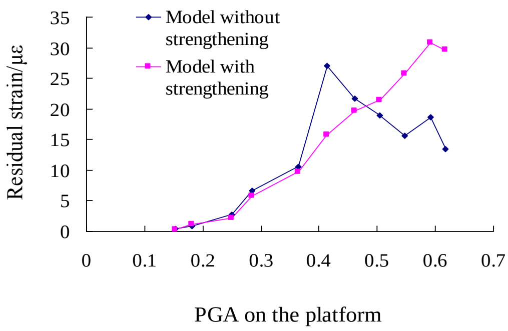
(b) Sensors [2] and [12] at the waist of dam upstream



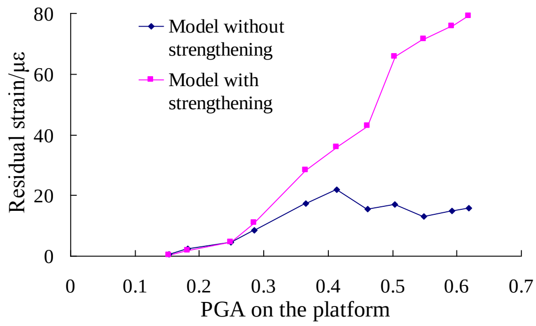
(c) Sensors [3] and [13] at the nape of dam upstream



(d) Sensors [4] and [14] at the nape of dam upstream

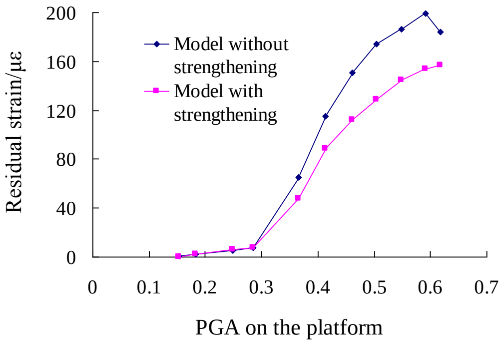


(e) Sensors [5] and [15] at the nape of dam upstream

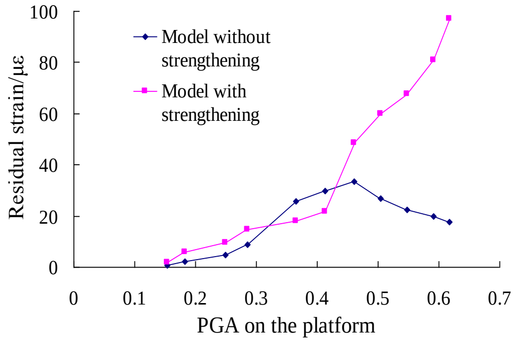


(f) Sensors [6] and [16] at the neck of dam downstream

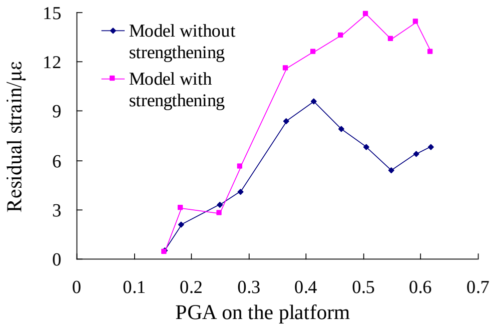
Fig. 14 Residual strains of various locations in the dam models with inputting PGA



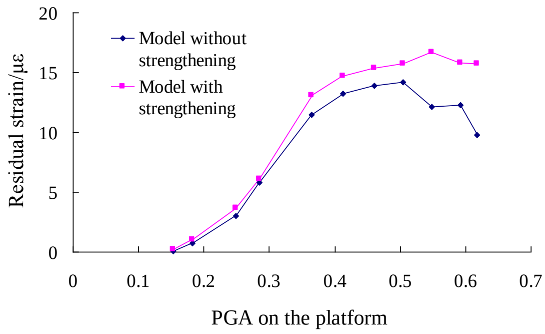
(g) Sensors [7] and [17] at the neck of dam downstream



(h) Sensors [8] and [18] at the neck of dam downstream



(i) Sensors [9] and [19] at the waist of dam downstream



(j) Sensors [10] and [20] at the heel of dam

Fig. 14 Continued

cracking. After the cracks appeared at the arc sections of both models (PGA=0.413), except FBG no. 14 and 17, all residual strains of locations at head of model with reinforcement are larger than those without strengthening. That is because the opening of crack of model without strengthening was very large, to make tensile stress near the areas release, but the development of the major crack of model with reinforcement was restricted by "reinforced bars", the stress near the major crack was released insufficiently in going on loading. It can be concluded from above discussion that accumulation of concrete damage in the dam is corresponding with the development of the residual strains during the earthquake.

4. Conclusions

The entire test series has been carried out to investigate the seismic response, damage mechanism and evaluate the safety of a 203m high gravity dam under strong earthquakes, but also to investigate strengthening effect of gravity dam with reinforcement in monolith for seismic resistance. From the results obtained, the following conclusions can be drawn:

1. A new concrete-like material was proposed to supply for similitude model testing. The model material contains very little cement to reduce its strength properties and can be readily

adjusted to various similarity scales. The components may be mixed in mass. It is also easily produced by conventional methods of producing normal concrete.

2. Based on characteristics of the model concrete, the method for simulating reinforcement concrete in small-scale model test was proposed to provide the basis for model test in which the gravity dam was strengthened with reinforcement in monolith for seismic resistance. En extra fine wire embedded into the model concrete as “reinforced bar”, the four-point bending specimen presented the same performances with that of reinforcement concrete in the laboratory. The simplified pull-out test showed that the adhesiveness between the model concrete and the wire met the requirements. Those indicated that embedding the wires into the model concrete could be used to simulate reinforced areas of high concrete dam.

3. The experimental study on the typical water retaining dam section models with and without the presence of reinforcement were conducted simultaneously on shaking table. It was found that the various behaviors of both models in the testing are believed to match the actual case (Wieland 2003), such as seismic responses and failure modes etc. When concrete cracking at the weak parts of dam model initiated, the nonlinear effect created very large changes in the dynamic response under a input motion. The rising acceleration amplification factors above the crack in this model actually become less due to reduction of its stiffness.

4. The results obtained in the experiment indicated that the most vulnerable part of them was the dam head. The PGA at which the first tensile crack appears at the dam neck plays a very important role in assessing the safety of gravity dam subjected to earthquake ground motions. When the first crack appeared at the neck of the model without strengthening, the acceleration was 0.365g, almost 1.454 times the design PGA. When the cracks ran through the model, the overloaded acceleration was 2.07 multiples of the design PGA. Those indicated the dam section has a good seismic performance.

5. It was shown from the results that although the model strengthened with reinforcement in monolith did not improve its tensile properties and the first cracking acceleration, the reinforced bars could restrict the development of the major crack. It is beneficial in maintaining the integrity of the dam head and preventing the crack penetrating rapidly throughout dam body and even threatening to topple down.

6. Based on the analysis of the corresponding relationship between the residual strains and the material damage accumulation of the models, the changes the residual strains were in step with those of fundamental frequencies, acceleration amplification factors, and strains of various locations with the increase of the PGA.

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