KSCE Journal of Civil Engineering (2018) 22(10):3980-3987
DOI 10.1007/s12205-018-1434-3

Structural Engineering

pISSN 1226-7988, eISSN 1976-3808
www.springer.com/12205

Experimental and Numerical Comparative Study on Gravity Dam-Reservoir Coupling System

Mingming Wang*, Jianyun Chen, and Weirong Xiao*****

Received September 18, 2017/Revised December 10, 2017/Accepted February 23, 2018/Published Online May 31, 2018

Abstract

A 203m high gravity dam-reservoir coupling system in earthquake is studied experimentally and numerically in this work. The dynamic model test is performed on a shaking table, and the dynamic process of the coupling system is simulated with two numerical methods. The natural frequency, hydrodynamic pressure on upstream and acceleration amplification factors along the dam height are obtained from the test and the methods. It is found that the results from FSCM agree better with those from test compared with AMM. So the FSCM should be the first choice to analysis the dam-reservoir coupling system interaction under earthquake. The AMM, which is frequently used in the Code for Seismic Design of Hydraulic Structures of many countries, needs to be modified by a factor smaller than 1. The factor varies along the height of the dam according to its shape, reservoir depth and higher modes and so on. Finally, the reduction factors of the AMM along dam height are suggested in this work.

Keywords: *dynamic model test, hydrodynamic pressure, fluid-solid coupling model, addition mass model, dam-reservoir interaction, shaking table*

1. Introduction

The hydrodynamic pressure of reservoir water on upstream surface of dam has a great influence on the dynamic response of the dam under the earthquake. Therefore, the dam-reservoir interaction must be taken into account in the analysis of the seismic response of the dam. As early as 1930s, Westergaard (1933) studied hydrodynamic pressure problem of the vertical upstream surface of rigid dam under earthquake, and proposed the Additional Mass Model (AMM) without considering the compressibility of water. Because the AMM is simple, practical, easy to calculate, and the calculation results of the model is partial to safety, so far the model was still accepted and adopted by the dam engineering community. At present, the AMM is still applied to simulation method of hydrodynamic pressure for seismic design of gravity dam or arch dam in the Code for Seismic Design of Hydraulic Structures of many countries. Dam-reservoir coupling interaction, however, are very complex, and previous studies have shown that the problem is closely related to the elasticity of dam body, the compressibility of reservoir water, the characteristics of reservoir sediment, the foundation-reservoir interaction, the sediment-reservoir interaction and the dam-foundation interaction (DU Xiuli and WANG Jinting, 2001). Although some achievements have been obtained in the study of the influence of the water compressibility on the hydrodynamic pressure (Chopra, 1967; Fenves and Chopra, 1985; Tan and Chopra, 1995; Du Xiuli *et al*., 2001; Wang Jinting, 2001; Du Jianguo, 2007; Gao Ruiqiang *et al.*, 2008; Chen *et al*., 2013; Khiavi, 2016; Kalateh and Koosheh, 2017; Gaohui Wang *et al.*, 2014), the results of hydrodynamic pressure calculated by different methods and models from different researchers and models are quite different, so far there is no unified viewpoint for considering the compressibility of water in studying dam-reservoir interaction. However, a noticeable problem in engineering is the influence degree of the water compressibility on the hydrodynamic pressure. The implementations of studying dam-reservoir interaction considering the effect of water compressibility and reservoir sediment are very complex and the related researches is not yet mature (Chen Houqun *et al.*, 1989). If want to give up the AMM, it is still need to conduct the thorough research in the dam-reservoir interaction.

With the development of Finite Element Method and Computer Engineering, many scholars are engaged in using numerical simulation method to solve the problem of dam-reservoir interaction, also because of the great expense and trouble operation, the experimental study on the aspect is relatively less all the time. However, the numerical analysis is restricted by a variety of

*Associate Professor, Faculty of Electric Power Engineering, Kunming University of Science and Technology, Kunming, Chenggong District, South Jingming Rd., No.727, 650500, China (Corresponding Author, E-mail: wang.ming.ming@163.com)
**Professor, State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian, Ganjingzi District, Linggong Road No.2, 116024, China (E-mail: eerd001@dlut.edu.cn)
***Associate Professor, Faculty of Electric Power Engineering, Kunming University of Science and Technology, Kunming, Chenggong District, South Jingming Rd., No.727, 650500, China (E-mail: 68708225@qq.com)

factors, such as simplification in mathematical model, approximation in constitutive parameters, simulation of infinite element foundation etc., the experimental measures can simulate engineering practice more closely. In view of this, the dynamic model test for retaining dam section of a 203m high gravity dam has been carried out to research responses of the dam-reservoir coupling system in earthquake. The hydrodynamic pressure, the natural frequency of the dam body and the acceleration amplification factors along the dam height are studied in the test. The experimental results and the numerical results (including the FSCM and the AMM) are compared in this paper. Based on the comparative analysis of the results, can give some improvement for the AMM used in dam engineering, in order to provide reference for the dam engineering practice.

2. Huangdeng Roller-compacted Concrete (RCC) Gravity Dam

The object of the investigation is Huangdeng RCC gravity dam which is built on the Lantsang in Southwest of China during 2009-2012. The zone is an important seismic active region in East Asian. The maximum height of the dam is 203 m, and the normal water level before the dam is 197 m, and the maximum length of the crest of the dam is 464 m. It consists of 20 monoliths, each about 25 m long. This dam is constructed 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.

The 12# retaining dam section of Huangdeng gravity dam as the test object, the dam material for RCC, the dynamic elastic modulus is 331.5 MPa, and the horizontal design peak acceleration is 0.251 g. The dynamic model test is proceeded in the Research Laboratory of earthquake engineering of Dalian University of Technology in China, and the main test equipment in the test included large simulation system of underwater earthquake, acquisition and processing system of digital signal (DSPS), water pressure sensor and acceleration sensor and so on.

In order to accurately reproduce the prototype dam, the model must follow certain similitude laws in the test. The prototype dam section is reduced at a scale to perform the dynamic model test on the shaking table. Based on the size of the prototype dam section and the loading capabilities of the shaking table as well as properties of model material, the scale for the model is a 1:100 geometric scale. Besides the three well-known basic similarity laws (Donlon, 1989; Ghobarah and Ghaemian, 1998; Ghaemmaghami and Ghaemian, 2008 and 2010), the reservoir water density scale and force scale are established from the similarity theory for the investigation. So the similarity scale for this model test 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 r represent respectively time, length, stress, acceleration, force and mass density; Subscript r is the ratio of these parameters in model and prototype dam. Superscript w and d represent respectively the reservoir water and dam in modeling system.

The model of retaining dam section is composed of two parts of the dam body and foundation. A concrete-like model material is used to construct the model of the dam section. Its dynamic elastic modulus can be controlled between 100 and 2000 MPa, and its poison ratio is about 0.2, and its density is about 2800 kg/m^3. The physical and mechanical properties similar to those of normal concrete. The all similarity scales can be acquired according to the similarity theory in the test, and calculated properties for the small-scale dam section model are listed in Table 1.

The dynamic model of dam section is 203 cm high and 25 cm thick, and weighs about 3.5 tons with the scale of 1/100. The foundation of the model are constructed with the model material which is the different from the physical and mechanical properties of the model material for dam section model. A tank with a size of 6.0 × 0.8 × 2.2 m is instilled on the water side of the model. The tank is filled with water to the designed height, and the water body vibrates together with the dam model to

Table 1. The Similarity Scales and Model Material Properties

Physical parameter	Scale factor	Ratio	Prototype value	Model value
Length	L_r	100	——	——
Dam density	ρ^d_r	0.857	2400 kg/m^3	2800 kg/m^3
Dynamic elastic modulus	$E^d_r = \rho^d_r L_r$	85.7	33.15GPa	0.38 GPa
Poisson ratio	μ_r	1	0.16	0.2
Water density	ρ^w_r	1	1000 kg/m^3	1000 kg/m^3
Time	$T_r = \sqrt{L_r}$	10	——	——
Acceleration	$A_r = 1$	1	0.251 g	0.253 g
Strain	ε_r	1	——	——
Force	$F_r = \rho^d_r L^3_r A_r$	857000	——	——

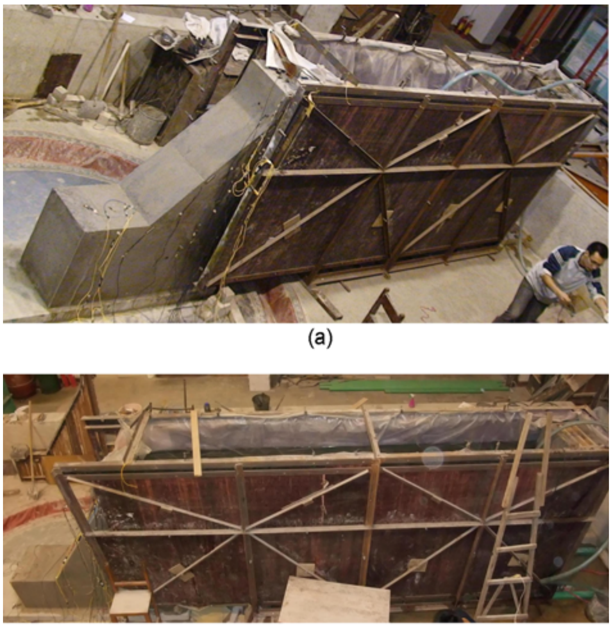

Fig. 1. The Model for the Dam-reservoir Coupling System: (a) The Model Cured for 24 h, (b) The Model of Full Reservoir

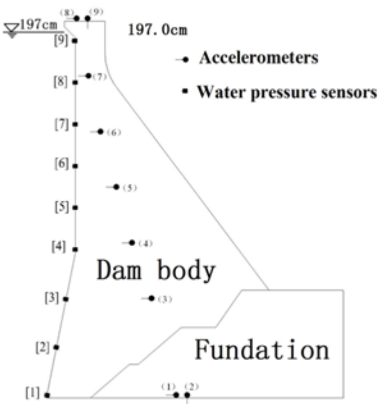

Fig. 2. The Sensor Layout on the Model

simulate the dam-reservoir interaction in the testing. The model for the dam-reservoir coupling system is shown in Fig. 1.

The sensor layout on the model is shown in Fig. 2. The test employees the water pressure sensors developed from Tianjin Harbor Engineering Research Institute in china. The sensor has the advantages of high precision, small size, convenient installation. Ten water pressure sensors are placed every 25 cm along height of the dam model to record the hydrodynamic pressure on the upstream surface of the dam model, and the specific installation method of water pressure sensors is shown in Fig. 3. Seven accelerometers are placed every 30 cm along height of the model

Fig. 3. Water Pressure Sensor

Fig. 4. Acceleration Sensor

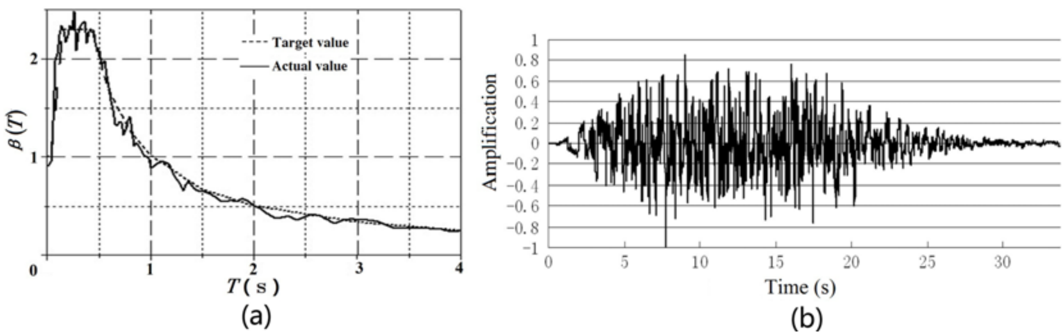

Fig. 5. Seismic Response Spectrum and Earthquake Wave: (a) Seismic Response Spectrum, (b) Earthquake Wave

Table 2. The Series of Tests

No.	Input conditions	Target PGA	Recorded PGA on platform	Remarks
1	White noise	—	0.051 g	Empty reservoir
2	White noise	—	0.05 g	Full reservoir
3	Earthquake wave	0.251 g	0.253	Full reservoir
4	White noise	—	0.052 g	Full reservoir

to record the accelerations in the horizontal direction along stream, and two are placed on the crest of the model and the supporting platform respectively, to record the accelerations in the horizontal direction along stream and the vertical direction. The specific installation method of the accelerometers is shown in Fig. 4.

Each earthquake accelerogram duration is reduced to 1:10 of the original duration from Table 1. The artificial wave of Qian'an seismic response spectrum is used as input the shaking table for the model. The PGA of horizontal seismic wave is 0.251 g, and the PGA of vertical direction is 2/3 that of horizontal direction in biaxial input ground motion. The seismic wave and its response spectrum is shown in Fig. 5. To measure the natural frequency of dam model before inputting seismic wave for studying dam-reservoir interaction, the model is excited by white noise (sine sweep) under the condition of full reservoir and empty reservoir, respectively. The series of tests are adopted, as shown in Table 2.

3. Finite Element Analysis

In order to verify the accuracy of the test setups, it is necessary to compare the experimental results with the numerical results. Two numerical analysis methods of the dam model are carried out for the testing specimen.

Two kinds of numerical models which are the Added Mass Model (AMM) and the Fluid-Solid Coupling Model (FSCM) are adopted to simulate effect of reservoir water for dam-reservoir interaction in finite element analysis. The models of finite element meshing include dam body, foundation and reservoir, as shown in Fig. 6. The finite element meshing of the FSCM is composed of 521 4-node isoparametric plane elements which include 228 dam elements, 73 foundation elements and 220 reservoir water elements; The finite element meshing of the AMM is composed of 301 4-node isoparametric plane elements, which include 228 dam elements and 73 foundation elements, and 27 additional mass elements to simulate the effect of reservoir water. All the material parameters of each part of two models are shown in the first column of Table 1. The input load for numerical analysis is the artificial earthquake wave of the PGA = 0.252 g that is the same as inputting excitation in the test. In the seismic analysis, the weight of dam and reservoir water needs to be considered simultaneously.

3.1 Westergaard's Additional Mass Model (AMM)

As is widely known, as early as 1933, under the assumption

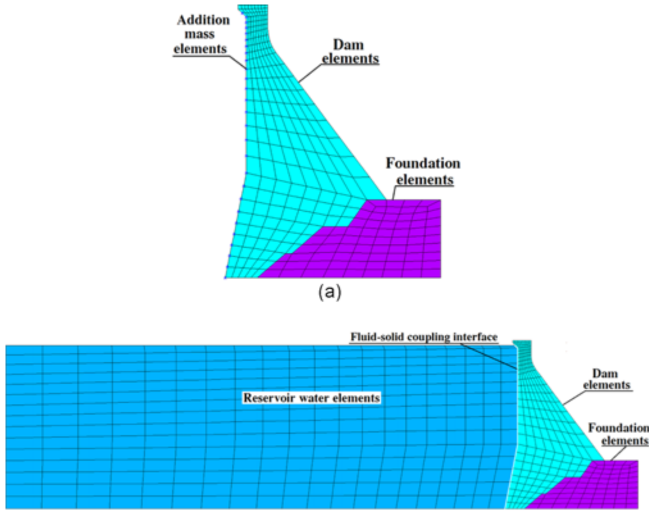

Fig. 6. Finite Element Model: (a) The AMM, (b) The FSCM

that the dam is rigid body and the upstream surface of dam is vertical, Westergaard studied the hydrodynamic pressures of dams under horizontal earthquake, and proposed the approximate hydrodynamic pressure formula,

$$P_w(h) = \frac{7}{8} a_h \rho_w \sqrt{H_0 h} \tag{6}$$

where $P_w(h)$, a_h, ρ_w, H_0, and h are hydrodynamic pressure at water depth of h, representative value of horizontal design seismic acceleration, density of water, maximum depth of reservoir, h waterhead at any point of upstream surface of dam, respectively.

According to Formula (6), the AMM can be expressed as

$$m_w(h) = \frac{7}{8} \rho_w \sqrt{H_0 h} \tag{7}$$

where $m_w(h)$ is additional mass of water depth of h in seismic analysis for large dam.

3.2 Fluid-solid Coupling Model Based on Lagrangian Formulation

Based on Lagrangian formulation, the displacements are selected as the variables in both fluid and structure domains (Calayir *et al.*, 1996; Olson and Bathe, 1983; Calayir and Karaton, 2005). Fluid is assumed to be linear elastic, inviscid and irrotational. The stress-strain relationships (2D) of the fluid undergoing small motion are given by

$$\begin{Bmatrix} P \\ P_z \end{Bmatrix} = \begin{bmatrix} \beta & 0 \\ 0 & \alpha_z \end{bmatrix} \begin{Bmatrix} \varepsilon_v \\ W_z \end{Bmatrix} \tag{8}$$

where P, β and ε_v are respectively the pressure (tension has a positive sign), the bulk modulus of fluid and the volumetric strain, and W_z is rotation about axis z, P_z and α_z are respectively the stress and constraint parameter related with W_z.

Including the small amplitude free-surface waves (sloshing waves) cause pressure. The pressure at the free-surface of fluid to produce small sloshing can be given by

$$P = -\gamma_w u_{fn} \tag{9}$$

where γ_w and u_{fn} are respectively the weight density of fluid and the normal component of the free-surface displacement.

The stiffness of free surface for fluid is obtained from the discrete form of Eq. (9). Finite element equations of motion for the fluid system can be expressed as

$$[M_f]\{a_f\} + [K_f]\{u_f\} = \{F_f^l\} \tag{10}$$

where $\{a_f\}$, $\{u_f\}$, $[K_f]$, $[M_f]$ and $\{F^l_f\}$ are respectively the nodal point vectors of acceleration and displacement for the fluid, the stiffness matrix (including the free surface stiffness), the mass matrix, and the load vector for the fluid system.

The coupled equations of the fluid-structure system needs to determine the interface condition. Because the fluid is assumed to be inviscid, only the displacement in normal direction to the interface is continuous at the interface of the system. The condition can be imposed by the penalty method (Calayir *et al*., 1996; Olson and Bathe, 1983; Yusuf Calayir and Muhammet Karaton, 2005). The motion equations on the interface of the coupled system can be given as

$$[M_c]\{a_c\} + [C_s]\{v_s\} + [K_f]\{u_f\} + [F_s^i] = \{F_c^l\} \tag{11}$$

where $[M_c]$, $[C_s]$, $\{a_c\}$ and $\{v_s\}$, $\{F^i_s\}$ and $\{F^l_c\}$ are respectively the mass matrix of the coupled system, the damping matrix of the structure, the relative acceleration and the load vectors for the coupled system, the relative velocity and the restoring force vectors for the structure system.

The $[C_s]$ is determined to be stiffness proportional as (El-Aidi and Hall, 1989)

$$[C_s] = b_d[K_s] \tag{12}$$

where b_d is determined by specifying a desired damping ratio at a given frequency, and $[Ks]$ is the stiffness matrix of structural.

The load vector $\{F^l_c\}$ under earthquake may be defined as

$$\{F_c^l\} = \{F_c^{sta}\} + [M_c]\{a_g\} \tag{13}$$

where $\{F_c^{sta}\}$ and $\{a_g\}$ are the static load vector and ground motion acceleration vector of the coupled system.

4. Analysis of Experimental and Numerical Results

4.1 Natural Frequency Analysis of Dam

According to transfer function from the platform to the top of the model with the using white noise sweeping for the model, the first two natural frequencies of the dam section model under various cases are obtained.

Under empty and full reservoir cases, the first natural frequencies of model dam in the test and two kinds of numerical models (the AMM and the FSCM) are shown in Table 3. Can be seen from the Table 3: (1) The natural frequencies of dam models under empty and full reservoir are respectively 23.5 Hz and 18.12 Hz from the test. The measured natural frequency of the dam model under full reservoir is 21.7% lower than that of empty reservoir. It indicates that reservoir water has obvious influence on the natural frequency of gravity dam in earthquake. Two numerical analysis results also show the same characteristics in this respect; (2) The first natural frequencies of dam model from the AMM and the FSCM are 27.5% and 21.3% lower than those of the empty dam model in numerical analysis, respectively. The natural frequencies from the FSCM is very close to the measured ones. However, the natural frequencies from the AMM has comparatively large difference with the results from the FSCM and the test. It shows that the FSCM can reflect the real characteristics of the response of the dam under seismic action more than the AMM.

Table 3. Measured and Predicted Fundamental Frequencies of Model

	Case/Model	Fundamental frequencies
Test results	Empty reservoir	23.5 Hz
	Full reservoir	18.4 Hz
Numerical Results	Empty reservoir	22.8 Hz
	The FSCM result	17.9 Hz
	The AMM result	16.6 Hz

4.2 Acceleration Distribution Analysis

The distributions of acceleration amplification factors along the height of the dam model from test and numerical methods (including the results of AMM and FSCM) are shown in Fig. 7. In the figure, it is obvious that the acceleration amplification factors are all increased obviously along the model height, especially at position of the dam neck and above.

The measured hydrodynamic pressure distribution along the model height are in good agreement with that of the FSCM. Compared with the FSCM, the acceleration amplification factors from the AMM are not significantly increased along the model height in the part above the dam neck. The reason is that the masses of addition mass elements to simulate reservoir water in the AMM is calculated based on the assumption which the dam

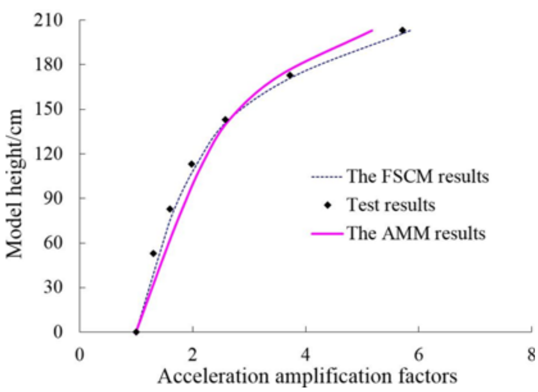

Fig. 7. The Distributions of Acceleration Amplification Factors Along the Model Height from Test and Numerical Methods

is rigid body, and the addition mass elements have no mechanical properties and are attached to the upstream nodes of dam model in the form of mass particles, so it can't simulate the interaction between dam and reservoir water, and the AMM can't simulate the relative motion on the contact surface between the dam and the reservoir during earthquake like the FSCM. In the elastic deformation of the dam under earthquake, the upper part of the dam has a large amplitude of vibration. The Large amplitude vibration can disturb the tension state of the liquid particles before the vibration, and cause the pressure wave acting on the dam body from reservoir water. The relative action could increase the vibration of the upper part of the dam. However, the AMM can't simulate the action, the fluid elements of FSCM can do it.

4.3 Hydrodynamic Pressure Analysis of Dam

The comparison of the hydrodynamic pressure from the test and the numerical methods (including the AMM and the FSCM) is shown the Fig. 8. From the figure, can be seen that the hydrodynamic pressure distribution along model height from the FSCM are in good agreement with that of dynamic model test, and the maximum hydrodynamic pressures from the test and the FSCM both appear at the middle on upstream surface of the dam model.

The hydrodynamic pressure distribution along the model height from the AMM is generally large, and is too large in high waterhead area. The reason is that the addition mass element is defined by a single node with concentrated mass components based on the assumption which the dam is rigid body. But it is not consistent with the actual situation of the elastic deformation of the dam body. Based on the analysis of Section 4.2, in the earthquake, the vibration of elastic dam body is increasing along the dam height, especially at position of the dam neck and above. According to Newton's second law (F = ma), the acceleration of water mass particles increases with the increase of dynamic dam response during the earthquake, which leads to an exaggerated effect of the AMM in simulating reservoir water action during the earthquake. The comparisons of the models frequencies shown in Table 3 also confirm the point.

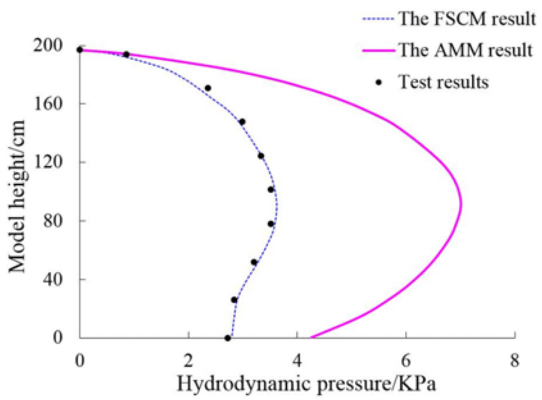

Fig. 8. The Comparison of the Hydrodynamic Pressure from the Test and the Numerical Methods

From the comparisons in the Fig. 8, the distributions of hydrodynamic pressures along the dam height from FSCM are in good agreement with those of the test except for the slight difference in the dam neck and above. It is because the increase of vibration of the reservoir water body near the free surface caused by the reflection of surface wave during testing increases the measurement results of the water pressure sensors on the upper part of the dam, but the influence is not very obvious from the Fig. 8.

5. Addition Mass Model Reduction Method

Houqun Chen *et al.* (1989) proposed to reduce the hydrodynamic pressure from the AMM to 1/2 for application in the dynamic analysis of arch dam. Deyu Li, et al (2003) pointed out that because of the gravity dam such as a massive body, although the error of reservoir water action characterized by the AMM wasn't obvious than that of arch dam, the model also exaggerated the effect of reservoir water. So the AMM applied to the seismic analysis of gravity dam-reservoir system should be given appropriate reduction.

It is complex to determine the hydrodynamic pressure reduction factor which is related to dam body shape, the water depth in front of the dam and higher modes of dam and so on. The calculation methods of the reduction factor of the AMM are different from considering the influence of different parameters.

From the contrastive analysis of the experimental and numerical (AMM) results, the hydrodynamic pressure from the AMM is generally large, and is too large in high waterhead area on upstream surface of dam. It shows that the reduction factor of hydrodynamic pressure along the dam height from the AMM is not a constant value. To take account of the experimental and numerical (FSCM) results, the ratios of results from the test to the AMM is used as the distribution reduction factors of hydrodynamic pressure along dam model height. The reduction factors are fitted by polynomial function with dam model height, shown in Fig. 9. As the figure to see, the fitting effects in middle and lower part of dam is very good, and the fitting effects of upper part of dam is a slight error. It is due to that the shallow

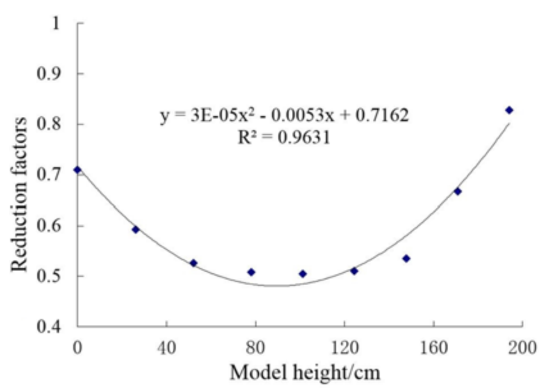

Fig. 9. The Reduction Factors are Fitted by Polynomial Function with Dam Model Height

water in reservoir acted on the wavefront effect produces the discrete result in earthquake.

6. Conclusions

The entire investigation series including dynamic model test and numerical simulation analysis has been carried out to investigate the seismic responses of a 203 m high gravity dam-reservoir coupling system under earthquakes. The experimental results are compared with results of two numerical models in the research. The following conclusions can be drawn:

1. A concrete-like material is applied in supply the dynamic model test. The model material which is a material of low mechanical properties can be readily adjusted to various similarity scales for producing small-scaled model. It is easy to obtain the density similar to concrete and foundation rock material, also easily produced by conventional methods of producing normal concrete.
2. On the shaking table, the dynamic model test of retaining section of a 203m high gravity dam is conducted to investigate the seismic responses of dam-reservoir coupling system. The experimental results are compared with the numerical results from the AMM and FSCM of simulating dam-reservoir coupling system. The experimental results are in agreement with those of the FSCM, and are different from those of the AMM.
3. Through the analysis, The AMM exaggerates the effect of reservoir water on the dam body during earthquake. So it is necessary to consider dam-reservoir interaction and prefer to use the FSCM in the dynamic analysis and seismic assessment carried out for the gravity dam.
4. The hydrodynamic pressure is related to the shape of dam body, the water depth of reservoir and higher mode of dam and so on, so it is impossible that the hydrodynamic pressure reduction factor from the AMM is constant value along the dam height. For the 200m and more than high gravity dam, it is suggested that the reduction factor from AMM along the dam height can be well represented by polynomials.

Acknowledgements

The authors are grateful to the reviewers for their very useful comments and suggestions. This research was financially supported by the National Nature Science Foundation of China (Grant No. 51669008), Foundation of State Key Laboratory of Coastal and Offshore Engineering in Dalian University of Technology in China (Grant No. LP1619).

References

Calayir, Y., Dumanoğlu, A. A., and Bayraktar, A. (1996). “Earthquake analysis of gravity dam-reservoir systems using the Eulerian and Lagrangian approaches.” *Computers and Structures*, Vol. 59, No. 5, pp. 877-890, DOI: 10.1016/0045-7949(95)00309-6.

Calayir, Y. and Karaton, M. (2005). “Seismic fracture analysis of concrete gravity dams including dam–reservoir interaction.” *Computers and Structures*, Vol. 83, Nos. 19-20, pp. 1595-1606, DOI: 10.1016/j.compstruc.2005.02.003.

Chen, H., Hou, S., and Yang, D. (1989). “Study on arch dam-reservoir water interaction under earthquake condition.” *Journal of Hydraulic Engineering*, Vol. 21, No. 7, pp. 29-39, (in Chinese).

Chen, J., Wang, M., and Fan, S. (2013). “Experimental investigation of small-scaled model for powerhouse dam section on shaking table.” *Structural Control and Health Monitoring*, Vol. 20, No. 5, pp. 740-752, DOI: 10.1002/stc.1489.

Chopra, A. K. (1967). “Hydrodynamic pressures on dams during earthquakes.” *Journal of the Engineering Mechanics Division,* ASCE, Vol. 93, No. EM6, pp. 205-223.

Donlon, W. P. (1989). *Experimental investigation of the nonlinear seismic response of concrete gravity dams*, Ph.D. Thesis, Earthquake Engineering Research Laboratory, California Institute of Technology, Pasadena, USA.

Du, J. (2007). *The Dynamic Interaction Analysis of Darn-Reservoir-Foundation Based on SBFEM*, Ph.D. Thesis, State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian, Liaoning Province, China, (in Chinese).

Du, X. and Wang, J. (2001). “Review of studies on the hydrodynamic pressure and its effects on the seismic response of dams.” *Journal of Hydraulic Engineering*, Vol. 32, No. 7, pp. 13-21, DOI: 10.3321/j.issn: 0559-9350.2001.07.003 (in Chinese).

Du, X., Wang, J., and Hung T. K. (2001). “Effects of sediment on the dynamic pressure of water and sediment on dams.” *Chinese Science Bulletin*, Vol. 46, No. 7, pp. 521-524.

El-Aidi, B. and Hall, J. F. (1989). “Non-linear earthquake response of concrete gravity dams Part 1: Modelling.” *Earthquake Engineering and Structural Dynamics*, Vol. 18, No. 6, pp. 837-851, DOI: 10.1002/eqe.4290180607.

Fenves, G. and Chopra, A. K. (1985). “Effects of reservoir bottom absorption and dam water foundation rock interaction on frequency response functions for concrete gravity dams.” *Earthquake Engineering and Structural Dynamics*, Vol. 13, No. 1, pp. 13-31, DOI: 10.1016/0148-9062(85)92284-3.

Gao, R., Gong, B., and Guo, J. (2008). “Study on effect of compressibility of water in dam-water interaction.” *Journal of Water Resources and Architectural Engineering*, Vol. 6, No. 1, pp. 106-108, DOI: 1672-1144(2008)01-0106-03, (in Chinese).

Ghaemmaghami, A. R. and Ghaemian, M. (2008). “Experimental seismic investigation of Sefid-rud concrete buttress dam model on shaking table.” *Earthquake Engineering and Structural Dynamics*, Vol. 37, No. 5, pp. 809-823, DOI: 10.1002/eqe.791.

Ghaemmaghami, A. R. and Ghaemian, M. (2010). “Shaking table test on small-scale retrofitted model of Sefid-rud concrete buttress dam.” *Earthquake Engineering and Structural Dynamics*, Vol. 39, No. 1, pp. 109-118, DOI: 10.1002/eqe.928.

Ghobarah, A. and Ghaemian, M. (1998). “Experimental study of small scale dam models.” *Journal of Engineering Mechanics,* ASCE, Vol. 124, No. 11, pp. 1241-48, DOI: 10.1061/(ASCE)0733-9399(1998)124:11(1241).

Gong, B. (1997). “Experimental research on gravity dam hydrodynamic pressure under earthquake.” *Journal of Hohai University*, Vol. 25, No. 1, pp. 98-102 (In Chinese).

Kalateh, F. and Koosheh, A. (2017). “Comparing of loose and strong finite element partitioned coupling methods of acoustic fluid-structure interaction: Concrete dam-reservoir system.” *KSCE Journal of*

Civil Engineering, KSCE, Vol. 21, No. 3, pp. 807-817, DOI: 10.1007/s12205-016-0276-0.

Khiavi, M. P. (2016). "Investigation of the effect of reservoir bottom absorption on seismic performance of concrete gravity dams using sensitivity analysis." *KSCE Journal of Civil Engineering*, KSCE, Vol. 20, No. 5, pp. 1977-1986, DOI: 10.1007/s12205-015-1159-5.

Li, D., Zhang, B., Wang, H., and Yu, Y. (2003). "A shaking table model test on dam-reservoir interaction of gratity dam." *Journal of China Institute of Water*, Vol. 1, No. 3, pp. 216-220, DOI: 1672-3031(2003) 03-0216-05, (in Chinese).

Olson, L. G. and Bathe, K. J. (1983). "A study of displacement-based fluid finite elements for calculating frequencies of fluid and fluid-structure systems." *Nuclear Engineering and Design*, Vol. 76, No. 2, pp. 137-151, DOI: 10.1016/0029-5493(83)90130-9.

Tan, H. C. and Chopra, A. K. (1995). "Earthquake Analysis of arch dams including dam-water-foundation rock interaction." *Earthquake Engineering and Structural Dynamics*, Vol. 24, No. 11, pp. 1453-1474, DOI: 10.1002/eqe.4290241104.

Wang, G., Zhang, S., Wang, C., and Yu, M. (2014). "Seismic performance evaluation of dam-reservoir foundation systems to near-fault ground motions." *Natural Hazards*, Vol. 72, No. 2, pp. 651-674, DOI: 10.1007/s11069-013-1028-9.

Wang, J. (2001). *The Analyses of Seismic Response of High Concrete Dam-Compressible Water-Sediment-Foundation Systems*, Ph.D. thesis, China Institute of Water Resources and Hydropower Research, Beijing, China, (in Chinese).

Westergaard, H. M. (1933). "Water pressures on dams during earthquakes." *Transactions of ASCE,* Vol. 98, pp. 418-433.