# SEISMIC SAFETY EVALUATION OF HIGH CONCRETE DAMS PART I: STATE OF THE ART DESIGN AND RESEARCH

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**ABSTRACT:**

Key issues for seismic safety evaluation of high concrete dams are reviewed: In Part I, for the pre-feasibility study stage, the conventional seismic design practice is summarized under the framework of the Chinese Specification for Seismic Design of Hydraulic Structures; for the stage of preliminary and final design, some advanced design and research are performed for further seismic safety evaluation of high concrete dams, mainly arch type exceeding 150m high with a large index of reservoir and power capacity. These include consideration of

(1) Effects of earthquake input mechanism and radiation damping due to infinite canyon;
(2) Effects of nonlinearity of contraction joint opening;
(3) Effects of damage and fracture behaviors in dams and strengthening;
(4) Effects of dam-reservoir interaction;
(5) Earthquake stability of arch dam-abutment system.

Procedures for considering the above factors are outlined. In Part II, engineering applications to high arch dams with a case study on the Dagangshan Arch Dam to resist the design earthquake are demonstrated and some concluding remarks are given.

**KEYWORDS: seismic safety, concrete dams, nonlinearities, damage-cracking, strengthening**

## 1. INTRODUCTION

In China, the growing demand for electricity and increasing pressure for carbon emission reduction due to global temperature change have accelerated the development of hydroelectric and high dam projects to meet new national goals to increase usage of clean and renewable energy. Nowadays, only 7 percent of the total energy consumption is supplied by hydro-power while 70 percent comes from burning coal, causing serious environmental problems. To reduce use of coal for power generation, the central government plans to invest US$265 billion to help obtain 15percent of its installed capacity from renewable sources including hydro-power by 2020. With total hydropower potential capacity of $540\times10^3$MW, the current developed capacity in 2007 is only 26 percent ($145\times10^3$MW). In the coming two decades, twelve hydropower bases, mainly in southwest China, including the upper reaches of the Yangtze and Lancang Rivers and their branches (Jinsha, Yalong and Dadu Rivers) are being developed with a total capacity of $290\times10^3$MW by 2020, 54 percent of the total hydro-power potential of the nation.

To accomplish the goals of hydro-power development, construction of a series of high dams up to 250-300 m in height with huge reservoir and flood overflow requirements is being implemented. These high dam projects are mostly located in seismically active region in southwest China, with design peak ground accelerations (PGA) of 0.20~0.56 g in terms of occurrence probability 0.02 within the period of 100 years. Therefore, seismic safety evaluation of the high dam projects is one of the key issues in the design and construction, together with the other crucial safety checks, such as foundation and abutment stability, high speed flood overflow through the dam and underground powerhouse stability. The main indexes of characteristic parameters of China's high concrete arch dams are listed in Table 1.1.

Table 1.1 Characteristic parameters of main arch dams in China

| Dam | River | Dam height (m) | Reservoir ($10^8$m$^3$) | Installation (MW) | Design flood (m$^3$/s) | Design PGA (g) |
|---|---|---|---|---|---|---|
| Longyangxia | Yellow | 178 | 247 | 1280 | 7040 | 0.237 |
| Ertan | Yalong | 240 | 58 | 3300 | 23900 | 0.20 |
| Laxiwa | Yellow | 250 | 11 | 5600 | 6000 | 0.20 |
| Xiaowan | Lancang | 292 | 151 | 4200 | 20600 | 0.308 |
| Xiluodu | Jinsha | 273 | 140 | 14400 | 50000 | 0.321 |
| Jinping-I | Yalong | 305 | 78 | 3300 | 6900 | 0.20 |
| Goupitan | Wu | 233 | 65 | 3000 | 27500 | — |
| Baihetan | Jinsha | 275 | 180 | 12000 | 40000 | 0.325 |
| Dagangshan | Dadu | 210 | 7.4 | 2400 | 8320 | 0.56 |

Over the past 20 years, with the world-record-height dams in design and construction and extremely strong earthquakes to be considered, the dam engineers and scientists have developed considerable knowledge regarding the seismic safety evaluation for concrete dams especially for arch dams. This paper reports the following aspects of state-of-the-art design and research on seismic safety analysis of high concrete dams:

1. A brief introduction of the conventional design practice in pre-feasibility study stage;
2. A summary of advanced design and research in preliminary and final design stage, especially for important projects exceeding 150 m high and large index of reservoir and power capacity. These include effects of the five aspects listed in the abstract.

## 2. CONVENTIONAL SEISMIC DESIGN PRACTICE

(1) According to the Chinese specifications for seismic design of hydraulic structures (DL-5073-2000), the linear elastic gravity method and multiple arch-cantilever method, both with pseudo-static design earthquake loadings, are being used for gravity dams and arch dams respectively. However, when the dam (arch and gravity) is categorized into Grade I or II (related to dam height, reservoir and power capacity, etc.) or the design intensity of earthquakes equals or exceeds 8 degrees (equivalent to PGA = 0.2g), it is recommended to use the dynamic finite element method (both response spectrum and time history analysis) as a supplemental check.
(2) In pseudo-static analysis of concrete dams, sectional linear prescribed and amplified factor curves are used as the inertial loads acting on the dam, e.g. the amplified curves for arch dams have a coefficient of 3.0 at the crest and 1.0 at the bottom with a uniform distribution along the arch axis. A reduction coefficient of 0.25 is applied for PGA used.
(3) In dynamic response spectrum analysis, the maximum amplification factor for design response spectrum is $\beta_{max}$=2.0 for gravity dams and 2.5 for arch dams respectively with predominant periods of 0.1s to $T_g$, where $T_g$

equals to 0.2s, 0.3s or 0.4s depending on the category of the rock foundation. In time history analysis, usually, either a time history produced from the design response spectrum of the specification or an artificial time history provided from seismic risk analysis at the site may be used. In dynamic analysis, the damping ratio of 3%-5% for arch dams and 5%-10% for gravity dams are assumed; the assumption of massless rock foundation with 1.0-1.5 times the dam height and added mass method derived from the Westergaard incompressible reservoir are usually considered. The earthquake input is acting on the truncated rock with uniform distribution along the truncated boundary. Dynamic modulus and strengths of concrete may have 30% increase compared with its static counterparts in safety check.

(4) In dynamic stability analysis for foundation and abutment safety, the rigid body limit equilibrium methods with actions of pseudo-static loading (acting both at the dam and abutment rock mass) + reservoir loads + gravity + temperature loads are still being used in design practice. The amplification factor $\alpha_d$ is 3.0 at the dam crest as mentioned before, but the factor for abutment rock $\alpha_r$ is assumed to be 1.0 (no amplification); the criterion of safety factor for abutment rock is 1.20.

## 3. ADVANCED SEISMIC DESIGN AND RESEARCH

### *3.1. Effects of Earthquake Input Mechanism and Radiation Damping Due To Infinite Canyon*

The modeling of infinite canyon and earthquake input mechanism are two crucial aspects for analysis of dam-foundation interaction. Within the past two decades, many sophisticated numerical models were developed for simulation of infinite canyons. These include but are not limited to: finite elements + infinite elements (FE + IE) [1,2], boundary elements (BE) [3,4], finite elements + boundary elements + infinite boundary elements (FE + BE + IBE) [5], finite elements + scaled boundary finite elements (FE + SBFE) [6], finite elements + transmitting boundaries [7] and finite elements + discrete parameter models including viscous dampers-springs-masses [8] (usually matrices defined at the interface). All these methods are proved to be applicable and effective for modeling infinite canyons of dams although each has its own merits and disadvantages in terms of computational efforts.

Regarding the earthquake input mechanism, several procedures have been proposed to study its effects and those of radiation damping on concrete dams, especially on arch dams. Among those, the most commonly used in current practice is the massless foundation model with uniform input acting at the truncated boundaries which was proposed by Clough [9]. The model considers the foundation flexibility but ignores the dam-foundation interaction including radiation damping and non-uniform input. Another input method is the so-called deconvolution approach by which the earthquake input can be deconvoluted using analytical solution or 1-D half-space model from specified free-field motions at the ground surface. This model is usually incorporated with viscous-spring or transmitting boundaries [10]. The third effective earthquake input method including rock mass for dam-canyon interaction is the free-field input method [9,11]. Earthquake excitations are imposed as the free-field motions at the dam-foundation interface directly; thereby a spatially non-uniform free-field input could be specified if it is available.

The research studying the effects of radiation damping due to infinite canyon and earthquake input mechanism include using frequency domain procedures, *e.g.* Zhang *et al* [2], Chopra *et al* [4] and Dominguez *et al* [3] and time domain procedures, *e.g.* Zhang & Jin *et al* [8,11] and Chen & Du *et al* [7].

From analysis of the Xiaowan, Xiluodu, Laxiwa, Jinping and Dagangshan arch dams, the conclusion of considering radiation effects of infinite canyon is that the reduction of the dam response may reach 25-40%

compared with the results by massless foundation model. Nowadays, there are two differing opinions in China concerning the reduction factor due to the radiation damping. One suggests that it may be considered as a potential safety factor but not to be considered in the design because the damping ratios of structures and foundations are complicated factors, and usually they are measured through prototype tests or seismic measurements in which the material and radiation damping are combined together. The other opinion suggests that we should use this benefit in the design by arguing that the measured responses of several arch dams in the world during moderate earthquake events were much smaller than that from numerical analysis provided the damping ratios of the structures are assumed to be around 0.05 [12]. Furthermore, it was also found that a much higher damping ratio as 8-15% was needed for approximately matching the field response records of the dams. However, the structural damping ratios obtained from forced vibration field tests and ambient measurements were quite low, only about 1-4% [13] (lower than 0.05). What causes this discrepancy? A rational comparison is of significance for understanding the effects of different earthquake input mechanisms on the response of arch dam-foundation-reservoir systems.

### *3.2. Effects of Nonlinearity of Contraction Joint Opening*

It is now commonly recognized that high arch dams will experience significant contraction joint opening during strong earthquakes. The experience of contraction joint opening in the Pacoima arch dam during the 1971 San Fernando and 1994 Northridge earthquakes [14,15] is a real example. Because of the contraction joint opening a drastic but instantaneous release of the arch action and substantial increase of the tensile stresses in the cantilever are evident. Due to this non-linear behavior, weakening of dam integrity causing cracking damage of cantilevers and breakage of waterstops between joints is a major concern to dam engineers.

The nonlinear behavior of arch dams due to contraction joint opening during strong earthquakes was first raised by Clough [16,17]. Fenves *et al* [18,19] presented a discrete 3-D joint element as a direct approach for simulation of the contraction joints. By using a time domain and discrete parameter procedure for modeling dam canyons, Zhang *et al* [20,21] combined effects of dam-canyon interaction with contraction joint opening. Meanwhile, a contact boundary approach presented by Bathe [22] is also used to analyze contraction joint behavior. Lua *et al* [23] developed a joint model to simulate both the opening-closing and shear slippage behavior considering shear keys at the contraction joints. Recently, Du *et al* [10,24] combined explicit FE method with transmitting boundary to study the effects of contraction joint opening on the response of Xiaowan arch dam, but only five joints were simulated; In addition, Chen *et al* [25], Sheng *et al* [26] and Wang *et al* [27] studied contraction joint opening behavior of arch dams by shaking table tests. Lin *et al* [28] also studied this nonlinear problem using the non-smooth Newton algorithm.

All the analyses and model tests mentioned above reveal that significant contraction joint opening is observed. From the results of Tsinghua research group, the maximum joint opening reaches 16.5 mm in Xiaowan Dam, 16.7 mm in Dagangshan Dam, and 11.6 mm in Xiluodu Dam. In these analyses, the concrete is assumed to be linear elastic. The massless foundation assumption for canyon rock is usually applied with a few exceptions, where the infinite mass canyon and non-uniform free-field or viscous-spring boundary input models are also considered together with nonlinear joint opening [29,56].

### *3.3. Effects of Damage and Fracture Behavior in Dams and Strengthening*

Due to the high intensity of design earthquake in certain dam sites such as Jin'anqiao, Xiaowan and Dagangshan, whose PGA reach 0.399g, 0.308g and 0.557g, respectively, large tensile stresses will inevitably occur at upper portions of gravity dams and cantilevers of arch dams. Dynamic damage and nonlinear fracture analysis have been performed to understand the cracking behavior of dams. In this aspect, both linear and nonlinear fracture mechanics models have been used in analysis of seismic cracking of concrete dams. In linear analysis, Pekau, Feng and Zhang [30] used the boundary element technique to calculate dynamic stress intensity factors and to reproduce the cracking profile of Koyna Dam due to the 1967 earthquake. Meanwhile, a shaking table test was performed for verification of the model. In nonlinear analysis, Wang *et al* [31] used finite element method and crack band theory to analyze the cracking behavior of Koyna Dam considering strain softening of concrete. Recently, in analysis of damage-cracking of 3-D arch dams, the plasticity-damage model of concrete presented by Lubliner *et al* [32] and later extended in analysis of damage cracking of Koyna Dam by Lee and Fenves [33] is used and the crack band theory by Bazant [34] is incorporated to ensure the uniqueness of fracture energy without introducing mesh sensitivity of the finite elements. The complete constitutive relationship for concrete including softening behavior can be obtained from rigid machine tests in static case. Thirty percent increase of the tensile strength is adopted for dynamic case. The average fracture energy is assumed to be around 300N/m for dam concrete. The results show evident damage areas occur at the upper portion of the cantilevers. The damage indices computed can then be converted into the equivalent crack width of the dam. Details of analysis and findings are described in Part II.

In order to improve earthquake-resistant capacity, several high arch dams under construction in China such as Xiaowan and Dagangshan Dams have been proposed to study some strengthening measures including cantilever reinforcements for alleviating the crack extension in dams under the design earthquakes, joint reinforcements or joint dampers for reducing the joint openings and reinforcement arch-belts for improving the integrity of dams. After a detailed comparison, the owners and designers of the Xiaowan and Dagangshan projects have decided to adopt cantilever reinforcements as the major strengthening alternative and joint dampers as a supplemental measure. In analysis of the response of arch dams with cantilever reinforcement strengthening, the influence of reinforced steel and tension stiffening effect due to steel-concrete interaction are considered. For analysis of cantilever reinforcements, a modified embedded reinforcement model is used. By stiffening the reinforced steel, the model is capable of considering the concrete-reinforcement interaction for lightly reinforced cantilever members (Compared with concrete dam body). In addition, a weighted zoning scheme for dividing plain and reinforced concrete sub-region by An *et al* [35] is adopted for simplification. Procedure of reinforcement or concrete stiffening [36,37] may be used to reflect the interaction between concrete and steel bars. The aforementioned procedures have preliminarily been used in analysis of strengthening design of the Jin'anqiao gravity dam and the Dagangshan arch dam. It is concluded that the strengthening measures have noticeable effects in controlling the damage index (equivalent to crack width) and extension of cracking. In addition, numerical models for other strengthening measures, such as joint reinforcements, joint dampers and reinforcement belts have been developed for analysis of their effects [21,38]. From the analysis, it is suggested that the Jin'anqiao gravity dam and Xiaowan and Dagangshan arch dams need reinforcement strengthening for crack control. The final designs require 20000t and 9400t of reinforced steel for Xiaowan and Dagangshan, respectively.

### *3.4. Effects of Dam-Reservoir Interaction*

It is recognized that dam-reservoir interaction is an important factor affecting response of concrete dams. Since high curvature arch dams are usually more flexible than gravity dams, a greater influence of arch dam-reservoir interaction than that of gravity dams in evident. The effects of water compressibility on arch dam response were comprehensively studied by Chopra and colleagues [39-41]. Under the frame work of Sino-US scientific cooperation in earthquake engineering, Clough *et al* [42-44] conducted a series of forced vibration field tests for investigation of arch dam-reservoir-foundation interaction. Valuable data related to dam-reservoir interaction were obtained. Yet the final conclusions concerning the practical significance of the compressibility effect of reservoir on dam response were not conclusive. The important finding is that among the three components of ground motions, the vertical component may have profound effects on the response of arch dams when the fundamental resonant period of the compressible reservoir is in coincidence with the period of vertical ground motion and a rigid reservoir bottom is also assumed. Considering that the effects of reservoir sediment and bottom rock absorption on the reduction of dam response are significant and that most important contributory earthquake components to the dam response are in stream and cross-stream directions rather than the vertical component, the compressibility of reservoir is usually neglected in most of our current design and research practice. Herein, the added mass method is commonly used for arch dam-reservoir interaction due to its simplicity and somewhat conservative nature. The finite element method with incompressible fluid assumption and three times of the dam height for reservoir length are usually used for obtaining the added mass coefficients. However, the compressibility of the water and the sediment effects in the reservoir are also studied in research level [45-47] and deserve further investigation, especially for 300m-high level arch dams.

### *3.5. Earthquake Stability of Dam-Abutment System*

The traditional seismic design and analysis of concrete dams focus on the response of dam structures from linear elastic to nonlinear damage and fracture states. Little, if any, research has even touched on the stability problems of dam-abutment system. Even in the static case, the dam and foundation or abutment are treated as a completely separate system using entirely different procedures, i.e., finite element models with different assumptions are usually used for the dam and rigid body limit equilibrium method for abutment. In reality, the dam-foundation behaves as an indivisible system during loading and earthquake process. Nowadays, some numerical models and computer codes in rock mechanics field become available. 3-D Discrete Element Code (3DEC) [48,49], Discontinuous Deformation Analysis code (DDA) [50], Particle Flow Code (PFC) [51] and Rigid Body Spring Elements (RBSE) [52] etc. have appeared to be promising and powerful tools for predicting the deformation and collapse response of jointed rock mass. So, it is possible now to combine the dam and the foundation (abutment) into one system using a continuous-discontinuous coupling procedure. The simulation of complete process of the structure-foundation rock starting from linear elastic state to complete collapse becomes possible. As a starting point of exploration, stability studies of post-cracking behavior of the Koyna gravity dam, and abutment failure of the Malpasset arch dam, static and earthquake stabilities of the Xiaowan arch dam-abutment and Xiluoduo arch dam-abutment system are examples of using DEM and RBSE for static and dynamic studies. Some interesting phenomena have been observed from the study. The details of the results may be found elsewhere [53-55].

## 4. CONCLUSIONS

Concluding remarks are summarized in Part II.

## REFERENCES

1. Zhang Chuhan and Zhao Chongbin. (1988). Effects of canyon topography and geological conditions on

strong ground motion. *Earthquake Engineering and Structural Dynamic* **16:1**, 81-97.
2. Zhang Chuhan, Wang Guanglun and Zhao Chongbin. (1988). Seismic wave propagation effects on arch dam response. *Proc. 9th World Conf. Earthquake Eng.*, Tokyo-Kyoto, **VI**, 367-372.
3. Dominguez and Maeso O. (1992). Model for the seismic analysis of arch dams including interaction effects. *Proc. 10th World Conf. Earthquake Eng*., Madrid, **8**, 4601-4606.
4. Chopra AK and Tan H. (1992). Modeling dam-foundation interaction in analysis of arch dams. *Proc. 10th World Conf. Earthquake Eng*., Madrid, **8**, 4623-4626.
5. Zhang Chuhan, Pekau OA and Jin Feng. (1992). Application of FE-BE-IBE coupling to dynamic interaction between alluvial soil and rock canyons. *Earthquake Engineering and Structural Dynamic* **21**, 367-385.
6. Yan Junyi, Zhang Chuhan and Jin Feng. (2004). A coupling procedure of FE and SBFE for soil-structure interaction in the time domain. *International Journal for Numerical Methods in Engineering* **59:11**, 1453-1471.
7. Chen Houqun, Du Xiuli and Hou Shunzai. (1997). Application of transmitting boundaries to nonlinear dynamic analysis of an arch dam-foundation-reservoir system. *Dynamic soil-structure interaction, current research in China and Switzerland* 1997 (Zhang Chuhan and Wolf JP, eds.), Beijing, International academic publisher, 115-124.
8. Zhang Chuhan, Jin Feng and Pekau OA. (1995). Time Domain procedure of FE-BE-IBE coupling for seismic interaction of arch dams and canyon. *Earthquake Engineering and Structural Dynamic* **24**, 1651-1666.
9. Clough RW. (1980). Non-linear mechanisms in the seismic response of arch dams. *Proc. Int. Res. Conf. Earthquake Eng*. Skopje, Yugoslavia, 669-684.
10. Xiuli Du, Yanhong Zhang and Boyan Zhang. (2007). Nonlinear seismic response analysis of arch dam-foundation systems-part I dam-foundation rock interaction. *Bulletin of Earthquake Engineering* **5**, 105-119.
11. Zhang Chuhan, Jin Feng and Wang Guanglun. (1996). Seismic interaction between arch dam and rock canyon. 11th *World Conf. Earthquake Eng.*, Mexico, Paper No. 595.
12. Proulxl J, Darbre GR and Kamileris N. (2004). Analytical and Experimental Investigation of Damping in Arch Dams Based on Recorded Earthquakes. 13th *World Conf. Earthquake Eng.*, Canada, Paper No. 68.
13. Hall JF. (1988). The dynamic and earthquake behaviour of concrete dams: review of experimental behaviour and observation evidence. *Soil Dynamic and Earthquake Engineering* **7:2**, 58-121.
14. Swanson AA and Sharma RP. (1979). Effects of the 1971 San Fernando earthquake on Pacoima arch dam. *Proc. 13th ICOLD*, New Delhi, Q.51., R.3.
15. Hall JF. (1995). Northridge earthquake of January 17, 1994 reconnaissance report, volume 1. *Earthquake Spectra* 11(Supplement C): EERI 95-03.
16. Clough RW. (1980). Non-linear mechanisms in the seismic response of arch dams. *Proc. Int. Res. Conf. Earthquake Eng*. Skopje, Yugoslavia, 669-684.
17. Niwa A and Clough RW. (1982). Non-linear seismic response of arch dams. *Earthquake Engineering and Structural Dynamic* **10**, 267-281.
18. Fenves GL, Mojtahedi S and Reimer RB. (1989). ADAP88: a computer program for nonlinear earthquake analysis of concrete arch dams. *Report No. EERC 89-12*, Earthquake Engineering Research Center, University of California, Berkeley, CA.
19. Fenves GL, Mojtahedi S and Reimer RB. (1992). Effect of contraction joints on earthquake response of an arch dam. *Journal of Structural Engineering* (ASCE) **118**, 1039-1055.

20. Zhang Chuhan, Xu Yanjie and Jin Feng. (1997). Effects of soil-structure interaction on nonlinear response of arch dams. *Dynamic soil-structure interaction*, International Academic Publishers: Beijing, 95-114.
21. Zhang Chuhan, Xu Yanjie, Wang Guanglun and Jin Feng. (2000). Non-linear seismic response of arch dams with contraction joint opening and joint reinforcements. *Earthquake Engineering and Structural Dynamics* **29**, 1547-1566.
22. Bathe KJ and Chaudhary A. (1985). A solution method for planar and axisymmetric contact problems. *International Journal for Numerical Methods in Engineering* **21:1**, 65-88.
23. Lua DT, Boruziaan B and Razaqpur AG. (1998). Modeling of contraction joint and shear sliding effects on earthquake response of arch dams. *Earthquake Engineering and Structural Dynamics* **27**, 1013-1029.
24. Xiuli Du and Jin Tu. (2007). Nonlinear seismic response analysis of arch dam-foundation systems-part II opening and closing contact joints. *Bulletin of Earthquake Engineering* **5**, 121-133.
25. Chen Houqun. (1994). Model test and program verification on dynamic behavior of arch dam with contraction joints. *Report No. SVL-94/2 IWHR*, July.
26. Sheng Zhigang, Zhang Chuhan, Wang Guanglun and Jin Feng. (2003). Shaking table tests and numerical analysis for nonlinear seismic behavior of an arch dam model with contraction joints. *Journal of Hydroelectric Engineering* **80:1**, 34-43. (in Chinese)
27. Haibo Wang and Deyu Li. (2006). Experimental study of seismic overloading of large arch dam. *Earthquake Engineering and Structural Dynamics* **35**, 199-216.
28. Lin Gao and Hu Zhiqiang. (2005). Earthquake safety assessment of concrete arch and gravity dams. *Earthquake Engineering and Engineering Vibration* **4:2**, 251-264.
29. Liu Xinjia, Xu Yanjie, Wang Guanglun and Zhang Chuhan. (2002). Seismic response of arch dams considering infinite radiation damping and joint opening effects. *Earthquake Engineering and Engineering Vibration* **1:1**, 65-73.
30. Pekau OA, Feng Lingmin and Zhang Chuhan. (1995). Seismic fracture of Koyna dam: case study. *Earthquake Engineering and Structural Dynamic* **24**, 15-33.
31. Wang Guanglun, Pekau OA, Zhang Chuhan and Wang Shaomin. (2000). Seismic fracture analysis of concrete gravity dams based on nonlinear fracture mechanics. *Engineering Fracture Mechanics* **65**, 67-87.
32. Lubliner J, Oliver J Oller S and Onate E. (1989). A plastic-damage model for concrete. *International Journal of Solids and Structures* **25:3**, 299-326.
33. Lee J and Fenves LG. (1998). A plastic-damage concrete model for earthquake analysis of dams. *Earthquake Engineering and Structural Dynamics* **27**, 937-956.
34. Bazant ZP and Oh BH. (1983). Crack band theory for fracture of concrete. *Materiaux Constructions* **16:93**, 155-177.
35. An X, Maekawa K, Okamura H. (1997). Numerical simulation of size effect in shear strength of RC beams. *Journal of Materials, Concrete Structures and Pavements,* JSCE, **35:564**, 297-316.
36. Gilbert R I, Warner R F. (1978). Tension stiffening in reinforced concrete slabs. *Journal of Structural Division*, ASCE, **104(ST12)**, 1885-1901.
37. Kwak H G, Filippou F C. (1990). Finite element analysis of reinforced concrete structures under monotonic loads. Report No. UCB/SEMM-90/14. Department of Civil Engineering, University of California, Berkeley, California.
38. Luo Bingyan, Xu Yanjie and Wang Guanglun. (2007). Nonlinear dynamic analysis of Dagangshan arch dam with considering damper reinforcement. *Journal of Hydroelectric Engineering* **26:1**, 67-70. (in Chinese)
39. Chakraparti P and Chopra AK. (1973). Earthquake analysis of gravity dams including hydrodynamic

interaction. *Earthquake Engineering and Structural Dynamics* **2**, 143-160.

40. Chakraparti P and Chopra AK. (1974). Hydrodynamic effects in earthquake response of gravity dams. *Journ. Am. Soc. Civil. Engrs* **100(ST-6)**, 1211-1224.
41. Hall JF and Chopra AK. (1980). Dynamic response of embankment, concrete-gravity and arch dams including hydrodynamic interaction. *Report No. UCB/EERC 80/39*, Earthquake Engineering Research Center, University of California, Berkeley.
42. Clough RW, Chang KT, Chen HQ, Stephen RM, Wang GL and Ghanaat Y. (1984). Dynamic response behavior of Xiang Hong Dian Dam. *Report No. UCB/EERC 84/02*, Earthquake Engineering Research Center, University of California, Berkeley.
43. Clough RW and Chang KT. (1984). Dynamic response behavior of Quan Shui Dam. *Report No. UCB/EERC 84/20*, Earthquake Engineering Research Center, University of California, Berkeley.
44. Clough RW and Ghanaat Y. (1987). Experimental study of arch dam-reservoir interaction. *Proceedings of Joint China-US workshop on Earthquake Behavior of Arch Dams*, Beijing.
45. Zhang Chuhan, Yan Chengda, Wang Guanglun．(2001). Numerical Simulation of Reservoir Sediment and Effects on Hydro-dynamic Response of Arch Dams．*Earthquake Engineering and Structural Dynamics* **30**, 1817-1837.
46. Xiuli Du, Jinting Wang and Tinkan Hung. (2001). Effects of sediment on the dynamic pressure of water and sediment on dams. *Chinese Science Bulletin* **46:6**, 521-524.
47. Qiu Liuchao, Jin Feng and Wang Jinting. (2004). Application of sponge layer method for radiation damping in analysis of dam-reservoir interaction. *Journal of Hydraulic Engineering* **1**, 46-51. (in Chinese)
48. Cundall PA. (1971). A computer model for simulating progressive large scale movement in blocky systems. *Proc. Symp. Int. Soci. Rock Mech.* **1**, Paper No. Ⅱ-8.
49. Cundall PA. (1988). Formulation of three-dimensional distinct element model, PartⅠ, A scheme to detect and represent contact in system composed of many polyhedral blocks, *Int. J. Rock Mech. Min. Geomech. Abstr.* **25**, 107-116.
50. Shi G.H.,Goodman R.E. (1985). Two dimensional discontinuous analysis. *Int. J. numer. anal. meth. geomech*. **9**, 541-556.
51. Cundall PA. (1990). PFC$^{2d}$ User's Manual (version 2.0). Minnesota: Itasca Consulting Group Inc.
52. Kawai T and Toi Y. (1978). New element models in discrete structural analysis. *Welding Journal (Miami, Fla), Soc of Nav Archit of Jpn* **16**, 97-110.
53. Hou yanli. (2005). A Coupling Rupture Model of Distinct Element and Fracture Mechanics for Concrete Dam-Foundations. Ph.D. dissertation, Tsinghua University, 2005. (in Chinese)
54. Cui Yuzhu, Zhang Chuhan, Jin Feng and Wang Guanglun. (2002). Numerical modeling of dam-foundation failure and simulation of arch dam collapse. *Journal of Hydraulic Endineering* **6**,1-8. (in Chinese)
55. Zhang Chong, Jin Feng and Xu Yanjie. (2007). Dynamic analysis of arch dam-abutment stability. *Journal of Hydroelectric Engineering* 26:2, 27-36. (in Chinese)
56. Zhang Chuhan, Pan Jianwen and Wang Jinting. Influence of seismic input mechanisms and radiation damping on arch dam response. *Earthquake Engineering and Structural Dynamics* (submitted).
57. Pan Jianwen, Wang Jinting and Zhang Chuhan. (2007). Analysis of damage and cracking in arch dams subjected to extremely strong earthquake. *Journal of Hydraulic Engineering* **38:2**, 143-149. (in Chinese)
58. Long Yuchuang, Zhang Chuhan and Jin Feng. Numerical simulation of reinforcement strengthening for high arch dams to resist strong earthquakes. *Earthquake Engineering and Structural Dynamics* (will appear in 2008).