Seismic Safety for Hydropower Engineering in China

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Abstract: In China the programs for developing the western region are carrying out successfully. Abundant hydropower potential, about 80% of the national total, is a superior resource in this region. The hydropower sustainable development is critical not only for providing safe and clean energy to meet the increasing demand for electricity to power economic progress of the country, but also for eradicating poverty in this region. Many dam sites with geology and topography suitable for high dam with excellent regulating reservoir but only a small amount of resettlement are in this region. However this region is also well known for its high seismicity and frequent occurrence. The seismic safety of large hydropower project with high dam is deeply concerned by our government and society. Therefore, an extensive research on seismic design of high dams has been carried out in recent years. A series of new conceptive progresses in seismic design of high dams have been initiated towards the new upsurge of hydropower construction in the 21st century in China. Technical perspectives, including advances in seismic research and design of high dams as well as in reservoir triggered seismicity around hydropower in this region are briefly introduced in this paper.

Keywords: seismic safety hydropower engineering arch dam input ground motion dynamic analysis dynamic behavior of dam concrete

1 Introduction

Water and energy and the affected environment are key factors constrain the economic development and environmental improvement of China. Based on the scenario studies, in the coming 20 years the demand of energy will double over the year 2000. The energy consumption in China relies basically on coal, about 77% of the whole country. The terrible environmental problems are caused by direct combustion of coal. At present China has been searching for the alternative energy supplies with the aim to reduce the share of coal. Up to now wind power, solar energy, geothermal, biogas and wave energy are only the auxiliary energy resources because of the limitation for geographic, economic and technical reasons. Hydropower, as a renewable and clean energy, with its potential ranked the world's first, plays an important role for sustainable development of energy and assure environment's security in China [1]. The abundant hydropower, about 80% of the national total, is a superior resource in the developing region of the Western China. But its utilization ratio is very low, only less than 10% has been used. To pursue sustainable, rapid and healthy development and to speed up the development in the Western region are the basic and macro strategies of economical development of Chinese government. Naturally, the rapid and sustainable hydropower development becomes critical not only for providing safe and clean energy to meet the increasing demand for electricity to power economic progress of the country, but also for eradicating poverty in this region. Many dam sites with geology and topography suitable for high dam with excellent regulating reservoir but only a small amount of resettlement are in this region. However, this region is also well known for its high seismicty and frequent occurrence. According to the statistics of the China Earthquake Administration, 82% of the strong earthquakes occurred in modern times in China were concentrated in this region. Many huge dams with rather high design acceleration (a_g) are located in this region, such as Jinping-I (H=305m,a_g=0.197g), Ertan(H=240m,a_g=0.20g), Longxiangxia(H=178m,a_g=0.23g), Xiaowan(H=292m,a_g=0.308g), Xiluodu(H=273m,a_g=0.321g), Baihetan(H=275m,a_g=0.325g), Hutiaoxia(H=278m,a_g=0.408g), Dagangshan(H=210m, a_g=0.542g) etc. All those are arch dams. Fig.1 shows the location map of major hydropower stations in China's 12 principal hydropower bases. Fig.2 is the epicenter distribution map of China.

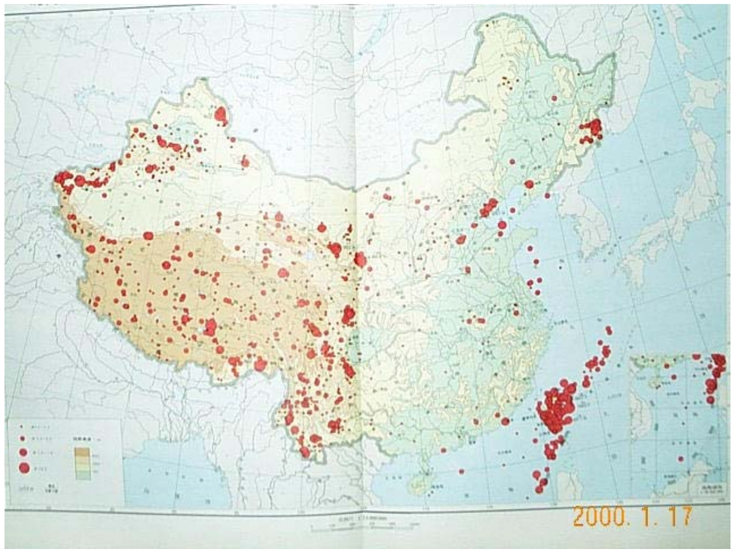


Fig 1 Location map of major hydropower stations in China

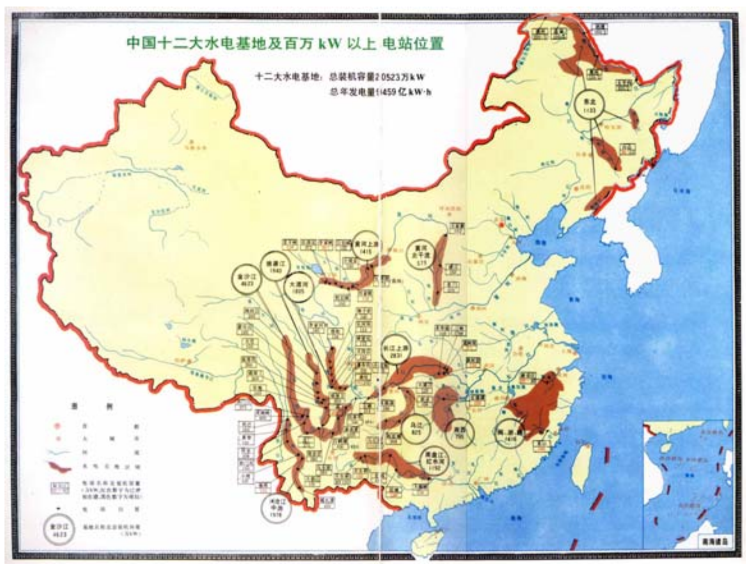


Fig 2 Epicenter distribution map of China

The problem of seismic phenomena is also associated with impounding of reservoir and is addressed as Reservoir Triggered Seismicity (RTS). This problem has been seriously considered in dam engineering circles due to its environmental impact and risk consideration [2].

As any accident of serious damage of high dam with huge reservoir during strong earthquake can inflict grave secondary catastrophe upon surrounding communities, the seismic safety of large hydropower project with high dam is naturally deeply concerned by our government and society. Facing a particular challenges in this key technical problem of hydropower development in China, an extensive research on seismic design of high dam has been carried out in recent years. A series of new conceptive progresses in seismic design of high dams have been initiated towards the new upsurge of hydropower construction in the 21st century in China.

2 Critical problems for seismic design of high dams in China

In order to evaluate the seismic safety of a dam, the input ground motion at dam site, the method for analyzing seismic action effects of dam, and the dynamic resistances of dam concrete are the three main factors which should be consistent with each other. With the aid of favorable circumstances in Western China arch dams have often been selected and studied prior to other dam types. Therefore, discussion of seismic safety of high arch dams is focused hereafter.

2.1 Site-specific input ground motion

The selecting input ground motion is the important presupposition for seismic safety evaluation. The peak ground acceleration (PGA), response spectrum, sometimes the duration is included are usually considered as main parameters of input ground motion. However, there are some critical problems deserved to be noticed[3].

As commonly recognized, the PGA has a lack of predictability in the near-field which is more important for high dam in severe seismic area. Also, it often occurs at high frequencies, which is of little engineering significance to large dams.

The so-called equal-hazard spectra still frequently used to date does not embody the physical characteristics of spectrum of a real earthquake, but reflect the envelope effect of earthquakes with different magnitudes and location.

For dam a dual levels of Maximum Credible Earthquake (MCE) and Operating Basis Earthquake (OBE) for seismic design becomes widespread. Actually, it is very unlikely that a dam cannot operate any more after the OBE with a return period ca 100-200 years will fulfill the requirements of MCE as the largest reasonable expected earthquake. Furthermore, both the MCE and its performance objective are equivocal and difficult to be quantified.

2.2 Seismic action effects of dams

Up to now the following more critical problems have not been satisfactorily considered in the seismic design of high arch dams[4]:

Opening of contraction joints within dam during strong earthquake;

Radiation damping of energy dispersion in far-field foundation;

Topography features and geological disturbances including all potential sliding blocks of arch dam abutments at both banks within the near-field foundation adjacent to dam;

Dynamic interaction of dam-foundation-reservoir system;

Special variation of seismic input along dam foundation.

Moreover, the stability of foundation rock at abutments is a decisive factor for seismic design of high arch dams. Nevertheless, the traditional approach of limit equilibrium method widely used in dam engineering for stability analysis of arch dam abutment blocks as a rigid body detached from the dam able to consider neither the deformation coupling and dynamic interaction between the dam and foundation nor the dynamic effects of the canyon banks during earthquake.

2.3 Dynamic behavior of dam concrete

The lack of sufficient dynamic tests and researches on behavior of dam concrete has already the bottleneck for seismic safety evaluation of high dams. Basically the small wet screened specimens by sieving the aggregates of more than 40mm were still used in engineering practice, while the coarse aggregates of 150mm has involved in multi-graded dam concrete long ago. Moreover, despite the fact that dam is always subjected to earthquake while being in operation under static loads with different initial stresses in its various positions. But the effect of static preload on dynamic behavior of dam concrete has usually been overlooked[5].

All the abovementioned critical problems feature the particular challenges in aspect of seismic safety for hydropower development in China.

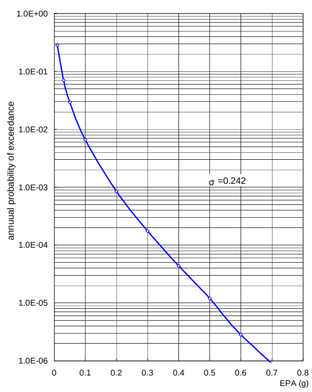
3 Latest advances in seismic research and design of high arch dams in China

Corresponding the aforementioned critical problems, the technical perspectives are also described in the aspects of main factors for seismic safety evaluation of high arch dams.

3.1 Site-specific input ground motion

Instead of the current peak ground acceleration (PGA), the spectrum related effective peak acceleration (EPA) is used in the seismic hazard evaluation of dam site. Based on the analysis of 145 accelerograms recorded at rock site in the Western United State, the EPA is defined as the spectral acceleration at period 0.2 second divided by an average amplification factor of 2.5. An attenuation relationship for EPA on the basis of regression model of Abrahamson was derived. Fig.3 shows the hazard curve of EPA from seismic hazard evaluation for Xiaowan arch dam.

The equal-hazard spectrum has been replaced by a hybrid method combining both probabilistic and deterministic approaches of selecting specific scenario earthquake with maximum probability and consistent with the design EPA at dam site. A more realistic site-specific design spectrum with definite probability of exceedance can be determined from the selected scenario earthquake as shown in Fig.4 for Xiaowan arch dam.



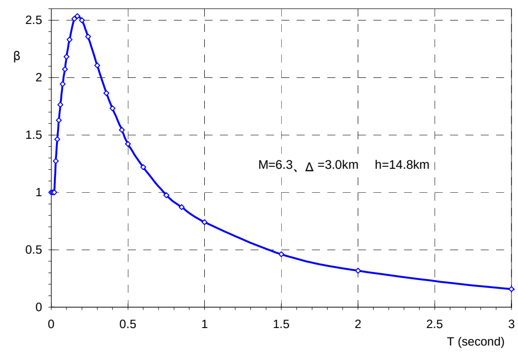


Fig 3 Hazard curve for Xiaowan dam Fig 4 Site-specific design spectrum w for Xiaowan dam.

Also, the MCE can be determined definitely. It is no other than a special kind of scenario earthquake with the upper limit magnitude and the shortest possible distance to dam site within the seismic source zone of maximum contribution. Moreover, a framework of performance-based seismic design with dual fortification earthquake levels of MDE (Maximum Design Earthquake) and MCE has been established to substitute for traditional dual levels of OBE and MCE. Besides, a more systematic and effective procedure for Reservoir Triggered Seismicity (RTS) has formed and widely used in practice in China. At present, the digital seismic monitoring of RTS and strong motion observation has been implemented in many hydropower projects. A digital monitoring system with 22 fixed and 8 movable stations has been in operation for the Three Georges Project before impounding of its reservoir. Also, the study on RTS by using Geological Information System (GIS) has been achieved.

3.2 Seismic action effects of dams

Recently, great efforts have been made in analyzing the seismic action effects of arch dams with consideration of all abovementioned critical problems simultaneously. A more realistic modeling with effective method for analyzing high arch dams has been developed and widely used in China.

In this model, the far-field foundation region is replaced by a set of artificial transmitting boundaries proposed by Professor Liao Z.P.[6]. Both contraction joints within dam and all boundary interfaces of abutment sliding blocks are treated on basis of dynamic contact theory with friction and cohesion. So, the effects of local opening and slipping and all joints can be taken into account. Also, a contact joint is set along the dam-foundation interface but with the initial strength of dam concrete. Such assumption allows cracking in this more vulnerable zone of high arch dam with contraction joints and evade the controversial problem of stress singularity at dam heel inevitably existed in finite element method.

The model of the whole system is discrete in space by finite elements and in time by central finite-differences. Its equation of motion is solved as a wave propagation problem by explicit integration in time domain [7].

The performance objective of limited local reparable damage for MDE is realized by ensuring the total main principal stresses in dam under the combination of static loads and the MDE within its dynamic strength capacity of dam concrete. However, the limit state of uncontrolled release water from reservoir for MCE should be identified by dynamic instability of the integrated dam-foundation system. The traditional approach used for stability analysis of arch dam abutment blocks is essentially a time-independent static method without consideration of the dynamic deformation coupling between the dam and foundation. It causes the results far from the real dynamic stability behavior of the integrated dam-foundation-reservoir system during strong earthquake.

From engineering point of view, a new conception from the abrupt junction of displacement responses of the system during earthquake as its criterion of stability assessment is suggested. The ratio of the seismic action caused the limit state with abrupt junction of displacement responses to that of MDE provided a so-called overload safety factor. Obviously, the damage criterion for MCE can be defined as the arch dam will withstand the MCE with a overload safety factor no less than 1.0.

Fig.5 shows the time histories of the displacement responses of dam at crown and abutments at crest for an imaginable ultimate earthquake causing instability of the Xiaowan arch dam with an EPA of 0.540 g. As its EPA for MDE and MCE are 0.300 g and 0.408 g respectively, their seismic overload safety factors can be estimated as 1.8 and 1.3 respectively.

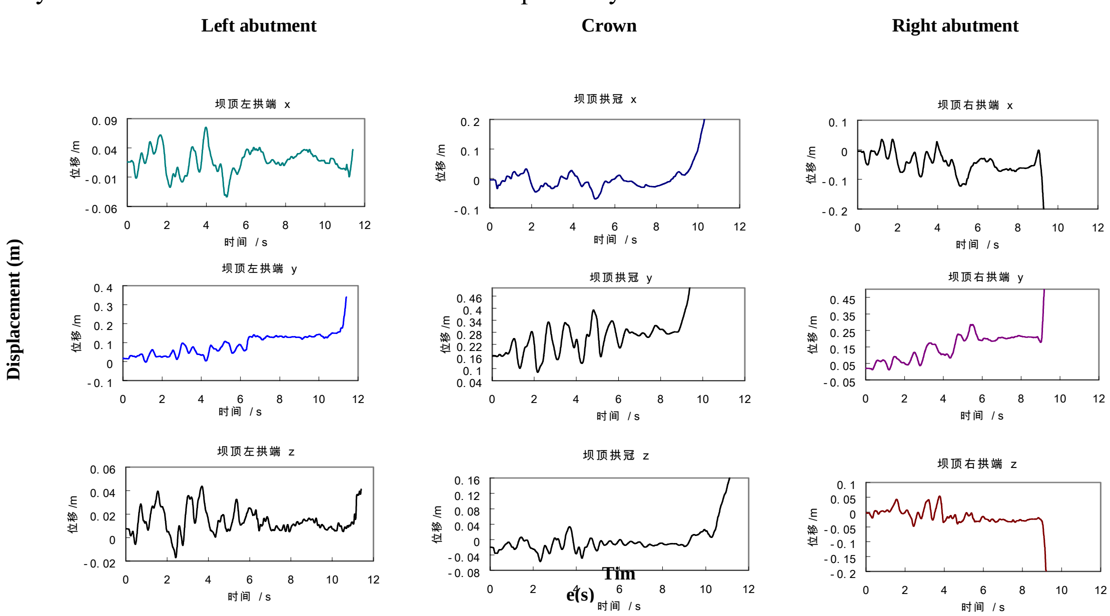


Fig.5 Time histories of the displacement responses of dam at crown and abutments at crest for an imaginable earthquake causing instability of the dam with EPA of 540 gal

3.3 Dynamic behavior of dam concrete

Dam concrete is distinct from ordinary concrete for its more heterogeneous of mixing multi-graded aggregates. Up to now most of the study of dynamic strength of dam concrete has focused on its strength increase under seismic action by comparing the results between unitary dynamic and static tests using small specimens after wet sieving for aggregates.

Recently, the flexural-tensile properties of dam concrete were studied by testing concrete beams simply supported with tri-point loading both in static state and in dynamic state with shock and triangle cyclic waves under different static preloads. Tests were carried out both for traditional wet-sieved small specimens of 150×150×1100 mm and for fully graded large specimens of 450×450×1700 mm.

Among the results one phenomenon turned out to be even somewhat contrary to conventional expectation, that the strain-rate effect corresponding to the earthquake responses of high arch dams increased with the static preloads as shown in Fig.6 [8][9].

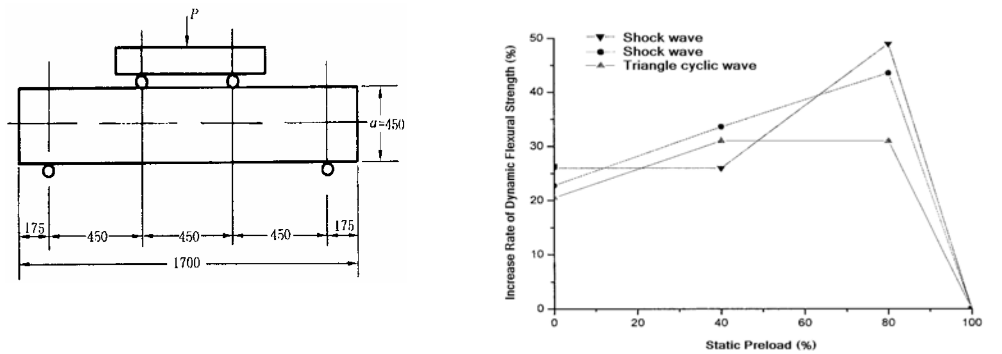
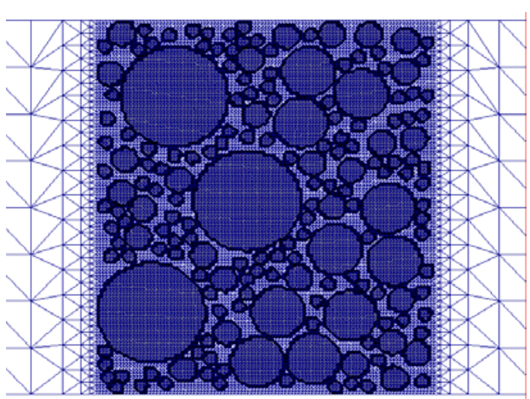


Fig.6 Sketch of test and strain-rate effect of fully graded concrete with different static preloads

In order to explain this phenomenon and also to investigate the failure mechanism of dam concrete under dynamic flexural-tensile loading with static preloads, a dynamic numerical analysis of the concrete specimen with meso-mechanical and dynamic damage constitutive model was carried out. In the meso-mechanical model, the discretization of the full-graded aggregates was completed using finite elements shown in Fig.7. All the locations and the tensile strength of aggregates, cement motor and their interfaces were distributed in a random way.

Based on the existed experimental data, the dynamic intensification function Ht($\dot{\varepsilon}$) and HE($\dot{\varepsilon}$) of strain rate $\dot{\varepsilon}$ for tensile tress and elastic modulus respectively as well as a damage variable function D(ε) of strain ε were involved. The results of a 2-dimensional analysis shown in Fig.8 (with different variation coefficients of random distributed tensile strength of the interfaces vt) revealed a conception that the strain-rate increase of dynamic strength is intensified by the soften effect of damage caused by the static preload.



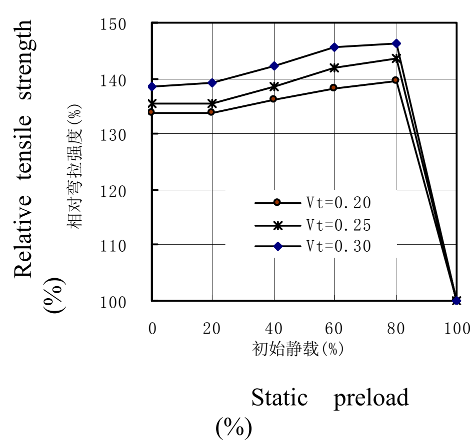


Fig 7 Finite element mesh of specimen Fig 8 Strain rate effect increase with static preload.

The experimental phenomenon reasonably explained by the analytical results might be of great significance for seismic safety assessment of large concrete dams. Meanwhile, a 3-dimensional analysis is in progress with application of a multi-scale computational method for mechanical parameters of composite materials with random grains.

4 Conclusions

1. Construction of high dams with huge reservoir in areas of high seismicity is inevitable in order to exploit the abundant hydropower potential and to eradicate poverty in the Western China.

2. Seismic safety of high arch dams is a particular challenge has to be faced and the special attention has to be devoted to for hydropower development in China.

3. Having no preceded to go by, a series of traditional conceptions not suitable for high dams against serious earthquakes must be broken by new ones on the basis of continued and extensive research efforts.

4. There is no insuperable technical barrier to guarantee the seismic safety of high arch dams in hydropower development in China.

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