EARTHQUAKE RESISTANCE OF LARGE DAMS IN CHINA

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SUMMARY

This paper briefly describes the main features of earthquake resistance of large dams inChina. Some typical outcomes of recent design and research activities developed alongwith the progress of dam construction in China are introduced.

EARTHQUAKE AND DAMS IN CHINA

China is situated between the two large active seismic belts in the world and is a country of high seismicity. China is also a country rich in hydropower resources. Abundant Hydropower potential about 70% of the national total, is concentrated in the south west and northwest of China. However this region is well known for its high seismic intensity and frequency of occurrence. As the area of region of intensity or greater (Chinese Seismic Intensity scale is quite similar to the Modified Mercalli Scale widely used in the world) reaches 79% of the area of the Chinese territory most of the dams are located in seismic area. As for dams with reservoir of volume more than 108 M3 more than 75% are located in the area of intensity of which 40% in the area of intensity more than and 13% in the area of intensity.For most critical projects such as the existing Longyanxia Dam of height 178m and the under construction Ertan Dam of height 240m as well as the designed Xiaowan Dam of height 292m and Xilodu Dam of height 273m both planned to be constructed in near future have a high design intensity of or and even the seismic safety becomes a control factor in the design for some of them.

Moreover, any accident of serious damage of a high dam with huge reservoir can inflict grave secondary catastrophe upon surrounding communities. In China more than half large and medium cities are located in the area of seismic intensity no less than of which 163 cities are at the risk of secondary hazard caused by serious damage of upstream reservoir during strong earthquakes. Among them 41 reservoirs are located in area of intensity and greater including Beijing and 8 capital cities of provinces such as Lanzhou and Chanchun.

Earthquakes may also result from impounding of water in reservoir itself. At present there are about 120 events in 29 countries have been recognized as reservoir-induced earthquakes of which 22 events occurred in China. Among the existed cases only four reservoirs induced earthquakes of magnitude 6 and greater Xinfengjiang Reservoir in China is one of them. In China the first reservoir induced earthquake occurred in Xinfengjiang Reservoir in October 1959. Based on the results of continued research the dam was strengthened before the major shock The extensive research works on Xinfengjiang reservoir-induced earthquakes have laid the foundation of seismic investigation of concrete dams in China. An another case of reservoir-induced earthquake at Wuxinjiang Project. was very similar to the case of Xinfengjiang. However, in this case based on an extensive research with joint effort of various departments to predict the tendency of reservoir-induced earthquake and to check the seismic behavior of the dam, a very expensive strengthening of the dam has been avoided. It has been shown from the above two examples that the decision-makings both for Xinfengjiang dams with strengthening and for Wuxijiang without strengthening were successful demonstrating the remarkable progress in study on reservoir-induced earthquakes and engineering treatment to them in China. At present in the design of each major dam in China detailed verification is made on the potentiality of reservoir-induced earthquakes. Based on the results of research and the experience of engineering practice in China with reference to the data of cases in other countries the Chinese experts have formed a more systematic and effective countermeasures against

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reservoir-induced earthquake [Wang,1995]. This approach has been widely used in many practical projects including the Three Gorges Project and accepted by the "Technical Specification for water Resources and Hydropower Engineering Geological Investigation" in China. Recently in the study of reservoir-induced earthquake in China the advanced digital GIS (Geological Information System) techniques have been used.

Since 1949 China has suffered several severe earthquakes in which some dams were damaged. Fortunately there were no large dams destroyed in these earthquakes otherwise, disaster would be terrible. Seismic behaviors of dams during these earthquakes notably effected on the seismic design of dams in China. The typical damage patterns of embankment dams during recent severe earthquakes in China are sliding, cracking, seepage, settlement, and damage to accessory structures. For concrete gravity dams and diamond-head buttress dams cracking at the top portion of the dam is the typical damage pattern most likely occurred.

SEISMIC ASPECT OF DAM DESIGN

In China the seismic design of dams is based on the design intensity of the project. When the dams designed based on the code are subjected to the influence of earthquakes with an intensity of less than the design intensity, the dams will continue to be serviceable with only ordinary repair. Normally the basic intensity of the dam site determined by the"Seismic zoning map in China" can be used as design intensity. In 1992 a new seismic zoning map in China compiled on the basis of probabilistic method of seismic hazard evaluation was issued. In the new map intensity ratings corresponding to a 10% of probability of exceedance in 50 years were provided and defined as basic intensity. A relationship between intensities and peak ground accelerations are provided by seismic design code in China. The intensity of corresponds to a peak ground acceleration of 0.1g 0.2g 0.4g . In China for hydraulic structures there is a specification of risk classification to rate the potential risk of the projects and structures into 5 classes associated with risk factors such as reservoir capacity potential downstream damage, etc.. In view of the extremely importance of retaining hydraulic structures of class 1 the design intensity should be one grade higher than the basic intensity of the area project located as required by the existing seismic design code and accepted in engineering practice in China. Furthermore according to the new Specifications in order to selecting peak ground acceleration for the hydraulic structures in project of Class 1 a site-specific seismic hazard evaluation should be carried out .

Based on a calibration of the defined intensity or design peak ground acceleration of each specified project and its probability of exceedance obtained from its site-specific seismic hazard evaluation as well as a statistic calculation with zero value of mean deviation of calibration results of all projects considered a probability of exceedance of 0.02 for a design reference period of 100 years for retaining structures of class 1 and of 0.05 for a design reference period of 50 years for other structures are accepted in the new specification. Also in this specification it is required that for a project with a dam higher than 100m and a reservoir capacity larger than 500Mm3 a special study on prediction of possible reservoir-induced earthquake and seismic monitoring shall be carried out, if there are active faults within the hydraulic regime of reservoir and if the regional and local geology and seismic records within the area may be judged to indicate potential for reservoir-induced seismicity with intensity more than.

The first"Specifications for seismic design of hydraulic structures (SDJ 10-78)"in China was compiled from 1974 and issued in 1978. Based on a series of studies on specific topics investigation and summarization of lessons learned from strong earthquakes having occurred in recent years in China and other parts of world as well as new abundant research achievements in earthquake engineering for dams and consideration of national conditions in China, a revised"Specifications for seismic design of hydraulic structures (DL 5073-1997)"in China was issued in 1997 with many essential modifications and supplements. Concerning the evaluation of seismic behaviors of dams two characteristic features of the revision of the Specification are worthy to be noted. The first one is the dynamic theory based seismic checking. When performing a dynamic linear analysis a response spectrum method is widely used. So the design response spectrum is another important seismic parameter. For seismic design of dams in China the design response spectra accepted in dam engineering practice are the generalized site-dependent response spectra in normalized format determined as the statistical mean value of the response spectra calculated from a serious of ground accelerograms of near-field earthquakes under the same soil condition. However the dynamic method for seismic checking of embankment dams is rather complicated due to the nonlinear properties of the dam materials. Up to now no identical view can be held in engineering practice concerning the approaches and criteria of dynamic analyses of seismic stability and permanent deformation for embankment dams. Furthermore the result obtained from different approaches usually significantly inconsistent with each other. It is apparent that any definite provision concerning the dynamic analysis of embankment dams for the specifications will be inconceivable. With prudence the pseudo-static method for seismic checking of embankment dams is recommended in the Specifications (DL 5073-1997). Based on the data from seismic records at existing dams and results of dynamic analyses with consideration of the non-linear properties of dam materials the values of the amplification factors at the dam crest in the pseudo-static method are recommended as 3.0,2.5 and 2.0 for design seismic intensities of and respectively in the Specifications (DL 5073-1997) instead of an identical value of 2.5 for all intensities in the Specification (SDJ 10-78). However for more critical embankment dams with high design seismic intensity as well as for liquefiable foundations a dynamic analysis is required. In this case only a guideline for such dynamic analysis is provided in principle in the appendix of the revised Specifications. Another characteristical feature of the new version of specifications is that the seismic reliability design is involved. The analytical techniques and corresponding criteria presently used in design of all countries to evaluate the performance of dams are deterministic. However the random characteristics both of actions and resistance in design of structures are more and more recognized in engineering practice. So the new enacted"Unified design standard for reliability of hydraulic engineering structures (GB 50199-94)"in China required a transition of the design from deterministic to reliability-based for structural design. Since characterizing the occurrence and expected magnitude of earthquakes is most meaningful in terms of probabilities use of reliability based algorithm and criteria to evaluate the seismic performance of dams is naturally a more reasonable and appropriate approach. The seismic checking of concrete dams is formally transformed into the ultimate limit-state equation with probability-based partial factors of both actions and resistance as well as a reliability-related structural factor.The seismic effects on dams are determined by the response spectrum analysis including the dynamic interactions of dam-foundation-reservoir. Both peak ground acceleration and normalized response spectra are taken as random variables [Chen, 1994b].

However for embankment dams to use seismic reliability design is rather unrealistic at present due to insufficiency of statistic data of material resistance even in static cases. So only the ultimate limit-state formula is adopted formally.

In general, for evaluation the seismic behavior of dams the revised Specifications (DL 5073-1997) has leapt over two critical steps in seismic checking as from pseudo-static to dynamic analysis with dynamic interactions of dam-foundation-reservoir and from deterministic to preliminary reliability design.

At the same time the glaring virtue of the Specifications (SDJ 10-78) as to pay great attention to the aseismic engineering measures was carried forward in the revised one.

RESEARCH ACTIVITIES

The flourish of dam construction after 1949 and the frequency of strong earthquake occurrence since the twentieth century in China give great impetus to the progress of earthquake engineering of dams in the country. Scientific research activities in this field have been conducted on an extensive national scope including basic and applied researches.

Dynamic Analysis

Great advances have been made in dynamic analysis of dams along with the construction of many large dams located in seismic regions. Only some typical examples are briefly introduced here. Recently a more effective and accurate approach to solve the dam-foundation interaction problem in time domain was developed by coupling the explicit finite element method with the transmitting boundary method [Liao, 1992] [Chen, 1997]. It is a numerical simulation of wave motion for dam-foundation system, in which all the following three important factors can be considered

(1)The spatial variation both in amplitude and phase of a seismic input along the canyon of dam base particularly for a high dam in deep valley which is more sensitive to the differential ground motion of dam abutments.

(2) The energy dispersion of seismic wave in the semi-infinite rock foundation media.

(3) The effects of the spatial topographical features of a canyon and the nonlinear behaviors of geological features almost unavoidably existed in the near-field foundation for every dam site.

In this approach a novel single-step method for dynamic analysis of concrete dams with joints was also used. In the method a two-level algorithm is employed for dealing with a nonlinear boundary conditions caused by the dynamic contact of interfaces. At the first level an explicit method is adopted to calculate nodal displacements of a dam-foundation-reservoir system with transmitting boundaries of the foundation without considering the effect of dynamic contact of interfaces and at the second level by introducing contact conditions of interfaces a group of equations of lower order is derived to calculate dynamic contact normal and shear forces on the interfaces. In this method both normal and shear can be considered and the contact conditions can be satisfied in a single step without iteration to avoid any assumptions of the coefficients of stiffness and the penetration of the joint interfaces of two sides. Moreover its explicit solution in time domain is fully consistent with the procedure of transmitting boundary method used for dynamic analysis of concrete dam. Also the width of a initial opening of the joint can be taken into account. So as a more convenient and efficient method for the analysis of dynamic contact problems it is now being used not only for the analysis of arch dam with contraction joints but also for some gravity dams with longitudinal vertical joints as well as for some arch dam with construction joint near the dam base in order to improve the stresses adjacent the base of the dam For the seismic safety of dams the dynamic stability of the foundation is more essential than the local dam strength during earthquake. Particularly for an arch dam more feasible seismic damages were caused by the unstability of the abutment rock mass as learned form the lessons of past earthquakes like Pacoima Dam during San Fernando (1971)and Northbridge (1994)earthquakes. Once a more critical potential slide block of the abutment foundation rock has been defined by geological engineers based on the geological features of the dam site concerned all the forces applied to the block can be calculated from the responses of the dam and foundation system by using the above-mentioned approach.. Then a time-dependant dynamic safety factor of the stability of the potential slide block can be determined by using conventional limit equilibrium method.

Model Tests

Since some idealizations and assumptions as well as uncertainties in selecting parameters are hard to avoid in dynamic analysis of such sophisticated system like dam special emphasis has been placed on the dynamic model test to improve and verify the analytical procedure and its results. For this purpose a number of shaking tables have been set up in China among which the more advanced one is the large triaxial earthquake simulator installed in the China Institute of water Resources and Hydropower Research (IWHR). It was indicated by famous international experts in this field as the world's best facility for testing concrete dam models [U.S.NRC, 1990]. Many dynamic model tests for large dams have been carried out on this facility for various purposes. Some typical examples also can briefly be described as follows.

(1)In order to study the cause of the damage of Xinfengjiang buttress dam during the major shock of magnitude 6.1 after impounding of the reservoir, a dynamic model test on a electromagnetic earthquake simulation shaking table with an input accelerogram recorded in the dam base on July 29.1967 has been carried out in 1973 [Shen, 1974]. The results showed that the stress response of the dam increases remarkably near elevation 108m where the cracks have been discovered. It is more worthy to be noted that a second peak stress at downstream appeared in the test which was verified by the cracks discovered while the reservoir water was drawn down after several years later.

(2)An experimental study of the joint opening behavior of high arch dam was carried out to verify the nonlinear analysis of arch dam with contraction joints during strong earthquake [Chen, 1996]. The experimental work used a model of a double curvature arch dam with its reservoir on the triaxial earthquake simulation shaking table at the Institute of Water Resources and Hydroelectric Power Research in Beijing. The results show that opening of contraction joints under seismic loading reduces arch tensile stresses and increases cantilever compressive stresses and the experimental results and the analytical results are close to each other.

Field Vibration Experiment

Even the design of shaking-table experiments employing physical models of concrete dams requires the introduction of limiting assumptions with regard to both the properties of the model structure reservoir water and foundation rock and the nature of the simulated boundary conditions in which it is situated. For these reasons the better evidence by far about the dynamic behavior of dams is that obtained from in-situ field vibration experiments. Field vibration experiments using either ambient or different forced input excitation are very useful in verifying the mathematical model of the dam system mainly at low-response amplitudes. Particularly if the compressibility of the reservoir water and the absorption effect of the silt deposit as well as the non-uniform input mechanism and radiation damping of the foundation are studied the field vibration experiment will be the unique approach for verifying the developed analytical procedures.

Many field vibration measurements of the vibration properties and response characters of large dams have been made in China during recent years. Since 1981 up to now a long-term cooperative research program directed toward evaluation of interaction effects in the dynamic behavior of arch dams has been carried out under the China-U.S Protocol for Scientific and Technical Cooperation in Earthquake Studies. The principal objectives of the research were to obtain improved understanding of the dynamic interaction mechanisms between an arch dam and its foundation rock as well as between the dam and its reservoir water and also to develop and verify dynamic response analysis procedures that would represent the interaction mechanism more realistically and conveniently. For this purpose a series of field tests have been carried out at dam sites of four arch dam in China and one in United States from 1981-1997. During these tests 4 synchronized rotating shakers and detonating explosive charges both in an array of bore holes in the foundation rock with water stemming and in rock surface under shallow water at upstream of the reservoir about 1 km away from the dam were used to excite the dam foundation-reservoir system.

Some important conclusions were drawn from the test

(1) For dynamic analysis of arch dam with consideration of dam-foundation interaction an analytical procedure taking account of the spatial variation of ground motions around the dam canyon seems more reasonable than the conventional approach with uniform input motion since the former appears in better agreement with the field experimental results.

(2) Considering the compressibility of reservoir water in the dynamic analysis of arch dam gave better agreement with field test results in comparison with the case of incompressible water. However the difference between them is not significant if the wave absorption at the lake bottom has been taken into account.

(3) The verified analytical procedures and corresponding programs seem available to be used in engineering practice.

SEISMIC MONITORING AND OBSERVATION

In China the first seismic monitoring surveys have been made for Xinfengjiang reservoir in 1960. Since than the seismic monitoring surveys have achieved remarkable progress with the rapidly developed dam construction in China. A Series of seismic monitoring networks have been set up in the potential reservoir-induced regions. Recently in China the seismic network for monitoring reservoir-induced seismicity have undergone revolutionary changes in terms of instrumentation data acquisition processing and interpretation. During recent eighteen years the F.M. transmission remote monitoring networks of reservoir-induced earthquake have been set up in 12 projects in China. The Seismograph configurations of these networks are fundamentally based on analog technology. However a final monitoring networks of reservoir-induced seismicity for Three Gorges Project is now developing using digital monitoring system. In contrast to the analog transmission systems digital data transmission has the decided advantage of error and distortion free transmissions and also the improved dynamic range.

Because real earthquakes provide the best test of earthquake performance it is essential that many more existing large dams were provided with adequate seismic instrumentation so that quantitative evidence can be obtained to be used in verifying seismic safety evaluation procedures. The lack of adequate earthquake input data is probably the greatest present impediment to progress toward improving the seismic safety evaluation procedures for large dams. The first strong motion observation has been set up in 1962 after the major reservoir-induced earthquake with a magnitude of M=6.1 in Xinfengiang buttress dam in order to provide information on the input ground motion at dam site and seismic response of the dam. Since than networks of strong motion observation have been installed in many large concrete and embankment dams in China and remarkable progress has been made in improving the instrumentation. To date almost in each large dam with high design seismic intensity a network of strong motion observation was set up as the seismic design code required in China. All the accelerographs installed in these dams are designed and manufactured in China. Most of them are multi-channels central recording system with magnetic digital recorder with a dynamic range of more than90 dB some accelerographs with analog recording are now being adapted. Most of the data recorded at dams are collected in the Earthquake Engineering Research Center of the Institute of water Resources and Hydropower Research. A special data processing software including the data playback and adjustment for preliminary determination of the base line instrument and base line correction using band-pass filters and calculation of response and Fourier spectra has been developed.

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