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INPUT GROUND MOTION SELECTION FOR XIAOWAN HIGH ARCH DAM

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SUMMARY

In this paper some special features of seismic input for design of large dams in China as well as the police decision, procedure and method of the input ground motion selecting for an extra high arch dam as Xiaowan dam with a height of 292m in area of high seismicity were presented. The site-specific design response spectrum based on the scenario earthquake with maximum probability and design effective peak acceleration (EPA) by seismic hazard evaluation was described. Finally, a new method of generating an artificial accelerogram compatible with object design response spectrum by using time domain method was involved. The result of selecting input ground motion parameters for Xiaowan project was illustrated.
Key words: large dam; ground motion; seismic hazard evaluation; design response spectrum; artificial accelerogram.

INTRODUCTION

As a common accepted principle, it is well known that for seismic design of a structure, the input ground motion should be consistent with the method of analysis of seismic effects and dynamic

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resistances of materials. The selecting input ground motion parameters are the important premise for seismic safety evaluation of structures, particularly, for the Xiaowan arch dam with a height of 292m and a design seismic intensity of Ⅸ degrees. Due to the recent rapid progress of computer's capabilities and numerical analysis techniques, to evaluate the safety of dams by simulating their behavior during an earthquake using dynamic analysis method becomes more widespread. To correspond such situation, the peak ground acceleration and response spectrum, sometimes the duration is included are considered as more critical ground motion parameters for seismic design. Since earthquakes are natural phenomena, inherently random primarily due to the tremendous uncertainties in the estimation of the ground behavior during an earthquake. It may be addressed probabilistically based on seismic hazard evaluation, which methodology is now widely used and initially developed by Cornell (1968). The outcome of the standard probabilistic analysis is an estimate of the annual probability of exceedance of peak ground acceleration at an engineering site due to known and postulated potential seismic sources. Based on the hazard curve, the consistent site-specific design response spectra and acceleration time histories can be developed. Principally, this is also the typical methodology used for input ground motion selecting of large dams in China. However, some special features of input ground motion selecting for large dams in China are described in this paper united in the typical example of Xiaowan arch dam.

SOME SPECIAL FEATURES OF INPUT GROUND MOTION SELECTING FOR LARGE DAMS IN CHINA

Considering the fact that any accident of serious damage of a high dam with huge reservoir can inflict grave secondary catastrophe upon surrounding communities, in China the seismic design of class 1,2 and 3 dams in seismic zones shall be regulated by the 《Specifications for seismic design of hydraulic structures》 (hereinafter abbreviated as Specifications). It is a compulsory Specifications issued by Ministries. The earthquake fortification classification depends on the dam class related mainly to the probable failure consequences and also the basic seismic peak acceleration of dam site. A new 《Seismic ground motion parameter zonation map of China》 was issued in August 2001 and was compiled on the basis of probabilistic method of seismic hazard evaluation. In the map the peak ground acceleration ratings corresponding to a 10% probability of exceedance in 50 years at smooth surface of ordinary still soil. The map is used to meet fortification requirement against earthquake for ordinary engineering projects, including small to medium dams. However, for dam of earthquake fortification class 1 a site-specific seismic hazard evaluation shall be carried out according to the《Code for seismic safety evaluation of engineering site》 as required in the Specifications. In this case a 2% probability of exceedance in 100 years (with an associated return period of 4950 years) is stipulated. The police decision for seismic design of large dam is described in the Specifications as follows: Dams designed base on this Specifications will be able to withstand the design ground motion; if some local damages occur, they will still be serviceable after ordinary treatment.

At present a dual performance criteria to address the safety and serviceability of dams through Maximum Credible Earthquake (MCE) and Operating Basis Earthquake (OBE) respectively is prevalent in many agencies. However, it has not been accepted by dam engineering in China, as it has remarkable defects both in defining the MCE more ambiguously and in establishing the unquantized failure criteria. It is in fact very unlikely that a dam that cannot operate any more after the OBE will fulfill the MCE requirements. Furthermore, the objectives and requirements for seismic design of large dams in China are quite similar to that for the OBE while its unitary design seismic input is a match for the MCE. Obviously, the Specifications in China actually set rather strict demands on the design seismic input for large dams.

Some further details are explained in the ensuing section for selecting of design ground motion parameters for Xiaowan arch dam.

DESIGN EFFECTIVE PEAK ACCELERATION BASED ON SPECIFIC SEISMIC HAZARD EVALUATION OF DAM SITE

The seismic hazard evaluation of dam site in China basically follows the approach traditionally used in international engineering practice. However, two distinctive characteristics are worthy of note.

First, the recurrence rate of events is specified not for each potential seismic source but for seismic belt with sufficient seismicity data. For more objectively reflect the non-uniform distribution of the recurrence rate of seismic belt both in time and space for different magnitude interval, a special distribution function (f_{i,m_j}) as weighted coefficient is involved to specify the weighted coefficient of the recurrence rate for magnitude interval m_j at i^{th} seismic source. The magnitude interval is usually taken as 0.5. The function(f_{i,m_j}) is determined by comprehensive estimation method based on the reliability of source identification, seismicity pattern, and the researches on the medium to long term seismic prediction.

Secondly, the seismic hazard evaluation for Xiaowan arch dam site is based on effective peak acceleration (EPA) instead of the current peak ground acceleration (PGA). 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. By analyzing 145 accelerograms with M≥4.5 recorded at rock sites in the western United States, an average normalized spectral with its peak at period 0.2 second and a amplification factor of 2.5 is obtained for events with different magnitude and distance intervals. Therefore, the EPA is defined as the spectral acceleration at period 0.2 second divided by an average amplification factor of 2.5. Then, an attenuation relationship for EPA is derived based on the regression model of Abrahamson (1997)[1] as follows:

$$\lg(EPA) = -0.0536 + 1.0241M - 0.0512M^2 - 1.3057\lg(R + 0.8566\exp(0.3396M)) \qquad (1)$$

Where the unit of EPA is gal, and the variance σ in the regression model is taken as a constant of 0.242 for convenience. The distribution map of potential seismic sources and the hazard curve after uncertainty rectification based on a logarithmic normal distribution assumption are shown in the Figure 1 and 2 respectively.

The design probabilistic level for Xiaowan arch dam has been decided as 10% in 600 years with an associated return period of 5695 years. From the hazard curve the corresponding design EPA is 300.16 gal.

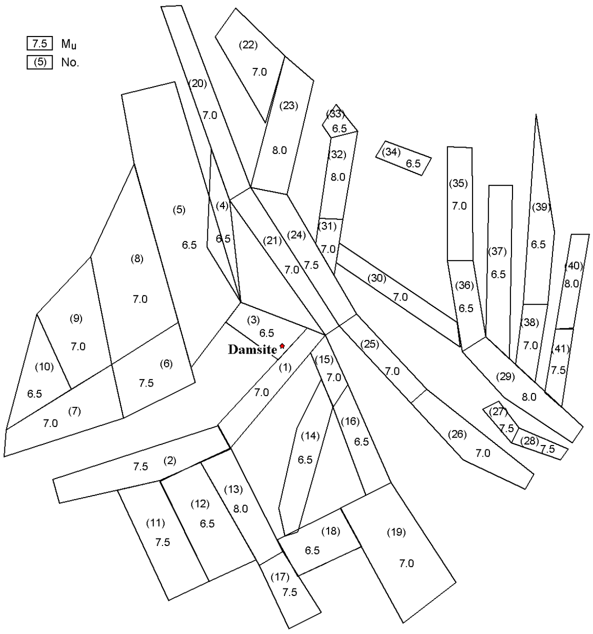


Fig.1 Distribution map of potential seismic sources for Xiaowan dam site

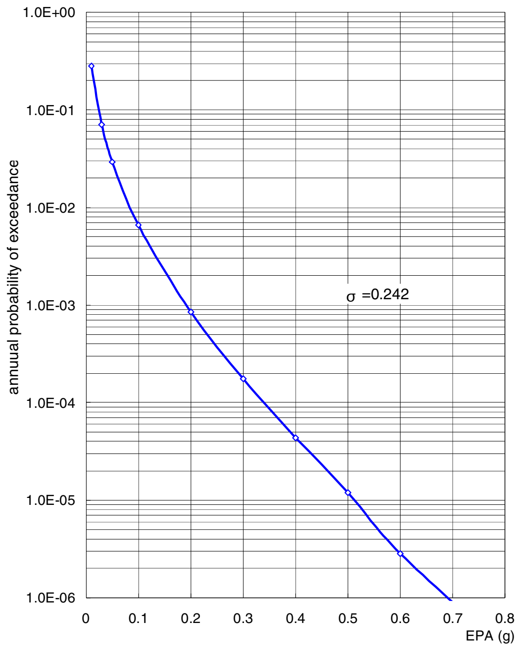


Fig.2 Hazard curve for Xiaowan arch dam

SITE-SPECIFIC DESIGN RESPONSE SPECTRUM FROM HAZARD- CONSISTENT SCENARIO EARTHQUAKE WITH MAXIMUM PROBABILITY

For seismic design the so-called equal-hazard spectra are frequently used. Upon specifying the design probability of exceedance, ordinates are read off from each spectral hazard curve with different period and are plotted against period to form the spectrum with the same probability of exceedance at each period. The equal-hazard spectrum is the result of many earthquakes with different magnitudes and locations. As a result, it does not reflect the physical characteristics of spectrum of a real earthquake associated with the actual magnitude and distance. Especially, as shown by practice, its spectral value near the period of 1 sec. is usually artificially amplified while it is of significant importance for high arch dam like Xiaowan. That is why a hybrid method combining both probabilistic and deterministic approaches of selecting specific scenario earthquake to determine the site-specific design response spectrum was provided for Xiaowan project. The conception of scenario earthquake was proposed by McGuire(1981,1995)[2], Ishikawa and Kameda (1988)[3], Chapman(1995)[4] and others. As an important premise, the peak ground acceleration at dam site of a scenario earthquake must be consistent with the value corresponding to the peak acceleration with design fortification probability of exceedance. However, in most cases, either the “hazard-consistent magnitude and distance” proposed by Ishikawa and Kameda, or the modal earthquake proposed by Chapman, the abovementioned presupposed requirement couldn’t be satisfied. Actually, it is always only a few potential seismic sources defined by seismic active faults having contribution to the design peak acceleration with fortification probabilistic level for large dams as required in the Specifications. Among them, to cause the design EPA at dam site, the earthquake located nearest to dam site along the major fault generally has a maximum contribution to the hazard curve, as usually a uniform space distribution within the source is assumed. Fig.3 shows the seismic resources contributing the design EPA at Xiaowan dam site. A scenario earthquake of magnitude m_{SE}=6.3 and distance Δ_{SE}=3km form source No.3 with maximum probability was determined to generate the site-specific design response spectrum (with damping ratio of 0.05) for Xiaowan arch dam as shown in Fig.4

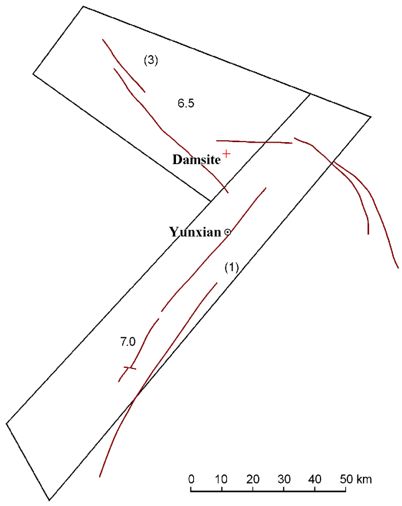


Fig.3 Seismic sources contributing design EPA at Xiaowan dam site

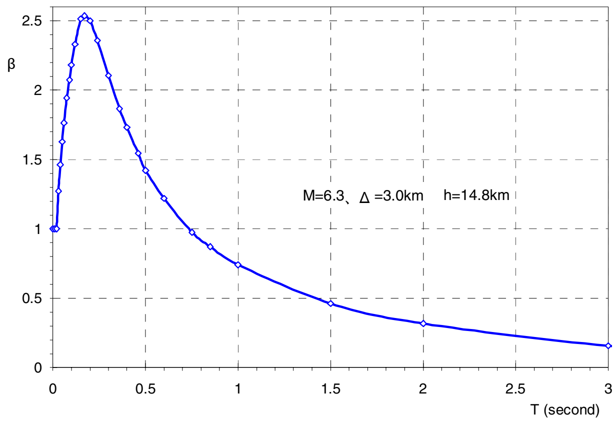


Fig.4 Site-specific design spectrurn consistent with EPA for Xiaowan arch dam

The annual probability of exceedance for the design acceleration response spectrum can be calculated according following formula:

$$P(m_{SE},\Delta_{SE}) = v\frac{A_{SE}\cdot f_{l,m_i} e^{-\beta(m_{SE}-m_0)}}{\sum_{i=1}^{n} A_i f_{l,m_i}\cdot e^{-\beta(m_i-m_0)}} \tag{2}$$

Where v is the recurrent rate of the i^{th} source with scenario earthquake; A_i, A_{SE} are the source areas associated with the l^{th} magnitude interval m_i and that of m_{SE} within the l^{th} seismic source respectively; f_{l,m_i} is the spatial distribution function of l^{th} source for m_j^{th} magnitude interval; m_0 is the lower limit magnitude; β is the coefficient in the Gutenberg-Richter formula of seismicity.

Assuming both the design peak acceleration and the normalized response spectrum are statistically independent random variables, the probability of the acceleration response spectrum should be the product of the probabilities of those two variables. Obviously, the probability of acceleration response spectrum provided by formula (2) has to be smaller than that of the peak acceleration, but never be equal-hazard.

DEVELOPMENT FOR DESIGN ACCELEROGRAMS

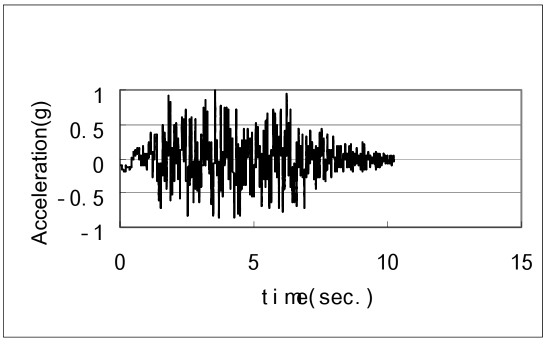
As in the seismic design of high arch dam like Xiaowan the nonlinear response analyses are required. So, development of the design accelerograms is necessary. A more reliable and efficient approach to generate the design artificial accelerogram compatible with the design response spectrum through variation arithmetic in time domain was developed for seismic design of Xiaowan arch dam [5]. In this approach the variation of the artificial accelerogram δa_0 can be expressed as follows, while taking the response of single degree of freedom system with frequency ω_l and damping ratio ξ_j to unit impulse $h_{jl}(t_{jl}^0 - \tau)$ as interpolation function with coefficient b_{jl}

$$\delta a_0(t) = \sum_{j=1}^{M} \sum_{l=1}^{N} b_{jl} h_{jl}(t_{jl}^0 - t) \tag{3}$$

Where t_{jl}^0 is the time with maximum response, M, N are the numbers of damping ratio ξ_j and spectral frequency ω_l respectively. Then the integration equations related the variations of artificial accelerogram δa_0 and response spectrum δS_{ik} can be translated into a set of algebraic equations for solving b_{jl} as follows:

$$\sum_{j=1}^{M} \sum_{l=1}^{N} b_{jl} \int_0^{t_{ik}^0} h_{jl}(t_{jl}^0 - \tau) h_{ik}(t_{ik}^0 - \tau) d\tau = \delta S_{ik} \tag{4}$$

In order to improve the integration calculation with higher efficiency and less computer memory a segment ally matching technique was used. Finally after solving b_{jl} for $\delta a_0(t)$ the artificial accelerogram can be easy acquired as $a(t) = a_0(t) + \delta a_0(t)$. The above-mentioned procedures were repeated to satisfy convergence precision. So, high convergence precision and high efficiency of the proposed method where fully proved by practice. The synthetic normalized accelerogram and spectrum match were plotted in Fig.5 and Fig.6, respectively.



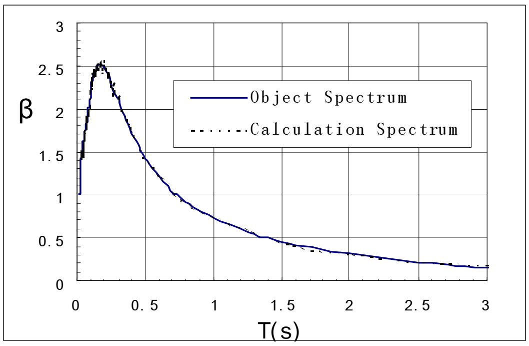


Fig.5 Synthetic normalized accelerogram **Fig.6 Spectrum match**

CONCLUSION

The input ground motion for Xiaowan arch dam of 292m high located in the area with high seismicity was carried out on the basis of a comprehensive study.

1. Instead of the traditional PGA the EPA was selected as more reasonable major input parameter for hazard evaluation of dam site with consideration of the spatial distribution function f_{l,m_i} for different magnitude interval of each source within a seismic belt.

2. Not the prevalent dual performance criteria, but a unique fortification criterion with a probability of exceedance of 2% in 100 years was accepted.
3. The frequently used equal-hazard spectrum was replaced by a more actual site-specific design spectrum from hazard-consistent scenario earthquake along the major fault with maximum probability.
4. A more efficient approach with high convergence precision for generating design artificial accelerogram compatible with design response spectrum by using time domain method but not the conventional frequency domain method was proposed.

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