Seismic Vulnerability Analysis of a Gravity Dam Based on Typical Failure Modes

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SUMMARY:
Seismic vulnerability analysis of dams is a key procedure in their seismic risk evaluation. A procedure for seismic failure process simulation which approximately considers heterogeneity of concrete is used. With consideration of uncertainty persistent in ground motion input as well as material properties of concrete, 180 nonlinear seismic analyses are performed based on which typical seismic damage modes are obtained. Then according to integrity of the dam itself and potential influence on downstream areas, five seismic damage levels including no damage, slight damage, moderate damage, severe damage and collapse of dam are formulated. Then by classifying status of the dam samples into different damage levels, vulnerability curves of the dam can be obtained. The presented procedure provides reference for seismic design and rehabilitation of gravity dams and can also be extended to seismic risk evaluation of arch dams.

Keywords: seismic vulnerability analysis, gravity dam, failure mode

1. GENERAL INSTRUCTIONS

The construction of large dams contributes greatly to the economic development, yet in the meantime poses threats to downstream areas. Up till now, quite some high concrete dams have been damaged by strong earthquake shocks. To name a few, Koyna gravity dam was shocked in the 1967 earthquake (M=6.5) and serious horizontal cracks were observed at the slope change area beneath the dam head; Pacoima dam underwent the San Fernando earthquake in 1971 (M=6.6) and Northridge earthquake in 1994 (M=6.8), permanent displacement of contraction joint occurred. Xinfengjian dam was damaged in 1962 earthquake (M=6.1) with penetrating cracks beneath the dam head. Sefid Rud Dam was damaged in the Manjil earthquake in 1990 and a horizontal crack at the dam head which almost penetrated through the dam occurred.

Great earthquakes have taken place frequently these years. The aseismic safety of large dams has become even important and seismic risk analysis of large dams has gradually drawn more attention by evaluating possible damage to the dam caused by earthquakes during its operation period. Seismic vulnerability analysis is one of the three procedures of seismic risk analysis. It provides the means to determine the probability distribution of the frequency pf occurrence of adverse consequences due to potential effects of earthquakes. It also helps to identify weak links of the dam concerning seismic aspect and provides reference for retrofitting.

Seismic fragility analysis was originally employed in analysis of nuclear power plants. Kennedy et al (Kennedy, 1980, 1984) proposed two methods for fragility analysis, namely Zion method and SSMRP method; Hirata et al (Hirata, 1991) obtained the relation between structural response and ground motion by data fitting, and presented the corresponding vulnerability curve based on reliability probability distribution function; Cărăusu et al (Cărăusu, 1996) presented an approach for vulnerability analysis of NPPs by fitting the relation between structural response and ground motion using bi-linear curves. As far as dams are considered, Tekie et al (Tekie, 2003) and Ellingwood et al (Ellingwood, 2001) presented the vulnerability curves for dam cracking, dam base sliding of gravity dams; Papadrakskis et al (Papadrakakis, 2008) performed the vulnerability analysis of Scalere dam as subjected to static loading using continuum strong discontinuity approach. Shen et al (Shen, 2008) proposed the concept of vulnerability analysis of dam-foundation system based on that of only the dam body as developed by Ellingwood.

Seismic fragility analysis, with fragility curve as the outcome, is an efficient approach for seismic risk analysis of engineering structures. But as far as concrete dams in seismically active regions are concerned, there still lacks a well established method. In the presented paper, based on substantive seismic failure simulation of gravity dams which considers heterogeneity of concrete as well as uncertainty in ground motion input and material capacity parameters, the seismic damage level of gravity dam is clarified, then seismic fragility curve of a gravity dam is formulated.

2. SEISMIC FAILURE MODELING OF GRAVITY DAMS

The methods for modelling nonlinearity of concrete structures generally falls into three categories: plastic mechanics, fracture mechanics and damage mechanics. Each category possesses its own advantages as well as disadvantages and has gained popularity in research. But there's up to now no single method that can model the whole response history of a concrete dam from elastic vibration, initiation of microcracks, propagation of cracks to final failure of the dam when subjected to strong earthquake shocks. The author proposed a relatively simple method which can simulate this whole process with a unified model (Zhong, 2011). Main points of this method are listed as follows. For detailed description please refer to the original literature.

a. Consideration of concrete heterogeneity

Concrete is highly heterogeneous in nature, consisting of aggregates, matrix, voids and so on. However, in conventional numerical analysis of concrete structures, concrete is always assumed as homogeneous and its heterogeneity is neglected. Actually, nonlinearity of concrete is closely related with initiation of microcracks, which can only be well modelled when concrete heterogeneity is considered. However, instead of precisely modelling all components in concrete dam, which is impossible yet unnecessary, the influence is considered in an approximate way. To be specific, the dam is discretized with very fine elements, and material properties are assumed to conform to Weibull random distribution.

b. Elastic damage constitutive relation

Concrete is a quasi-brittle material, as verified by the acoustic emission when concrete fails. In addition, since element size is very small, anisotropy and nonlinearity of concrete can be neglected, and simple elastic-brittle damage constitutive relation can be assumed. Considering the computers available for numerical simulation, the size is not small enough (0.3m in the present simulation), post-peak slope section and residual strength section following the descending section of stress-strain curve are introduced to revise the constitutive relation. Mohr-Coulomb criterion with tension cut-off is used as the failure criterion.

c. Uncertainty and randomness of ground motion and material capacity properties

The ground motion for a certain dam site is decided based on seismic hazard analysis, which produces a hazard curve concerning the peak ground acceleration (PGA). And the PGA for design and analysis is a value that has a predefined probability according to the design standard. This PGA is a conservative value yet may not be the one with the probability of most frequent occurrence. So for complete seismic risk analysis, the uncertainty of PGA should be considered.

In addition, the dynamic analysis of dams requires the generation of mathematical models, which attempt to depict the physical world through the use of idealized assumptions so that the analysis becomes tractable. In this process, the elements of the mathematical model are ascribed definitive properties which have been arrived at through lab test, field investigations, analytical studies and published data. Inevitably, there is uncertainty concerning the application of all experimental data as well as data scatter in the basic experiments.

3. IDENTIFICATION OF SEISMIC DAMAGE LEVELS

When subjected to strong ground motions, gravity dams may be damaged in different modes. Typical seismic damage modes can be extracted based on that, and then seismic damage levels can be identified according to the corresponding consequences. This is an indispensable step before seismic vulnerability analysis can be performed. Strictly speaking, classification of seismic damage levels should be established based on document survey of dams actually damaged by earthquakes in history, or on a large number of simulation of dams subjected to strong earthquakes, or on both. But obviously none of the three approaches are possible. And since the presented paper focuses on bringing forward an approach for vulnerability analysis rather than establishing a standard for vulnerability assessment, and the shape of cross sections for gravity dams are similar, only a typical gravity dam section is employed for this research.

Detailed description of the numerical simulation is stated in Section 4 and here only a part of the results are presented. Based on the result of numerical simulation, typical failure modes of the dam are extracted as shown in Figure 1. In Figure 1(a), the dam kept intact and no visible cracks were found. For cases shown in Figures 1(b) to (g), the dam suffered damage to different degrees. Sharp change of dam slopes, dam heel and downstream dam face were weak parts and cracks tended to occur around these locations. From Figure 1(b) to (d), the damage situation of the dam got more serious, but consequence was limited to the dam itself and no disastrous flood was expected. While for cases shown in Figure 1(e) to (g), penetrating cracks occurred at the lower half of the dam and the dam basically failed to retain its water impounding function.

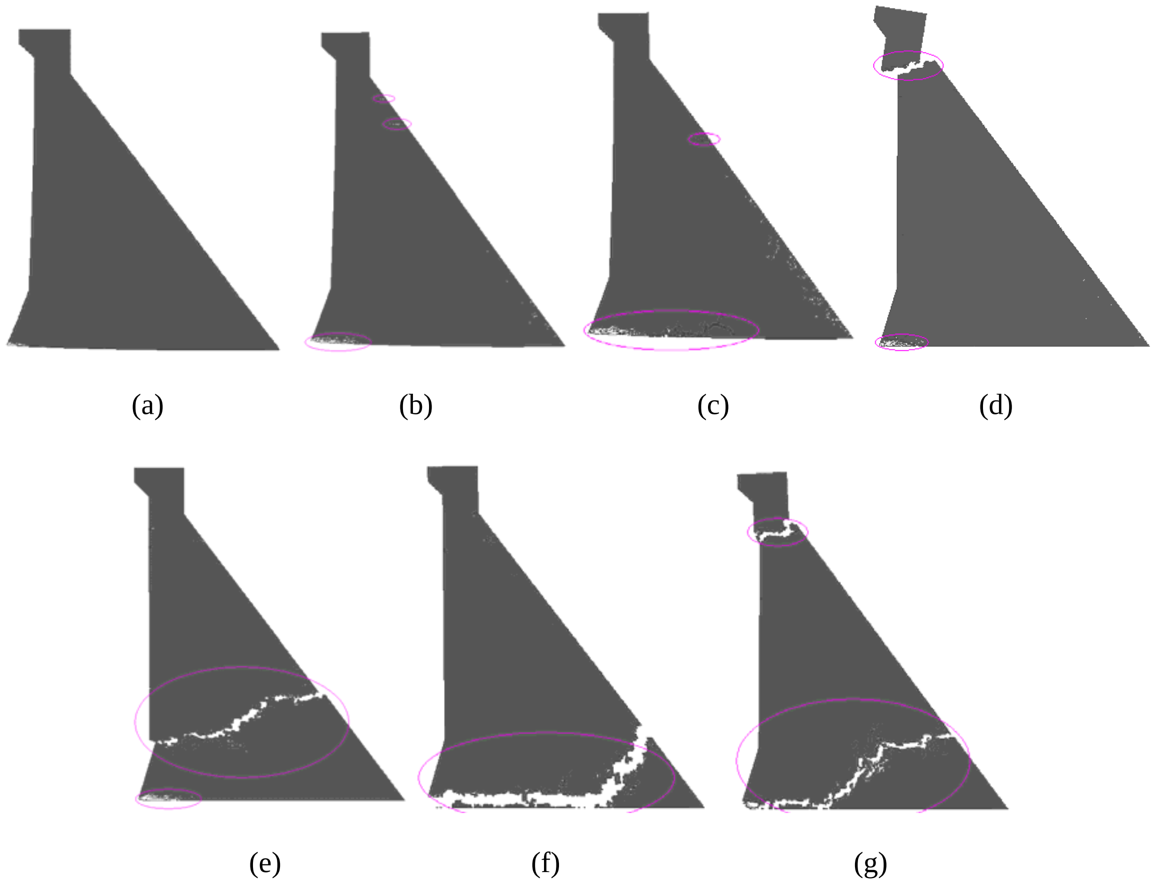

Fig.1 Typical failure modes of dam

The identification of damage levels is based on the simulation result of seismic damage mode, as well as considering the seriousness of possible consequences and cost for retrofitting. The corresponding regulation in the standard for building structures is also taken as reference. Five levels are suggested, i.e. complete dam, slight damage, medium damage, serious damage, collapse of dam. The sketch map is shown in Figure 2 and the details of each level are as follows.

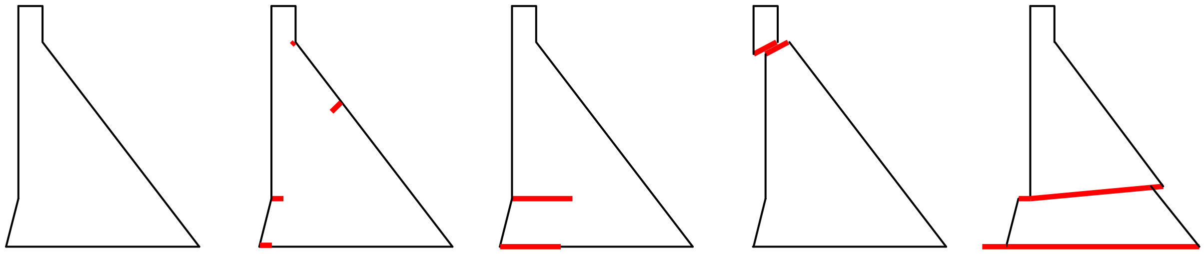

Fig.2 Identification of damage levels

Level I Complete dam: the dam is complete, with only local microcracks which don't influence normal functioning of the dam;
Level II Slight damage: localized macrocracks occur, with length shorter than one third of the cracking path, and the dam can restore normal function with minor repair in a short time;
Level III Medium damage: more cracks over the dam body occur, with length longer than one third of the cracking path, yet the dam is not broken and can restore normal function with major repair;
Level IV Serious damage: cracks penetrates through the dam, dam head gets broken off, recovery is almost impossible;
Level V Collapse of dam: dam is broken off at lower half of the dam body, water pounding function is totally lost, recovery is impossible.
It's to be noted that this identification is based on numerical simulation of only one dam together with empirical judgement, which make it less complete and objective. With more extensive numerical simulation on different gravity dams and more documents on gravity dams actually damaged by earthquakes, the presented work can be improved.

4. VULNERABILITY ANALYSIS

4.1. Procedure for vulnerability analysis

In vulnerability analysis of structures, the probability of structures suffer damage to different degree when subjected to earthquake shocks of different intensity is investigated, and the final result is given in the form of fragility curve. For seismic fragility analysis of gravity dams, two approaches are available. On the one hand, based on document survey of seismic damage of gravity dams, the statistic relation between damage level and earthquake intensity can be established. This approach is more credible and objective. But it only effectively applies to dam with similar seismic environment, site condition as well as state of the dam as the reference dam, which is not realistic since abundant document should be available. On the other hand, the approach based on numerical simulation is a promising alternative. Based on Monte-Carlo simulation of seismic failure process of dams of different geometry, material, site condition, the relation between damage level and PGA can be constructed. It's easy to implement and can avoid the scarcity of seismic damage document of dams. However, the numerical model used for failure simulation is very important.
In this analysis, the aforementioned model that approximately considers influence of the concrete heterogeneity is employed. Uncertainty in ground motion and material properties of dam are considered. The flowchart for this analysis is shown in Figure 3.

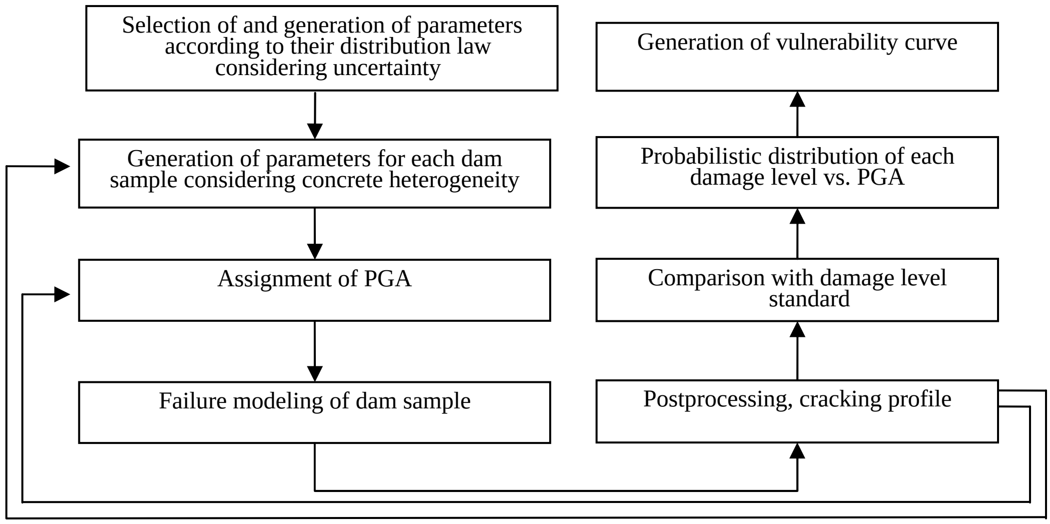

Figure 3. Flow chart for vulnerability analysis

4.2. Models and parameters

The dam section employed is the non-flow section of Jin'anqiao gravity dam in China. The maximum height of the section is 114m. In all 180 numerical analyses have been performed to simulate the nonlinear behaviour of the dam in strong earthquakes. Uncertainty of peak ground acceleration is considered based on the probability density curve of the site as shown in Figure 4. The design PGA of the dam is 0.399g, so besides design PGA, cases with acceleration amplitudes corresponding to 0.2g, 0.3g, 0.5g, 0.6g, 0.8g are also calculated. Distribution of various material capacity parameters are taken from standard on design of NPPs (ASCE, 1980), as shown in Figure 2. More detailed information on geometry of the dam, material properties, loading condition can be referred to in literature (Zhong, 2011).

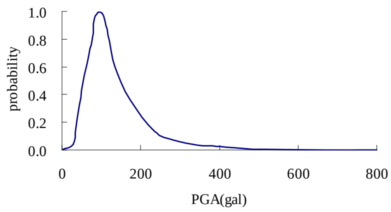

Figure 4. Probability distribution of peak ground acceleration

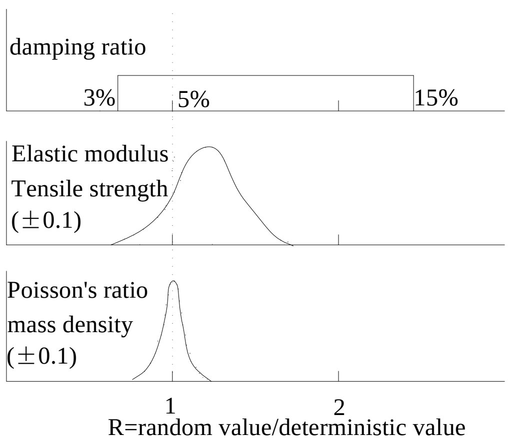

Figure 5. Probability distribution of material parameters

4.3. Vulnerability curve

Analyses of thirty samples of the dam subjected to ground motions corresponding to six PGAs respectively are performed, and this resulted in 180 nonlinear responses (including failure process) of the dam. In some cases, the dam keeps stable and no cracks occurred, while in other cases cracks occurred but didn't penetrate through the dam, and still in some cases the cracks penetrated through the dam and dam breakage was resulted. Typical failure modes of the dam were extracted and are shown in Section 3. According to the damage level identification, each of the 180 dam was categorized to a certain level, and based on that vulnerability curve can be constructed, as shown in Figure 7.

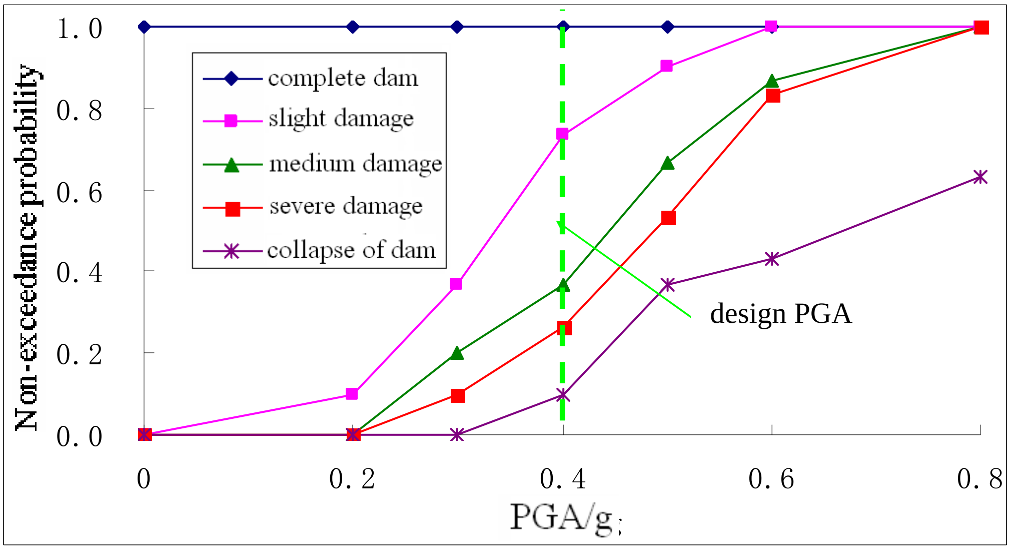

Fig.7 Fragility curves of dam

As can be seen from the figure, with the increasing of PGA, the probability of dam without cracking (Level I) is decreasing, and the probability of dam failure is increasing. Since heterogeneity of concrete as well as uncertainty of material properties are considered, dam can suffer serious damage in relatively weaker ground motion and also suffer slight damage in relatively stronger ground motion. However, the probability of damage is increasing with the increasing of PGA as a whole, which is in accordance with empirical judgment. From the vulnerability curve in the figure, damage can be expected for ground motion of different amplitude, and with the intensification of ground motion, the degree of damage is increased. For ground motion corresponding to design PGA (0.399g), the probability for medium damage and above is 36.67%, the probability for dam failure is 10.00%. For ground motion with a magnitude of twice the design PGA (approximately 0.8g), the probability for dam failure is increased to 63.33%.
According to the above analysis including damage mode and vulnerability curve, for the dam subjected to acceleration time history with an amplitude of 0.399g, corresponding to 2% of non-exceedance probability, reinforcement measurement is necessary for the dam heel, upstream faces as well as slope changing position at the dam head and upstream face.

5. CONCLUSION

Based on consideration of concrete heterogeneity, uncertainty and randomness of ground motion input and material properties of concrete, typical failure modes of a gravity dam is extracted through extensive nonlinear failure process simulation. Damage levels including five levels, i.e. complete dam, slight damage, medium damage, serious damage and collapse of dam are identified, an approach for seismic vulnerability analysis of gravity dam is presented.
When subjected to design ground motion, for the dam without seismic reinforcement, the probability for medium damage and above is 36.67%, and the probability for collapse of dam is 10.00%. So it's suggested that seismic reinforcement measurements be employed.

The approach for seismic vulnerability analysis and the vulnerability curve obtained provide certain reference to seismic design, seismic reinforcement as well as seismic risk analysis of gravity dams.

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REFERENCES

ASCE (1980). Seismic Analysis and Design, Chapter 5, Structural Analysis and Design of Nuclear Plant Facilities, America.

Cărăusu, A., Vulpe, A.(1996). Fragility estimation for seismically isolated nuclear structures by high confidence low probability of failure values and bi-linear regression. *Nuclear Engineering and Design* **160:3**, 287-297.

Ellingwood, B., Tekie, P.(2001). Fragility analysis of concrete gravity dams. *Journal of Infrastructure Systems* **7:2**, 41-48.

Hirata, K., Kobayashi, Y., Kameda, H. and Shiojiri, H.(1991). Fragility of seismically isolated FBR structure. *Nuclear Engineering and Design* **28:2**, 227-236.

Kennedy, R.(1980). Seismic fragilities for nuclear power plant risk studies. *Nuclear Engineering and Design* **59:2**, 315-338.

Kennedy, R., Ravindra, M.(1984). Seismic fragilities for nuclear power plant risk studies. *Nuclear Engineering and Design* **79:1**, 47-68.

Papadrakakis, M., Papadopoulos, V. (2008). Vulnerability analysis of large concrete dams using the continuum strong discontinuity approach and neural networks. *Structural Safety* **30:3**, 217-235.

Shen, H., Jin, F., Zhang, C.(2008). Performance-based Seismic Fragility Analysis of Concrete Gravity-Foundation System. *China Civil Engineering Journal* **25:12**, 86-91.

Tekie, P., Ellingwood, B.(2003). Seismic fragility assessment of concrete gravity dams. *Earthquake Engineering and Structural Dynamics* **32:14**, 2221-2240.

Zhong, H., Lin, G., Li, X. and Li, J. (2011). Seismic failure modeling of concrete dams considering heterogeneity of concrete. *Soil Dynamics and Earthquake Engineering* **31**, 1678-1689.