Seismic Risk Analysis of Low-Tower Cable-Stayed Bridge

GU Yin, ZHONG Hua, ZHUO Weidong
College of civil engineering Fuzhou university, Fuzhou, Fujian, China

SUMMARY:
Seismic risk analysis requires analysis of seismic risk and structural seismic vulnerability analysis. A risk probability analysis procedure is proposed for taking into account the randomness of the earthquake input and material of structure. The uncertainty of the input ground motion simulation is studied by considering the probability distribution of site seismic intensity. Material uncertainty is considered by sampling method. A low tower cable-stayed bridge is studied for the project study. The samples are obtained by combination of the incremental dynamic analysis and Latin Hypercube sampling. The nonlinear finite element analysis for low tower cable-stayed structure is made by fiber model. The damage index of low tower cable-stayed bridge structure is studied. The damage probability is determined by defining four damage states namely, minor, moderate and serious and collapse. The strain was used for damage index of tower and piers. The displacement was used for damage index of bearings. The fragility curves are established based on the behavior of various components and integral performance of the bridge. The law of probability of earthquake risk of the low tower cable-stayed bridge is deeply analyzed. The main beam and the tower are the main force component, its mechanical properties of the low tower cable-stayed bridge is different with the general cable-stayed structure. The results will provide technical support for the earthquake risk analysis and operational management.

Keywords: *low- tower cable-stayed bridge*, *seismic risk probability analysis*, *Latin Hypercube sampling*, *incremental dynamic analysis*

1. INTRODUCTION

The experience in the Wenchuan earthquake shows that the damaged bridges have important influence to the recovery of city. Disaster Reduction, as well as disaster risk assessment, prediction of earthquake damage and loss, development of disaster reduction policy has been a matter which was concerned by the government and experts in the world extraordinarily. Risk assessment initially used in important structures. Howard H. M. Hwang(1988) studied the safety assessment of the nuclear power plants by the seismic hazard analysis and seismic vulnerability analysis. After that, the risk probability method for seismic assessment is introduced to the other important structures including the bridges(Lupoil A. 2003, Malla S.1988, R.A. Khan 2006, John B.Mander 2007) . The cable-stayed bridge with low tower is a new type of bridge structure system, which is cooperated system incorporating the concrete cable-stayed bridge and the girder bridge structure. It has been widely used in many counties because of its good performance(CHEN Cong-chun 2007).

It is necessary to evaluate the earthquake risk of bridges with different type. The risk should be lower than the expectation for the system security of the transport. The lower tower and cable-stayed bridge is a new type of bridge. Its performance is different with the normal cable-stayed bridge. Its seismic vulnerability should not be analyzed with statistics method. A useful method of risk analysis for irregular bridge is structure dynamic analysis combined with probability theory. The probability of structure damage has been studied extensively(R.A. Khan 2006). John B. Mander(2007) use finite element for nonlinear IDA(increment dynamic analysis). The results are made of integration into a probabilistic risk model for seismic risk assessment. Tao,etc(2006) evaluate the seismic risk for Chongming cross river in Shanghai by fuzzy comprehensive assessment method, and propose a measure for risk reduction. Qiao,etc,(2010) adopt the recurrence interval method to calculate the probabilistic of seismic risk of the continuous rigid-frame bridge during construction, determine the risk level of the damage and make the corresponding decision. Lu.etc,(2010) proposed an improvement cloud map method considering the uncertainty both of the earthquake and the structure by Sampling techniques of Latin hypercube(LHS), and expanded the Probability seismic demand analysis to model, vulnerability and hazard Analysis. Huang.etc,(2009)adopted the LHS method for Probability seismic demand analysis, which devoids a large amount of sampling work with Monte-Carlo Method. Feng Qinghai.(2008) proposed a Probability seismic risk assessment method combined the IDA and MC method.

In this paper, the Mechanical Behavior of the lower tower cable-stayed bridge structure has been studied by dynamic method and probabilistic method. The seismic vulnerability of structure and its damage probability has been analyzed considering the seismic risk.

2. ANALYSIS OF SEISMIC RISK PROBABILITY

In general practice, seismic hazard is defined as the probability that a certain level of earthquake ground motion will occur at a site within a given time interval; seismic risk is the probability that some type of failure will occur due to earthquake, measurable in terms of damage, financial loss or even casualties. The fragility of structures is expressed in terms of vulnerability, and the relationship between risk and hazard can then be written in terms of the simple equation:

$$\text{Risk}=\text{Hazard}\times\text{Vulnerability} \tag{1}$$

where vulnerability is the probability that, given a certain level of ground motion, damage will occur.

The seismic hazard depends on the site geological conditions and the potential seismic source activities; needs to determine that the intensity of the earthquake may be in a specific area, and give the probability of occurrence of earthquakes of various magnitudes.

The uncertainty of the structural system resistance is affected by the randomness of material strength and stiffness, boundary conditions of uncertainty, and the uncertainty of the time-varying factors. This would inevitably lead that the same structural system will show a different dynamic response even with the incentive of the same seismic wave. Therefore, it is also necessary to consider the resistance of the structure from the perspective of probability.

The seismic probabilistic risk assessment process of lower-tower cable-stayed bridge is shown in Figure 1.

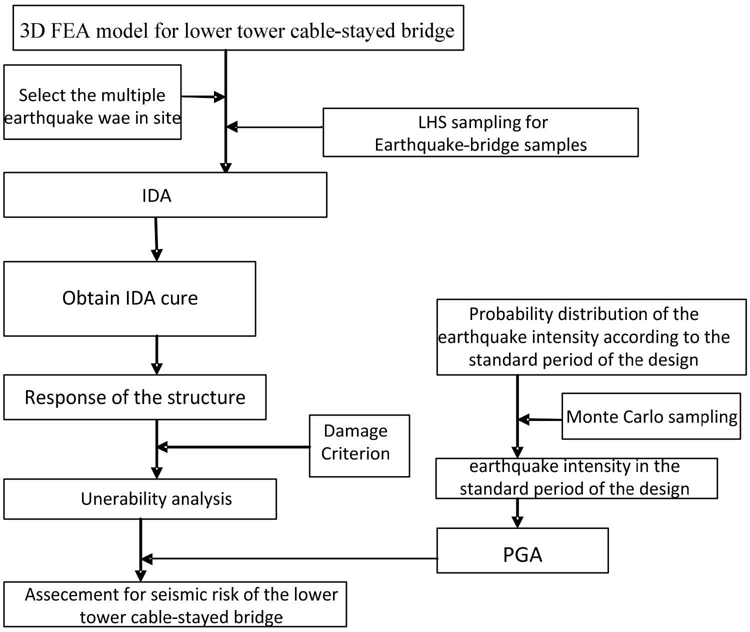

Figure 1. Bridge seismic probabilistic risk assessment procedures

3. PRINCIPLES OF LHS SAMPLE AND ITS PROCEDURES

Latin Hypercube Sampling, referred to as LHS, is a uniform sampling method with the less sample variance(Hoshino N. 2000). Compared with Monte Carlo sampling methods, the LHS sample method is more accurately reflected distribution of mean value in the probability function of the input. The sampling numbers are greatly induced with higher computational efficiency.
Random function with multiple variables:

$$g(Z) = g(Z_1, Z_2, \cdots, Z_k) \tag{2}$$

The basic steps for LHS procedure are as follows:
(1) variables Z_i (i = 1, ···, k) in function of the random were divided into *n* interval with equal probability. The probability of Z_i falling on any interval is 1 / n.
(2)The value of Z_i (i = 1, ···, k) is chosen randomly in *n* equal probability interval divided in the previous step. The value of the corresponding random vectors (z_{i1}, z_{i2}, ···, z_{in}) (i =1, ···, k) is obtained.
(3) The random vectors (z_{i1}, z_{i2}, ···, z_{in}) (i = 1, ···, k) are combined randomly with no coincidence to get a dimension of an n × k sample matrix.
(4) The probability characteristic values of each element of each row in the sample matrix is introduced into equation (1) for computing the corresponding gi, (i = 1, ···, k). The samples can be analyzed with probability characteristic value, such as the sample mean, variance, and so on.

In general, earthquake demand parameters (EDP) can be represented as a complex form of random function by random vector of structural parameters and ground motion random variables. It is stated as follows:

$$EDP = g(X, Y) \tag{3}$$

in which $X = (X_1, X_2, \cdots, X_k)$ is represented as random of structure; Y is characterization of earthquake random.

4. MONTE CARLO SAMPLING FOR THE SEISMIC INTENSITY

China's Seismic Fortification Levels is designed generally based on the basic intensity. Check the seismic hazard analysis of China's 45 cities and towns in the literature studied by Gao Xiaowang(1985). It meets China's actual situation to adopt the probability of the type III extreme value distribution to fit the seismic intensity distribution.

Type III extreme value distribution can be expressed as:

$$F_{\text{III}}(x) = \exp\left[-\left(\frac{\omega - x}{\omega - \varepsilon}\right)^{K}\right] \tag{4}$$

in which, ω is upper limited value; General seismic intensity is taken as 12 degrees; ε is a value occurring most frequently with probability of exceedance equaling to $1\text{-}e^{-1}$(0.632) in a given period; *K* is a parameter of shape.

The three methods to determine K is described below: (1) quantile value; (2) least square method on minimizing the ensemble mean square error of the estimation; (3) maximal likelihood method. Three methods to estimate the value of the shape parameter K are listed by LIU HUixian(1981)· The least squares method is the best method from the point of view of fitting. But from the practical engineering point of view, the basic intensity of the corresponding K value meets the accuracy requirements. This article takes the latter.

The probability distribution functions $F_{\text{T}}(i)$ follows the extreme value type III distribution within T=50 years. The probability distribution function in any t year is:

$$F_{\mathrm{t}}(i)=\left[F_{\mathrm{T}}(i)\right]^{t/T}=\left[\exp(\frac{\omega-i}{\omega-\varepsilon})^{K}\right]^{t/T}=\exp\left[-\frac{t}{T}(\frac{\omega-i}{\omega-\varepsilon})^{K}\right] \tag{5}$$

In this paper, the conversion relationship, between ground motion peak acceleration A and the seismic intensity I, follows the equation listed by LIU HUixian(1985):

$$A=10^{(I.Log2-0.01)} \tag{6}$$

in which unit of A is *gal*. Due to statistical analysis, the seismic intensity is a continuous variable. In fact, the seismic intensity is a random variable.

5. SEISMIC VULNERABILITY CURVES

According to the theory assumption, the probability density function of the elements of the lower tower cable-stayed bridge can be expressed in the manner of lognormal distribution function shown in follows:

$$f(a)=\frac{1}{\sqrt{2\pi}\eta a}\exp[-\frac{1}{2}(\frac{\ln a-\lambda}{\eta})^{2}] \tag{7}$$

in which a is value of PGA; λ and η are mean and standard deviation for describing a component met injury state.

Probability density functions in Eq.(7) is integrated within its definition area. The cumulative probability distribution function of the lower tower cable-stayed bridge is shown below:

$$F(a)=\frac{1}{2}+\frac{1}{2}\mathrm{erf}\left[\frac{\ln a-\lambda}{\eta\sqrt{2}}\right] \tag{8}$$

The response of the damage element is studied by IDA method under wave combined of longitudinal, transverse and vertical directions. According to the damage state defined above, the probability of the damage for any degree is calculated for different intensity of seismic waves from 0.1g~1.0g. Use Lsqcurvefit, a nonlinear fitting function, to fit the cumulative damage probability distribution function of the various components at all levels of damage. The probability distribution of the damage of the various components at all levels can be obtained by choosing more precise fitting parameters in the different strength of an earthquake. Finally, draw the vulnerability curves of the various components of the damage state at all levels and make relevant analysis.

6. SEISMIC VULNERABILITY ANALYSIS OF THE SHORT TOWER CABLE-STAYED RIDGE

6.1 Project Overview

The overall structure of the main bridge arrangement is shown in Figure 2. The example is a prestressed concrete girder with lower tower cable-stayed bridge and single towers with double cable plane. The span of the main bridge is 60m +60m. The main bridge length is 120m. The wide of bridge is 16.65m. The tower and beam is consolidated in the location of the connection. The bridge site type is Class I with the seismic intensity of 7 degrees. The peak ground acceleration is 0.1g. The standard period of the design is 100 years.

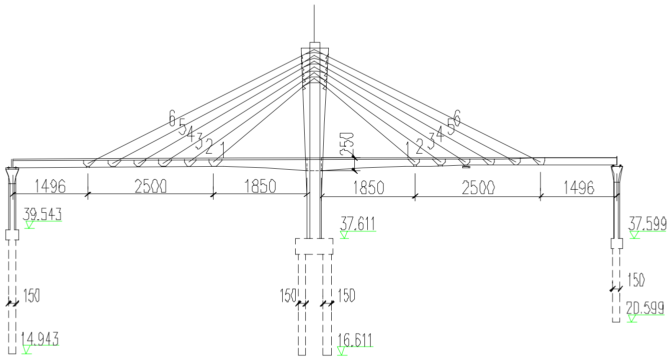

Figure 2. Main bridge overall structure layout

6.2 Damage Limit States And Damage Index

There defines four damage level for elements. The main tower and side pier can be simulated by fiber model. The stress and strain of reinforce bar and concrete can be obtained from software analysis directly. The damage index of tower and side pier can be defined by material strength. The main girder can be modeled by element of elastic beam with strength and damage index proposed by Hwang(2001).The damage principle of cable can be defined by strength index which is ultimate tensile strength of prestressed strand. So there are only two damage levels for the cable. It is common to use displacement as a damage index for bearings. The details listed by ZHENG Wenting(2011).

6.3 FEA Model

A three-dimensional finite element analysis model of full-bridge is created with X-axis along the bridge, the Y-axis crossing bridge and the vertical Z-axis in the global coordinate system. Use nonlinear beam-column element to simulate the main tower and the side piers with fiber cross section. Girders and bridge deck are adopted a flexible beam-column element (ElasticBeamColumn) to simulate. The cable is simulated by truss. The bearing is considered by Zero-Length Element composed of six springs. A spring is on behalf of one degree of freedom directions. The concrete constitutive model is created by Concrete01 Material, named amendment Kent-Park concrete material model, which is proposed by Scott et al. Its stress - strain relations can be divided into the rise and fall of two parts. Selected Steel02, named Giuffre-Menegotto-Pinto model, for the reinforcement model proposed by Menegotto M.(1973). The skeleton curve of the constitutive relation is a bilinear line, which reflects the Bauschinger effect. It is a common model using in the nonlinear seismic analysis.

6.4 Ground Motion – Bridge Sampling With LHS

Select the concrete compressive strength, steel yield strength and reinforced elastic modulus of the material parameters as random variables for random of the material of bridge. According to the probability distribution of the corresponding types of concrete compressive strength, yield strength of reinforced steel and the modulus of elasticity in the code *Unified standard for reliability design of highway engineering structures*（GB/T50283-1999）, the 50 sampling of bridges are obtained by LHS method. The selected seismic waves are shown in Fig.2.

It is shown in Fig.2 that the mean values of the response spectrum of the seismic waves selected in 0 ~ 2s interval are closed to the values of specification recommendations on the Class I site. The former is greater than the latter. The fundamental vibration period of the lower tower cable-stayed structure is generally less than 2s. The selected 50 seismic waves has been standardize and proportionally enlarged or reduced to form the time history curves with PGA value of 0.1g to 1.0g acceleration. The increment is 0.1g. Fifty models selected from fifty ground motion - bridge samples are used for IDA analysis.

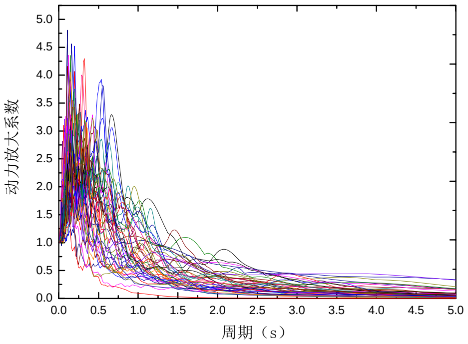

Figure 3. Response spectra of 50 seismic waves

6.5 Mente-Carlo Sampling Of The Seismic Intensity

The type of site of the Xian'gang bridge is Class I. The seismic intensity is 7 degrees with probability of exceedance for 63.2%. The value of the intensity occurring most frequently is 5.45 degree. So the equation for parameter K is:

$$1\text{-}0.1=\exp\left[-\left(\frac{12-7}{12-5.45}\right)^{K}\right]\Rightarrow K=8.32 \tag{9}$$

Substitute K into equation (5), distribution probability of seismic intensity in any t years is:

$$F_t(i)=\exp\left[-\frac{\mathrm{t}}{50}\left(\frac{12-i}{12-5.45}\right)^{8.32}\right] \tag{10}$$

According to the Monte Carlo described previously, random numbers Generated. 10000 random numbers fitting the type III of distribution of the extreme value are extracted. 10000 values of PGA are generated.

$$RandPGA(i)=10^{Rand(i)\log(2)\text{-}0.01} \tag{11}$$

6.6 Seismic Risk Analysis Of Low Tower Cable-Stayed Bridge

Consider seismic risk probability in t years, Seismic Vulnerability Analysis is made by IDA method computing 50 seismic-bridge sampling extracted by LHS method. The peak ground acceleration values, which structures reach the damage degrees under various seismic waves, are obtained. Then for each seismic wave, if 10000 seismic intensity random numbers are drawn by Monte Carlo sampling method, there are 10000 value of corresponding PGA. Then there are a total of 10000×50=500000 values of PGA. The numbers of PGA which is greater than or equal to the aforementioned values of damage degree are calculated. For example, when main tower reached the light damage, there are 272 PGA exceeding the damage degree. The seismic risk probability is:

$$\frac{272}{500000}\times 100\%=0.054\% \tag*{（12）}$$

The same method is used for calculating the seismic risk probability of each damage degree from t=10 to t=100 years. Shown in Fig.4, I, II, III and IV denotes the minor damage, moderate damage, serious damage and collapse, respectively. The damage probabilities of the elements in the different period of years are shown in the figure 4. The risk probabilities of exceeding the minor and medium damage have significant value. The risk probabilities of serious damage and collapse have a very small percentage. The risk probabilities of exceeding damage of main tower under longitudinal direction are bigger than that under transverse input direction. Under the longitudinal input, the risk probabilities of exceeding damage of r side piers are smaller than that of the main tower. Under the transverse direction, the risk probabilities of exceeding damage of side piers are bigger than that of the main tower. Compared with the response of two side piers, the height of the pier has effect on the probability of damage in both longitudinal and transverse directions. There is almost no damage in main girder. The bearings are most vulnerable element in longitudinal direction.

Considering the damage state of each component, the damage probability of the bridge system under the earthquake in service life period is shown in Fig.6. The probability of incidence of damage of the whole bridge is very small during the standard period of the design. The probability of occurrence of severe damage and collapse is close to zero. The structure is relatively safe.

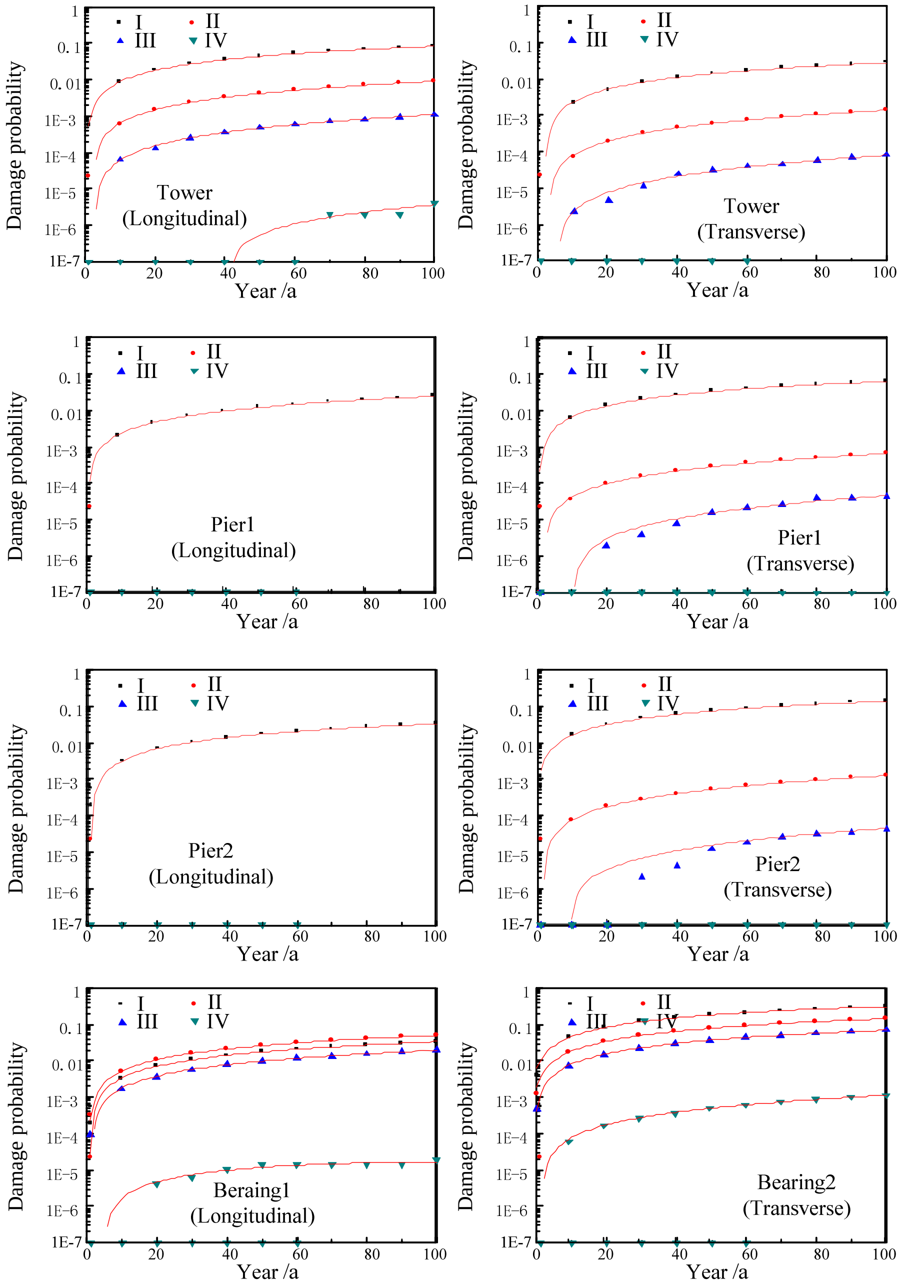

Figure 4. Damage probability of each component under the earthquake in service life period

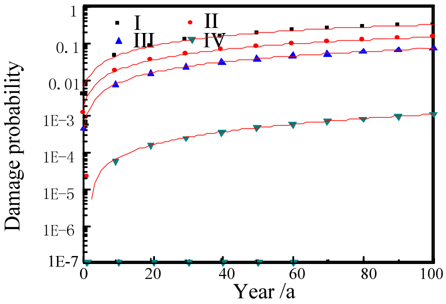

Figure 5. Damage probability of the bridge system under the earthquake in service life period

7. CONCLUSION

The LHS method, used for considering the material randomness, is combined with the multiple seismic waves for vulnerability analysis. Based on the analysis of seismic vulnerability of the bridge and the randomness of the seismic waves, of which intensity and PGA values are sampling drawn by Mente Calro method for avoiding the complex integrals, the seismic risk probability of the main members of the lower tower cable-stayed bridge is studied.

Some conclusions are drawn by numerical analysis for the typical lower-tower cable-stayed bridge: In addition to side piers, seismic risk probability of the elements of the lower-tower cable stayed bridge in longitudinal direction is larger than that in transverse direction. It should be focus on the seismic risk probability of the bearings and main tower.

This method makes up for the shortcomings of the seismic vulnerability analysis which only considers the structural damage neglecting the probability of earthquake. It is necessary to strengthen risk management of this kind of the bridge with complex system in the future by the seismic risk probability.

ACKNOWLEDGEMENTS

Project supported by the National Science Foundation of China (Grant No. 51108088) and Natural Science Foundation of Fujian Province, China(Grant No. 2010J01287).

REFERENCE:

Howard H. M. Hwang.(1988). Seismic probabilistic risk assessment and seismic margins studies for nuclear power plants. *Probabilistic Engineering Mechanics*, **3:4**, 170-178.

Lupoil A, Franchin P, Schotanus M.(2003). Seismic risk evaluation of RC bridge structures. *Journal of Earthquake* Engineering *and* Structural Dynamics, **32**, 1275–1290.

Malla S.(1988). Safety and reliability of the cable-system of cable-stayed bridges under stochastic earthquake loading. Master thesis.Bangkok (Thailand): Asian Institute of Technology.

R.A. Khan, T.K. Datta, S. Ahmad.(2006). Seismic risk analysis of modified fan type cable stayed bridges. *Engineering Structures*. **28:9**, 1275-1285.

John B.Mander, Rajesh P. Dhakal, Naoto Mashiko and Kevin M.Solberg.(2007). Incremental dynamic analysis applied to seismic financial risk assessment of bridges. *Engineering Structures*. **29:10**:, 2662-2672.

CHEN Cong-chun, ZHOU Hai-zhi, XIAO RU-cheng.(2006). Recent Research Advancement of Extradosed Cable-Stayed Bridge. *World Bridges*. **1**,70-73. (in Chinese)

John B.Mander, Rajesh P. Dhakal, Naoto Mashiko and Kevin M.Solberg.(2007). Incremental dynamic analysis applied to seismic financial risk assessment of bridge. *Engineering Structures*. **29**:**10**, 2662-2672.

Tao Lubin.(2006). Project risk analysis theory and practice: Shanghai Chongming cross-river channel engineering. Shang hai : Tongji University Press. (in Chinese)

QIAO Meili; DU Jinsheng; WANG Kaijian.(2010). Analysis of Seismic Risk for Long-span Continuous Rigid-frame Bridges during Construction. *Journal of Highway and Transportation Research and Development.* **27:11**, 78-82. (in Chinese)

LÜ Dagang; YU Xiaohui; PAN Feng; WANG Guangyuan.(2010). Probabilistic seismic demand analysis of structures based on an improved cloud method. *World Earthquake Engineering*. **26:1**, 7-15. (in Chinese)

HUANG Mingang.(2009) seismic vulnerability, risk and risk analysis for Reinforced concrete continuous beam bridge. Harbin: Harbin Institute of Technology. (in Chinese)

Feng Qinghai.(2008) Seismic vulnerability and risk probability analysis for Large bridge. Shanghai: Tongji University. (in Chinese)

Hoshino N, Takemura A.(2000) On reduction of finite sample variance by extended Latin hypercube sample. *Bernoulli*. **6:6**, 1035 - 1050

Gao Xiaowang, Bao Aibin.(1985). PROBABILISTIC MODEL AND ITS STATISTICAL PARAMETERS FOR SEISMIC LOAD. *Earthquake Engineering and Engineering Vibration*. **5:1**, 13～22. (in Chinese)

LIU HUixian, LU Rongjian, CHEN Dasheng.(1981). A proposal of the amendments to the old seismic intensity scale. The 4th Earthquake Engineering Research Report of Chinese Academy of Sciences(1-13), Institute of Engineering Mechanics. Beijing: Science Press. (in Chinese)

Hwang H，Liu J，Chiu Y．(2001). Seismic fragility analysis of highway bridges．Center for Earthquake Research and Information，The University of Memphis.

ZHENG Wenting. (2011). Seismic probabilistic risk assessment of lower-tower Cable-stayed bridge. Fuzhou University. (in Chinese)

Menegotto M., Pinto, P E.(1973). Method of Analysis for Cyclically Loaded Reinforced Concrete Plane Frames Including Changes in Geometry and Non-Elastic Behavior of Elements under Combined Normal Force and Bending.Proceedings, IABSE Symposium on Resistance and Ultimate Deformability of Structures, Lisbon, 15-22.