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STUDY ON THE DYNAMIC CHARACTERISTICS OF DAMAGE PROBABILITY OF GRAVITY DAM

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ABSTRACT

Probabilistic analysis is very significant in concrete gravity dam. In particular, the damage characteristics of concrete can result in nonlinear response of concrete gravity dams and in consequence probabilistic analysis for the damage of those is difficult. The proposed solution is essentially a first-order approximate probabilistic analytical approach for the damage of concrete gravity dams, based on pseudo-excitation method. The proposed method involves the following contents. Firstly, pseudo excitation method and Mazar damage model were utilized to analyze how to calculate the expected value and variance of the damage of dam, which was excited by random earthquake load and static load in the initial condition. Then the evolutive process of probability distribution of tension damage of dam was analyzed in the damage condition based on perturbation theory. Finally, a numerical example was given to verify and analyze the convergence and stability of this model. The results indicate that, compared to pseudo excitation method, the proposed method has the salient features of probabilistic analysis for nonlinear response of concrete gravity dam.

Keyword : Gravity dam; Damage; Probabilistic analysis; Perturbation theory; Pseudo excitation method; Mazar damage model.

1. INTRODUCTION

The theory and methods of probabilistic analysis have been developed significantly during the last thirty years and have been documented in an increasing number of publications. These improvements in structure reliability theory and the attainment of more accurate quantification of the uncertainties associated with structural loads and resistances have stimulated the interest in the structure reliability analysis. Although from a theoretical point of view the field has reached a stage where the developed methodologies are becoming widespread, the quantitative assessment and classification of the reliability is still a complex and difficult task.

It has now been widely recognized that the most reasonable method for dealing with such multiple excitation problem is the random vibration approach. Among a great deal of research activities, the reach work by Kiureghian^[1] and Ernesto^[2] are representative. They all developed their research about the seismic analysis of long-span structures based on random vibration approach. Nevertheless, when solving the high degree random differential equations, they all faced unacceptable computational efforts. Compared to these algorithms, Lin^[3] proposed a pseudo-excitation method, which was an accurate and highly efficient algorithm series for linear structural stationary random response analysis, to deal with dynamic response of structures subject to random seismic excitation. In this method, the determination of random response of a linear structure was converted to the determination of response of the structure under a series of harmonic loads. By using this algorithm series, the aforementioned difficulties in the stationary random response computations of long-span structures have been satisfactorily resolved. Based on this algorithm, Lin^[4] et al. analyzed non-stationary random responses of linear structures subjected to evolutionary random excitation. The analytic thought was that the random excitation was first transformed into a pseudo excitation to generate deterministic equations of motion, which were then solved by means of a modified high precision direct integration method. Furthermore, Lin^[5] et al. developed the inverse pseudo-excitation method for dealing with loading identification problems. Then, Lin^[6] et al. utilized this algorithm to make probabilistic analysis for long-span structures such as long-span bridges^[7], non-uniform beams^[8] and so on. Other researchers carried out a rigorous series of algorithms in order to improve and develop pseudo-excitation method. Xu^[9] et al. presented a new algorithm for buffeting analysis of long span bridges, featured mainly by a complete finite element approach and a pseudo-excitation method and then used this algorithm to make fully coupled buffeting analysis of Tsing Ma suspension bridge^[10] and vibration analysis of wind-excited structures^[11]. Then, based on the pseudo-excitation method, Xu^[12,13] et al. and Zhang^[14] et al. also presented closed-form solution for seismic response of adjacent buildings connected by hydraulic actuators with linear quadratic Gaussian (LQG) controllers. Based on the pseudo-excitation method, Sun^[15] et al. presented a formulation for fully coupled buffeting analysis of long-span cable-supported bridges, in which dynamic coupling between modes of vibration, dynamic forces on bridge deck and towers and cables, and varying wind speed and structural properties along the bridge deck and towers and cables can be taken into consideration.

Li^[16] et al. utilized pseudo-excitation method for the random vibration analysis of seismic responses of tall buildings. Xue^[17] et al. utilized the pseudo-excitation method to make a random vibration study of structures under multi-component seismic excitations. Li^[18] et al. extended the pseudo-excitation method with the stochastic orthogonal polynomial expansion method to make response analysis of stochastic parameter structures under non-stationary random excitation. Nevertheless, the pseudo-excitation method only was utilized to analyze linear structures because this method was derived from superposition principle, which only was applied to linear structures.

The damage course of concrete gravity dams is a non-linear course, thus the pseudo excitation method need to be extended for analyzing the damage course of concrete gravity dams. In this paper, the pseudo excitation method was extended for analyzing damage probability of concrete gravity dam. Firstly, pseudo excitation method and Mazar damage model were utilized to analyze how to calculate the expected value and variance of the damage of dam in the initial condition. Moreover, based on perturbation theory, the evolutive process of those was analyzed in the damage condition. Finally, a numerical example was given to verify and analyze the convergence and stability of this model.

2. BRIEF INTRODUCTION ON PSEUDO EXCITATION METHOD

At time $t \in T$, autocorrelation function of stationary random process $x(t)$ is given by

$$R_{xx}(\tau) = E[x(t)x(t+\tau)] = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} x(t)x(t+\tau) dF(x,t;x,t+\tau) \quad (1)$$

Where $E(\#)$ denotes the expected value of variable #.

Fourier transform pairs are consisted of auto-spectral density function $S_{xx}(f)$ and

Autocorrelation function $R_{xx}(\tau)$, it can be written as

$$S_{xx}(f) = \int_{-\infty}^{\infty} R_{xx}(\tau) e^{-2\pi j f \tau} d\tau \quad (2)$$

$$R_{xx}(\tau) = \int_{-\infty}^{\infty} S_{xx}(f) e^{2\pi j f \tau} df \quad (3)$$

From Eqs. (1)-(3), it can be seen that

$$E_{xx}^2 + D_{xx}^2 = R_{xx}(0) = \int_{-\infty}^{\infty} S_{xx}(f) df \quad (4)$$

Where E_{xx} and D_{xx}^2 denote the expected value and variance of $x(t)$.

When $E_{xx}=0$, D_{xx}^2 can be determined from $S_{xx}(f)$.

Pseudo excitation method is the numerical methods for $S_{xx}(f)$ and the basic principle of the pseudo excitation method is depicted as Fig. 1

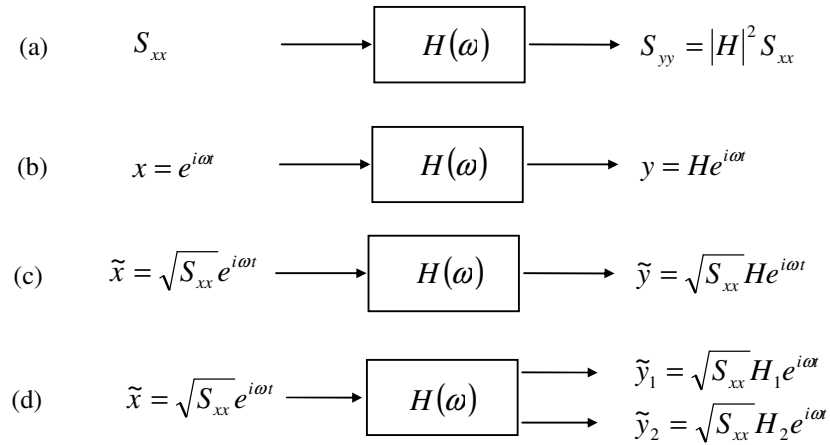


Fig. 1.The basic principle of the pseudo excitation method

Linear system under single-point and stationary random excitation $x(t)$, the response power spectrum of that is given by

$$S_{yy} = |H|^2 S_{xx} \quad (5)$$

This relationship is depicted as Fig.1 (a), the meaning of frequency response function H is depicted as Fig.1 (b). When the harmonic excitation $e^{i\omega t}$ of single-point is applied in the linear system, the corresponding response $y = H e^{i\omega t}$. It is worth noting that pseudo excitation is constructed by excitation, which was $e^{i\omega t}$ multiplied by constant $\sqrt{S_{xx}}$. The pseudo excitation is given by

$$\tilde{x}(t) = \sqrt{S_{xx}} e^{i\omega t} \quad (6)$$

The response can also be multiplied by the same constant. It is depicted as Fig.1 (c). Still using $(\tilde{\#})$ to represent the corresponding pseudo response of variable $(\#)$, it should be noted from Fig.1 (c) that

$$\tilde{y}^* \tilde{y} = |\tilde{y}|^2 = |H|^2 S_{xx} = S_{yy} \quad (7)$$

$$\tilde{x}^* \tilde{y} = \sqrt{S_{xx}} e^{-i\omega t} \cdot \sqrt{S_{xx}} H e^{i\omega t} = S_{xx} H = S_{xy} \quad (8)$$

$$\tilde{y}^* \tilde{x} = \sqrt{S_{xx}} H^* e^{-i\omega t} \cdot \sqrt{S_{xx}} e^{i\omega t} = H^* S_{xx} = S_{yx} \quad (9)$$

Where $(\#)^*$ denotes the conjugate of $(\#)$.

If considering two pseudo responses \tilde{y}_1 and \tilde{y}_2 depict as Fig.1 (d), it could be seen that

$$\tilde{y}_1^* \tilde{y}_2 = H_1^* \sqrt{S_{xx}} e^{-i\omega t} \cdot H_2 \sqrt{S_{xx}} e^{i\omega t} = H_1^* S_{xx} H_2 = S_{y_1 y_2} \quad (10)$$

$$\tilde{y}_2^* \tilde{y}_1 = H_2^* S_{xx} H_1 = S_{y_2 y_1} \quad (11)$$

From aforementioned analysis, it should be noted that

$$S_{yy} = \{\tilde{y}\}^* \cdot \{\tilde{y}\}^T \quad (12)$$

$$S_{xy} = \{\tilde{x}\}^* \cdot \{\tilde{y}\}^T \quad (13)$$

$$S_{yx} = \{\tilde{y}\}^* \cdot \{\tilde{x}\}^T \quad (14)$$

Thus it can be obtained that

$$S_{ff} = |\tilde{f}|^2, S_{\sigma\sigma} = |\tilde{\sigma}|^2, S_{\varepsilon\varepsilon} = |\tilde{\varepsilon}|^2 \quad (15)$$

Where f , σ and ε denote internal force, stress and strain, respectively.

3. THE ESTABLISHMENT OF PROBABILISTIC ANALYTICAL MODEL FOR DAMAGE IN INITIAL CONDITION

Here, all random variables are assumed to obey Gaussian distribution. Because other distribution form can be translate into Gaussian distribution easily, and Gaussian distribution is extensively applied in the analysis of random variables.

When dam is excited by static and random seismic load, the element's strain of dam is random variable. From static analysis of the dam, the initial expected value $E(\varepsilon_k)$ of strain of element k is obtained. And the initial variance $D(\varepsilon_k)$ of strain of element k can be derived as follow.

The vibration equation of gravity dam is determined as

$$M\ddot{V} + C\dot{V} + KV = F(t) \quad (16)$$

Where \ddot{V} , \dot{V} and V denote acceleration, velocity and displacement of nodes in dam model, respectively; K , C and M denote stiffness matrix, damping matrix and mass matrix of dam model, respectively; $F(t)$ denotes random seismic load.

From Eq.(16), it should be noted that gravity dam under random seismic load is a linear system. Accordingly, the pseudo excitation method can be utilized in aforementioned system. The pseudo excitation is constructed as

$$\tilde{F}(t) = \sqrt{S_f(\omega)} e^{i\omega t} \quad (17)$$

Where $\tilde{F}(t)$ and $S_f(\omega)$ denote pseudo excitation and the power spectrum density of random seismic load, respectively.

Through the pseudo excitation method, the initial power spectrum density of the strain of element k is determined as

$$S_{\varepsilon_k}(\omega) = \tilde{\varepsilon}_k \times \tilde{\varepsilon}_k^* \quad (18)$$

Where $\tilde{\varepsilon}_k$ denotes pseudo strain response of element k .

Thus the initial variance $D(\varepsilon_k)$ of strain of element k is given by

$$D(\varepsilon_k) = \int_0^{+\infty} S_{\varepsilon_k}(\omega) d\omega \quad (19)$$

Mazar damage model, which is only related to strain as damage constitutive equation, is a widely used isotropic damage model for concrete^[19, 20] because this model is simple to compute. And the value of damage indicates elasticity modulus reduction proportion. In this paper, this model is utilized to describe the tension damage of element k as

$$\begin{cases} \Omega_{T,k} = 0 & \varepsilon_k \leq \varepsilon_f \\ \Omega_{T,k} = 1 - \frac{\varepsilon_f(1-A_T)}{\varepsilon_k} - \frac{A_T}{\exp(B_T(\varepsilon_k - \varepsilon_f))} & \varepsilon_k > \varepsilon_f \end{cases} \quad (20)$$

In which $0.7 \leq A_T \leq 1, 10^4 \leq B_T \leq 10^5, 0.5 \times 10^{-4} \leq \varepsilon_f \leq 1.5 \times 10^{-4}$.

Where ε_f and $\Omega_{T,k}$ denote damage threshold and tension damage value of element k .

It is worth noting that ε_k and $\Omega_{T,k}$ are directional, and ε_k and $\Omega_{T,k}$ are divided into horizontal direction x and vertical direction y in two dimensions, respectively.

In initial step, the element's strain is assumed to obey normal distribution, based on this physically motivated hypothesis, the expected value $E(\Omega_{T,k})$ of tension damage of element k can be determined through expression(20) as

$$E(\Omega_{T,k}) = \int_{-\infty}^{+\infty} \Omega_{T,k}(\varepsilon_k) \varphi(\varepsilon_k) d\varepsilon_k = \int_{-\infty}^{+\infty} \Omega_{T,k}(\varepsilon_k) \frac{1}{\sqrt{2\pi D(\varepsilon_k)}} \exp\left(-\frac{(\varepsilon_k - E(\varepsilon_k))^2}{2D(\varepsilon_k)}\right) d\varepsilon_k \quad (21)$$

Where $\varphi(\#)$ is probability density function of variable $\#$.

The second moment $E(\Omega_{T,k}^2)$ of tension damage of element k is given by

$$E(\Omega_{T,k}^2) = \int_{-\infty}^{+\infty} \Omega_{T,k}^2(\varepsilon_k) \varphi(\varepsilon_k) d\varepsilon_k = \int_{-\infty}^{+\infty} \Omega_{T,k}^2(\varepsilon_k) \frac{1}{\sqrt{2\pi D(\varepsilon_k)}} \exp\left(-\frac{(\varepsilon_k - E(\varepsilon_k))^2}{2D(\varepsilon_k)}\right) d\varepsilon_k \quad (22)$$

So the variance $D(\Omega_{T,k})$ of tension damage of element k is given by

$$D(\Omega_{T,k}) = E(\Omega_{T,k}^2) - (E(\Omega_{T,k}))^2 \quad (23)$$

And the mean square deviation $\bar{D}(\Omega_{T,k})$ of tension damage of element k is given by

$$\bar{D}(\Omega_{T,k}) = \sqrt{D(\Omega_{T,k})} \quad (24)$$

4. The establishment of probabilistic analytical model for damage in damage condition

In this section, $A \circ B$ denotes that the corresponding elements of matrix A and B are multiplied.

In initial condition, the expected value and mean square deviation of tension damage of element k are determined. From static analysis of the dam, in which the tension damage value of element k is $E(\Omega_{T,k})$, the expected value $E(\varepsilon_k)$ of strain of element k is determined.

Then the vibration equation of gravity dam is rewritten as

$$M\ddot{V} + C\dot{V} + (I - R(\Omega_T)) \circ KV = F(t) \quad (25)$$

Where $R(\Omega_T)$ is the whole tension damage matrix composed of tension damage of elements; I is unit matrix.

$R(\Omega_T)$ is given by

$$R(\Omega_T) = \left[\sum_{k=1}^{NE} [M]_k^T \Omega_{T,k} \int_{V_k} [B]_k^T [I] [B]_k dV [M]_k \right] \quad (26)$$

Where $[M]_k$ denotes the position of element k in dam, $[B]_k$ denotes strain matrix of element k , $[I]$ is the 3×3 identity matrix, NE is the number of elements.

Because $R(\Omega_T)$ is random matrix, perturbation method is utilized to analyze tension damage of dam. Eq.(25) can be rewritten as

$$M\ddot{V} + C\dot{V} + (I - E(\Omega_T)) \circ KV - \gamma \bar{D}(\Omega_T) \circ KV = F(t) \quad (27)$$

And the variance of the power spectrum density of the strain of element k is given by

$$\begin{aligned} D(S_{\varepsilon_k}(\omega)) &= D\left(\tilde{\varepsilon}_{k,0} \times \tilde{\varepsilon}_{k,0}^* + (\tilde{\varepsilon}_{k,0} \times \tilde{\varepsilon}_{k,1}^* + \tilde{\varepsilon}_{k,1} \times \tilde{\varepsilon}_{k,0}^*) \Upsilon + \Upsilon^2 \tilde{\varepsilon}_{k,1} \times \tilde{\varepsilon}_{k,1}^*\right) \\ &= (\tilde{\varepsilon}_{k,0} \times \tilde{\varepsilon}_{k,1}^* + \tilde{\varepsilon}_{k,1} \times \tilde{\varepsilon}_{k,0}^*)^2 D(\Upsilon) + (\tilde{\varepsilon}_{k,1} \times \tilde{\varepsilon}_{k,1}^*)^2 D(\Upsilon^2) \end{aligned} \quad (34)$$

Because Υ obeyed standard normal distribution, Υ^2 obeyed gamma distribution. It can be obtained that

$$D(\Upsilon) = 1, D(\Upsilon^2) = 2 \quad (35)$$

Substituting Eq.(35) into equation(34), it can be obtained that

$$\begin{aligned} D(S_{\varepsilon_k}(\omega)) &= (\tilde{\varepsilon}_{k,0} \times \tilde{\varepsilon}_{k,1}^* + \tilde{\varepsilon}_{k,1} \times \tilde{\varepsilon}_{k,0}^*)^2 + 2(\tilde{\varepsilon}_{k,1} \times \tilde{\varepsilon}_{k,1}^*)^2 \\ &= 2|\tilde{\varepsilon}_{k,1}|^4 + 4(\text{Re}(\tilde{\varepsilon}_{k,0} \times \tilde{\varepsilon}_{k,1}^*))^2 \end{aligned} \quad (36)$$

$D(\varepsilon_k)$ is assumed to obey normal distribution in damage condition, and then it can be obtained that

$$\begin{aligned} E(D(\varepsilon_k)) &= \int_0^{+\infty} E(S_{\varepsilon_k}(\omega)) d\omega \quad (37) \\ D(D(\varepsilon_k)) &= \int_0^{+\infty} D(S_{\varepsilon_k}(\omega)) d\omega \end{aligned} \quad (38)$$

Then ε_k and $D(\varepsilon_k)$ are both random variables, and the probability density function

$\varphi(\varepsilon_k, D(\varepsilon_k))$ of ε_k is rewritten as

$$\begin{aligned} \varphi(\varepsilon_k, D(\varepsilon_k)) &= \varphi_1(\varepsilon_k, D(\varepsilon_k)) \times \varphi_2(D(\varepsilon_k)) \\ &= \frac{1}{\sqrt{2\pi D(\varepsilon_k)}} \exp\left(-\frac{(\varepsilon_k - E(\varepsilon_k))^2}{2D(\varepsilon_k)}\right) \times \frac{1}{\sqrt{2\pi D(D(\varepsilon_k))}} \exp\left(-\frac{(D(\varepsilon_k) - E(D(\varepsilon_k)))^2}{2D(D(\varepsilon_k))}\right) \quad (39) \\ &= \frac{1}{2\pi \sqrt{D(D(\varepsilon_k)) D(\varepsilon_k)}} \exp\left(-\frac{(\varepsilon_k - E(\varepsilon_k))^2}{2D(\varepsilon_k)} - \frac{(D(\varepsilon_k) - E(D(\varepsilon_k)))^2}{2D(D(\varepsilon_k))}\right) \end{aligned}$$

The expected value $E(\Omega_{T,k})$ of tension damage of element k can be determined as

$$\begin{aligned}
 E(\Omega_{T,k}) &= \int_{-\infty}^{+\infty} \int_0^{+\infty} \Omega_{T,k}(\varepsilon_k) \varphi(\varepsilon_k, D(\varepsilon_k)) dD(\varepsilon_k) d\varepsilon_k \\
 &= \int_{-\infty}^{+\infty} \Omega_{T,k}(\varepsilon_k) \int_0^{+\infty} \frac{1}{2\pi\sqrt{D(D(\varepsilon_k))D(\varepsilon_k)}} \exp\left(-\frac{(\varepsilon_k - E(\varepsilon_k))^2}{2D(\varepsilon_k)} - \frac{(D(\varepsilon_k) - E(D(\varepsilon_k)))^2}{2D(D(\varepsilon_k))}\right) dD(\varepsilon_k) d\varepsilon_k
 \end{aligned} \quad (40)$$

The second moment $E(\Omega_{T,k}^2)$ of tension damage of element is given by

$$\begin{aligned}
 E(\Omega_{T,k}^2) &= \int_{-\infty}^{+\infty} \int_0^{+\infty} \Omega_{T,k}^2(\varepsilon) \varphi(\varepsilon, D(\varepsilon)) dD(\varepsilon) d\varepsilon \\
 &= \int_{-\infty}^{+\infty} \Omega_{T,k}^2(\varepsilon) \int_0^{+\infty} \frac{1}{2\pi\sqrt{D(D(\varepsilon))D(\varepsilon)}} \exp\left(-\frac{(\varepsilon - E(\varepsilon))^2}{2D(\varepsilon)} - \frac{(D(\varepsilon) - E(D(\varepsilon)))^2}{2D(D(\varepsilon))}\right) dD(\varepsilon) d\varepsilon
 \end{aligned} \quad (41)$$

So the variance $D(\Omega_{T,k})$ and mean square deviation $\bar{D}(\Omega_{T,k})$ of tension damage of element k can be determined according to Eqs.(23),(24).

It is worth noting that $E(\Omega_{T,k})$ and $\bar{D}(\Omega_{T,k})$ are divided into horizontal direction x and

vertical direction y in two dimensions, respectively. So the total expected value $E_{total}(\Omega_{T,k})$

and mean square deviation $\bar{D}_{total}(\Omega_{T,k})$ of tension damage of element k are given by

$$E_{total}(\Omega_{T,k}) = \sqrt{(E_x(\Omega_{T,k}))^2 + (E_y(\Omega_{T,k}))^2} \quad (42)$$

$$\bar{D}_{total}(\Omega_{T,k}) = \sqrt{D_x(\Omega_{T,k}) + D_y(\Omega_{T,k})} \quad (43)$$

The iteration procedure for the total expected value and mean square deviation of tensile damage of elements of dam are according to equation(31),(33),(36)~(43) until they gradually converge to certain error range. And then the probability distribution of tensile damage of elements of dam is determined.

4. NUMERICAL EXAMPLE

The gravity dam is 160m high. The normal pool level (NPL) is 155m deep. The level of the back of the dam is 10m deep. The elevation of upstream and downstream broken-line sloping surface relative to foundation plane are 80m and 140m, respectively. The concrete strength of the gravity dam is C20. The finite element model of the gravity dam is divided into 2432 elements. The model consists of 8-node iso-parametric plane elements for the dam and foundation. The density of the dam $\rho=2450\text{kg/m}^3$, and Poisson ratio $\nu=0.18$. The elastic modulus of dam $E=2.86\times 10^{10}\text{Pa}$. The damping ratio of dam $\zeta=0.05$. The density of rock

foundation $\rho=2700\text{kg/m}^3$, and Poisson ratio $\nu=0.25$. The elastic modulus of rock foundation $E=3.90\times 10^{10}\text{Pa}$. The damping ratio of rock foundation $\zeta=0.05$. The parameters of Mazar damage model $A_T=0.8, B_T=5\times 10^4, \varepsilon_f=0.5\times 10^{-4}$. The static load includes gravity load, hydro static and uplift pressure while random load includes seismic load whose horizontal peak acceleration is $0.251g$ and vertical peak acceleration is $2/3$ of horizontal peak acceleration. The power spectrum density of seismic load is given by

$$\left\{ \begin{array}{l} S_f(\omega_k) = \frac{2\xi}{\pi\omega_k} [S_a^T(\omega_k)]^2 \frac{1}{-2\ln(-\frac{\pi}{\omega_k T_d} \ln p)} \\ \Delta\omega = 2\pi / T_d \\ \omega_k = \Delta\omega k \quad k = 1, 2, 3, \dots, N \\ N = \frac{T_d}{\Delta t} \end{array} \right. \quad (44)$$

Where $S_a^T(\omega_k)$ and ξ are target response spectrum and damping ratio, respectively;

p ($p \leq 0.15$) and T_d are exceeding response spectrum probability and duration of ground motion, respectively; N and Δt are the number of trigonometric series and time step, respectively.

The dam model and monitoring points are depicted as Fig.2. The iterative procedure of expected value of tension damage of monitoring point 1,2 and 3 are depicted as Fig.3. The iterative procedure of the contour map for expected value of tension damage is depicted as Figs.4-9. The iterative procedure of the contour map for mean-square deviation of tension damage is depicted as Figs.10-15. The iterative procedure of contour map for probability distribution of tension when damage threshold =1.00 is depicted as Figs.16-21.

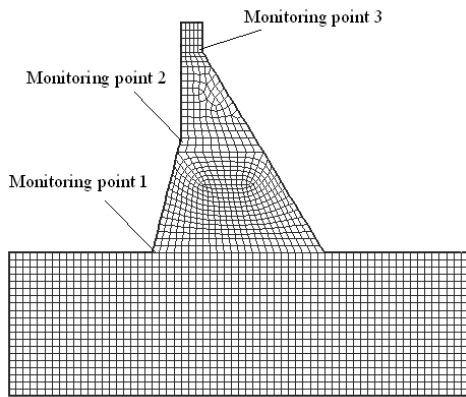


Fig. 2 The sketch for. dam system and monitoring points

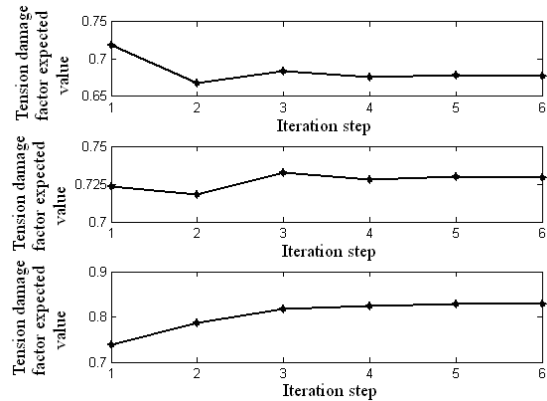


Fig. 3 Tension damage factor expected value iterative procedure

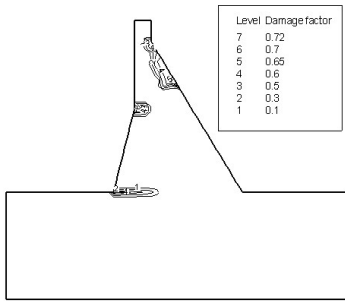


Fig. 4 The contour map for expected value of tension damage (iteration step=1)

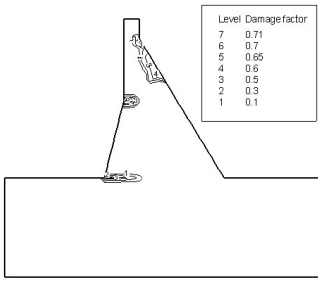


Fig. 5 The contour map for expected value of tension damage (iteration step=2)

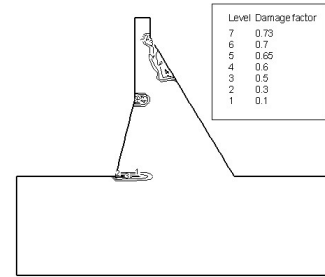


Fig. 6 The contour map for expected value of tension damage (iteration step=3)

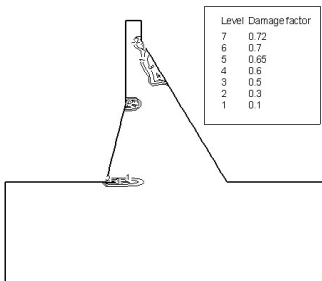


Fig. 7 The contour map for expected value of tension damage (iteration step=4)

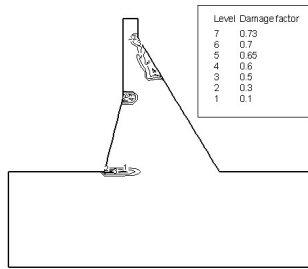


Fig. 8 The contour map for expected value of tension damage (iteration step=5)

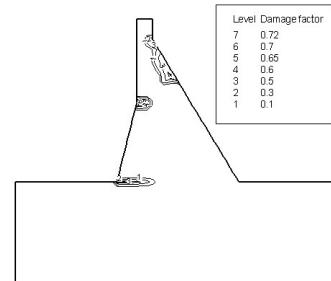


Fig. 9 The contour map for expected value of tension damage (iteration step=6)

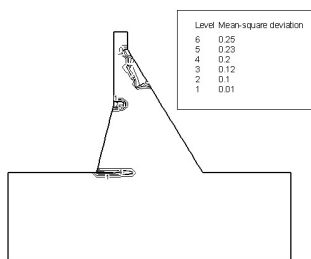


Fig. 10 The contour map for mean-square deviation of tension damage (iteration step=1)

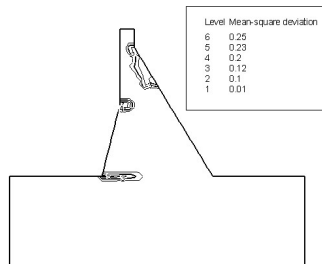


Fig. 11 The contour map for mean-square deviation of tension damage (iteration step=2)

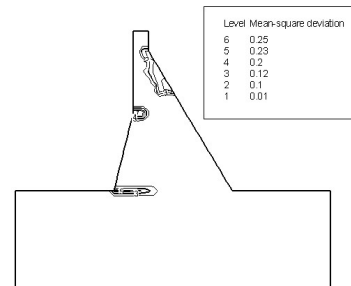


Fig. 12 The contour map for mean-square deviation of tension damage (iteration step=3)

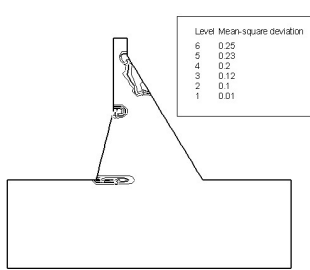


Fig. 13 The contour map for mean-square deviation of tension damage (iteration step=4)

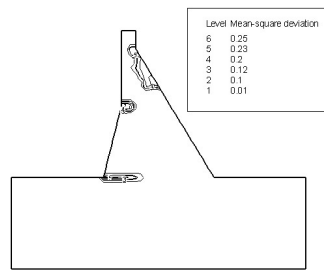


Fig. 14 Tension damage factor mean-square variance contour map (iteration step=5)

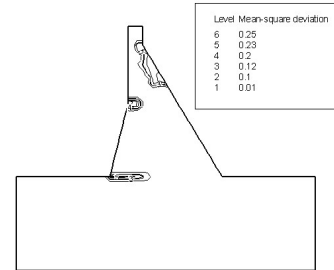


Fig. 15 Tension damage factor mean-square variance contour map (iteration step=6)

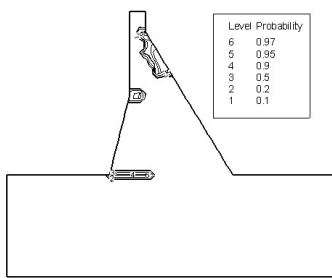


Fig. 16 The contour map for tension damage factor threshold =1.00 (iteration step=1)

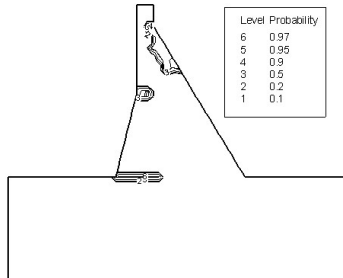


Fig. 17 The contour map for tension damage factor threshold =1.00 (iteration step=2)

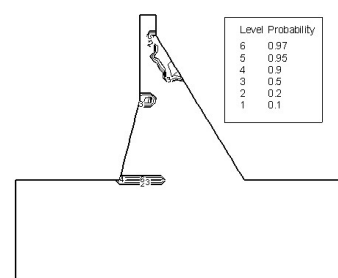


Fig. 18 The contour map for tension damage factor threshold =1.00 (iteration step=3)

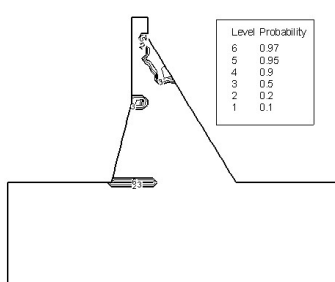


Fig. 19 The contour map for tension damage factor threshold =1.00(iteration step=4)

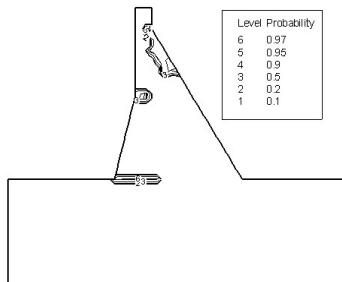


Fig. 20 The contour map for tension damage factor threshold =1.00(iteration step=5)

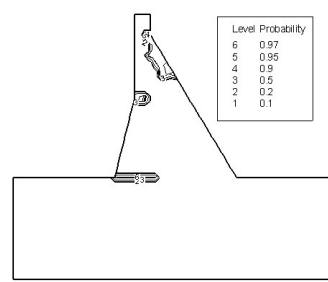


Fig. 21 The contour map for tension damage factor threshold =1.00(iteration step=6)

5. DISCUSSION

From Fig.3, it becomes apparent that the convergence rate of this paper's model, which is utilized to compute the expected value and mean-square deviation of tension damage of dam, is fast. The iterative procedure is steady usually in iteration step 6. From Figs.4-9, it appears that tension damage is concentrated in upstream and downstream broken-line sloping surface and dam heel. So these places need to reinforce. From Figs.10-15, it is shown that the mean-square deviation of tension damage is concentrated in upstream and downstream broken-line sloping surface and dam heel. It elucidates that these places are highly stochastic. Furthermore, it is instructive to shown that the contour map for the expected value and mean-square are similar. From Figs.16-21, it is shown that the probability of reaching damage threshold=1.00 is increasing with the iterative procedure.

6. CONCLUSION

In this paper, an improved model is presented for analyzing damage probability of concrete gravity dam. Given the numerical simulation, the performance of the proposed method is deemed satisfactory. The proposed solution can make probabilistic analysis for the damage and nonlinear response of concrete gravity dam.

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