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Seismic Performance Analysis and Anti-Seismic Measures for High Concrete Face Rockfill Dam Based on Stochastic Dynamic Theory

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Abstract: Concrete face slab is the main anti-seepage component of high concrete face rockfill dams (CFRDs), so it is of great significance to restrain the seismic cracking of concrete face slab. This paper selects horizontal joints as the main anti-seismic measures to suppress concrete face slab cracking. Multiple groups of seismic ground motions are generated based on spectral expression-random function non-stationary model. The seismic performance of CFRDs with horizontal joints is evaluated based on stochastic dynamic theory. This paper evaluates the anti-seismic performance of horizontal joints along with the dam height and dam axis. In addition, the tensile stress of the typical element selected is calculated before and after setting horizontal joints based on the generalized probability density evolution method (GPDEM). The results show that the application of horizontal joints will significantly reduce the tensile stress along the slope of the concrete face slab under the random ground motions to effectively restrain the seismic cracking of the concrete face slab.

Keywords: high concrete face rockfill dams; concrete face slab; anti-seismic measures; horizontal joints; stochastic dynamic theory; generalized probability density evolution method.

1 Introduction

With the increase of the high dams in regions with high seismic risk, earthquake damage has become a serious issue that cannot be ignored. High concrete face rockfill dams (CFRDs) play an important role in these dams (Xu and Zeng 2011). In case of an earthquake, the face slab as the main impervious core is very vital for the normal operation of high face rockfill dams(Arici 2013).

In case of an earthquake, one of the main damage characteristics of the face slab is the horizontal cracks in the middle and upper part of the face slab due to the ultra-high dynamic stress(Xu et al. 2015). Once leakage occurs because of cracks, it will do great harm to the dams.

To solve this problem, several anti-seismic measures have been suggested to restrict rockfill deformation. Researchers mainly put forward improvement suggestions for panel materials, such as increasing reinforcement ratio, steel fiber, and replacing panel materials. (Kong et al. 2000; Qu et al. 2020). In 2017, from the perspective of improving the panel structure, Zhang et al. (Zhang et al. 2017) set up the horizontal joint to release the high tensile stress during the earthquake with the help of the opening deformation of the horizontal joint. Compared with the measures of improving the panel material, setting up the horizontal joint has attracted attention because it is more direct and simple (Ma and Chi 2016).

Previous research on seismic horizontal joints mostly focused on changing the model and simulation method to describe the panel stress more accurately, without considering the randomness of ground motions(Qu et al. 2021). Existing studies have shown that the influence of randomness of ground motion on the dynamic response of CFRDs can not be ignored (Pang et al. 2021). Therefore, considering the randomness of ground motions, it is very necessary to analyze the effect of seismic measures of applying permanent horizontal joints to the face slab from the perspective of stochastic dynamic theory.

In recent years, with the continuous enhancement of the understanding of seismic non-stationary, some non-stationary ground-motion models and engineering structure calculation methods considering the non-stationary ground motion intensity and frequency have also been proposed. Among them, the generalized probability density evolution method (GPDEM) has attracted extensive attention because of its high efficiency and high precision (Huang et al. 2015). Compared with the traditional Monte Carlo method, GPDEM does not need extensive simulation data, which saves time significantly. And the theory has made good progress in uncertain reliability analysis and large-scale nonlinear structures nowadays. For high CFRDs, its excellent applicability has also been proved(Pang et al. 2021).

The purpose of this paper is to evaluate the reducing effect of the horizontal joint on the high tensile stress of the face slab under seismic shaking based on the principle of random dynamics. Firstly, the random dynamic calculations are carried out for the established finite element model. Secondly, the information on setting horizontal joints is determined according to the calculation results and existing studies. Thirdly, based on the random dynamic theory, the effect of the horizontal joint on the maximum tensile stress reduction of the face slab is evaluated. Fourthly, the stress reduction effect of typical elements is analyzed by combining GPDEM. Finally, conclusions are provided in the last section of this paper.

2 Generalized probability density evolution theory

The GPDEM was proposed by Li et al.(J. Li and Chen 2004). In this method, the probability density evolution equation is established for the stochastic dynamic system. Then the physical quantities of interest are solved by combining the initial conditions and boundary conditions. In recent years, the applicability of this theory to large nonlinear structures has been proved (Li 2016).

When the random parameters are determined by selecting points in the probability space, the partial differential equation of the random dynamic system can be expressed as a set of deterministic dynamic equations(Li and Chen 2004):

$$\frac{\partial p_{\mathbf{Z\Theta}}(z,\boldsymbol{\theta}_{\mathrm{q}},t)}{\partial t}+\sum_{j=1}^{m}\dot{Z}_{\mathrm{j}}(\boldsymbol{\theta}_{\mathrm{q}},\ t)\frac{\partial p_{\mathbf{Z\Theta}}(z,\boldsymbol{\theta}_{\mathrm{q}},t)}{\partial z_{\mathrm{j}}}=0\ q=1,2,\cdots,n_{sel} \tag{1}$$

Where refers to the joint probability density function (PDF) $(\mathbf{Z},\mathbf{\Theta})$, in which the source random factors are completely described $\mathbf{\Theta}$. $\mathbf{Z}$ refers to the physical quantity studied. The augmented system composed of is a conservative probability system, which follows the law of probability conservation.

The engineering structure can be solved by various numerical simulation methods such as the finite element method and finite difference method. The initial condition of Eq. (1) is:

$$p_{\mathbf{Z\Theta}}(\boldsymbol{z},\boldsymbol{\theta}_{\mathrm{q}},t)\,|_{t=t_0}=\delta(\boldsymbol{z}-\boldsymbol{z}_0)P_{\mathrm{q}} \tag{2}$$

The boundary conditions are:

$$p_{\mathbf{Z\Theta}}(z,\boldsymbol{\theta},t)\,|_{z_{\mathrm{j}}\to\pm\infty}=0,\ j=1,2,\cdots,m \tag{3}$$

The discrete numerical solutions can be obtained by bringing in the initial conditions and boundary conditions. The solutions $p_{\mathbf{Z}}(z,t)$ can be obtained by accumulating all the above discrete numerical solutions:

$$p_{\mathbf{Z}}\left(z,t\right)=\sum\nolimits_{q=1}^{n_{\mathrm{sel}}}p_{\mathbf{Z\Theta}}\left(z,\boldsymbol{\theta}_{\mathrm{q}},t\right) \tag{4}$$

3 Example analysis

3.1 Model establishment

Nonlinear finite element numerical calculations for a typical CFRD are carried out with a height of 300 m based on GEODYNA(Zou et al. 2005). The upstream dam slope gradient is 1:1.4. The downstream dam slope is 1:1.65 (Comprehensive dam slope). And the river valley is an asymmetrical river valley with a bank slope gradient of 1:1. The dam is filled in 40 layers. The face slab is poured in three phases. The water is stored 10m below the dam crest. The thickness of the face slab is taken as 0.3 + 0.0035 h (h is the distance from the dam crest) according to the code for the design of concrete face rockfill dams (SL228-2013). The cushion gravel zone and transition zone were positioned beneath the concrete face slabs and were assigned thicknesses of 4 m and 6 m respectively.

The three-dimensional finite element network of the dam is shown in Figure 1, which is divided into 73648 nodes and 71892 elements. Hexahedral isoparametric elements and a few degenerated tetrahedral elements are used for the face slab and dam body. 8-node and a small number of 6-node spatial Goodman contact surface elements are set at the interface between the panel and the rockfill. 8-node spatial joint elements are used for the vertical joints and peripheral joints of the panel.

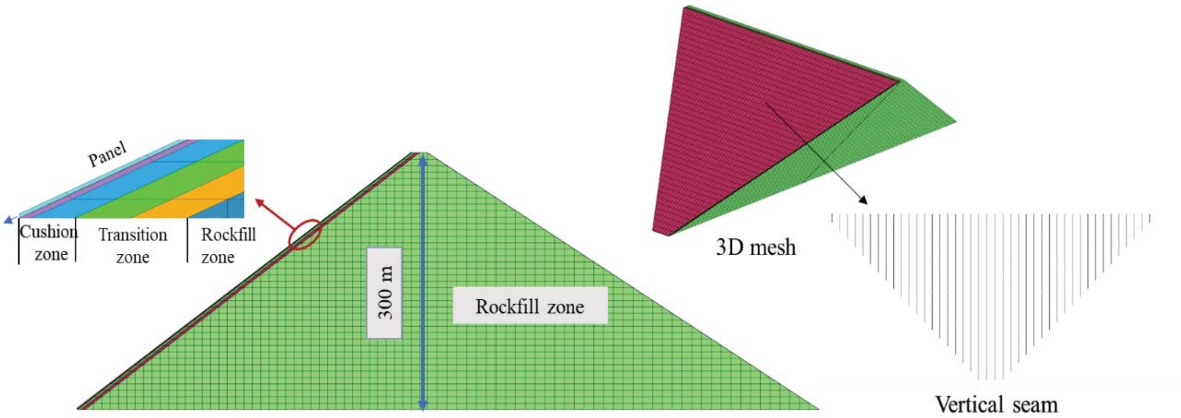


Figure 1. Finite element mesh of the dam.

3.2 Constitutive model and material parameters

In this paper, the Duncan-Chang E-B model is used for static calculation and the equivalent linear model is used for dynamic calculation. The simplified joint model proposed by Zou et al.(De-gao et al. 2009) is used for the calculation of peripheral joints and vertical joints, etc. The parameters proposed by (Gu et al. 2009) are used for the calculation of contact surface. In the dynamic calculation, the nodes at the bottom of the dam are completely constrained. The hydrodynamic pressure is simulated by the additional mass method. The concrete material of slabs was simulated using a linear elastic model. The above constitutive models and parameters refer to(Zhang et al. 2017).

3.3 Ground motions input

89 groups of random ground motions are generated based on the spectral expression-random function non-stationary random ground motion model (Pang et al. 2018). The horizontal peak acceleration of ground motion is 0.340g. The vertical acceleration is regarded as 2/3 of the horizontal acceleration. The specific information on earthquake motion refers to (Rong et al. 2021).

3.4 Horizontal seam setting

Figure 2 is the stress distribution obtained by averaging the maximum dynamic tensile stress along the slope direction of the slab under multiple groups of random ground motions. It can be seen that the higher tensile stress area is mainly distributed between 0.6 H-0.95 H (H is the dam height) in height and 0.3 L (L is the crest length) along the dam axis; Figure 3 shows the average stress distribution of slope-direction stress for combined static and seismic loadings in the intact slab along with the dam height and dam axis respectively. It can be seen that the maximum along slope tensile stress height is 0.85 H and the distribution length ranges from 0.35 L to 0.65 L. The above calculation results are consistent with the high along slope dynamic tensile stress distribution area analyzed by Zhang et al. (Zhang et al. 2017). Based on the calculation results of dynamic and static superimposed average tensile stress (Figure 3) and referring to Figure 2 of dynamic tensile stress distribution, this paper adopts to set permanent horizontal joints at the height of 0.85 H and 0.35 L-0.65 L along the dam axis.

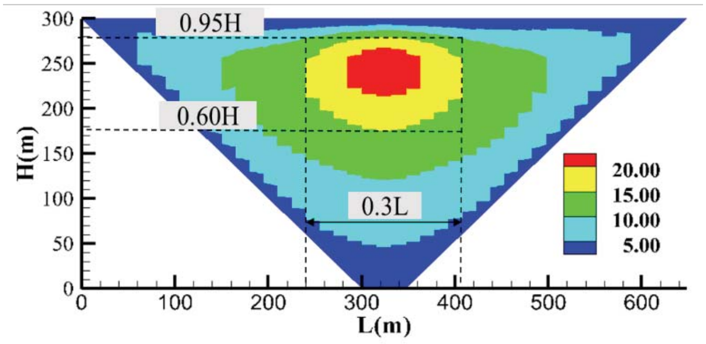
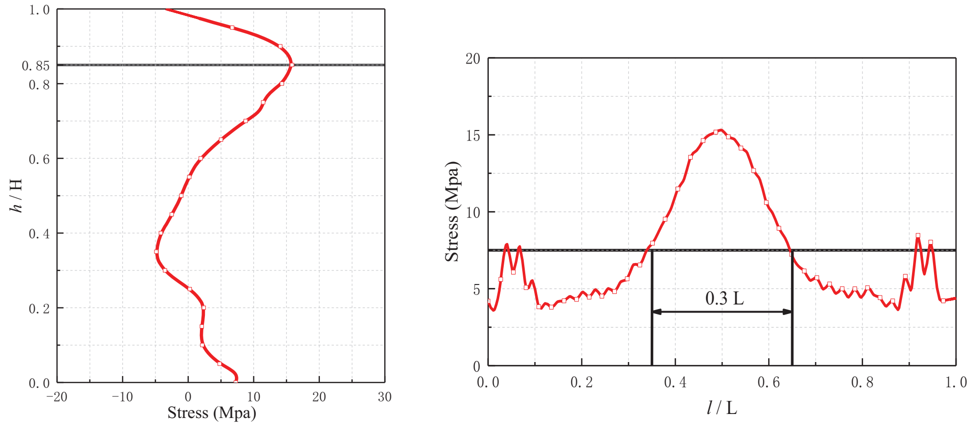


Figure 2. Distribution of maximum slope-direction tension in slabs.



(a) (b)

Figure 3. Maximum slope-direction stress for combined static and seismic loadings in the intact slab (Note: Compression is negative): (a) Along with the dam height; (b) Along the dam axis.

4 horizontal joints performance

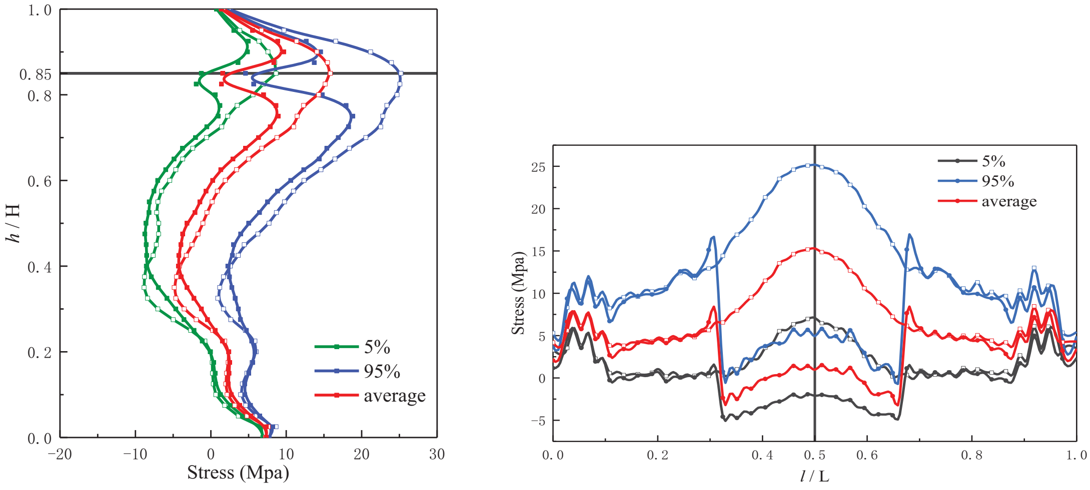
To evaluate the anti-seismic performance of the horizontal joint for high tensile stress along the slope during the earthquake more comprehensively and accurately, the tensile stress of the panel under the random ground motions is calculated before and after the horizontal joint is applied and analyzed from the following two angles: 1) Calculate the stress distribution of the slab with different exceedance probabilities along with the dam height (at 0.5 L) and along the dam axis (at 0.85 H); 2) The equivalent extreme fireworks method based on generalized probability density evolution theory is used to analyze the reduction of tensile stress of the selected typical elements.

4.1 performance along with dam height and dam axis

In this section, the distribution of the face slab tensile stress along the research direction under the action of 89 groups of random ground motions is obtained. Take 5% and 95% exceedance probability and the average value for the calculation results (95% exceedance probability is the stress value with a 95% guarantee rate for all random ground motion inputs, and the concept of 5% exceedance probability is similar), to analyze the effect of the horizontal joint, as shown in Figure 4.

Table 1 shows the reduction effect of the horizontal joint on the unit stress at the location of the horizontal joint and the maximum unit stress of the upper half of the panel along the dam height direction (corresponding to Figure 4 (a)). Table 2 shows the reduction effect of the horizontal joint on the unit stress at the location of the horizontal joint and the maximum unit stress of the panel along the setting direction of the horizontal joint (corresponding to Figure 4 (b)).

Firstly, the maximum tensile stress along the slope at the setting of the horizontal joint is analyzed. The stress reduction effect is very significant, which can avoid the occurrence of large tensile stress and avoid the tensile damage to the slabs. Secondly, the influence area of the horizontal joint is analyzed. In the range of 0.75 H-0.9 H along the direction of dam height, the effect of the horizontal joint on the reduction of tensile stress along the slope is obvious, and in other areas far away, the horizontal joint has no obvious effect on its stress distribution. When analyzing the stress distribution along the dam axis, there will be a stress increase at the left and right ends of the horizontal joint, which should be the influence of stress concentration. The influence of this effect should be considered when setting the horizontal joint. Finally, on the whole, the application of horizontal joints can significantly reduce the maximum tensile stress along the slope, whether along the dam axis or along with the dam height, and the effect can reach 20% - 50%, which is consistent with the previous calculation results of separate ground motion by Zhang et al. (Zhang et al. 2017).



(a) (b)

Figure 4. Under different conditions slope-direction stress for combined static and seismic loadings in the intact slab (Note: Compression is negative): (a) Along with the dam height; (b) Along the dam axis.

Table 1. Seismic effect of the horizontal joint along with dam height (0.5 L).

conditions	Original panel (Mpa)	Element stress at joint (Mpa)	Stress reduction effect (%)	The maximum stress in the middle and upper part after adding joint (Mpa)	Stress reduction effect (%)
5%	8.66	-1.26	100	4.97	42.61
95%	25.21	4.60	81.75	18.84	25.27
average	15.86	1.58	90.03	7.64	51.83

Table 2. Seismic effect of the horizontal joint along dam axis (0.85 H).

conditions	Original panel (Mpa)	Element stress at joint (Mpa)	Stress reduction effect (%)	Maximum stress after adding joint (Mpa)	Stress reduction effect (%)
5%	7.09	-2.11	100	5.71	19.46
95%	25.20	4.92	80.56	15.46	38.65
average	15.29	0.96	93.72	7.64	50.03

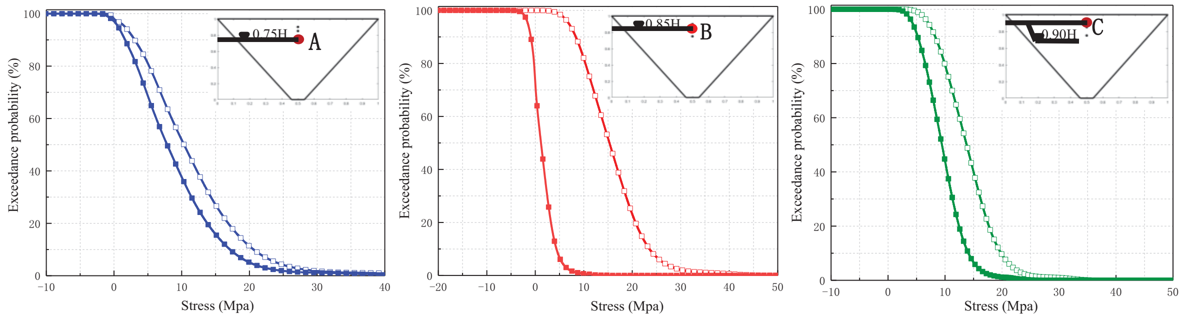
4.2 Influence of horizontal joint on typical element stress

Based on the probability density evolution theory and the equivalent extreme value analysis method, this section studies the stress distribution of the horizontal joint on the typical unit considering the randomness of ground motions. Select the typical units at the application position of the horizontal joint (0.85H), above (0.90H), and below (0.75H) respectively to obtain the stress exceedance probability before and after adding the horizontal joint. Further, the seismic effect of the horizontal joint is obtained from the perspective of the maximum tensile stress distribution along the slope of typical elements (as shown in Figure 5).

Table 3 shows the stress-reduction effect of the horizontal joint on the selected typical unit with a corresponding exceeding probability of 5%, 25%, 50%, 75%, and 95%.

It can be seen that the reduction effect of the horizontal joint on high tensile stress decreases with the increase of distance, while the downward reduction speed is slower than upward. It is further proved that in the area of 0.75 H-0.90 H, the reduction effect of the horizontal joint on the tensile stress along the slope direction of the panel under seismic shaking is 20% or more.

For the place where the horizontal joint is set (0.85 H), only less than 25% of all ground motions will produce tensile stress greater than the dynamic tensile strength of concrete (3 Mpa), which proves the effectiveness of applying the horizontal joint to protect the anti-seepage safety of concrete face rockfill dams.



(a) (b) (c)

Figure 5. Stress exceedance probability of different typical elements (Note: Compression is negative): (a) Unit A; (b) Unit B; (c) Unit C.

Table 3. Seismic effect of the horizontal joint along dam axis (0.85 H).

Exceedance probability	Unit A			Unit B			Unit C		
	Original panel (Mpa)	Jointed panel (Mpa)	Stress reduction effect (%)	Original panel (Mpa)	Jointed panel (Mpa)	Stress reduction effect (%)	Original panel (Mpa)	Jointed panel (Mpa)	Stress reduction effect (%)
5%	24.00	20.05	16.46	26.28	5.48	79.15	21.76	15.60	28.31
25%	15.50	12.53	19.16	19.62	2.82	85.63	16.91	11.85	29.92
50%	10.36	7.84	24.32	10.28	1.14	88.91	13.78	9.45	31.42
75%	6.94	4.12	40.63	11.16	-0.08	100.72	10.60	7.07	33.30
95%	1.56	0.62	60.26	6.90	-1.52	122.03	7.07	4.30	39.18

5 Conclusion

In this paper, considering the influence of randomness of ground motions and combined with probability density evolution theory, the effect of the horizontal joint on the reduction of tensile stress along slope during an earthquake is analyzed from two angles. The conclusions are as follows:

1) The horizontal joint has a significant effect on reducing the tensile stress along the slope of the panel. The tensile stress of the unit near the horizontal joint is reduced by more than 75%, which is consistent with the previous research results.

2) For the place where the horizontal joint is set, only less than 25% of all ground motions will produce tensile stress greater than the dynamic tensile strength of concrete, which proves the effectiveness of applying the horizontal joint to protect the anti-seepage safety of concrete face rockfill dam.

3) The influence area of the horizontal joint is roughly 0.2 H up and down. The model in this paper is that the tensile stress is reduced by more than 20% when the height is between 0.75 H-0.9 H.

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