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The Influence of Lenticle in Overburden on the Seismic Response of Concrete Face Rockfill Dam

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Abstract

Lenticle is a kind of local site largely encountered and has important influence on ground motion. However, little research has been done on the influence of lenticle on the seismic response of dam. In this paper, in the conditions of with and without lenticle in overburden, the finite element method is used to analyze the dynamic response of absolute acceleration and displacement of concrete face rockfill dam. And the influence of lenticle on the dynamic response of concrete face rockfill dam is studied. The research shows that the peak values of the dynamic response of absolute acceleration and displacement of rockfill body and panel of dam with lenticle are significantly smaller than that of rockfill body and panel of dam without lenticle. The effect of lenticle on the peak values of the dynamic response of absolute acceleration and displacement at the top of dam rockfill body and panel is greater than that on the middle and bottom of dam rockfill body and panel. The effect of lenticle on peak values of the dynamic response of absolute acceleration and displacement of the panel of dam is significantly greater than that on the rockfill body of dam.

Keywords

Lenticle, Concrete face rockfill dam, Seismic response, The finite element method.

1. Introduction

In sedimentary areas such as coastal areas, lakes and rivers, lenticle are a kind of local sites that are often encountered. In recent years, the influence of lenticle on seismic movement has been paid great attention to. Liang Jianwen e.g. [1-2] used finite-factor method to study the nonlinear amplification effect of lenticle body on seismic motion and its effect on seismicity in uniform field on bedrock. He Ying e.g. [3] used Monte Carlo method to randomly generate a sample of the lenticle section to study the effect of the lenticle section shape on the extreme value of surface dynamic response. On the basis of considering the nonlinearity of the site soil and lenticle body medium, Han Bing e.g. [4] systematically studied the effect of the lenticle on the seismic response of the upper structure in the deep soft soil field. The results show that the lenticle has a significant effect on the seismic movement of the surface and the upper structure of the site. The above research is based on foundation and housing construction projects, the impact of lenticle on the seismic response of the dam body has not been studied, this paper takes a rockfill body and panel of dam as the research object, uses finite yuan method to study the impact of the lenticle on the seismic response of the rockfill body and panel of dam, in order to provide theoretical basis for the seismic design of the panel pile stone dam.

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2. Text The basic principle of seismic response analysis of CFRD

2.1 Dynamic equilibrium equation and its solution

The power balance equation of the system consisting of panel pile stone dam and dam base is after finite yuan dispersion:

$$[M]\{\ddot{\delta}\}+[C]\{\dot{\delta}\}+[K]\{\delta\}=\{F(t)\} \tag{1}$$

in which $[M]$ is the mass matrix; $[C]$ is the damping matrix; $[K]$ is the strength matrix; $\{\ddot{\delta}\}$, $\{\dot{\delta}\}$ and $\{\delta\}$ are acceleration, velocity and displacement arrays of nodes respectively; $\{F(t)\}$ is the node seismic load array.

Since the dynamic stress-strain relationship of rockfill and foundation soil of dam body is nonlinear, Equation (1) is a nonlinear equation set, and the linear acceleration method is adopted in this paper to solve it gradually by integral [5].

2.2 Earth and stone model

Duncan-zhang e-B model is used for static analysis of overburden and dam rockfill, and the pre-seismic confining pressure required for dynamic analysis can be obtained through static analysis. Dynamic analysis using the equivalent linear viscoelastic model, the assumption of rockfill dam body and dam foundation overburden soil as a viscoelastic body, with the equivalent shear modulus G and equivalent damping ratio λ reflect stone dynamic stress-strain relationship of soil nonlinearity and hysteresis of the two basic dynamic characteristics, and the equivalent shear modulus G and equivalent damping ratio λ are expressed as the function of dynamic shear strain γ. In the equivalent linear viscoelastic model, Hardin-Drnevich model is most widely used, and its main expression is:

$$G=G_{\max}/(1+\gamma/\gamma_r) \tag{2}$$

$$\lambda=\lambda_{\max}(1-G/G_{\max}) \tag{3}$$

in which $G_{\max}$ is the maximum dynamic shear modulus; γ_r is the reference shear strain; $\gamma_r=\tau_{\max}/G_{\max}$, Where $\tau_{\max}$ is the maximum shear stress; $\lambda_{\max}$ is the maximum damping ratio.

According to the results of dynamic triaxial test of soil and rock, the maximum dynamic shear modulus $G_{\max}$ can be expressed as:

$$G_{max}=KP_a(\sigma_0'/P_a)^n \tag{4}$$

in which K is the modulus coefficient; n is the modulus index; σ_0' is the average effective stress; Pa is the atmospheric pressure; $G_{\max}$, σ_0' and Pa use the same dimension.

2.3 Interface model

The concrete face plate and the rockfill of dam body are two kinds of materials with different properties. Under the action of load, it may slip along the contact surface and deformation discontinuous phenomenon may occur. It is necessary to set up a contact surface element without thickness between the face plate and the rockfill body. The stress-strain relationship of the contact surface is:

$$\begin{Bmatrix}\Delta\tau_1\\ \Delta\tau_2\end{Bmatrix}=\begin{bmatrix}k_{s1} & 0\\ 0 & k_{s2}\end{bmatrix}\begin{Bmatrix}\Delta\gamma_1\\ \Delta\gamma_2\end{Bmatrix} \tag{5}$$

$$k_{s1}=\left(1-R_f\frac{\tau_1}{\sigma_n \tan\delta}\right)^2 K_1\gamma_w\left(\frac{\sigma_n}{P_a}\right)^n \tag{6}$$

$$k_{s2}=\left(1-R_f\frac{\tau_2}{\sigma_n \tan\delta}\right)^2 K_2\gamma_w\left(\frac{\sigma_n}{P_a}\right)^n \tag{6}$$

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in which K_1, K_2, R_f, n are linear index, which are determined through experiments; δ is the interface friction angle of the contact surface; γ_w is the bulk density of water; P_a is the atmospheric pressure.

3. An engineering example

3.1 Project summary

The crest elevation of a certain face rockfill dam is 3168.0m, the maximum dam height is 108.2m, the crest width is 10.0m, the upstream dam slope is 1:1.4, the downstream dam slope is 1:35, and the normal water level of the reservoir is 3165.0m. Adopt concrete impervious wall, the impervious wall is connected with the concrete toe board at the upper part, the lower part is deep into the bottom of the covering layer, and the impervious curtain is connected below. The river bed of the dam base has nearly 100m thick overburden, which is mainly composed of sand gravel. There is a lenticle in the overburden layer, assuming that the lenticle is uniform and isotropic silting clay. The buried depth of the lenticle is d =10m, the width is a =300m, and the thickness is b =6m. The dam profile is shown in Figure 1.

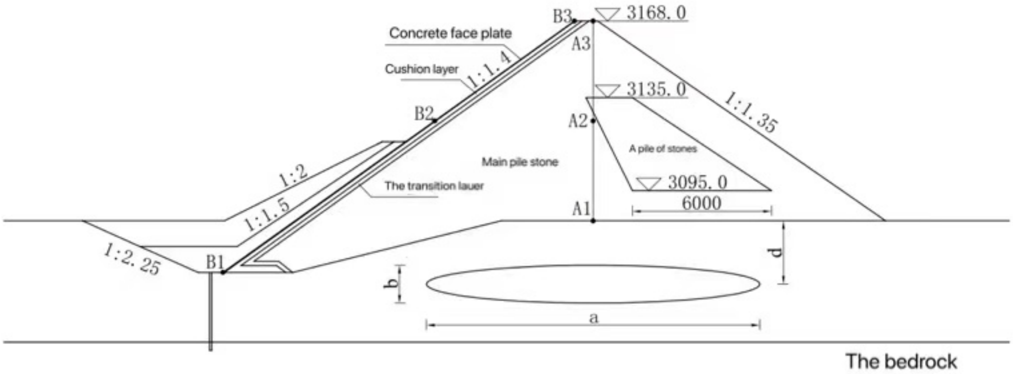

Fig. 1 The generalized section of the dam

3.2 Finite element model

The boundary of the dam finite element model is all fixed by truncating the boundary [6]. The vertical direction was taken to the bedrock surface, and the distance between the upstream and downstream boundaries in the horizontal direction was selected according to reference [7]. In this paper, the width of the lenticle was 2.5-4 times, and the stability of the calculated results was checked.

3.3 Calculated parameters

Static and dynamic calculation parameters of overburden and rockfill materials involved in the calculation process are selected by referring to literature [7-8], as shown in Table 1-3. Linear elastic model is adopted for concrete panel, density $\rho_d = 2400\text{kg/m}^3$, elastic modulus $E = 2.0 \times 10^4$MPa. Parameters of contact surface between panel and rockfill are shown in Table 4.

Table 1. The calculation parameters of Duncan-Zhang E-B model

materials	K	n	R_f	C/(kPa)	φ_0 / (°)	$\Delta\varphi_0$ / (°)	K_b	m	K_{ur}	ρ / (g · cm^{-3})
cushion layer	1150	0.23	0.78	20	41.9	3.1	410	0.26	2200	2.13
transition layer	1560	0.24	0.82	15	45.3	5.0	580	0.16	2700	2.14
main pile stone	1040	0.30	0.81	30	48.8	8.7	495	0.30	2000	2.04
second pile stone	980	0.32	0.84	30	47.8	7.5	460	0.32	1950	2.01
covering	950	0.36	0.78	25	43.5	5.0	405	0.30	1900	2.11

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Table 2. The maximum dynamic shear modulus test parameters $\boldsymbol{K}$ and $\boldsymbol{n}$

materials	$\boldsymbol{K}$	$\boldsymbol{n}$	$\boldsymbol{\nu}$
cushion layer	3532.6	0.571	0.33
transition layer	3338.4	0.627	0.33
Primary (secondary) stone pile	2902.2	0.568	0.33
covering	2348.1	0.606	0.33
lenticle	190.8	0.5	0.47

Table 3. The test data of dynamic shear modulus ratio and dynamic damping ratio

$\boldsymbol{\sigma_3' = 200kPa}$			$\boldsymbol{\sigma_3' = 1000kPa}$		
γ	G/G_{max}	λ	γ	G/G_{max}	λ
0.000 006 1	100.00	1.64	0.000 004 65	100.00	1.38
0.000 008 8	99.31	1.87	0.000 006 07	99.88	1.51
0.000 012 7	96.97	1.90	0.000 013 80	97.94	2.01
0.000 020 9	88.33	2.26	0.000 018 60	97.52	2.19
0.000 056 3	74.87	2.51	0.000 050 00	86.12	2.95
0.000 104 0	66.68	3.92	0.000 100 00	75.28	3.09
0.000 257 0	53.65	4.93	0.000 200 00	66.69	3.69
0.000 558 0	42.16	6.16	0.000 500 00	52.41	4.45
0.000 839 1	34.48	7.96	0.001 100 00	38.18	5.75
0.001 850 0	22.42	8.69	0.001 400 00	32.69	6.42

Table 4. The parameters of contact surface

materials	parameter				
	K_1	K_2	n	R_f	δ
Contact surface	4800	4800	0.56	0.74	36.6

3.4 Seismic time history curve

The seismic response analysis in this paper adopts the equivalent linear method, which is reasonable for the seismic acceleration less than 0.3g. In order to reduce data interference, filtering is needed. During the calculation, the input ground motion is the seismic wave after filtering the high frequency (25Hz), the horizontal peak acceleration of bedrock surface is 0.1g, and the duration of ground motion is 40s. The acceleration time-history curve is shown in Fig. 2. For dynamic analysis, seismic waves as shown in Fig. 2 were used in the horizontal and vertical directions. The peak acceleration in the vertical direction was 2/3 of that in the horizontal direction. The input method of seismic wave is acceleration time history.

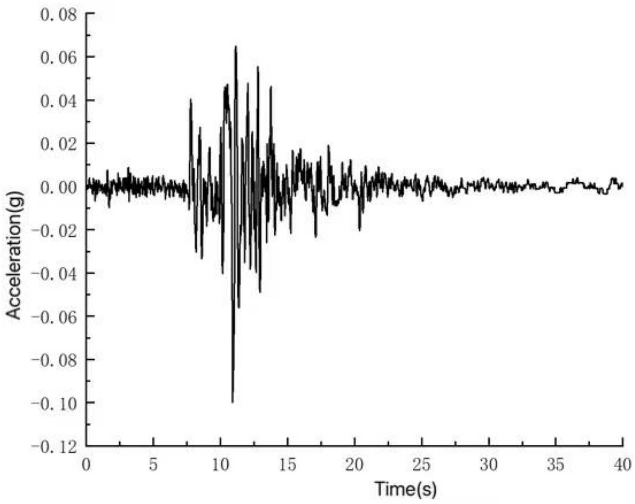


Fig. 2 The acceleration-time curve

3.5 Dynamic response analysis of dam body

3.5.1 Dynamic response analysis of rockfill

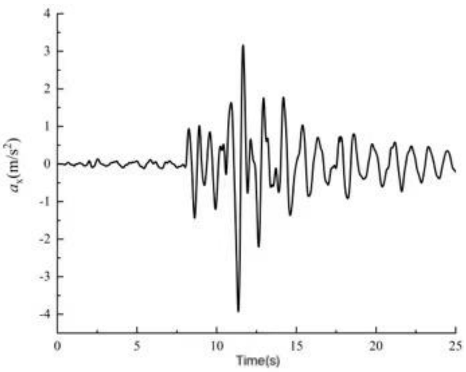
In order to understand the absolute acceleration response and dynamic displacement characteristics of dam rockfill in detail, three typical nodes were selected from the dam top to the dam bottom at the dam axis to analyze the absolute acceleration response peak and dynamic displacement. The three typical nodes of the dam rockfill are node 990 (A3), node 4551 (A2) and node 1255 (A1), as shown in Fig. 1.

Table.5 shows the peak value of absolute acceleration response and its magnification of three typical nodes of dam rockfill. It can be seen from Table 5 that the absolute acceleration response of these three typical nodes is related to their positions in the dam body, and the absolute acceleration response of nodes at the dam top is greater than that of other parts. The absolute peak acceleration and magnification ratio of typical nodes of the dam without lenticle in the overburden are greater than 1.0, while those with lenticle are less than 1.0, indicating that the silty clay lenticle in the gravel overburden has weakened the seismic response of the dam.

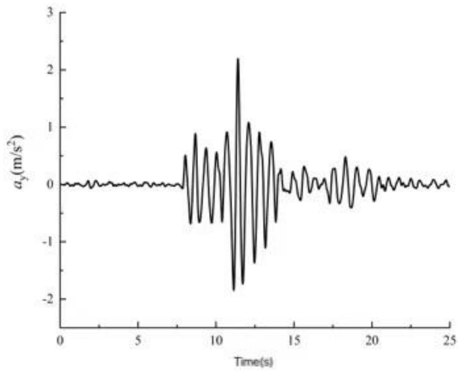
To reduce the length, only the absolute acceleration time-history curve of typical node 990 (A3) at the dam top is listed, as shown in Fig.3. It can be seen from Fig.3 that the lenticle has little influence on the time nodes of the absolute peak acceleration of nodes, but has a great influence on the absolute peak acceleration.

Table 5. The peak value and magnification of absolute acceleration response of typical nodes of rockfill body

	No lenticle				Contain the lenticle			
Node	a_x (m/s^2)	magnification	a_y (m/s^2)	magnification	a_x (m/s^2)	magnification	a_y (m/s^2)	magnification
990	3.93	4.00	2.19	3.35	0.57	0.58	0.78	1.20
4551	1.56	1.59	1.29	1.97	0.48	0.49	0.61	0.94
1255	1.01	1.03	0.72	1.10	0.40	0.41	0.50	0.77

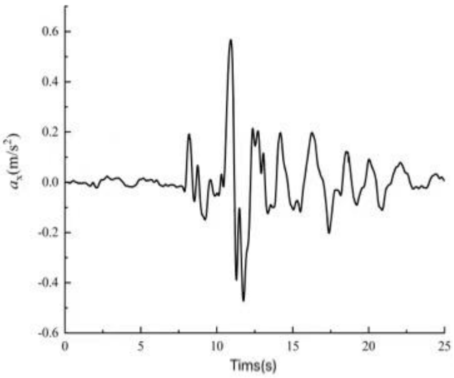


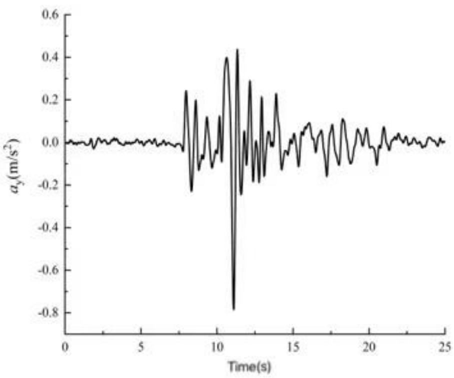
Time history curve of acceleration along river



Vertical acceleration time history curve

(a) No lenticle





Time history curve of acceleration along river Vertical acceleration time history curve

(b) Contain the lenticle

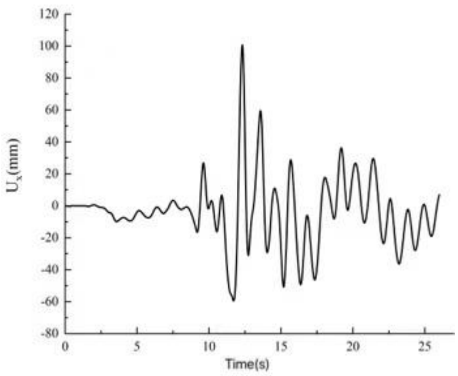
Fig. 3 The acceleration-time curve of rockfill body node 990(A3)

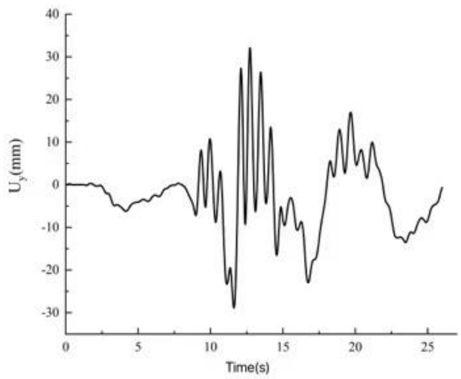
Table.6 shows the dynamic displacement peaks of three typical nodes of dam rockfill. Because the overburden layer is gravel, its mechanical properties are close to that of the dam body rockfill material, and the dynamic response of the dam is quite severe. The dynamic displacement of the three typical nodes above is all more than 20mm. From the foundation to the crest, the dynamic displacement of rockfill increases gradually, which accords with the general law of earth motion displacement response of earth-rock dam. The dynamic displacement of the dam crest without lenticle is larger than that of the dam crest with lenticle, and there is little difference between the two for the middle and bottom of the dam.

Fig.4 shows the dynamic displacement time-history curve of typical node 990 (A3). It can be seen from Fig. 4 that the dynamic displacement of typical node 990 (A3) without lenticle and with lenticle has basically the same variation rule of everywhere vibration, and the time nodes of maximum dynamic displacement are basically the same, but the lenticle reduces the maximum dynamic displacement of typical node 990 (A3).

Table 6. The peak value of dynamic displacement of typical nodes of rockfill body

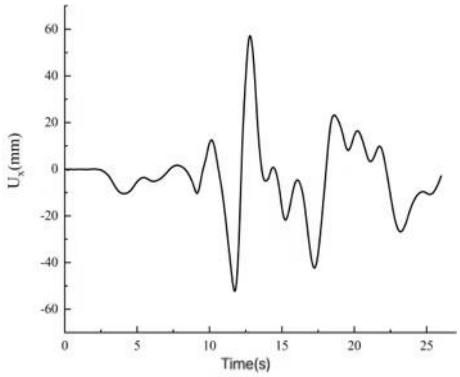
	No lenticle		Contain the lenticle	
Node	Ux(mm)	Uy(mm)	Ux(mm)	Uy(mm)
990	100.73	32.13	57.22	28.20
4551	54.78	25.81	53.12	27.33
1255	42.67	24.90	48.76	26.15



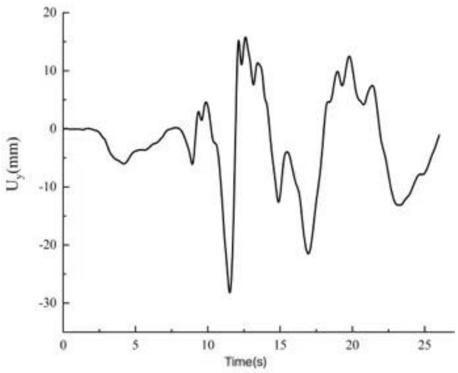


Time history curve of acceleration along river Vertical acceleration time history curve

(a) No lenticle



Time history curve of acceleration along river



Vertical acceleration time history curve

(b) Contain the lenticel

Fig. 4 The dynamic displacement time-history curve of typical node 990 (A3)

3.5.2 Dynamic response analysis of panel

In order to understand the absolute acceleration response and dynamic displacement characteristics of the dam face in detail, three typical nodes were selected from the dam top to the dam bottom on the upstream surface of the dam, and the absolute acceleration response peak value and dynamic displacement were analyzed. The three typical nodes of the dam panel are node 115 (B3), node 170 (B2) and node 151 (B1), as shown in Fig.1

Table.7 shows the peak values of absolute acceleration response and their magnification at three typical nodes of the dam face. It can be seen from Table.7 that the absolute acceleration response of these three typical nodes is related to their positions in the dam. The peak value and amplification of absolute acceleration response of the node at the top of the panel is much larger than that of the node at the middle and bottom of the panel. The absolute acceleration response peak and its magnification ratio of typical node in panel with lenticle in overlay are much smaller than that of typical node without lenticle in overlay, and the absolute acceleration response of panel with lenticle in overlay is weakened by lenticle. In addition, by comparing Table.5 and Table.7, it can be found that the lenticle in the overburden has a greater influence on the absolute acceleration response of the panel than the rockfill.

To reduce the length, only the absolute acceleration time-history curve of typical node 115 (B3) of the panel is listed, as shown in Fig.5. It can be seen from Fig. 5 that the absolute acceleration of 115 (B3) at the typical node of the panel with and without a lenticle has basically the same variation law of the vibration in place. The peak absolute acceleration of 115 (B3) at the typical node of the panel with a lenticle is slightly delayed, and the peak absolute acceleration obviously decreases

Table.7 The peak value and magnification of absolute acceleration response of typical nodes of panel

	No lenticle				Contain the lenticle			
node	a_x (m/s^2)	magnification	a_y (m/s^2)	magnification	a_x (m/s^2)	magnification	a_y (m/s^2)	magnification
115	6.51	6.63	8.43	12.9	2.54	2.59	3.63	5.55
170	1.78	1.81	2.18	3.33	0.97	0.98	0.98	1.50
151	1.49	1.52	1.03	1.58	0.52	0.53	0.69	1.05

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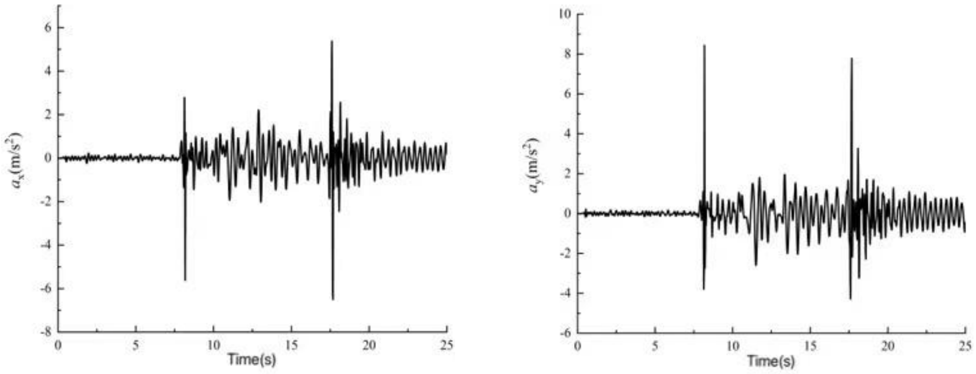
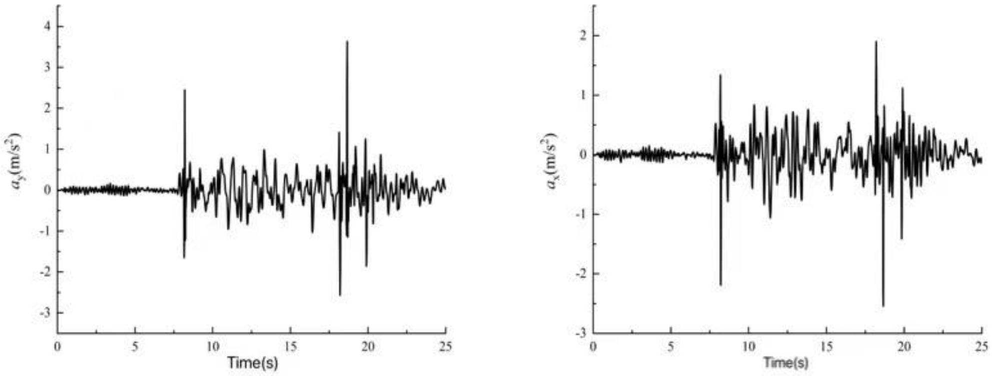


Time history curve of acceleration along river   Vertical acceleration time history curve

(a) No lenticle



Time history curve of acceleration along river   Vertical acceleration time history curve

(b) Contain the lenticle

Fig. 5 The acceleration-time curve of panel node 115(B3)

Table.8 shows the dynamic displacement peaks of three typical nodes of the dam face. As can be seen from Table 8, the dynamic displacement response of the dam face plate is relatively intense, the peak value of the dynamic displacement of the typical nodes at the top and middle of the face plate is relatively large, and the dynamic displacement of the face plate gradually increases from the bottom to the top. The dynamic displacement peaks of the top and middle of the dam panel without lenticle are larger than those of the top and middle of the panel with lenticle. The dynamic displacement peak of the panel bottom without lenticle is close to that of the panel bottom with lenticle

Fig.6 shows the time-history curve of dynamic displacement of typical node 115 (B3) of panel. It can be seen from Fig.6 that the dynamic displacement of typical node 115 (B3) of panel with and without lenticle has basically the same variation law of vibration in place, but the dynamic displacement peak of typical node 115 (B3) of panel with lenticle is obviously smaller than that of typical node 115 (B3) of panel without lenticle.

Table 8. The peak value of dynamic displacement of typical nodes of panel

	No lenticle		Contain the lenticle	
Node	Ux(mm)	Uy(mm)	Ux(mm)	Uy(mm)
115	141.49	193.66	113.45	156.18
170	86.64	101.49	73.68	76.78
151	44.32	23.47	41.85	23.16

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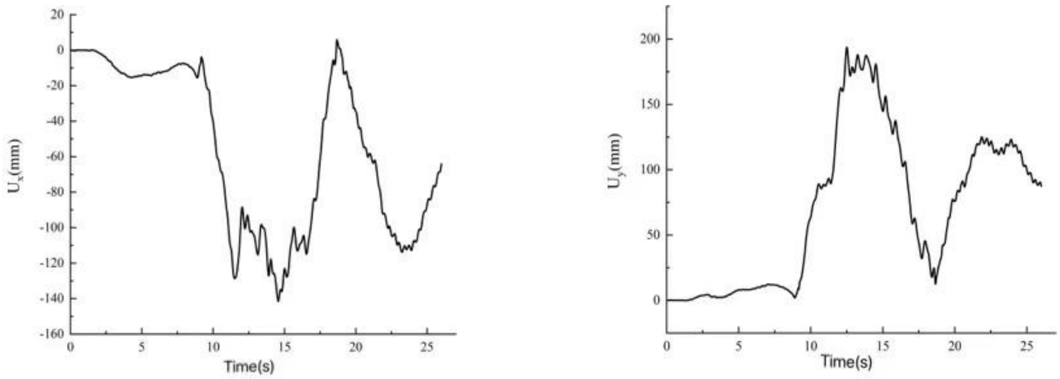
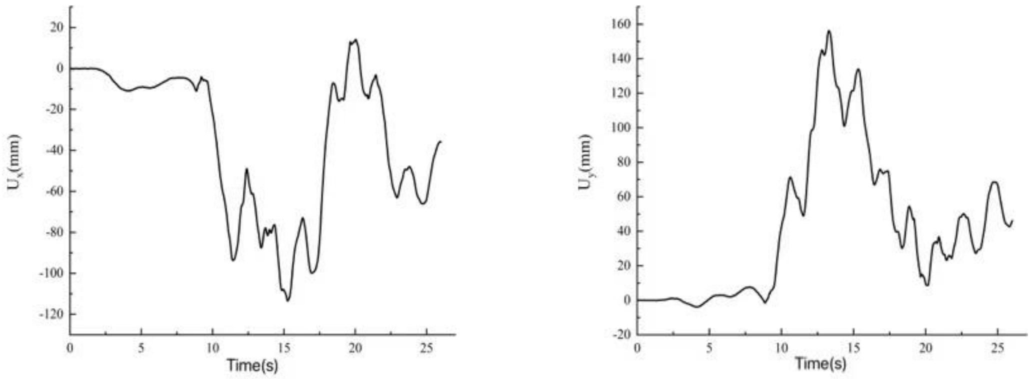


Time history curve of acceleration along river Vertical acceleration time history curve

(a) No lenticle



Time history curve of acceleration along river Vertical acceleration time history curve

(b) Contain the lenticle

Fig. 6 The dynamic displacement-time curve of panel node 115(B3)

4. Conclusions

In this paper, the finite element method is used to analyze the seismic response of face rockfill DAMS with and without lenticle in overburden, and the influence of lenticle on the absolute peak acceleration and dynamic displacement of face rockfill DAMS is studied.

(1) The existence of lenticle changes the dynamic response of rockfill dam, and the absolute peak acceleration and dynamic displacement of rockfill dam and concrete face change obviously.

(2) The peak values of absolute acceleration and dynamic displacement of rockfill and concrete slab with lenticle are obviously smaller than those of rockfill and concrete slab without lenticle.

(3) The influence of lenticle on the peak values of absolute acceleration and dynamic displacement at the top of dam rockfill and concrete slab is greater than that at the middle and bottom of dam rockfill and concrete slab.

(4) The influence of lenticle on the peak values of absolute acceleration and dynamic displacement of concrete slab is obviously greater than that of rockfill.

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