ANTI-SEISMIC ANALYSIS OF SHUANGJIANGKOU ROCK-FILL DAM CONCERNING VISCOUS-SPRING ARTIFICIAL BOUNDARY

LI Tongchun[1], LI Hongen[2], ZHAO Lanhao[2] and TIAN Jingyuan[3]

1.Professor, College of Water Conservancy and Hydropower Engineering, Hohai University
Nanjing, Jiangsu, P.R. China (210098)
2.Doctor, College of Water Conservancy and Hydropower Engineering, Hohai University
Nanjing, Jiangsu, P.R. China (210098)
3. Doctor, Chengdu Hydroelectric Investigation＆Design Institute, China Hydropower Consulting Group,
Chengdu (610072)
Email:lhe_hhu@163.com

ABSTRACT :

The anti-seismic reliability of high rock-fill dam is directly related to the operation safety of the dam built on the deep overburden layer. As an example, traditional fixed boundary with massless foundation and viscous-spring artificial boundary concerning radiation damping of foundation are separately applied in the dynamic response analysis of Shuangjiangkou core wall rock-fill dam. The latter can simulate the practical boundary conditions better. The calculation results show that the dynamic responses of the dam are small, which can satisfy the stability request. Meanwhile, the viscous-spring artificial boundary method decreases the dynamic response results of acceleration by 15%~30% comparing with which in the traditional fixed boundary with foundation of no weight, which should be taken into account in the dynamic response analysis with regard to the rock-fill dam.

KEYWORDS: dynamic response, Shuangjiangkou rock-fill dam, viscous-spring artificial boundary, radiation damping of foundation, massless foundation

1.INTRUDCTION

The anti-seismic reliability of high rock-fill dam is directly related to the operation safety of the dam built on the deep overburden layer. In recent years, significant results have been made both on the application of theories and the engineering practice [Zhang Bingyin, Yu Yuzhen, Zhang Jianmin, 2003]. However, fixed boundary with massless foundation method is widely used in engineering practice. It can not simulate the actual boundary of rock-fill dam accurately resulting calculation error.

When vibration of structure under seismic motivation occurs, energy of fluctuation transfers to foundation from structure. There will be reflection of waves on the limited interception of artificial boundary. It will cause the oscillation of waves, resulting in simulating distortion. The most effective way to solve this problem is to introduce artificial boundary conditions. Therefore, scholars proposed a variety of artificial boundaries[Liao Zhenpeng, 1997], such as viscous boundary [Lysmer J., Kulemeyer R. L.,1969], paraxial approximation boundary [Clayton R., Engquist B., 1977], transmitting boundary[Liao Zhenpeng, Huang Kongliang, Yang Baipo, 1984]and viscous-spring boundary [Deeks A. J., Randolph M. F., 1994], so as to solve the problem of the waves reflection on the limited interception of artificial boundary. Of all these artificial boundaries, the viscous-spring boundary is of high precision, simple and practical, easy to be realized in program. It has been successfully applied in dynamic analysis of arch dam and gravity dam[He Xiangli, Li Tongchun, 2006, Niu Zhiwei, Li Tongchun, 2007] while less in rock-fill dam. In this paper, the viscous-spring boundary is adopted in the dynamic response analysis of Shuangjiangkou rock-fill dam. Its results are compared with those calculated by method of the fixed boundary with massless foundation. The anti-seismic ability of Shuangjiangkou rock-fill dam is verified while the effects of foundation radiation damping to rock-fill dam are discussed.

2. BASIC THEORIES

2.1Dynamic equilibrium equation

The dynamic equilibrium equation for the dynamic analysis is

$$[M]\{\ddot{\delta}\}+[C]\{\dot{\delta}\}+[K]\{\delta\}=M\{R\} \tag{2.1}$$

Where, $[M]$ is mass matrix, $[C]$ is damping matrix and $[K]$ is stiffness matrix. $\{\delta\},\{\dot{\delta}\},\{\ddot{\delta}\}$ are respectively relative displacement, velocity and acceleration of node. $\{R\}$ is load matrix of node which is seismic acceleration.

2.2Static and dynamic constitutive equations

Duncan-Chang E-B[Qian Jiahua, Yin Zongze, 1996] model is adopted for static calculation. The tangent elastic modulus is written as

$$E_t = K\cdot P_a\cdot\left(\frac{\sigma_3}{P_a}\right)^n\cdot\left[1-R_f\frac{(\sigma_1-\sigma_3)}{(\sigma_1-\sigma_3)_f}\right]^2 \tag{2.2}$$

Tangent volume modulus is

$$B = K_b\cdot P_a\cdot\left(\frac{\sigma_3}{P_a}\right)^m \tag{2.3}$$

c, φ, k, k_{ur}, n, k_{b}, m, R_{f} are material constants and could be obtained by triaxial test.

Equivalent linear viscous-elastic model is applied during dynamic calculation. The maximum shear modulus of material is

$$G_{\max} = K\cdot Pa\cdot\left(\frac{\sigma'_m}{Pa}\right)^n \tag{2.4}$$

Where K and n are material constants and $\sigma'_m=(\sigma'_1+\sigma'_2+\sigma'_3)/3$.

After regression analysis of experiment data for $G/G_{\max}$ and damping ratio λ, the relationships of G-γ (dynamic shear strain) and λ-γ can be obtained.

2.3 Viscous-spring artificial boundary

Viscous-spring boundary was proposed by Deeks[Deeks A J, Randolph M F,1994] basing on the research of viscous boundary. Physical components were adopted to form artificial boundary with good stability of low-frequency. In the practical problems, geometry proliferation of scattered waves, which are caused by local irregular area or structure basis, normally exist. Therefore, the hypothesis of cylinder-wave(2D) or spherical wave(3D) for scattered waves is more reasonable. The motion equation of cylinder-wave in polar plane is:

$$\frac{\partial^2 w}{\partial t^2}=c_s^2\left(\frac{\partial^2 w}{\partial r^2}+\frac{1}{r}\frac{\partial w}{\partial r}\right) \tag{2.5}$$

Where w is the displacement out of plane for medium. c_s is shear velocity ($c_s=\sqrt{G/\rho}$), G is shear modulus, ρ mass density.

For the cylinder-wave from coordinate origin, the solution of following form is adopted,

$$w = (r,t) = \frac{1}{\sqrt{r}} f(t - \frac{r}{c_s}) \tag{2.6}$$

Shear stress can be obtained by using equation (2.6) and $\tau(\gamma,t) = G\,\partial\omega/\partial\gamma$,

$$\tau(r,t) = -G\left[\frac{1}{2r\sqrt{r}} f\left(t - \frac{r}{c_s}\right) + \frac{1}{c_s\sqrt{r}} f'\left(t - \frac{r}{c_s}\right)\right] \tag{2.7}$$

The velocity of any point can be written as

$$\frac{\partial w(r,t)}{\partial t} = \frac{1}{\sqrt{r}} f'\left(t - \frac{r}{c_s}\right) \tag{2.8}$$

Substituting equation (2.6) and (2.8) into equation (2.7), we can get the following relation of a random point B.

$$\tau(r_b,t) = -\frac{G}{2r_b} w(r_b,t) - \rho c_s \frac{\partial w(r_b,t)}{\partial t} \tag{2.9}$$

It can be easily seen that boundary can be cut off on the radius of γ_b, while applying viscous damper C_b and linear spring K_b, shown in Fig.1.

$$C_b = pc_s, K_b = \frac{G}{2r_b} \tag{2.10}$$

The artificial boundary condition with $\gamma = \gamma_b$ has the same form of equation(2.9). If the distance (γ_b) from wave source to boundary can be precisely calculated, the coefficients of physical components on the boundary can be confirmed, so as to eliminate the reflection of scatted wave on artificial boundary, which means that the precise simulation of wave transmission from limited area to infinite area can be realized.

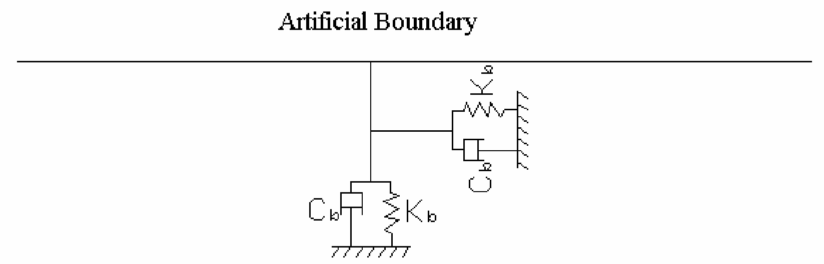


Fig.1 Sketch of visco-spring artificial boundary

Supposing $\omega_0(x,y,t)$ as known input wave field whose incident angle is random, for any point B on the artificial boundary, the condition of accurately simulating wave input is that the equivalent loads imposed on the boundary should ensure that the displacements and stresses on artificial boundary are the same to the origin wave field.

$$\omega(x_B, y_B, t) = \omega_0(x_B, y_B, t) \tag{2.11}$$

$$\tau(x_B, y_B, t) = \tau_0(x_B, y_B, t) \tag{2.12}$$

Where τ_0 is the stress caused by displacement in origin continuum.

To realize the wave input, stress $F_B(t)$ is supposed applying to point B on the artificial boundary. Artificial boundary and physical components on it (spring and damper) are separated by using the detachment concept in mechanic analysis(shown in Fig.2), so the stress of boundary node can be written as

$$\tau(x_B, y_B, t) = F_B(t) - f_B(t) \tag{2.13}$$

The motion equation of physical component composed by spring and damper is

$$f_B(t) = C_b w_0(x_B, y_B, t) + K_b w_0(x_B, y_B, t) \tag{2.14}$$

Substituti equation(2.12) and (2.14) into equation(2.13),

$$F_B(t) = \tau_0(x_B, y_B, t) + C_b \omega_0(x_B, y_B, t) + K_b \omega_0(x_B, y_B, t) \tag{2.15}$$

From equation(2.15), the total load $F_B(t)$ applying on the artificial boundary can be got and the fluctuation input on artificial boundary is realized.

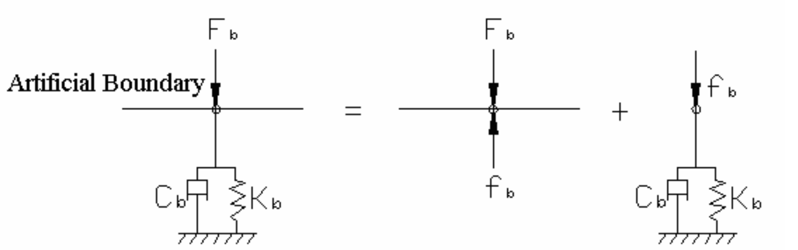


Fig.2 Mode of load-applying sketch on visco-spring artificial boundary

3. ANTI-SEISMIC ANALYSIS OF SHUANGJIANGKOU ROCK-FILL DAM

3.1 Calculating model

Shuangjiangkou rock-fill dam is one of the key projects in the development of the Dadu river basin. It is a vertical core wall rock-fill dam with the height of 314m. The typical section of the dam is shown in Fig.3. Fig.4 shows the 3D FEM grid of the dam. The total elements of the FEM grid are 13795 while the total nodes are 15323. Point A near the top of dam in Fig.2 is set to be a controlling point to investigate dynamic response of the dam.

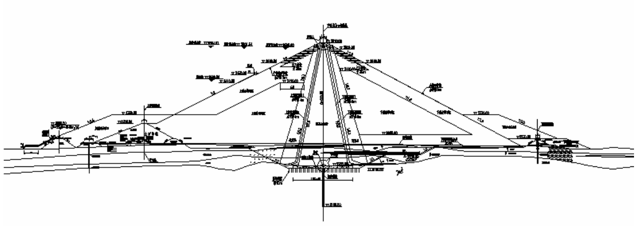


Fig.3 Typical section of Shuangjiangkou dam

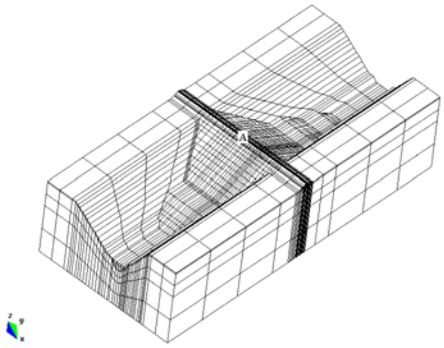


Fig.4 3D FEM grid

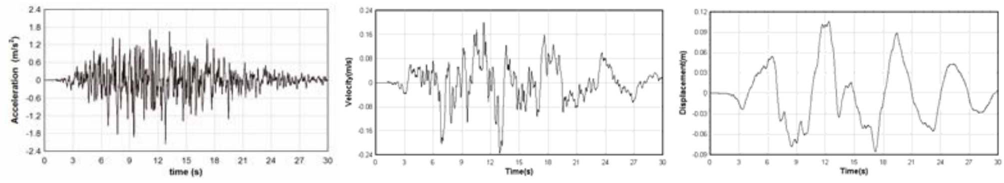
Duncan-Chang E-B model is adopted for static calculation and the parameters are shown in Table 1. For the dynamic calculation, the equivalent linear visco-elastic model is applied. Because there are too many parameters for dynamic calculation, they can be found in reference [Feasibility study report of Shuangjiangkou hydropower station in Sichuan Province, 2008]

Table 1. Parameters for Duncan-Chang model

Material	Dry Density(t/m^3)	φ_0 (˚)	$\Delta\varphi$ (˚)	c (t/m^2)	R_f	K	n	K_{ur}	K_b	m
overburden layer③	2.05	37	/	1.6	0.81	961	0.18	2000	485	0.23
overburden layer②	2.03	37	/	1.0	0.84	810	0.23	1600	352	0.31
overburden layer①	2.06	39	/	1.7	0.81	1050	0.21	2100	519	0.25
Core wall	2.10	31.0	/	3.5	0.88	447	0.51	900	255	0.51
Anti-filter 1	2.00	42.7	3.8	0	0.72	1141	0.20	2200	423	0.23
Anti-filter 2	2.02	45.7	5.7	0	0.73	1396	0.23	2800	451	0.25
Transition	2.09	47.3	6.4	0	0.79	960	0.25	2000	357	0.34
Upstream Rock	2.12	41.8	3	0	0.71	1050	0.25	2100	500	0.25
Downstream Rock	2.09	50.7	8	0	0.74	1234	0.28	2400	696	0.29

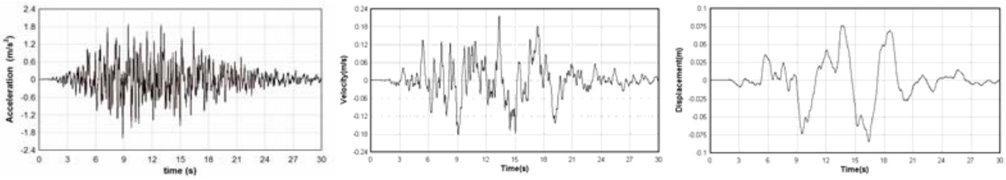
3.2 Analysis of calculation results

In order to study the impact of foundation radiation damping to the dam dynamic response, traditional fixed boundary with massless foundation model and viscous-spring artificial boundary are separately adopted in calculations. When the former one is applied, the boundary of the dam is fixed, the weight of foundation is not considered and seismic inertia forces of three directions are directly applied on dam body(shown in Fig.5~7(a)). The peak values of three directions accelerations are 2.15m/s^2, 1.99m/s^2 and 1.43m/s^2. When the latter one is applied, velocities and displacements (shown in Fig.5~7(b)(c)) are input on the side and bottom of the foundation, springs and dampers are set on the boundary and the weight of foundation is considered to study the effect of foundation radiation damping.



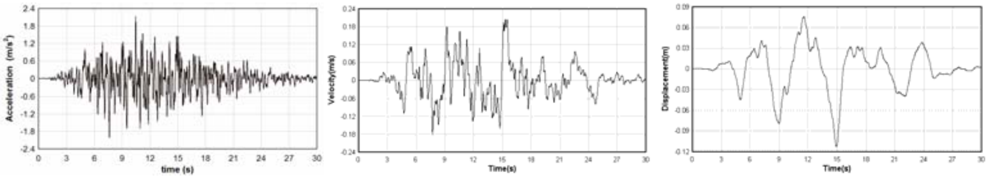
（a） （b） （c）

Fig.5 Time-history curve of X direction acceleration, velocity and displacement of seismic wave



（a） （b） （c）

Fig.6 Time-history curve of Y direction acceleration, velocity and displacement of seismic wave



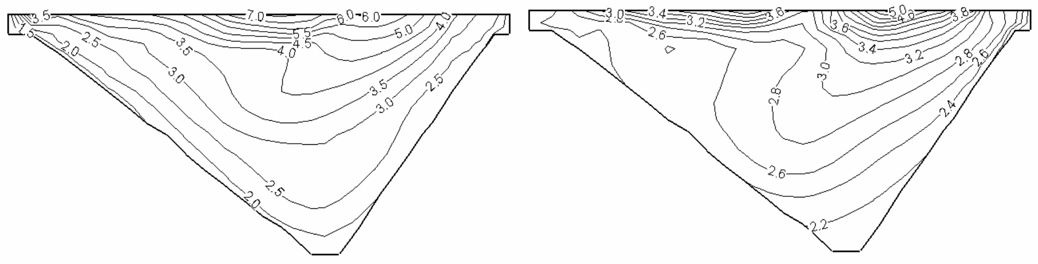
（a） （b） （c）

Fig.7 Time-history curve of Z direction acceleration, velocity and displacement of seismic wave

Comparison of dynamic results by two kinds of boundaries is shown in Table 2. The maximum acceleration response is 7.030 m/s^2 (in fixed boundary of X direction) and it occurs near the top of the dam. In this table, there are some differences of dynamic response by applying the two different boundaries, however, the dynamic response of dam is not great. The distributions of maximum acceleration response under the two different boundaries are similar, shown in Fig.8. When viscous-spring boundary is applied, the dynamic response of dam decreases. The reduction ratio of X direction acceleration response is most obvious, which is -27.9%, while for Y direction is -18.4% and for Z direction is -17.9%. Effect of viscous-spring artificial boundary to acceleration response of point A is shown in Fig.9. From this figure, the effect of viscous-spring boundary is notable and should be considered in calculation process.

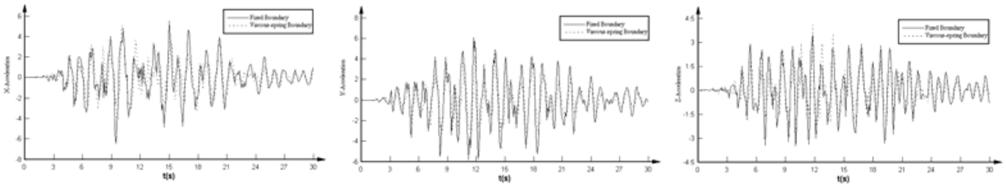
Table 2. Comparison of dynamic results by two different boundaries

Conditions	Maximum Acceleration Response(m/s^2)			Ample Coefficient		
	X	Y	Z	X	Y	Z
Fixed Boundary	7.030	6.796	5.419	3.27	3.42	3.79
Viscous-spring Boundary	5.068	5.545	4.451	2.36	2.79	3.11
Difference	-1.962	-1.251	-0.968	-	-	-
Reduction Ratio	-27.9%	-18.4%	-17.9%	-	-	-



(Fixed Boundary) (Viscous-spring Boundary)

Fig.8 Acceleration response of X direction



（a） （b） （c）

Fig.9 Effect of viscous-spring artificial boundary to acceleration response of point A

4.CONCLUSIONS

Taking Shuangjiangkou core wall rock-fill dam as an example, traditional fixed boundary with massless foundation and viscous-spring artificial boundary concerning radiation damping of foundation are separately applied in the dynamic response analysis of the dam. Comparing to the acceleration response of traditional fixed boundary method, the response of viscous-spring boundary method reduces by 15%~30%. The effect of applying viscous-spring boundary and considering the foundation radiation damping is notable. Therefore, the application of viscous-spring artificial boundary in dynamic response analysis of rock-fill dam should be paid great attention.

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