Advances in Structural Mechanics
Volume 1 Issue 1 No. 3
Published Online July 10 2022

Stress analysis of polymer diaphragm wall for earth-rock dams under static and dynamic loads

Jianguo Xu, Chengcheng Liu

School of Environment and Hydraulic Engineering, Zhengzhou University, Zhengzhou 450000, China

Abstract: Compared with plastic concrete and normal concrete, the polymer diaphragm wall has the characteristics of light weight, early strength, environmental conservation and durability. During its construction, it has speedy, economic, and practical characteristics and few influences on the dam. The polymer diaphragm wall has been successfully used in earth-rock dams. But at present the static and dynamic characteristics of earth-rock dams are seldom studied. The Duncan-Chang *E-B* nonlinear model is used and the contact element is set up between the diaphragm wall and the dam for the FEM model. A comparison of stresses on the diaphragm wall among polymer, plastic concrete and normal concrete under static and seismic loads shows that the stress on the polymer diaphragm wall is the least and it is not easy to be failed. The polymer diaphragm wall for earth-rock dams has preferable security.

Keywords: Polymer diaphragm wall, earth-rock dam, FEM model, stress analysis

1 Introduction

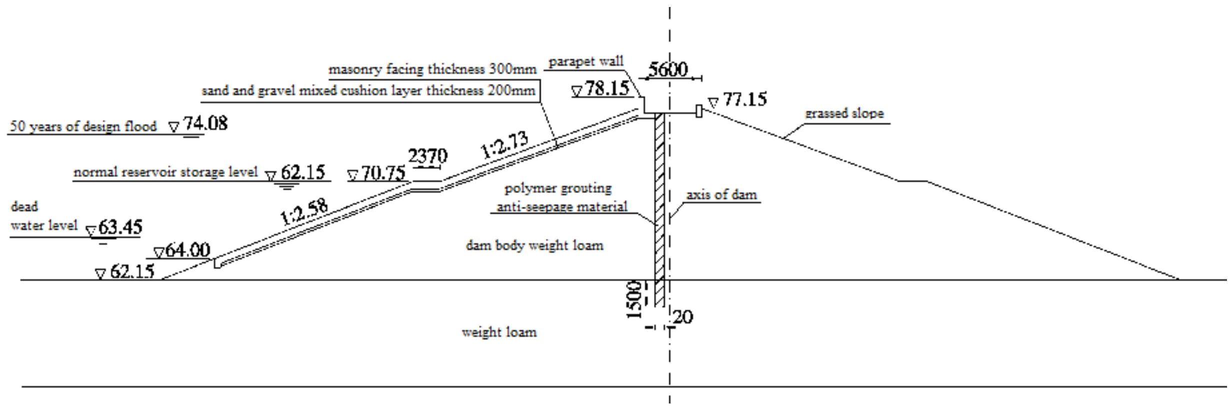

Fig. 1 Sketch of polymer diaphragm wall for an earth-rock dam

Seepage reinforcement is the main engineering measure of managing defective and dangerous reservoir dams[1], technologies which commonly used in projects including grouting and diaphragm walls .Among which, high-strength concrete or plastic concrete diaphragm wall have been widely applied in dam reinforcement engineering and thereby achieved good results. But at the same time, the defects also emerged. For example, high stress problems caused by high elastic modulus of the concrete diaphragm wall, lower strength and impermeability as well as poor durability of plastic concrete diaphragm walls. Besides, higher cost due to thicker wall ,larger area of construction site scene, longer construction period and even bigger disturbance to the original dam are also problems.

Based on the actual demands of engineering construction, increasingly widespread attention at home and abroad have drown on the study and application of organic polymer chemical grouting materials represented by polymers with expensive properties from 1970s and a wealth of achievements have been obtained[3].In China, under the joint efforts of Zhengzhou University and other units, a complete set of fast repair polymer grouting technology has been successfully researched and developed, it means a breakthrough progress have been made in the field of theoretical research and engineering application. Compared with traditional grouting reinforcement techniques, polymer grouting has many obvious advantages such as speedy, light weight, good impermeability, thinner diaphragm wall, safe and environmental materials, durability and so on. Although at present great progresses have been made on materials, equipment, and constructional technologies of grouting in and abroad, studies refer to the theory of polymer grouting are seldom. A large number of literature only introduce material characteristics, grouting technologies and construction effects of polymer,rarely involved in grouting mechanism and the stress and strain analysis of diaphragm wall under the static and dynamic load[8-11]. The commercial software ALGOR is adopted to establish dam static and dynamic analysis model considering nonlinearity of soil and the contact element is set up between the dam and the diaphragm wall to simulate open or contact state.The differences of stress distribution and failure characteristics among the polymer,plastic concrete and normal concrete diaphragm wall under the static and seismic loads are compared and analyzed on the basis of an example computation and analysis,which provide theoretical analysis reference for design and construction of the diaphragm wall.

2 Calculation model and material parameters of dam polymer diaphragm wall

Jiulong reservoir dam situated in Xinyang Henan is an homogeneous earth dam with good engineering geological conditions as the length of the crest is about 340m and the dam foundation is consist of weight loam,fine sand and mica-quartzose schist(show in figure 1). In order to handle the dam body seep from upstream to downstream,along the dam vertical direction about 0.5m away from the dam axis build a polymer diaphragm wall using grouting technology .The dam top elevation is 77.15m , the dangerous construction section is 1+500~1+200,and the length of the diaphragm wall is 215m.

2.1 Basic assumptions

To simplify the calculation,FEM analysis adopt several assumptions as follows:
(1)Earth-rock dam is simplified to a plane strain problem;
(2)The dam body and foundation use the Duncan-Chang E-B nonlinear model;
(3)Leave out the change of the dam body in-situ stress before excavation and grouting,the internal stress of the dam is equal to the hydrostatic pressure and the soil pressure.

2.2 Mechanics parameters of polymer materials

Study results are shown in table 1, as well as in figure 2 and figure 3 based on the data obtained in the density and elastic modulus tests of non water reaction type polyurethane polymer materials[6-7] and experiments of relationships between material density and tensile strength or compressive strength.

Table 1. Elastic modulus and density of polymer materials

Sample number	1	2	3	4	5	6	7	8	9	10
Density /(g.cm^{-3})	0.16	0.27	0.29	0.35	0.36	0.40	0.42	0.47	0.49	0.53
Elastic modulus /Mpa	18.2	20.3	40.8	109	136	202	214	218	225	229

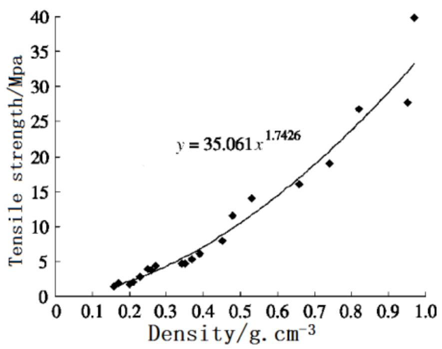

Fig. 2 Relationship between tensile strength and density of polymer materials

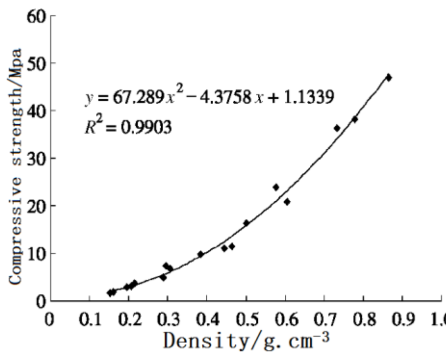

Fig. 3 Relationship between compressive strength and density of polymer materials

2.3 Foundation and dam body materials

The relationship between dam body and foundation stress-train of earth-rock dam can be described with nonlinear Duncan-Chang E-B model[12],

$$E_t = Kp_a\left(\frac{\sigma_3}{p_a}\right)^n\left(1-R_f\frac{(1-\sin\varphi)(\sigma_1-\sigma_3)}{2c\cos\varphi+2\sigma_3\sin\varphi}\right)^2 \quad (1)$$

$$B_t = K_b p_a\left(\frac{\sigma_3}{p_a}\right)^m \quad (2)$$

Where E_t=tangent elastic modulus;B_t=bulk modulus;σ_1 and σ_3 represent the maximum and minimum principal stress respectively;p_a=atmospheric pressure;R_f=damage ratio;K=number of elasticity modulus;n=index of elasticity modulus;K_b=number of bulk modulus;m=index of bulk modulus;c and φ are termed as cohesion and internal friction angle of soil expressed in the following Eq.(3)

$$\varphi = \varphi_0 - \Delta\varphi lg\left(\frac{\sigma_3}{p_a}\right) \quad (3)$$

When the material is unloaded

$$E_{ur} = K_{ur} p_a \left(\frac{\sigma_3}{p_a}\right)^{n_{ur}} \quad (4)$$

Where,E_{ur}=unloading elasticity modulus ;n_{ur}=index of unloading elasticity modulus;$\Delta\varphi$=ratio of internal friction angle[13].

Table 2 Parameters of dam materials and bed rock

materials	gravity(dry) /(kN·m^{-3})	gravity(wet) /(kN·m^{-3})	K	K_{ur}	n	R_f	K_h	m	c /(kN·m^{-2})	φ /(°)	$\Delta\varphi$ /(°)
Soil of dam body	16.0	1932	300	360	0.5	0.95	200	0.4	14.6	29.5	0
Soil of dam base	16.5	19.6	300	360	0.5	0.95	200	0.4	14.6	29.5	0
gravel	15.4	18.6	470	564	0.5	0.77	400	0.4	0	32.5	0
bedrock	19.6	21.6	720	850	0.7	0.86	530	0.6	0	44.0	5.0

2.4 Contact element[14]

Contact element is set up between diaphragm wall and soil to simulate the states of relative sliding,slip and separate occurred between interfaces.Assuming that F_s and F_n are ,in order,the frictional force and the normal force,K_t and K_n are named as viscosity coefficient and normal stiffness,u is the tangential displacement and d represents the distance of contact points.

(5)

3 Compute results and analysis

Using ALGOR software to mesh the earth-rock dam with 8 node isoparametric element,where the materials of dam body,dam foundation,bedrock and diaphragm wall are all set in the light of different material groups.The Duncan-Chang nonlinear model is chosen in the FEM analysis and the contact element is established between the diaphragm wall and the soil.The earth-rock dam polymer diaphragm wall is 5cm in thickness,the material density is about in a range between 0.1 to 0.2 g/cm^3 ,the elastic modulus of polymer material is equal to 20Mpa,the tensile and compress strength are equal to 2.12Mpa and 2.94Mpa.By contrast,the diaphragm wall of plastic and normal concrete are set the same thickness of 20cm,and yet each own their distinct physical properties.For plastic concrete ,the gravity is 18.7KN/m^3,the elastic modulus is 2000Mpa,and the values of tensile and compressive strength are 0.3Mpa and 2.5Mpa orderly,while for normal concrete,the gravity is 23KN/m^3,the elastic modulus is 2500Mpa,with the tensile strength 1.5Mpa and the compressive strength 25Mpa.Calculation and analysis for the three kinds of diaphragm walls above are doing under two working conditions,and the vibration frequency and modal analysis are also carried out at the same time .During the period of seismic acceleration time-history analysis ,E-centro seismic wave of 0.6g amplitude modulation is used.The seismic acceleration is set along the cross-section of the earth-rock dam provided that the integral damping matrix treated as the Rayleigh damping.

Condition 1:stress analysis of earth-rock dam under dead weight and hydrostatic pressure;

Condition 2: dynamic stress analysis of earth-rock dam under the action of Elcentro earthquake wave of 0.6g amplitude modulation.

The force diagrams of FEM under static load as figure 4 and figure 5 shown,yet the maximum stress distribution under kinds of conditions reveal in figure6~9(with the unit of Mpa).Table 3 exhibits the comparison of horizontal and vertical displacement of upstream and downstream among three kinds of diaphragm walls while chart 11 compares the maximum stress time travel curve under seismic load.Form 4 makes a comparison of the calculation results of natural frequency,figure13 and figure 14 shows the maximum stress of diaphragm walls under the static and seismic load respectively.

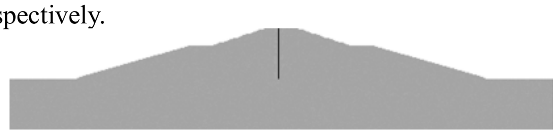

Fig. 4 Model of earth-rock dam with diaphragm wall

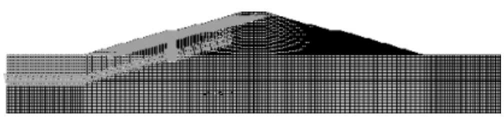

Fig. 5 Earth-rock dam under gravity and hydrostatic **stress**

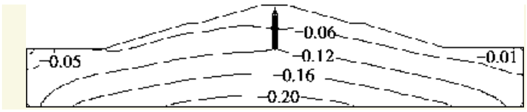

Fig. 6 Isoline of maximum compression stress of plastic concrete diaphragm wall under static load

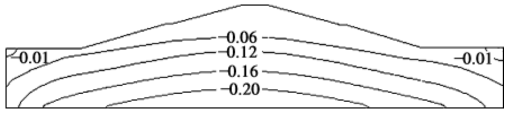

Fig. 7 Isoline of maximum compression stress of polymer diaphragm wall under static load

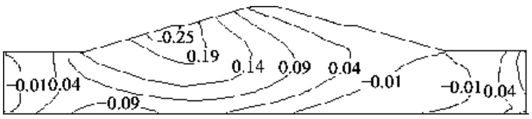

Fig. 8 Isoline of maximum stress of polymer diaphragm wall under earthquake

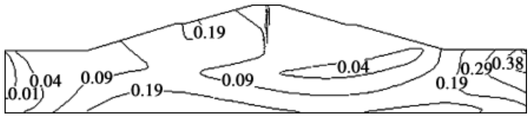

Fig. 9 Isoline of maximum stress of normal concrete diaphragm wall under earthquake

Table 3. Comparison of dam displacements under static load

polymer/mm				Plastic concrete/mm				Normal concrete/mm			
upstream		downstream		upstream		downstream		upstream		downstream	
flat	vertical	flat	vertical	flat	vertical	flat	vertical	flat	vertical	flat	vertical
4.0	-34	2.1	-32	3.1	-32	2.8	-30	2.3	-29	2.0	-27

Computational analysis above shows that polymer diaphragm wall coordinates well with the deformation capacity of the dam body soil under the condition of bearing due to the smaller material modulus,contrary to this ,as for plastic concrete and normal concrete ,greater stress(greater stress emerge in diaphragm wall illustrated in stress contour maps by figure 6 and figure 9) emerge in the diaphragm wall after loading deformation,which result from poor abilities to change coordinately(as shown in figure 12).Earth-rock dams under seismic dynamic load are just similar to static situations.Therefore,the internal stress value of polymer diaphragm wall is much less than that of normal concrete as well as plastic concrete proved by finite element numerical analysis of earth-rock dams under static and dynamic load.For condition 1,the diaphragm wall

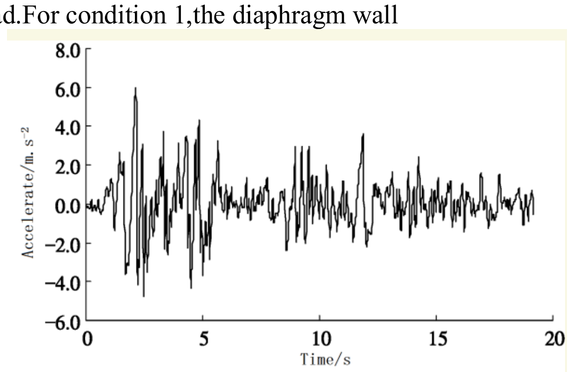

Fig. 10 Time-history of 0.6g Elcentro earthquake acceleration

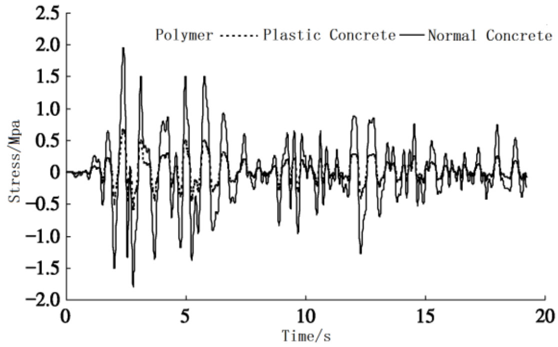

Fig. 11 Comparison of maximum stresses of diaphragm wall under earthquake

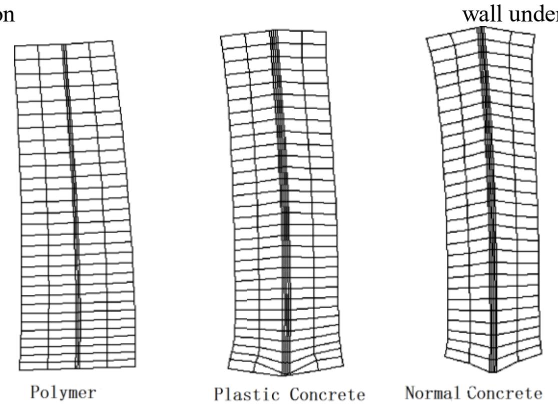

Fig. 12 Deformation of diaphragm wall under static load

maximum compressive stress of normal concrete and plastic concrete are 4.39Mpa and 2.32Mpa respectively, yet 0.183Mpa for polymer material(as Figure 13 shows).As for material ultimate compressive strength, polymer is 2.94Mpa while plastic concrete is 2.5Mpa,as we can see, the later one is close to failure limit, by contrast ,the former one still has a lot of safety stock. For condition 2,the internal maximum stress of diaphragm wall made of normal concrete and plastic concrete are far greater than polymer(figure 14) when compare the maximum stress time-history curves of the three which formed via carrying out the earthquake time-history response analysis by virtue of inputting the seismic wave. The maximum tensile stress in normal concrete and plastic concrete are respectively reached to 2.01Mpa and 0.71Mpa, conversely, that for polymer is merely 0.27Mpa. Moreover,the tensile strength limit of polymer material is about 2.12MPa,while the values of that for normal concrete and plastic concrete materials are 1.5Mpa and 0.3Mpa,that means plastic and normal concrete are already exceed the limit of rupture, whereas polymer diaphragm wall is far away from its failure limit. Besides, based on the nature frequency computational comparison of earth-rock dams with three diaphragm walls made of different materials, we can draw a conclusion that the natural vibration frequency increased slightly in turn as with the earth-rock dam diaphragm wall structures using material of polymer, plastic concrete and normal concrete on condition that under the same vibration mode of same order frequency(as shown table 4), inevitably, it has a direct relationship with an orderly increase of diaphragm wall materials' elastic modulus.

Table 4 Comparison of frequencies of diaphragm walls rad/s

Order	Polymer concrete	Plastic concrete	Normal concrete
1	7.82	7.82	7.81
2	11.55	11.59	11.64
3	13.08	13.08	13.08
4	14.44	14.46	14.47
5	15.92	15.93	15.93
6	16.65	16.66	16.66
7	18.26	18.25	18.24
8	18.75	18.79	18.83
9	20.53	20.53	20.53
10	22.31	22.34	22.34

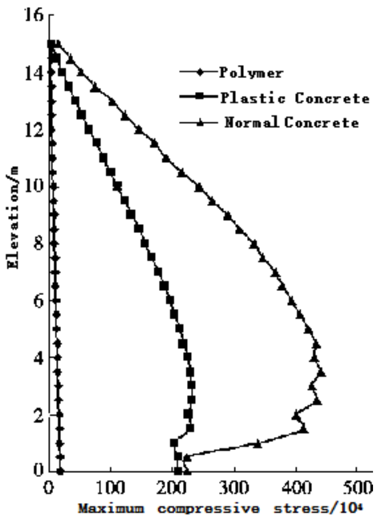

Fig. 13 Comparison of maximum stresses of diaphragm walls under gravity and hydrostatic stress

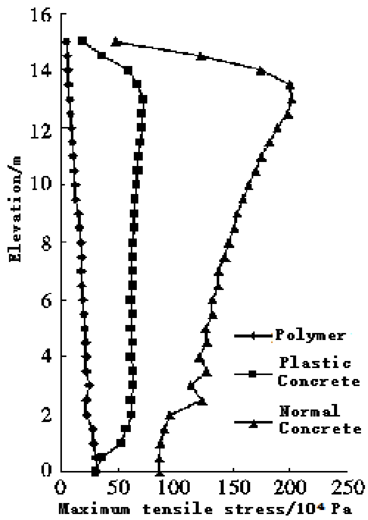

Fig. 14 Comparison of maximum stresses of diaphragm walls under earthquake

4 Conclusions

(1)By comparing the inner maximum compressive stress values of diaphragm walls made of three kinds of materials (polymer,plastic concrete or normal concrete) under dead weight and hydrostatic pressure,we can find that polymer diaphragm wall is the smallest one,and the plastic is greater yet the normal concrete one is the greatest under the identical condition.Further,the internal stress of plastic concrete diaphragm wall has already closed to the compressive failure limit,however,polymer diaphragm wall has preferable security due to that the ompressive stress is far less than the ultimate value.Analysis show that it has a closely relationship with the elastic modulus of diaphragm wall material.Great effect is made on deformation coordinated property between diaphragm wall and soil body for the reason that soil elastic modulus is far less than concrete material.

(2)Contrasted diaphragm wall dynamic stress values of the three when earthquake acceleration is inputted by means of time-history analysis,the result obviously reveal that the maximum stress value within the diaphragm wall of normal concrete and plastic concrete are far greater than polymer diaphragm wall .Considering the ultimate tensile strength of 3 kinds of materials,it can easily draw a conclusion that plastic concrete and normal concrete diaphragm wall have already exceeded the tensile stress limit,on the contrary,the polymer diaphragm wall is far less than failure limit,that was to say the polymer diaphragm wall still has high security reserves.

(3) Based on natural frequency calculation of earth-rock dams under the same order frequency of vibration mode,it's confirmed that the natural frequency slightly increased according to the order of polymer,plastic concrete and normal concrete.Following this ,a conclusion can be drown that it has a direction relationship with the slightly increase of materials elastic modulus.

(4)Polymer grouting has many advantages when compared with the traditional grouting reinforcement technology.Specifically,it has the characteristic of speedy,light weight,good permeability,thinner size of diaphragm wall,environmental materials,durability as well as better coordinated deformation compatibility with the dam soil.Account for the advantages above, the inner stress value of polymer diaphragm wall always less than the limit stress.At present,the polymer material and diaphragm grouting technology is undoubtedly a very excellent reinforcement material and technology for dam constructions,which is worth for deep research and promoting.

Reference:

[1] YANG Qi-gui. Prospect and status of reinforcement technology of dangerous reservoir in China[J]. Yangtze River, 2011, 42(12): 6–11. (in Chinese)

[2] HUANG Rong-wei. Application of low elastic modulus concrete anti-seepage wall in embankment dams[J]. Dam & Safety, 2006(3): 50–53. (in Chinese)

[3] ALEX N. Irreversible changes in the grouting industry caused by polyurethane grouting: an overview of 30 years of polyurethane grouting[C]// Proceedings of 3nd International Specialty Conference on Grouting and Ground Treatment, New Orleans, USD: ASCE, 2003.

[4] WANG Fu-ming, ZHANG Bei, SHI Ming-sheng, et al. Research on polymer grouting technology and equipment for embankment reinforcement[R]. Zhengzhou: Research Report of Significant Public Project of Henan Province, 2009. (in Chinese)

[5]GUO Cheng-chao, WANG Fu-ming, ZHONG Yan-hui. Research on polymer grouting technology for cement concrete pavement void[J]. Highway, 2008(10): 232–236. (in Chinese)

[6] LIU Zhi-yuan. Experimental investigation on engineering properties of polymer grouting material[D]. Zhengzhou: Zhengzhou University, 2007. (in Chinese)

[7] LIU Yong. Experimental properties investigation of polyurethane polymer and concrete[D]. Zhengzhou: Zhengzhou University, 2009. (in Chinese)

[8] LI Jiu-hong, XU Jian-guang. Research on crack grouting in concrete dams[J]. Journal of Hydroelectric Engineering, 2007, 26(3): 63–68. (in Chinese)

[9] GE Jia-liang. Development and prospect of chemical grouting techniques[J]. Chinese Journal of Rock Mechanics and Engineering, 2006, 25(S2): 3384–3392. (in Chinese)

[10] AHMET V, SULEYMAN D. Grouting applications in the Istanbul metro, Turkey[J]. Tunneling and Underground Space Technology, 2006, 21: 602–612.

[11] MA Xiao-hua, LIANG Guo-qian. Numerical analysis on stress and deformation of the earth-rock dam cutoff wall using low elastic modulus concrete[J]. Water Power, 2011, 37(4): 51–54. (in Chinese)

[12] DUNCAN J, CHANG C. Non-linear analysis of stresses and strains in soil[J]. Journal of Soil Mechanics and Foundation Division, American Society of Civil Engineering, 1970, 96(6): 1629–1653.

[13] PENG Cheng-shan, ZHANG Xue-ju. Effect of friction elements on stress deformation of concrete diaphragm wall of earth-rock dam[J]. Journal of North China Institute of Water Conservancy and Hydroelectric Power, 2007, 28(4): 11–14. (in Chinese)

[14] YANG Ling-qiang, WU Jia-qing, QIN Bing. The nonlinear analysis of diaphragm wall in earth dam[J]. Rock and Soil Mechanics, 2007, 28(S0): 277–280. (in Chinese)