Simulation analysis of bauxite tailings reservoir in complex geological conditions

Through the development of 20 years, the 3D-modelling has already become mature. It is used now, more and more popularly in the modelling of the complicated process of modern mine. In this study, its three dimensional numerical model for seismic response analysis is set up based on the ABAQUS and the results show the liquefied region of tailings pond first appears in the saturation region of sedimentary area, then develops towards the saturation region inside dry beach,and the location of the liquefied region is directly related to the 3D terrain of the tailing dam, which shows the necessity of the 3D dynamic analysis of the tailing with complex terrain

Keywords: *3D-modelling, tailings reservoir, bauxite, geology.*

1. Introduction

About 9 hundred million tonnes metal and nonmetal ores, coal, gravel are mined in the world every year while waste rock and tailings about three billion tonnes. Using the tailing pond to store the tailing is still the main treatment. In China, there are 12000 tailings ponds according the statistical data. The stability of the tailings dam not only refers to the safety and economy of mine's producing, but also relates to the people's life, property and environment round the reservoir downstream. Most of the tailings dams in China are built by upstream embankment method and most of the dams are with high saturation line. Saturation tailings material is easy to be liquefaction during the earthquake or the vibration load, which would lead to dam breaking. In the 21st century, China's seismicity are very active, including Wenchuan earthquake in 2008, Yushu earthquake in 2010 and Yaan earthquake in 2013. The latest code for seismic design is of special structure has and new claim to dynamic response of tailings pond. Therefore it is important to research dynamic response of tailings pond.

The most important content of dynamic time-history analysis of tailings pond is liquefaction analysis. For now, mainly the calculation model of liquefaction analysis includes effective stress method and total stress method. The most representative achievements of total stress method is Seed's theory. With the development of finite element method, seismic time-history analysis of tailings pond is widely used. At present most analysis use two-dimensional analysis method, a small number of 3-dimensional analysis just give the liquefaction distribution of the typical section, and there are only a few studies on the evolution process of liquefied zone of tailings pond with the complex terrain of tailings pond. In this paper, the tailings pond with the complex terrain is selected. The dynamic analysis model of tailings pond in complex terrain is set up in ABAQUS, the effective stress method is used to analyze the liquefied region by the secondary development of the ABAQUS. Furthermore, the liquefaction characteristics including evolution process of liquefied region and the three-dimensional distribution characteristics in tailings pond during the earthquake are shown through 3D visualization.

Dr. Zhang Min, School of Resources and Environmental Engineering, Guizhou Institute of Technology, Guizhou province, China. E-mail: 51595459@qq.com

2. Related theories of dynamic analysis

2.1 Non-linear static constitutive model

First, the analysis should start with non-linear static analysis that can analyse static stability of tailings pond and provide confining pressure distribution of every element before earthquake. Code suggests that the analysis uses Duncan-Chang model. The E-B model of Duncan-Chang is shown in formula (1).

$$\left.\begin{aligned} E_l &= Kp_a\left(\frac{\sigma_3}{p_a}\right)^n\left[1-\frac{R_f(1-\sin\phi)(\sigma_1-\sigma_3)}{2c\cos\phi+2\sigma_3\sin\phi}\right]^2 \\ B &= K_m p_a\left(\frac{\sigma_3}{p_a}\right)^m \\ B &= \frac{E_l}{3(1-2v_i)} \end{aligned}\right\} \quad \dots \quad (1)$$

where K, n, K_m, m, c, φ and R_f are material parameters, P_a is atmospheric pressure.

2.2 Dynamic constitutive model of tailing sand

Dynamic constitutive model of tailing sand has lots of results, such as Hardin-Drnevich model, Iwan model and so on.

This kind of model should confirm two important parameters, dynamic shear modulus and damping ratio function. Based on the equivalent viscoelastic model, Shen Zhu-jiang improved viscoelastic plasticity model by introducing potential function of residual volumetric strain and residual shear strain, there are also other models, such as Martin-Finn-Seed model, hyperbolic elastic plastic model and so on. In this paper Shen Zhu-jiang model is used to determine dynamic shear modulus and damping ratio function as shown in formula (2). Pore pressure model is shown in formula (3).

$$\left.\begin{aligned} G &= \frac{K_2}{1+K_1\gamma_c} p_a \sqrt{\frac{\sigma_m}{p_a}} \\ \lambda &= \lambda_{max} \frac{K_1\gamma_c}{1+K_1\gamma_c} \\ \gamma_c &= \sqrt[4]{\gamma_d^{\,3}} \Big/ \sqrt{\sigma_m} \end{aligned}\right\} \quad \cdots \quad (2)$$

$$\left.\begin{aligned} \Delta\varepsilon_v &= C_1 \gamma_d^{\,C_2} \exp\left(-C_3 S_1^{\,2}\right) \frac{\Delta N}{1+N_c} \\ \Delta\gamma &= C_4 \gamma_d^{\,C_5} S_1^{\,2} \frac{\Delta N}{1+N_c} \\ \Delta u &= k_{ur} \sqrt{\sigma_m} \Delta\varepsilon_v \end{aligned}\right\} \quad \cdots \quad (3)$$

where K_1, K_2, λ_{max}, c_1, c_2, c_3, c_4 and c_5 are material parameters.

2.3 Liquefaction criterion

The methods of dynamic liquefaction discrimination of tailing sand include total stress method and effective stress method. Total stress method needs count the average shear stress (τe) of soil unit during the earthquake firstly. Then under the same conditions, the shear stress of resistance liquefaction (τl) is defined by experiments. If τe>τl, the sand results in liquefaction. Effective stress method claims that when pore water pressure is bigger than confining pressure, we can ensure the soil unit is liquefied.

3. Characteristics of 3D liquefaction

3.1 Project overview

A tailings pond in Guizhou province in China is built in valley type by the upstream embankment method. Its starter dam is built by permeable rock height of which is 50m, ratio of front slope is 1:2.2, ratio of inner slope is 1:1.8. The embankment is built by hydraulic filling, height of which is 120m, ratio of front slope is 1:5, the minimum dry beach width is 240m. Total dam height is 170m. Base on seismic ground motion parameter zonation map of China and code, seismic intensity of this region where the tailing pond locates is 7 degree, and the seismic dynamic time-history analysis should do to study the seismic respond of the tailing pond.

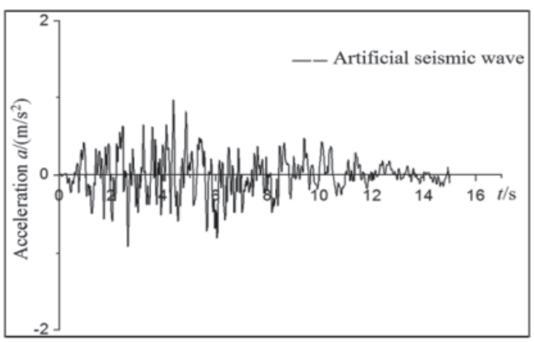

Fig.1 Time-history curve of artificial seismic wave

3.2. Selection of earthquake waves

According to the pond's location on the seismic zoning map in China, peak acceleration of seismic wave should choose 0.1g, earthquake duration time is 15s. First, the artificial seismic time-history is generated based on the design response spectrum, peak acceleration, duration time, as shown in Fig.1. In order to verify the rationality of artificial seismic wave, response spectrum analysis of the artificial seismic wave is done by Duhamel integral, and the result shows that it meets the design response spectrum well (Fig.2).

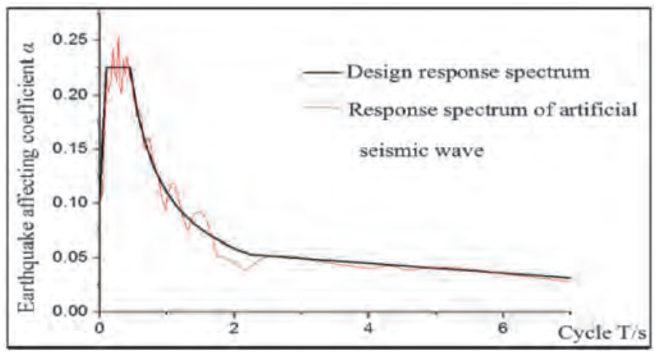

Fig.2 Curve of design response spectrum and response spectrum of artificial seismic wave

3.3 Three-dimensional model of tailing ponds with complex terrain

A three-dimensional numerical model of tailings pond is set up based on the terrain of the reservoir. Origin of coordinates located in foot vertex of starter dam, X-axis

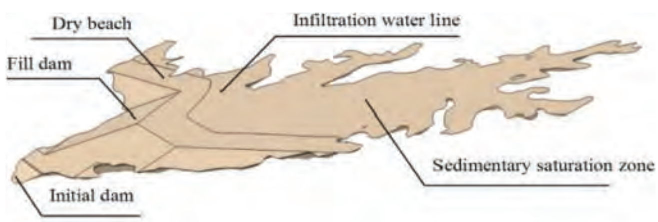

Fig.3(a) 3D model of tailings pond

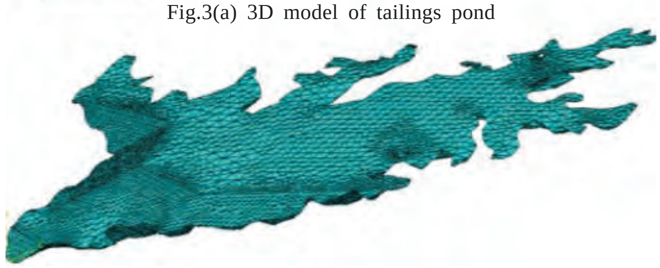
Fig.3(b) 3D Numerical model of tailings pond

positive direction is the direction from downstream to upstream, and the positive direction of Z-axis is vertically up. For convenience of the analysis, it is called sedimentary saturation zone where sedimentary area is covered with water (Fig.3(a)). Numerical model of tailings pond use 4 node tetrahedral elements, as shown in Fig.3(b). Horizontal acceleration along the ditch is inputted to bottom of tailings pond. The basic physical parameters of tailings pond are shown in Table 1.

TABLE 1: BASIC PHYSICAL INDEXES AND MECHANICAL INDEXES OF MATERIAL

Category	Natural density (kN/m^3)	Saturated density (kN/m^3)	Friction angle (°)	Cohension (kPa)
Rockfill	22	22.5	33	0.01
Medium sand	136.9	17.4	33	0.54
Fine sand	17.1	17.8	29	4.3
Silty sand	18.3	19.1	20	6.7

TABLE 2: NON-LINEAR STATIC PHYSICAL INDEXES AND MECHANICAL INDEXES OF MATERIAL

Category	K	n	R_f	K_{ur}	K_b	m
Medium sand	160	0.83	0.78	535	72	0.4
Fine sand	216	0.68	0.68	584	86	0.35
Silty sand	210	0.62	0.65	532	78	0.31

TABLE 3: NON-LINEAR STATIC PHYSICAL INDEXES AND MECHANICAL INDEXES OF MATERIAL

Category	k1	k2	C1	C2	C3	C4
Medium sand	9.7	568	0.003	0.75	1	0.9
Fine sand	10	560	0.003	0.75	1.2	0.7
Silty sand	9.8	657	0.002	0.75	1.2	0.8

3.4 THREE-DIMENSIONAL NON-LINEAR STATIC ANALYSIS

There is not Duncan-Chang constitutive model in material database of ABAQUS, but users can set up Duncan-Chang model in ABAQUS through user subroutines. The basic idea is: First, the current strain of element and strain increment of current step is passed to the subroutines through the interface of ABAQUS. According to the test parameters (Tables 1 and 2), we can calculate the tangent modulus Et and bulk modulus of elasticity Bt referring to formula (1), then calculate the solid tangential Poisson ratio. Basing on the tangent modulus and Poisson ratio, the element stiffness matrix can be gotten, and integrating with strain increment the stress increment can be sure. In this model Duncan-Chang E-B model is used to non-linear static analysis of tailings pond, the calculation results are shown in Fig.4.

The static stress level is less than 1 which shows that the tailings pond is stability under the static force.

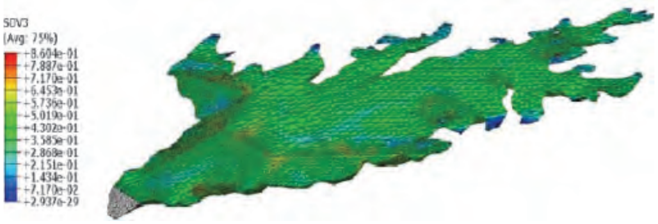

Fig.4 Static stress level of tailings pond

Fig.5 Liquefied region of 4s (unsaturated region is translucent

3.5 REALIZATION OF THE SHEN ZHU-JIANG MODEL IN ABAQUS

Shen Zhu-jiang dynamic constitutive model can achieve in ABAQUS by user subroutines. Specifically the idea is: First, the current strain and its increment, stress of element in current step pass to the subroutines through the interface of ABAQUS, then shear modulus and damping ratio of mine tailing is determined through formula (2). Element stiffness matrix and damping matrix which confirmed by constitutive relations of viscoelastic linear model combined with strain increment would get stress increment. Plastic strain increment and pore pressure increment can be determined by formula (3) when equivalent cyclic number ΔN in current period by using Martin's method. Shen Zhu-jiang model can be run successfully in ABAQUS. The parameters of Shen Zhu-jiang model is shown in Table 3.

3.6 THREE DIMENSIONAL ANALYSIS OF LIQUEFACTION OF TAILINGS POND

The earthquake wave is divided into 15 periods to analyse the seismic response, and the dynamic response analysis of the tailing pond is completed. In the post processing, semi-transparent display of unsaturated tailings sand above the phreatic surface has achieved so that liquefaction distribution of the tailing sand blow the phreatic surface can be shown clearly inside the pond. The three-dimensional distribution characteristics and evolution process of liquefied region in the process of earthquake are studied on this basis. This study can reveal characteristics of seismic liquefaction of tailings pond in complex terrain. Liquefied region distribution of pond is known as in Figs.5 to 11 about 4s, 5s, 6s, 8s, 10s, 12s and 15s after earthquake happened.

Fig.5 shows that few sporadic liquefied regions appeared

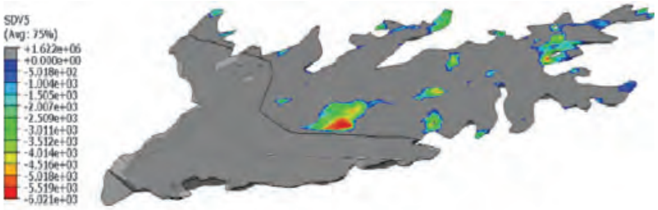

Fig.6(a) Liquefied region of 5s (unsaturated region is translucent)

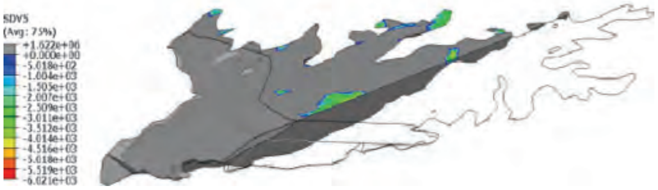

Fig.6(b) Liquefied region of the typical section of 5s

on deposited beach of tailings pond when the earthquake continued for 4s. The region mainly distributed in the saturation area of deposited beach and the small thickness of covering with tailing sand.

The Fig.6(a) shows that the saturation area of deposited beach appeared liquefied region obviously when the earthquake continued 5s. Thickness of liquefied region is small from the section of the liquefied region (Fig.6(b)).

Fig.7(a) shows that the liquefied region of deposited beach develops obviously which has covered most of the deposited beach and larger part of the liquefied region is located along the main direction of the mine ditch, but the tailing sand blow the phreatic surface internal dry beach is not liquefaction yet. Thickness of liquefied region has increased from the section of the liquefied region (Fig.7(b)) which still behaves as shallow liquefaction. The reason is that: the seismic wave is strong shocking from 3s to 6s, and the range of liquefied regions is developing rapidly in this period of time. Meanwhile, the liquefied regions mainly

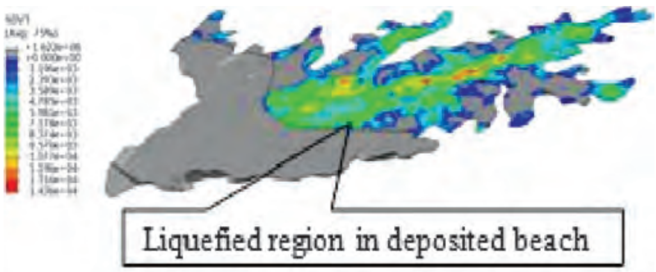

Fig.7(a) Liquefied region of 6s (unsaturated region is translucent)

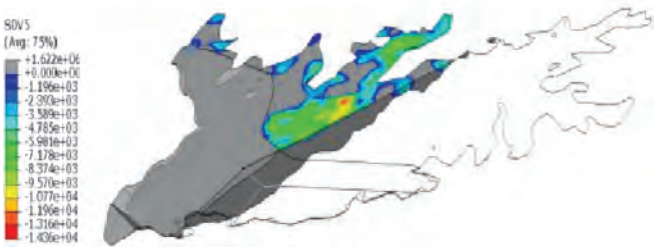

Fig.7(b) Liquefied region of the typical section of 6s

distribute in the surface of the saturation area of deposited beach where is easily liquefied because of low confining pressure of tailing sand.

Fig.8(a) shows that the liquefied regions are found all over the surface of the saturation area of deposited beach when the earthquake continued for 8s, and the liquefied regions develop to the saturation area blow the phreatic surface internal dry beach with thickness of liquefied region is increasing significantly (Fig.8(b)). This is because pore water pressure of sand cumulatively increased over time and after the surface sand liquefaction, the effective confining pressure of sand around reduces and leads to further development of the liquefaction region.

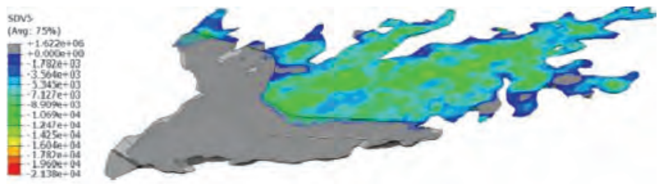

Fig.8(a) Liquefied region of 8s (unsaturated region is translucent)

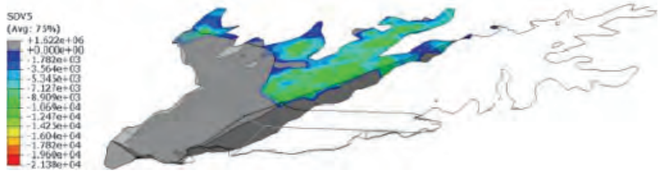

Fig.8(b) Liquefied region of the typical section of 8s

Fig.9 shows that thickness of liquefied region of deposited beach increased significantly and the region is developed beyond the position of infiltration line to tailing dam. There is a small scope of liquefied region has shown blowing the phreatic surface of embankment. It is notable that liquefied region of embankment is not shown along the main direction of the ditch. Though the dynamic response along the main direction of the ditch is most prominent, the phreatic line's depth of the section is greater than the other position where the sand is in higher confining pressure. So, liquefied region of embankment is not necessarily happened in the section of the main direction of the ditch. This could explain that the liquefaction of the dam mainly depends on the dynamic response and buried depth of phreatic surface,

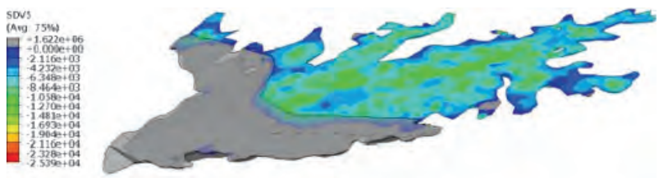

Fig.9(a) Liquefied region of 10s (unsaturated region is translucent)

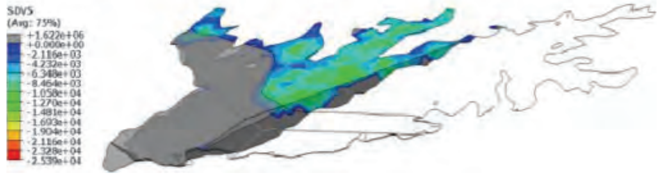

Fig.9(b) Liquefied region of the typical section of 10s which shows that it is necessary to do 3D dynamic analysis of tailings pond in complex terrain. If the model uses 2D analysis, sensible section needs to be chosen according to the landform, otherwise the analysis conclusion of the liquefied region cannot reflect the real situation.

Fig.10 shows that liquefied region blow the phreatic surface is further developing but still has a small thickness when the earthquake continued 12s.

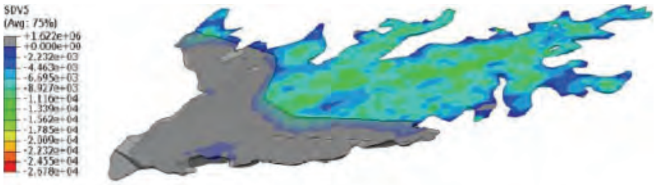

Fig.10(a) Liquefied region of 12s (unsaturated region is translucent)

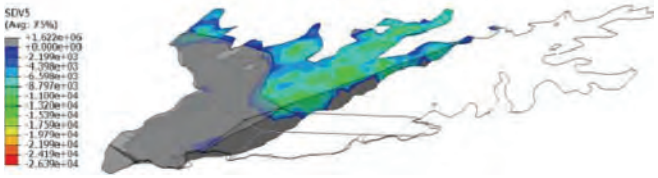

Fig.10(b) Liquefied region of the typical section of 12s

Fig.11 shows that the deposited beach of tailings pond has a large area of liquefaction that the region is deep into the saturation area blows the phreatic surface of internal dry beach, meanwhile a local liquefied region happens in the embankment where the saturated tailings blow the phreatic surface and the thickness of the liquefied region is less than 2m. The section of main ravine has not happened liquefied region, as shown in Fig.11(b).

From above analyses, when the earthquake happens, the liquefaction region will first appear in saturation area of the deposited beach, and gradually extend to saturation area of dry beach with the liquefaction depth increasing, then finally the liquefaction will happen in the dam because of big confining pressure here.

Meanwhile, it is noticed from Fig.11, the liquefied region in the dam does not locate in the section of the main direction of the ditch where as strong earthquake response exists, indicating location of liquefied region is greatly influenced by the terrain of the tailing pond, so it is necessary to use 3D dynamic analysis method in tailings pond of complex terrain.

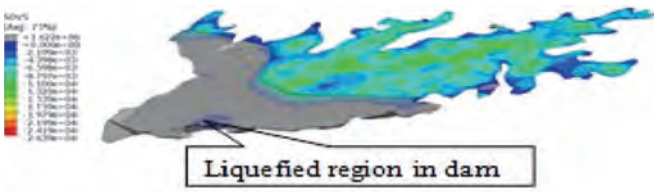

Fig.11(a) Liquefied region of 15s (unsaturated region is translucent)

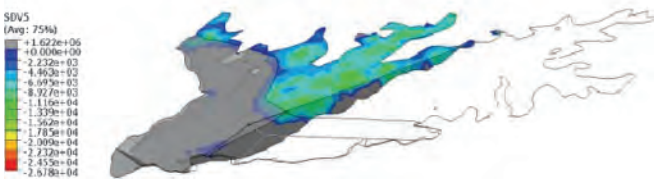

Fig.11(b) Liquefied region of the typical section of 15s

4. Conclusions

According to the tailings pond with complex terrain, its computational model is set up. By the secondary development of the ABAQUS, the three-dimensional dynamic analysis is carried out for the tailings pond, and the three-dimensional visualization of the liquefied region in the tailings pond is achieved. On this basis, the three-dimensional distribution characteristics and evolution process of liquefied region in the tailings pond is analyzed, and some conclusions are drawn as follow:

Firstly, the liquefied region of tailings pond first appears in the saturation region of sedimentary area, then develops towards the saturation region inside dry beach and the depth of the liquefied region increases gradually. Though the liquefied region of deposited beach has little impact on stability of tailings pond, once dam break and liquid sand would add to the amount of leak sand of tailings pond, so liquefied region of deposited beach should be paid attention to earthquake hazard evaluation. Liquefied region in the tailing dam appears later, and its location is directly related to the terrain of the tailing pond. In fact liquefied region in the dam may not locate around the section along the main channel of the tailing dam because of buried depth of phreatic surface is bigger and the confining pressure on the saturation tailing sand is higher even though where the dynamic response is stronger. For this reason, the location and scope of liquefied region should be confirmed by 3D dynamic analysis of the tailing with complex terrain.

5. Acknowledgement

This work was supported by Guizhou Natural Science Foundation [Qian(2017)1410].for which the author expresses her appreciations.

References

1. Liu, Hou-xiang, Liao, Xue, Li, Ning, Yu, Zhi-fang and Pan, Xu-dong (2008): "Seismic response analysis of high tailing dams using effective stress finite element method," *Journal of vibration and shock*, Volume 27, Issue 1, pp:65-72, 2008.
2. Hu, Zai-qiang, Li, Hong-ru, Chen, Cun-li and Dai, Zhong-hai (2010): "Seismic response analysis and stability evaluation of the Lixi tailings Dam," *Journal of Northwest A&F University (Nat. Sci. Ed.)*, Volume38, Issue 9, pp: 215-221, 2010.
3. Sheng, Zhu-iang (2000): Theory of soil mechanics, vol. 1st edition, China Waterpower Press, 2000.
4. Xie, Ding-yi (2011): Soil mechanics, vol. 1st edition, Higher education Press, Beijing, 2011.
5. Qi, Qinglan (2011): Numerical simulation and engineering application of the seepage field for the tailings reservoir, vol. 1st edition, China Waterpower Press, 2011.