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Study on Wetting Deformation of Earth-Rockfill Dam based on P-Z Model

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Abstract: When earth-rockfill dam's coarse aggregates are immersed in water under certain stress, particles will be lubricated and immersed mineral particles will soften so they will slip against each other, break, and realign. Thus deformation will occur and the stress will redistribute in the soil mass. The deformation is called wetting deformation since it happens when dry soil becomes wet while the stress state remains unchanged. This paper studies the mechanism and analytical approach of wetting deformation. It devises a method for calculating wetting deformation based on single-line method and P-Z constitutive model and then applies the method to the static calculation of Shuangjiangkou earth-rockfill dam. It is proved that this method can reasonably reflect the influence of dam's wetting deformation on its general deformation during the storage period.

Keywords: *Coarse aggregates; wetting deformation; P-Z model; volumetric strain; axial strain; stress level*

1. Introduction

After earth-rockfill dam retains water, particles of coarse aggregates will be lubricated and immersed mineral particles will soften so they will slip against each other, break, and realign. Thus deformation will occur and the stress will redistribute in the soil mass, which is usually detrimental to the dam. Many scholars[1,2] at home and abroad have obtained a series of great achievements after conducting researches from the perspectives of wetting tests on coarse aggregates and changes in soil's mechanical properties etc. For instance, considering that immersed earth-rock mixtures would soften, Li Guoying et al.[3] introduced the concept of capillary suction and then the immersed earth-rock mixture's softening process equaled to capillary suction's losing process; Shen Zhujiang[4] proposed general suction theory, general effective stress principle, steady state void ratio, and steady state principle and based on these, he then suggested the law of suction losing of soil's wetting deformation so that we could study soil's collapse and swelling at the same time; Fumagalli and Bertacchi et al. proved that wetting could reduce internal friction angle of earth-rock mixture through test; Li Guangxin, Kong Xianjing, Zhang Shaohong, and Li Peng et al.[5-8] conducted experiments and found that wetting could reduce material's strength and cohesion and elasticity modulus declined sharply while Poisson's ratio remained almost the same; Bao Huafu's experimental study revealed that wetting caused marked changes in deformation parameters and strength properties of earth-rock mixtures and the changes could not be replaced by saturated soil parameters so wetting deformation's impact on soil parameters could not be ignored. Meanwhile, studies have shown that wetting deformation of earth-rockfill dam's coarse aggregates is influenced by initial water content, initial dry density, fine content, particle size, particle-size distribution, aggregate type, loading conditions, stress level, and immersion and wetting time etc. As for wetting deformation calculation model, scholars [9-16] at home have conducted researches based on double-line and single-line methods in recent years but when applied those models to practical engineering, marked differences existed between the calculation results and actual measurement results. In conclusion, at present, researches on wetting deformation are developing slowly and the urgency is to determine the main influence factors of wetting deformation and to establish a reasonable calculation model.

2. The Mechanism of Wetting Deformation

When earth-rockfill dam's coarse aggregates are immersed under certain stress, particles will be lubricated and immersed mineral particles will soften so they will slip against each other, break, and realign. Thus deformation will occur and the stress will redistribute in the soil mass. The deformation is called wetting deformation since it happens when dry soil becomes wet while the stress state remains unchanged.

Wetting deformation is caused by the wetting of dry soil under invariable stress. The calculation principle is to first assume that immersed rockfill is restrained and will not deform. Fig. 1 shows the changes of element wetting stress state. Before immersion, the element stress is, σ_d. Assume that the element is separated from rockfill and suppose force at the element boundary is, P_d. Then assume that a rigid arm is put on the rockfill element. The rockfill element is immersed and saturated so the wetting may change the element strain but the assumed rigid arm prevents the deformation.

Let σ_s and P_s respectively represent the stress after immersion and rigid arm's force on the element, and then stress relaxation caused by wetting before and after the immersion is $\sigma_s - \sigma_d$ and change in the force is, $P_s - P_d$. The rigid arm is assumed so it should be unrigged after the element is saturated. Exert the nodal force F, equal and opposite to the force $P_s - P_d$ on element rockfill to offset the assumed restraint of rigid arm on rockfill element during immersion process so as to unrig the rigid arm. The rockfill element will deform under the force and this is the natural deformation of the element in immersion process. The nodal force F is the equivalent nodal force of wetting deformation.

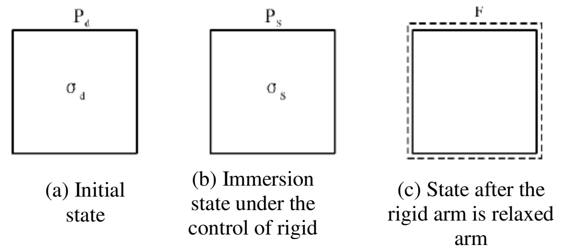

Figure 1: *Changes in stress state of rockfill element*

3. The Analytic Approach of Wetting Deformation

Before 1970s, scholars around the world usually employed the unidirectional consolidometer to study wetting deformation. Although the one-dimensional consolidometer was simple to use, its stress state and deformation conditions did not accord with the reality and could only measure the relationship between vertical pressure and vertical wetting strain. After 1970s, "single-line" and "double-line" methods have been universally applied to studying wetting deformation. The so-called "single-line" method is to follow certain loading path to reach certain stress state in the dry state and then conduct immersion, wetting, and saturation while keeping the stress state unchanged and the deformation reflects the amount of wetting deformation under this stress; and the so-called "double-line" method is to respectively conduct tests in the dry and wet states to get corresponding stress-strain relationships and then adopt the difference between deformation in the dry and wet states under the same stress as the amount of wetting deformation caused by immersion under the stress. Nobari and Duncan conducted the above two tests on triaxial apparatus with sand and found that the results were close so they thought single-line method could be replaced by double-line method. Zuo Yuanming and Yin Zongze performed wetting deformation experiments on sand-gravel material and rockfill material. They discovered that compared with double-line method, single-line method had greater axial strain and smaller volumetric strain. Li Guangxin also made tests and found that wetting deformation obtained through double-line method was smaller than through single-line method. In 1977, Liu Zude conducted experiments on the wetting deformation of earth dam's weathered sand in Zhangjiazui Reservoir through single-line method and triaxial apparatus and studied the stress-strain relationship and additional wetting deformation of wetted soil under complex stress conditions. Later this method was applied to experimental studies on sand-gravel material and rockfill material across the world. "Double-line" method uses the deformation differences between saturated sample and weathered sample during shearing process under the same stress to calculate wetting deformation, which is inconsistent with practical wetting deformation process, loading paths and practical wetting deformation results. "Single-line" method, however, accords with the practical wetting process and most scholars suggest it should be applied to soil wetting tests.

At present, the calculation of earth-rock mixture's wetting often employs complete stress-strain relationship, which is not suitable for practical finite element calculation. Based on this, this paper uses soil increment stress-strain relationship in the study.

Suppose the element stress $\{\sigma_d\}$ is before immersion. Assume it is reached by the scale-up of n-class stress increment, and then the stress increment of every class is:

$$\{\Delta\sigma\} = \{\sigma_d\} / n \tag{1}$$

For increment of every class, use element stiffness matrix in the dry state $[D_d]$ to calculate strain increment $\{\Delta\varepsilon\}$:

$$\{\Delta\varepsilon\} = [D_d]^{-1} \{\Delta\sigma\} \tag{2}$$

Where, the stiffness matrix $[D_d]$ is the dry-state nonlinear elastic or elastoplastic matrix relative to the present stress state. Accumulate $\{\Delta\varepsilon\}$ of increment of every class, and the aggregate strain before immersion is $\{\varepsilon_d\}$.

Assume the stress remains unchanged before and after immersion and stress increment of every class after immersion is still $\{\Delta\sigma\}$, and then the wet strain of every class is:

$$\{\Delta\varepsilon_w\} = [D_w]^{-1} \{\Delta\sigma\} \tag{3}$$

Where, $[D_w]$ is the element stiffness matrix in the saturated state. Accumulate $\{\Delta\varepsilon_w\}$ of increment of every class, and the aggregate strain after immersion is $\{\varepsilon_w\}$. If we assume that wetting deformation is restrained, the initial strain caused by wetting deformation is:

$$\{\Delta\varepsilon\} = \{\Delta\varepsilon_d\} - \{\Delta\varepsilon_w\} \tag{4}$$

Then, convert the assumed initial strain into the equivalent nodal load,

$$\{F\} = \sum \iint [B]^T [D_w] \{\Delta\varepsilon\} \, dA \tag{5}$$

$\sum$ denotes the summation of all wetted elements; [B] is the geometric matrix of wet elements.

From equivalent nodal load {F}, the additional displacement and additional strain of soil caused by wetting deformation can be obtained. To simplify calculation, {F} can be calculated together with water pressure or nodal load converted from seepage pressure and uplift force etc.

The equivalent nodal load converted from wetting deformation does not actually exist, so in order to maintain static equilibrium, the stress corresponding to the strain increment caused by wetting deformation should be deducted from wetting element stress,

$$\{\sigma\} = [D_w][B][\delta]^e - [D]\{\Delta\varepsilon\} \tag{6}$$

4. Study on Wetting Deformation Based On P-Z Model

The P-Z model[17-22] based on the generalized plastic mechanics theory was proposed by Pastor and Zienkiewicz, which could describe the static and dynamic characteristics of soil under the condition of cyclic loading or uniaxial loading, and drainage or not. When calculating plastic deformation by this model, it is not necessary to predefine the yield surface and plastic potential surface, and the yield surface and the plastic potential surface can be deduced through loading direction vectors and loading or unloading direction vectors of plastic potential. However, the static and dynamic characteristics of P-Z model have been seldom studied at home and abroad so far. In view of this, this paper carried out triaxial tests and shaking table tests on core materials of Shuangjiangkou earth-rockfill dam, which verified the precision of P-Z model parameters and further reflected dynamic characteristics of core materials. The generalized plasticity matrix of P-Z model is expressed as:

$$\begin{cases} \boldsymbol{D}_{Lep} = \boldsymbol{D}_e - \dfrac{\boldsymbol{D}_e \boldsymbol{n}_{gL} \boldsymbol{n}^{\mathrm{T}} \boldsymbol{D}_e}{H_L + \boldsymbol{n}^{\mathrm{T}} \boldsymbol{D}_e \boldsymbol{n}_{gL}} \\ \boldsymbol{D}_{Uep} = \boldsymbol{D}_e - \dfrac{\boldsymbol{D}_e \boldsymbol{n}_{gU} \boldsymbol{n}^{\mathrm{T}} \boldsymbol{D}_e}{H_U + \boldsymbol{n}^{\mathrm{T}} \boldsymbol{D}_e \boldsymbol{n}_{gU}} \end{cases} \tag{7}$$

where subscripts "L"and "U" denote loading and unloading respectively; $\boldsymbol{n}_{gL}$ and $\boldsymbol{n}_{gU}$ are plasticity direction vectors under loading and unloading conditions respectively; $\boldsymbol{n}$ is direction vector; and H_L and H_U are plasticity moduli under loading and unloading conditions respectively. There are 12 parameters in P-Z constitutive model, including M_g, M_f, α_g, α_f, β_0, β_1, H_0, γ_{DM}, H_{u0}, γ_u, K_{evo} and K_{eso}, of which γ_{DM}, H_{u0} and γ_u are related to dynamic analysis. The derivation and calibration of parameters are shown in Table 1.

***Table 1**: Explanation of P-Z model's parameters*

Parameters	explanation
K_{evo}	Elastic parameter, determined by initial slope of loading curve between spherical stress and axial strain.
K_{eso}	Elastic parameter, determined by initial slope of loading curve between deviatoric stress and axial strain.
H_0	Plasticity modulus, determined by void ratio and initial slope of loading and unloading curve between spherical stress and axial strain.
α_g	Material constant, determined by expansion ratio and stress ratio of deviatoric and spherical stress.
M_g	Determined by the relation curve of spherical stress and deviatoric stress.
M_f	Determined by $M_f = D_r M_g$, where D_r is the relative density of soil.
α_f	Material constant
β_0	Material constant
β_1	Material constant
γ_{DM}	Dynamic parameter, determined by slope of first repeated loading curve
H_{u0}	Dynamic parameter, determined by beginning slope of first unloading curve
γ_u	Dynamic parameter, determined by slope of first unloading curve

4.1 Research approach

Wetting deformation is influenced by confining pressure, stress level of wetting, dry density of dam material, fine content, and initial water content etc. According to previous results of wetting experiments on coarse aggregates, after wetting, coarse aggregates often follow the following patterns: a. coarse aggregates' wetting deformation is usually between dry and saturated sample and the dry and saturated samples are upper and lower boundary lines of wetting deformation; b. under the same confining pressure σ_3, the greater the wetting stress level S^w is, the greater the wetting axial deformation is; c. under the same confining pressure σ_3, wetting volumetric strain increases with increasing wetting stress level S^w. According to those patterns, in the calculation, the influence of material wetting on dam can be considered in the following ways:

(1) Fit previous experiments on coarse aggregates' dry and saturated samples, determine two groups of P-Z model parameters for one material, and get the fitting curves of upper and lower boundary lines of wetting deformation;

(2) Use an appropriate attenuation function to fit wetting stress level S^w- wetting axial deformation under different confining pressures, and obtain the function relationship between stress level S^w and wetting axial deformation under different confining pressures; under different confining pressures, adopt linear function to fit the function relationship between wetting volumetric strain and wetting stress level S^w;

(3) In the calculation, only upper stream's rockfill material is considered to be influenced by wetting deformation and P-Z model parameters corresponding to dry sample is adopted before the dam retains water; before storage, calculate the average main stress of immersed elements in upper stream's rockfill at that time (used to approximate confining pressure) and stress level S^w, and achieve the wetting deformation of immersed elements through interpolation in the fitting function obtained in step 2;

(4) After storage, besides changing boundary conditions and water loading conditions necessary for finite element model, adopt P-Z model parameters of wet sample and use Formula 5 to convert wetting deformation got in step 3 into equivalent nodal force and exert it on the dam. The additional deformation is wetting deformation.

The specific calculation method is as follows: adopt single-line method to get the relationship curves of axial strain and stress level $\varepsilon_a \sim \sigma_s$ and of volumetric strain and stress level $\varepsilon_v \sim \sigma_s$ under different confining pressures; based on the present element Gaussian point's stress state, calculate the present confining pressure and stress level; determine approximate test curve in test curve set according to present confining pressure and calculate corresponding axial strain and volumetric strain from test curve based on present Gaussian point's stress level; and finally distribute axial strain and volumetric strain in the aggregate strain of present load to consider wetting deformation. The specific process is as follows:

1) Measure $\varepsilon_a \sim \sigma_s$ and $\varepsilon_v \sim \sigma_s$ curves under different confining pressures through experiment:

$\sigma_3 = 0.8MPa$: record the first set of $\varepsilon_a \sim \sigma_s$ and $\varepsilon_v \sim \sigma_s$ curves;

$\sigma_3 = 1.6MPa$: record the second set of $\varepsilon_a \sim \sigma_s$ and $\varepsilon_v \sim \sigma_s$ curves;

$\sigma_3 = 2.4MPa$: record the third set of $\varepsilon_a \sim \sigma_s$ and $\varepsilon_v \sim \sigma_s$ curves;

2) Based on present element Gaussian point's stress, obtain the confining pressure (e.g. $\sigma_3 = 1.0MPa$) and stress level is σ_s. Through the interpolation of present confining pressure in the test curve, it can be known that the first and second sets of curves need interpolation. According to confining pressure, calculate the coefficient of every curve as follows:

$$\begin{cases} a_1 = \dfrac{1.6-1.0}{1.6-0.8} = 0.75 \\ a_2 = 1-0.75 = 0.25 \end{cases} \tag{8}$$

Then use present stress level σ_s to interpolate in the first and second sets of test curves to get axial strain (ε_{a1} and ε_{a2}) and volumetric strain (ε_{v1} and ε_{v2}). Based on the coefficients of two curves to calculate the axial strain and volumetric strain of present element Gaussian point:

$$\begin{cases} \varepsilon_a = a_1\varepsilon_{a1} + a_1\varepsilon_{a1} \\ \varepsilon_v = a_1\varepsilon_{v1} + a_1\varepsilon_{v1} \end{cases} \tag{9}$$

3) Distribute the obtained axial strain and volumetric strain in the components of aggregate strain of present load. For the distribution of volumetric strain, averagely allocate strain for all directions,

$$\varepsilon_x' = \varepsilon_x - \frac{1}{3}\varepsilon_v,\ \varepsilon_y' = \varepsilon_y - \frac{1}{3}\varepsilon_v,\ \varepsilon_z' = \varepsilon_z - \frac{1}{3}\varepsilon_v \tag{10}$$

For the distribution of axial strain, we need first use axial strain to calculate deviatoric strain and then distribute. As for conventional triaxial compression test, calculate volumetric strain and deviatoric strain as follows:

$$\begin{cases} \varepsilon_v = -\left(\varepsilon_1 + 2\varepsilon_3\right) \\ \varepsilon_s = -\dfrac{2}{3}\left(\varepsilon_1 - \varepsilon_3\right) \end{cases} \tag{11}$$

Where ε_1 is axial strain ε_a. Eliminate ε_3 and get calculation formula of deviatoric strain:

$$\varepsilon_s = -\frac{1}{3}\left(3\varepsilon_1 + \varepsilon_v\right) \tag{12}$$

For plastic deviatoric strain

$$d\varepsilon_s = \frac{2}{3} de_{ij} de_{ij} ,\; de_{ij} = \alpha_{ij} \frac{\partial q}{\partial \sigma_{ij}} \tag{13}$$

Assume that distribution coefficients of all deviatoric strain variables are constant, namely α_{ij} is constant. Distribution coefficient α can be calculated through the obtained wetting deviatoric strain and present Gaussian point, $\frac{\partial q}{\partial \sigma_{ij}}$, and distribute axial strain as follows:

$$\varepsilon_{ij}^{'} = \varepsilon_{ij} - \alpha \frac{\partial q}{\partial \sigma_{ij}} \tag{14}$$

4.2 Test curve fitting and parameter determination

Like determining P-Z model parameters, determine model parameters of rockfill material's dry and wet samples. The test curves and fitting curves of dry and wet samples under various confining pressures is exhibited in Fig. 2 and Fig. 3.

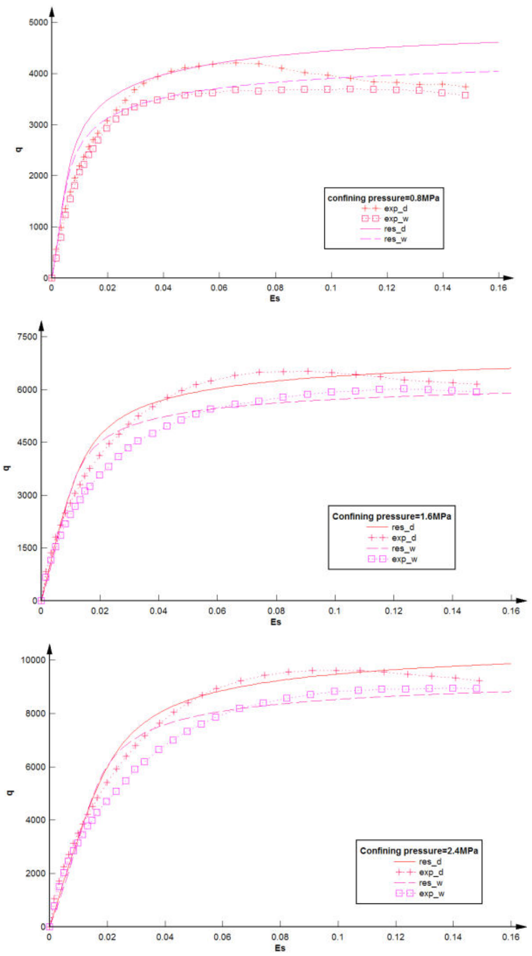

Figure 2, *Test curves and P-Z model fitting curves of dry and wet samples (confining pressure 0.8MPa, 1.6MPa, 2.4MPa; exp-experimental point; res-fitting point; d-dry sample; w-wet sample)*

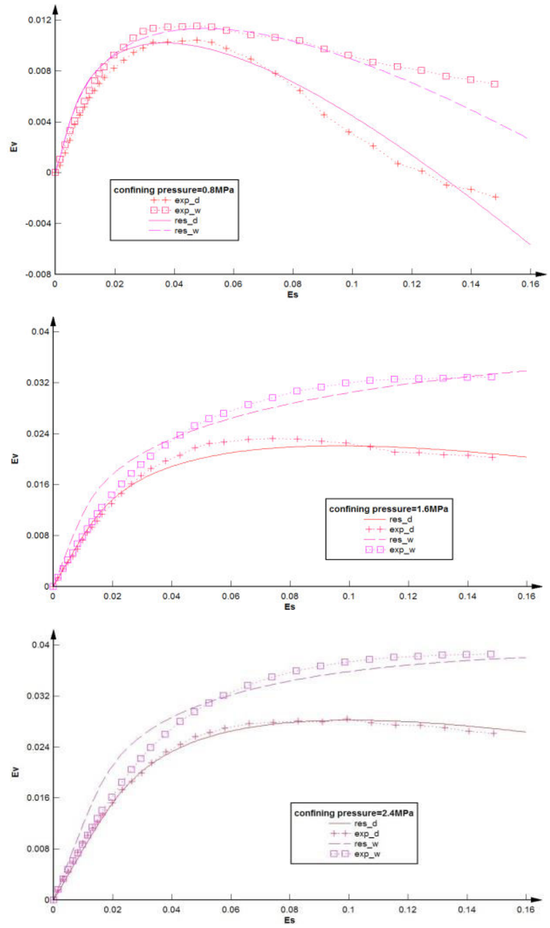

Figure 3, *Test curves and P-Z model fitting curves of dry and wet samples (confining pressure 0.8MPa, 1.6MPa, 2.4MPa; exp-experimental point; res-fitting point; d-dry sample; w-wet sample)*

Relationship curve of wetting axial strain and stress level can be fitted using the following attenuation function:

$$\varepsilon_a^w = \varepsilon_{a0} + b\exp(aS_w) \tag{15}$$

Where, ε_a^w is wetting axial strain; ε_{a0} is wetting axial strain of wetted dry sample under no confining pressure; a and b are fitting coefficients.

Based on results of coarse aggregates wetting experiments, parameters of fitting wetting axial strain and wetting stress level under various confining pressures are shown in Table 2.

Table 2*: Parameters of fitting relationship between wetting axial strain and stress level*

Confining pressure (MPa)	ε_{a0} (%)	a	b
0.8	0.02	4.6	0.02
1.6	0.05	4.7	0.018
2.4	0.08	4.9	0.019

Relationship curve of wetting volumetric strain and stress level can be fitted through the following linear function:

$$\varepsilon_v^w = \varepsilon_{v0} + cS_w \quad (16)$$

Where, ε_v^w is wetting volumetric strain; ε_{v0} is wetting volumetric strain of wetted dry sample under no confining pressure; c is fitting parameter. The parameters of fitting relationship between wetting volumetric strain and stress level are presented in Table 3.

***Table 3**: Parameters of fitting relationship between wetting volumetric strain and stress level*

Confining pressure(MPa)	ε_{v0} (%)	c
0.8	0.02	0.48
1.6	0.07	0.6
2.4	0.1	0.7

5. Project Case

Shuangjiangkou reservoir dam is vertical wall rockfill dam which is 314m high; the dam crest is 16.00m wide; and the upstream dam slope is 1:2.0 while the downstream dam slope is 1:1.8. The core wall has a 4.00m-wide crest and the upstream and downstream dam slopes are both 1:0.2. The joint parts of core wall and dam abutments on both sides consist of highly plastic clay with the horizontal thickness of 4.00m. On the core wall, two layers of filtration are respectively set at the upper and lower stream. The filtration of upper stream is 4m thick horizontally while filtration of lower stream is 6m thick horizontally. Transition layers are set respectively between filtration layers at upper and lower stream and rockfill. The finite element calculation model is depicted in Fig. 4.

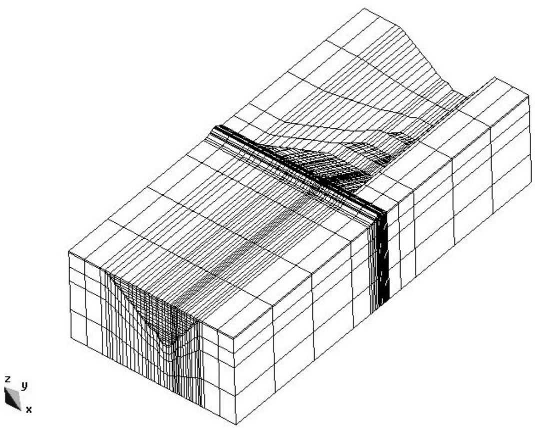

***Figure 4,** Three-dimensional finite element calculation model*

Table 4 shows the maximum displacement of dam and its percentage in dam height considering the working conditions of wetting deformation in static calculation. The calculation method considering wetting deformation is the above method.

***Table 4**: maximum displacement and percentage in dam heightin static calculation*

	longitudinal displacement (cm)		axial displacement (cm)		sedimentation (cm)
	upstream	downstream	Toward left bank	Toward right bank	sedimentation
time of completion	23.14	55.32	33.21	22.61	285.74
Proportion in dam height (%)	0.07	0.18	0.11	0.07	0.910
Storage period	22.10	59.73	33.18	22.73	286.67
Proportion in dam height (%)	0.07	0.19	0.11	0.07	0.913

According to the calculation results in the table, the maximum longitudinal displacement downstream at time of completion is 55.32cm, accounting for 0.18% of dam height while the maximum longitudinal displacement downstream during storage period is 59.73cm, accounting for 0.19%, which indicates that dam displaces downstream under water pressure. As for axial displacement of the dam, the maximum longitudinal displacement toward left bank of dam axis at time of completion is 33.21cm, accounting for 0.11% of dam height while the maximum longitudinal displacement toward right bank is -22.61cm, accounting for 0.07%,. This occurs at the middle part of dam abutment on right bank. After storage, the values are 33.18cm and 22.73cm. It can be seen that dam's axial displacement toward left bank is slightly greater than that toward right bank, which results from valley's dissymmetry. For dam's sedimentation, the maximum sedimentation at time of completion is 285.74cm, accounting for 0.91% of dam height while during storage period; the maximum is 286.67cm, accounting for 0.913%. The calculated sedimentation becomes larger since material wetting deformation's influence is considered after storage.

5. Conclusions

This paper studies the wetting deformation mechanism and analytical approach of coarse aggregates of earth-rockfill dam. Based on single-line method and test data, parameters of P-Z constitutive model are fitted and the result is applied in the static calculation of Shuangjiangkou earth-rockfill dam. It is proved that after considering the effect of wetting deformation, displacement and sedimentation during storage period become larger. Therefore this method reasonably reflects dam's wetting deformation during storage period and accords with engineering practice.

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