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Study on slope stability and reinforcement measures of an earth-rock cofferdam on deep overburden foundation

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Abstract. Slope stability and reinforcement measures of an earth-rock cofferdam on deep overburden foundation are studied in the paper. Slope stability is analysed by using FEM strength reduction method, considering seepage, based on ABAQUS. Two different reinforcement measures are taken: vibro-replacement stone columns and concrete anti-sliding piles. As a result of the research, conclusions are made: overflow happens on the slope near bottom of the foundation pit in layer Q^{al-1}, where permeability coefficient is quite large compared to that of other layers; Both the vibro-replacement stone columns and concrete anti-sliding piles increase the stability; Vibro-replacement stone columns should be used as the final reinforcement measure, since vibro-replacement stone columns can be constructed before the foundation pit excavation and they can also conduce to drainage in foundation pit. This deep overburden foundation is characterized by complex geological conditions and poor mechanical properties. Therefore, the successful construction of the project has a certain reference and application value.

1. Introduction

Cofferdams are frequently used temporary structures [1] and important to the construction of dams as they can provide dry land condition [2] for the dams being built on the foundation pits. The challenge from dealing with deep overburden foundation is more and more severe [3] since water conservancy projects including cofferdams sometimes have to be constructed on deep overburden foundation when the geologically favored foundations are unavailable. Since accidents of overburden buildings, especially hydraulic structures, are mainly caused by seepage failure of foundations, large subsidence or slope instability [4], researches on seepage analysis and slope stability of high earth-rock cofferdams on deep overburdens are essential. Reinforcement measures are also indispensable if relevant stability analysis or site monitoring anticipates slope instability. Vibro-replacement stone columns [8-10] can be used to reinforce soft soil layer in foundation while concrete anti-sliding piles [11-13] can be an appropriate reinforcement measure for unstable slopes.

An earth-rock cofferdam on deep overburden foundation is studied in the paper. Its foundation contains 60m deep overburden which is divided in 6 layers according to different mechanical properties. Particularly, the overburden has 31.4m deep low liquid limit clay. Depths of foundation pit

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slope and cofferdam are 65m and 60m respectively, as a result, the depth of downstream slope gets 125m.

Four cases are chosen: namely, in Case A the downstream foundation pit is unexcavated, in Case B it is excavated but not reinforced, in Case C it is excavated and reinforced by vibro-replacement stone columns (reinforcement depth is 40 m, reinforced layers are Q^{L-3}, $Q^{L-2-③}$ and $Q^{L-2-②}$), and in Case D it is excavated and reinforced by concrete anti-sliding piles embedded from foundation pit slope into the bedrock.

2. Methodology

In this paper, slope stability is analyzed by using strength reduction method and considering seepage effect, based on ABAQUS. Seepage lines during steady state are figured out according to pore pressure calculation, and then safety factor is calculated, followed by the determination of the position of the most dangerous sliding body.

2.1Theories for fluid-solid coupling analysis

When the continuum method is used, the solid phase and the fluid phase can be regarded as overlapping continuums, and thus the porous medium system can be replaced by an ideal continuous system [5]. Based on this principle, a governing equation is established on ABAQUS.

The stress balance of solid materials can be expressed by virtual work principle [6], at given time t, the virtual work principle in a volume domain can be expressed as:

$$\int_V (\boldsymbol{\sigma}' - \chi\mu_f \boldsymbol{I}) : \delta\varepsilon \, dV = \int_S \boldsymbol{t}\delta\boldsymbol{v}dS + \int_V \boldsymbol{f}\delta\boldsymbol{v}dV + \int_V sn\rho_f \, \mathrm{g}\delta\boldsymbol{v}dV \tag{1}$$

Where, $\boldsymbol{\sigma}'$ is the effective stress, $\delta\varepsilon = \mathrm{sym}(\frac{\partial\delta\boldsymbol{v}}{\partial\boldsymbol{x}})$ is the virtual deformation rate, $\delta\boldsymbol{v}$ is the virtual velocity field, $\boldsymbol{t}$ is the surface force per unit area, $\boldsymbol{f}$ is the volume force per unit volume (fluid mass not included), s is the saturation of solid materials, n is the porosity of solid materials, ρ_f is the fluid density, and g is the gravitational acceleration.

By the displacement finite element method and the Lagrange formula to discretize the virtual work equation, the finite element meshes can be obtained. When the fluid flows through these elements, it needs to meet the continuity equation, in order to make the amount of fluid flowing in a time increment equal to the increase rate of fluid volume:

$$\frac{d}{d_t}\left(\int_V \frac{\rho_\mathrm{f}}{\rho_\mathrm{f}^0} \, sndV\right) = -\int_S \frac{\rho_\mathrm{f}}{\rho_\mathrm{f}^0} \, sn\boldsymbol{n}\boldsymbol{v}_\mathbf{f}dS \tag{2}$$

Where, $\boldsymbol{v}_\mathbf{f}$ is the flow velocity, $\boldsymbol{n}$ is the direction of external normal line on surface S. The equation (2) is nondimensionalized by using ρ_f^0, the reference density of the fluid.

ABAQUS can directly couple seepage field and stress field, therefore no repeated iteration of these two fields is need and all results can be achieved by the continuous solution, based on time course [5].

2.2Strength reduction method

Strength reduction is attained by dividing the strength parameters *C* and *φ* by reduction coefficient F_S (also a field variable), as a result, new parameters *C'* and *φ'* form. This repeats continuously until the slope loses its stability [5,7]. When the slope becomes instable, corresponding F_S will be chosen as the safety factor. Strength parameters can be formulated as below:

$$C = C' / Fs \tag{3}$$

$$\varphi = \arctan(\tan\varphi' / Fs) \tag{4}$$

In the paper, appearance of inflection point of displacement of a point on the cofferdam is chosen as the valuation standard for the slope instability.

3. Project and its modelling

The overburden foundation contains, from top to bottom, sand pebble layer (Q^{al-5} layer, 1.4-4.6m deep), muddy powder sand and clay sand layer (Q^{L-3} layer, 14.7-18.1m deep), sandy and low liquid limit clay layer (Q^{L-2} layer, 31.4m deep, this layer is also divided into 3 sublayers according to small difference between their geotechnical properties), and pebble, stone and sand layer (Q^{al-1} layer, 13.1m deep). Cofferdam body consists of 4 sections: Section A, B, C and Section D. Anti-seepage system comprises plastic concrete cutoff-wall and geomembrane.

Sectional view of the cofferdam and the foundation can be seen from Figure 1, and geotechnical properties are given in detail in Table 1.

In case C, the analysis is made by giving alternative properties to the area reinforced by vibro-replacement stone columns, which can be seen from Table 2.

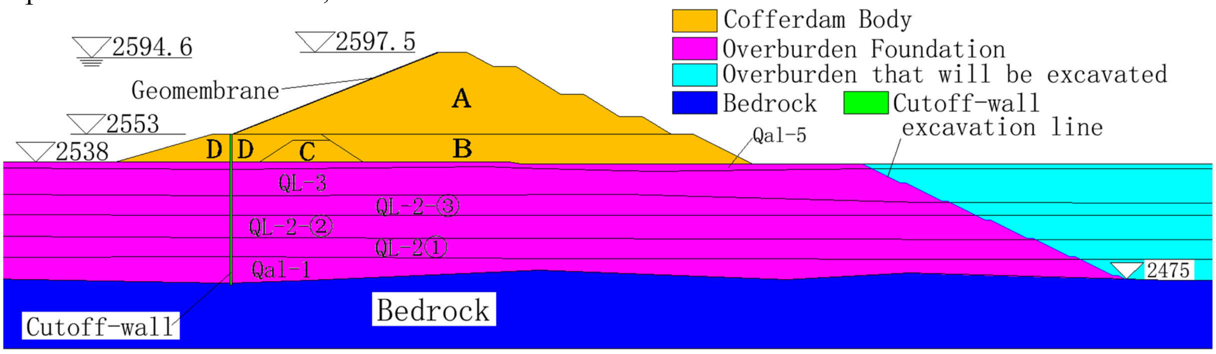

Figure 1. Sectional view of the cofferdam and its foundation

Table 1. Geotechnical properties

Material/Layer	Density/ kg·m^{-3}	E/MPa	v	k/ m·s^{-1}	c/KPa	φ/ °
Bedrock	2800	15000	0.25	5×10^{-6}	800	45
Q^{al-1}	1950	35	0.25	1×10^{-4}	10	36
$Q^{L-2①}$	1830	4	0.4	3×10^{-7}	29	12
$Q^{L-2-②}$	1840	5	0.4	1.7×10^{-6}	22	13
$Q^{L-2-③}$	1820	4	0.4	3.4×10^{-7}	29	12
Q^{L-3}	1850	5.5	0.4	4.1×10^{-6}	20	13.5
Q^{al-5}	2100	45	0.35	1×10^{-3}	0	35
A	2240	50	0.35	5×10^{-4}	0	38
B	2200	40	0.4	5×10^{-3}	0	32
C	2060	40	0.3	5×10^{-5}	0	32
D	2100	30	0.24	5×10^{-4}	0	25
Cutoff-wall	2000	750	0.2	1×10^{-9}		
Geomembrane	226	484	0.3	2×10^{-10}		
Concrete piles	2400	30000	0.2			

Table 2. Geotechnical properties of the area reinforced by vibro-replacement stone columns

Layer	Density/ kg·m^{-3}	E/MPa	v	k/ m·s^{-1}	c/KPa	φ/ °
Q^{L-3}	2026	15	0.4	4.1×10^{-6}	7.3	27
$Q^{L-2-③}$ and $Q^{L-2-②}$	1989	12	0.4	3.4×10^{-7}	6.3	26

FEM models are built for all cases (Figure 2-4): Model1 is for Case A (8796 elements, 11165 nodes), Model2 is for Case B and C (7336 elements, 9765 nodes), and Model3 is for Case D (32866 elements, 36972 nodes). C3D8P is chosen as the elements type, except C3D8 for concrete piles.

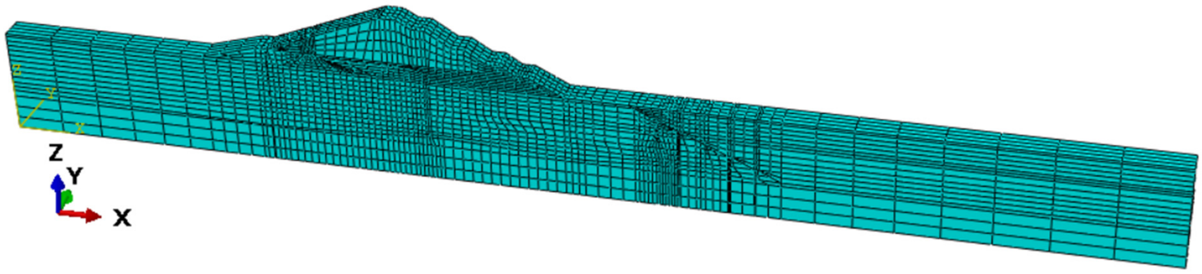

Figure 2. Model 1

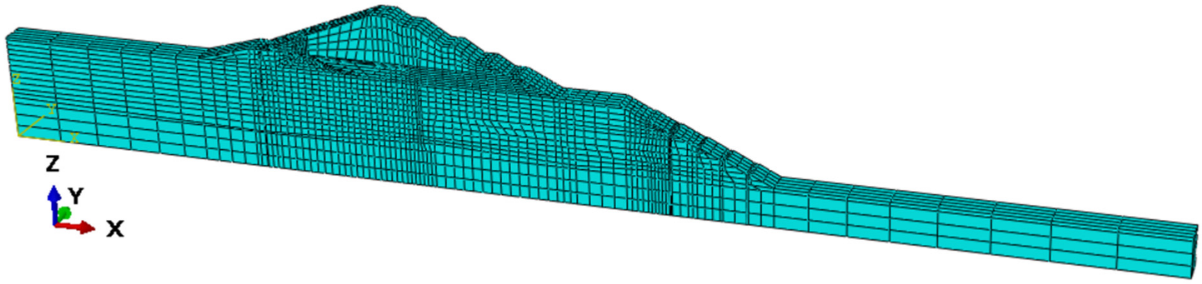

Figure 3. Model 2

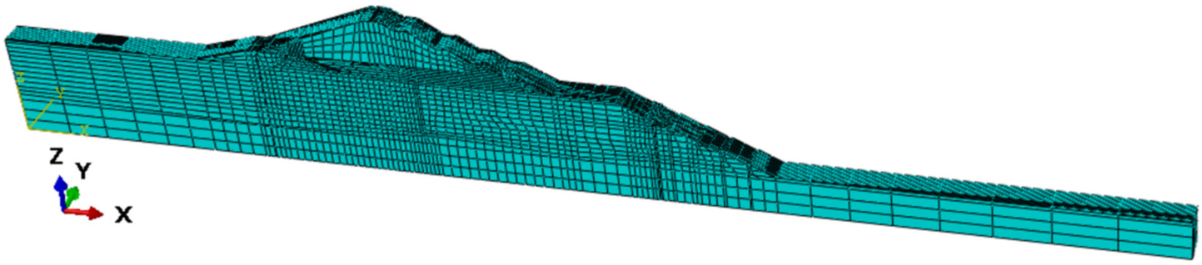

Figure 4. Model 3

4. Discussions

4.1Results of pore pressure calculation

Pore pressures under free surface, shown in Figure 5-8 (unit: KPa), indicate that the geomembrane and concrete cutoff-wall reduce the pore pressure of the cofferdam and the overburden on downstream side, and excavation of foundation pit changes the distribution of pore pressure and the position of overflow point.

Precisely, the positions of overflow points in Case B, C and D are on the slope near bottom of the foundation pit (in layer Q^{al-1}, where permeability coefficient is quite large compared to that of other layers) while in Case A the position of overflow point is on bottom of downstream slope of the cofferdam.

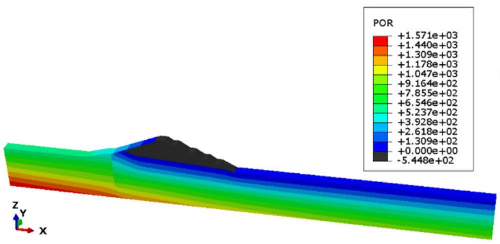

Figure 5. Pore pressure under free surface in Case A

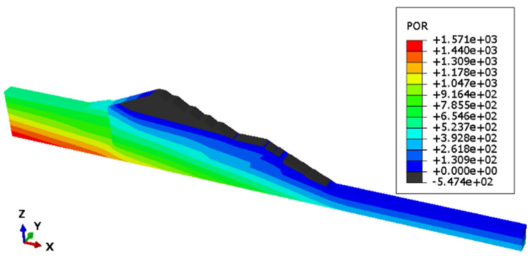

Figure 6. Pore pressure under free surface in Case B

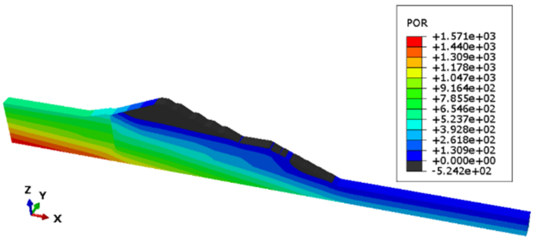

Figure 7. Pore pressure under free surface in Case C

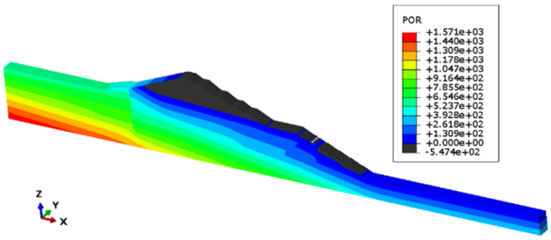

Figure 8. Pore pressure under free surface in Case D

4.2Results of slope stability

According to the valuation standard for the slope instability, the safety factors of slopes in Case A, B, C and D are 1.366, 1.219, 1.328 and 1.337 respectively, as in Figure 9.

The positions of the most dangerous sliding bodies are shown by incremental displacements during the last increment in the step of strength reduction, as in Figure 10-13 (unit: m). The landslides in Case A and D occur at the downstream slope of the cofferdam whereas in Case B and C landslides happen on the slope induced by foundation pit excavation.

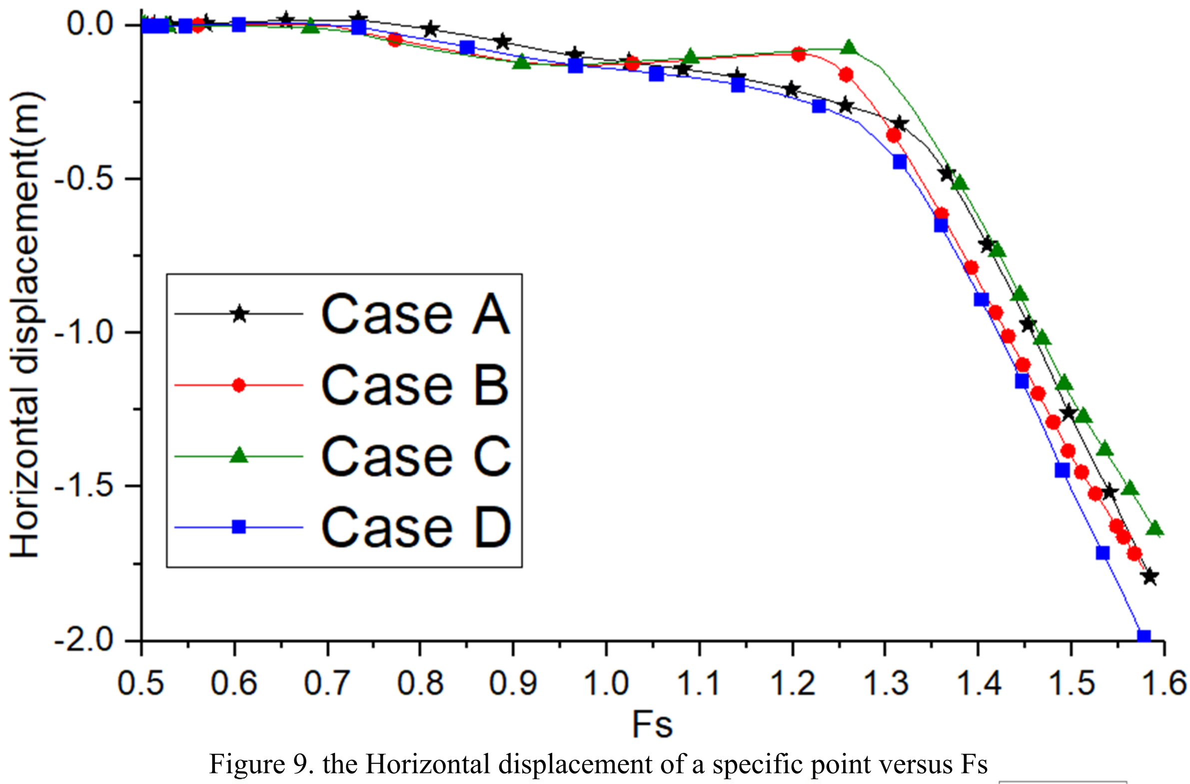

Figure 9. the Horizontal displacement of a specific point versus Fs

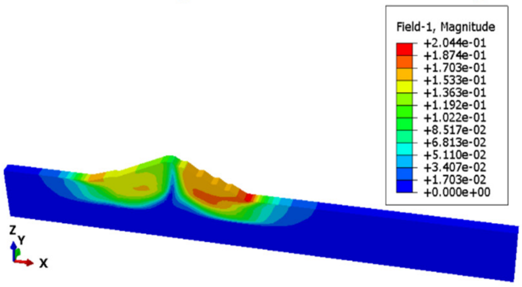

Figure 10. Incremental displacement in Case A

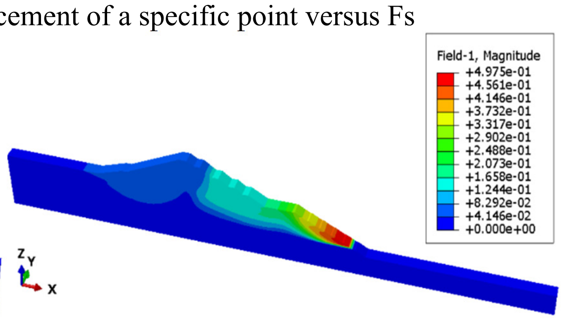

Figure 11. Incremental displacement in Case B

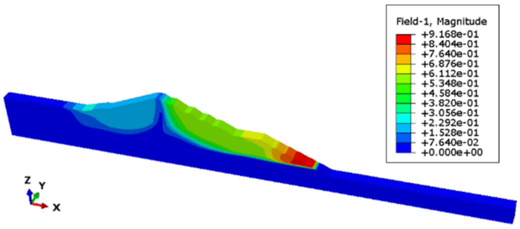

Figure 12. Incremental displacement in Case C

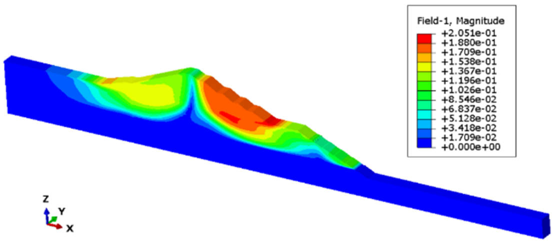

Figure 13. Incremental displacement in Case D

5. Conclusion

Slope stability of an earth-rock cofferdam on deep overburden foundation and the contributions of reinforcement measures for increasing the stability are studied in the paper. As a result, following conclusions are drawn:

- The position of overflow point achieved by seepage analysis corresponds to the bottom of the most dangerous sliding body in exception of the slope reinforced by concrete anti-sliding piles.
- Foundation pit excavation reduces the stability of the cofferdam: the safety factor declines from 1.366 to 1.219 after the excavation of downstream foundation pit.
- Both the vibro-replacement stone columns and concrete anti-sliding piles increase the stability: safety factors increase from 1.219 to 1.328 and 1.337 respectively.
- Vibro-replacement stone columns should be chosen as the final reinforcement measure when the effectiveness of both measures studied in the paper is almost the same, because vibro-replacement stone columns can be constructed before the foundation pit excavation and they can also conduce to drainage in foundation pit.

Acknowledgments

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