Effects of Permeability Coefficient on Deformation and Stability of the Rock Bank Slope

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Abstract. In order to examine the effects of permeability coefficient on deformation and stability of high steep bank slope, this thesis is set in the reservoir water fluctuation project of one high steep bank slope, uses a series of Geo-Studio finite element analysis software to make two-dimensional numerical simulation tests under two conditions in case of reservoir water slow change, studies the influence of permeability coefficient in continuous water levels fluctuation throughout the process on deformation and stability of bank slope, and mainly analyzes its impact effect on deformation and displacement of slope rock mass, “approximate creeping” and bank slope safety factor. The results show that the increase in permeability coefficient has a relatively small displacement influence on all observation points along X, Y direction, in continuous water levels fluctuation throughout the process, the greater permeability coefficient of rock mass near the slope at each stage means the smaller safety coefficient of bank slope.

Introduction

Practice indicates that the fluctuation of water levels has a significant effect on slope instability after the reservoir impoundment. Morgenstern N. [1] reported 16 cases of dam upstream face landslides due to a sudden drop of water levels. Jones [2] et al. investigated some landslides occurred in 1941-1953 in the adjacent areas of Roosevelt Lake, where the Pleistocene glacial deposits were distributed, its results show: 49% landslides occurred in the initial stage of reservoir impoundment in 1941-1942, 30% occurred in two occasions where the water levels dropped by 10-20 m, and others were small landslides occurred in other periods. In Japan, about 60% of the reservoir landslides occur during the dropping period of reservoir water levels, the remaining 40% occurred during the rising period of water levels, including the initial impoundment. At present, a lot of researches have been performed on the mechanism of slope instability due to the fluctuation of reservoir water levels and the variation characteristics of stability coefficient [3,4]. Present studies on water-rock cycles reflect the significant weakening effect of rock mass [5]. A lot of studies have been done on the calculation and variation characteristics of downslope seepage line under the fluctuating effect of reservoir water levels [6,7]. However, most studies study the sudden change of water levels, while fewer observe the slow change of water levels, the regular conclusion for the impact of fluctuation of reservoir water levels on slope stability often varies if different slope masses are studied, especially there is few literature about the impact of certain factor (e.g.: permeability coefficient [4], soil-water characteristic curve [8]) on slope deformation and stability throughout the continuous fluctuation of water levels, objectively, a factor should always have certain impact on slope throughout the rising process and holding process in prior stage, the neglect of a factor on “full dynamic process” throughout the fluctuation of reservoir water levels obviously does not satisfy the engineering realities.

This thesis uses a series of GeoStudio finite element software (i.e.: SLOPE/W, SEEP/W and SIGMA/W) to make coupling simulation, and intends to study the impact of permeability
coefficient under continuous water levels fluctuation throughout the process on slope deformation and stability.

Theory of Phreatic Surface Landslide Mass

The variation range of groundwater levels will reduce with the rise of water levels, then the change speed of slope free water surface will decrease, the height of seepage line is lowered. To this end, we can change the following conditions: increase the fluctuation speed of water levels or the drainage rate of rock-soil layer; or reduce the permeability coefficient of rock-soil layer or the thickness of saturated aquifer. The variation range of groundwater levels will increase with the fall of water levels, then the change speed of slope free water surface will increase, the height of seepage line is lowered. To this end, we can change the following conditions: decrease the fluctuation speed of water levels or the drainage rate of rock-soil layer; or increase the permeability coefficient of rock-soil layer or the thickness of saturated aquifer [7].

Numerical Test Scheme Design

The slope finite element model used in numerical simulation is shown in Fig.1. The formation lithology of the left bank slope is mostly siltstone and shale. The physical and mechanical parameters of the rock and soil are shown in Tab.1. The design of fluctuation speed in case of water levels slow change is shown in Tab. 2. The design of numerical simulation in case of water levels slow change is shown in Tab. 3.

Figure 1. The slope finite element model used in numerical simulation.

Table 1. The physical and mechanical parameters of rock and soil.

| The Category of Rock and Soil | Elasticity Modulus (GPa) | Poisson's Ratio | Natural weight (kN/m³) | Cohesion (MPa) | Internal Friction Angle (°) |
|------------------------------|--------------------------|----------------|------------------------|---------------|-----------------------------|
| Weak-weathered siltstone     | 10                       | 0.21           | 26.3                   | 0.37          | 33                          |
| Weak-weathered shale         | 3                        | 0.32           | 26.3                   | 0.32          | 31                          |
| Fresh siltstone              | 13.5                     | 0.21           | 26.4                   | 0.6           | 34                          |
| Fresh shale                  | 4.5                      | 0.32           | 26.4                   | 0.34          | 32                          |

Table 2. The design of fluctuation speed in case of water levels slow change.

| Scheme          | Water level fluctuation 53-98-53(m) | Corresponding reservoir water level (m) | Velocity of water level fluctuation (m/day) | Consumption time(day) | Elapsed time(day) |
|-----------------|-------------------------------------|----------------------------------------|--------------------------------------------|-----------------------|-------------------|
| Slow change     | 0-33                                | 142-175                                | 3.3                                        | 10                    | 10                |
|                 | 33-53                               | 175-195                                | 4                                          | 5                     | 15                |
|                 | 53                                  | 195                                    | 0                                          | 365                   | 380               |
|                 | 53-98                               | 195-240                                | 0.12                                       | 375                   | 755               |
|                 | 98                                  | 240                                    | 0                                          | 365                   | 1120              |
|                 | 98-53                               | 240-195                                | 0.12                                       | 375                   | 1495              |
|                 | 53-33                               | 195-175                                | 0                                          | 365                   | 1500              |
|                 | 33.0                                | 175-142                                | 0.33                                       | 10                    | 1510              |
|                 | 0                                   | 142                                    | 0                                          | 365                   | 1875              |
Table 3. The design of numerical simulation in case of water levels slow change.

| Influence factor | Time       | Condition | Permeability coefficient(cm/s) |
|------------------|------------|-----------|-------------------------------|
| Permeability     | Whole process | C 1-S | 1e-4                          |
| coefficient      |             | C 2-S | D                            |

Note: ①“C i-S”: Condition i-slow change, i =1, 2. ②“D”: The value of permeability coefficient in Tab. 3 means that the permeability coefficient of rock-soil mass above the bottom boundary of moderate weathering line, between the bottom boundary of moderate weathering and the top boundary of aquitard, below the top boundary of aquitard is 1e-2 cm/s, 1e-3 cm/s, and 1e-4 cm/s respectively.

Displacement Analysis for Calculation Result

In the entire bank slope, the displacement observation is done on three portions which are divided by height, i.e.: 1/3 height in the upper part of slope, 1/3 height in the middle part of slope, and 1/3 height in the lower part of slope, and 14 observation points are selected from each portion and numbered in top-down order: No.1 thru 14 observation point, the height difference between adjacent observation points is about 5m, Illustrating the displacement of observation points within 1/3 height in the middle part of slope, the coordinates of 1/3 height in the middle part of slope in descending order is (483, 269) – (507, 205), The displacement-time curves for observation points within 1/3 height in the middle part of slope is shown in Fig. 2. We make the following analysis:

Influence when the permeability coefficient increases: At C2-S, the displacement influence along X, Y direction is relatively small, the decrease of curve discreteness is relatively small, and the lower overall performance of the observation points means the higher sensitivity.

Law of “approximate creeping”: At Day 15-380 and Day 755-1120, the influence law when the permeability coefficient increases is similar to the above analysis. Its general variation law: the displacement along X direction will increase with time, and the displacement in Y direction will increase with time at Day 15-380, but decrease with time at Day 755-1120.

Figure 2. The displacement-time curves for observation points within 1/3 height in the middle part of slope.

Slope Safety Factor Analysis for Calculation Result

The bank slope stability is calculated using Morgenstern-Price method [9] in limit equilibrium analysis, the factor of safety-time curve of bank slope is as shown in Fig. 3.

Influence when the permeability coefficient increases: At C2-S, the overall performance of safety coefficient shows a downward trend, the curve characteristics are analyzed as follows: the overall performance of curve increases, decreases then increases when the water levels rises. But at the maximum constant water levels, the overall performance shows a downward trend. The overall performance of curve decreases, then increases from Day 1500 when the water levels falls. When the water levels of bank slope reaches the minimum, the overall performance of curve increases then tends to be stable. Although the overall performance of bank slope safety coefficient when the permeability coefficient increases is relatively small, the safety coefficient is generally higher than 1.6. Despite the relatively influence with respect to the overall performance of displacement, the displacement value is relatively large.
Summary
Through the above-described numerical simulation and comparison, this thesis mainly draws the following conclusions:

(1) The increase in permeability coefficient has a relatively small displacement influence on all observation points along X, Y direction, in continuous water levels fluctuation throughout the process, the greater permeability coefficient of rock mass near the slope at each stage means the smaller safety coefficient of bank slope.

(2) When the permeability coefficient increases, the better overall performance of observation points within 1/3 height in the lower part means the higher sensitivity, while the poorer overall performance of observation points within 1/3 height in the upper or middle part of slope means the higher sensitivity. Although the variation law of “approximate creeping” for the observation points in each region is different, the influence law is similar to the overall displacement analysis for each region.

(3) To draw a relatively reliable conclusion, the stability analysis of bank slope should not solely depend on the solution to safety coefficient of bank slope, but it should be combined with the displacement of observation points to make a comprehensive analysis and evaluation.

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