The Theoretical Research and Finite Element Analysis of Toe Weight on the Earth and Rockfill Dam Reinforcement

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Abstract

Toe weight is widely employed in the earth and rockfill dam reinforcement projects, but the theoretical analysis of its impact on the earth and rockfill dam is very vague and the sizes of the toe weight block are mostly determined empirically. In this paper, it researches and discusses the impact of weight block in front of the reservoir dam to the static and dynamic characteristics of earth and rockfill dam through combining the theoretical calculation with the numerical simulation analysis methods based on the specific engineering example. It shows that the length and height of the toe weight block together with the internal friction angle of the material greatly affect the stability of the dam. The length, height and the economic height ratio of the dam are obtained by optimization. The toe weight block length should be 0.45-0.55 times the length of the dam. The toe weight block height should be at least larger than 0.19 times the dam height. The larger is the height of toe weight block, the larger the safety coefficient is. But the toe weight block height should not be larger than 0.3 times the dam height. Placing weight block in front of the reservoir dam can effectively improve the initial stress of dam foundation, and enhance the capability to resist the liquefaction.

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Keyword: toe weight; earth and rockfill dam; APDL; finite element analysis; initial stress

1. Introduction

The reservoirs have exhibited good performance on flood control and drought relief. Since most of medium and small reservoirs were built in the early 1950s to late 1970s, without being maintained for many years, their capability to flood control and the normal performance have been inhibited [1]. Of the dilapidated reservoirs in China, large parts of the reservoirs are the clay core wall and coarse sand-gravel
shell. The density of the shell sand backfill is low, and cannot meet the code requirements that the relative density should not be less than 0.8. In recent years, the studies have shown that the relationship between stress and strain of soil exhibits significant nonlinearity and hysteresis under dynamical loads. With the augment of the dynamic load force and duration, the dynamic soil pore water pressure will be gradually developed, diminishing the soil strength. Even the liquefaction phenomenon is exhibited in loose saturated sand and light sub-clay, posing great hazard to the dam safety. Of all the sand-shell foundation reinforcement measures, using rock riprap as kentledge is a more effective and economical way, the most commonly used reinforcement measures by the designers. However, the length and height of the toe weight block are not regulated in codes and the manuals. The study of the theory about the toe weight needs to be carried on further. The reasonable dimensions of weight block are imperative to clarify [2-6].

2. The reinforcement mechanism for toe weight block on the upstream of earth and rockfill dam

The load application method is to throw excavation spoil or other materials to applying pressure on the toe of the dam. As the weight body is located in the toe of the dam body, namely the sliding body parts, it can make the best of the ballast, and effectively increased the initial stress of liquefied materials on the foundation. Meantime it can effectively solve the problems of sliding and liquefaction of the toe area, and prevent the soil flowing out of the foundation (plastic flow). The load application method can be applied to the stability reinforcement for the dam toe region with various types of soil materials. It can be put into the underwater construction, with construction simple, construction period short, cost low, environment friendly, and are widely used in the medium and small reservoir dam toe area reinforcement projects.

3. Static analysis

Base on the dam reinforcement mechanism for the toe weight, the small and medium size reservoir Yangzhuang reservoir is selected as an example to calculate the theoretical analysis. The study for the impact of the length and height of the toe weight block to the dam safety coefficient is carried out.

3.1 Construction generalization

Reservoir Yangzhuang is located in the Xinyi River Jun Qiu River tributary on the river owned, and controls drainage area 36 km². The Yangzhuang reservoir began construction work on November 1959, roughly completed in June 1960, with a total capacity of 10,003,000 m³ (the calculation results). It is a medium-sized reservoir with multifunctions, such as flood control, irrigation, aquaculture and other utilizations. Design standards for flood control are once every hundred years, the Millennium flood checking. Minimum safety coefficient of the dam to be allowed is 1.30 at normal condition, 1.15 at extreme cases. According to geological reports and preliminary survey and design, the upstream slope revetment is damaged, with the sand-shell density low, sliding stability inadequate. The safety coefficient is calculated as 1.126, not meeting the specifications. The main technical indicators are showing as following: dead water level is 151.7m; constant storage level is 165.00m; flood level for once in a century design is 168.28m; millennium checking flood level is 169.22m.

3.2 Calculation model and calculation parameters

The Yangzhuang dam sand shell wall cross-section at 0+330 is selected as typical analytical cross-section model, With 26.2m height, crest width 6.6m, crest elevation 170.8m, upstream slope ratio1:3.0, the upstream station closure elevation 160.0m, width 2.0m, the downstream dam slope ratio 1:2.75.
Computational model cross-sectional picture is showed in Figure 1.

Figure 1 Dangerous landslide areas of the dam before reinforcement

According to the geological reports for the Yangzhuang reservoir reinforcement, the calculated cross-section parameters are selected, as is showed in Table 1.

Table 1. Static calculation parameters

| Materials                              | Wet densities (kN/m³) | Cohesive force (kPa) | Internal friction angle (°) |
|----------------------------------------|-----------------------|----------------------|-----------------------------|
| coarse sand-gravel of dam foundation   | 16.3                  | 5.50                 | 32.1                        |
| coarse sand-gravel of upstream shell   | 17.2                  | 0.40                 | 31.7                        |
| clay core wall                         | 19.8                  | 23.90                | 21.4                        |
| coarse sand-gravel and soil of downstream shell | 15.8 | 0.51                | 30.8                        |
| ripped-rock weights                   | 22.0                  | 0.00                 | 36.0                        |

Bishop simplified method is selected as the calculation method, and anti-sliding safety coefficient is

\[ K = \frac{\sum [(W \pm V) \sec \alpha - \mu b \sec \alpha \tan \varphi + c b \sec \alpha \left[ 1/(1 + \tan \alpha \tan \varphi / K) \right)]}{\sum [(W \pm V) \sin \alpha + M_i / R]} \]  

(1)

3.3 Calculation program

3.3.1 The stability of the dam under the influence of different toe weight block length

The paper tentatively assumes that the height of the weight block is 6m and the ratio between the height of the weight block and the height of the dam is 1:4.367. Different weight block lengths are adopted, including 0, 2, 4, 5, 6, 7, 8, 10, 12. The corresponding ratio is calculated, while the safety coefficient has been calculated using the internal friction angle of different materials. The results are shown in Figure 2.

Figure 2 The stability of the dam under the influence of different weight block length

It can be inferred from Figure 2: the safety coefficient is in positive relationship with the weight length when the length is below 12.0m, namely 0.46 times the dam length. The safety coefficient will not
increase with the augment of the weight block height when the height of the weight block is above 13 m. The safety coefficient is in positive relationship with the internal friction angle of the materials. The performance of the materials has influence on the stability of the dam. The larger the internal friction angle is, the better is the stability of the dam.

### 3.3.2 The safety coefficient under the influence of different weight block height

The paper tentatively assumes that the weight block length is 12m and the ratio between the length of the weight block and the height of the dam is 1:2.18. Different weight block heights are adopted, including 0, 2, 4, 5, 6, 7, 8, 10, 12. The corresponding ratio has been calculated, and the results are shown in Figure 3.

![Figure 3](image)

**Figure 3.** The stability of the dam under the influence of different weight block height

It can be inferred from Figure 3: the safety coefficient is in positive relationship with the weight length. The safety coefficient augments with the height of the weight block. The safety coefficient changes insignificant when the weight block height is small, while increasing significantly when the height is above 4.5m, namely exceeding 0.175 time of the dam height. When the height is above 5m, namely 0.191 time of the dam height, the safety coefficient will exceed the values that the codes allow.

Based on the above data and analysis, the weight block length should be about 0.45-0.55 times the dam height, and the weight block height should be at least 0.191 times the dam height. The higher the weight block is, the higher is the safety coefficient. But the weight block height is not allowed larger than 0.3 times of the dam height, otherwise will result in excessive investment, difficult construction and resources wasted. Internal friction angles of the dam materials have some certain impact on the stability of the dam. Under the same condition the greater the internal friction angle is, the better is the stability of the dam.

### 4. Numerical Analysis

#### 4.1 ANSYS and APDL introduction

ANSYS software is multi-function finite element analysis software integrating many disciplines, including structure, thermodynamics, fluidics, electromagnetic, acoustics. As one of the most popular finite element software, it features good performance, convenience, fast calculation, etc. The software is preferred by engineers, and is widely used in many spheres, such as the nuclear industry, railway, petroleum and chemistry, aviation, machinery manufacturing, energy, traffic, national defence, electronics, civil engineering, shipbuilding, biomedical, light industry, mining, water conservancy.

Three parts are included in the ANSYS software, such as the pre-processing module, the analysis and calculation module and the post-processing module. ANSYS Parametric Design Language provides the users with auto-complete finite element analysis function by the means of the intelligent analysis. APDL extends beyond the traditional finite element analysis limits to the more advanced operations, including the sensitivity study, the library of parametric modelling, the design modification and optimization [7].
4.2 Model building

The structure of the earth dam is simple. The force distribution of the cross-section perpendicular to the structure length is same basically, and the longitudinal length of the dam is much larger than its cross-sectional length, so the choice of unit cross-section as the analysis strain plane is feasible. According to survey data, the finite element reservoir model is established. According to reservoir survey data the finite element model was established. The dam is divided into five parts, including the dam foundation, the upstream shell sand, clay core wall, the downstream shell sand, and toe weight block. The simulation of different weight block sizes is realized by using element birth and kill technology[8-10]. Established model is shown in Figure 4.

Figure 4 Model diagram before and after the dam reinforcement

4.3 Calculation and analysis

Through the finite element analysis results, the 40 nodes on the foundation are selected from upstream to downstream, using the List command to list the contact stress in all directions. The effect of toe weight to x direction was showed by figure5.

Figure 5 The effect of toe weight on x-stress of dam foundation

The result shows that toe weight can effectively augment initial x-stress of the foundation soil, especially significant on the dam axis on the upstream. The further from the toe weight, the more insignificant its effect is. Stress near the dam axis is greatest, basically the x-axis symmetry, diminishing along the direction of upstream and downstream.

Figure 6 The effect of toe weight on y-stress of dam foundation

The effect of toe weight to x direction was showed by figure 6. It inferred that toe weight can effectively augment initial y-stress of the foundation soil, especially significant on the dam axis on the upstream. The further from the toe weight, the more insignificant its effect is. Stress near the dam axis is greatest, basically the x-axis symmetry, diminishing along the direction of upstream and downstream.
The effect of toe weight to xy-shears was showed by figure 7. It inferred that toe weight can effectively augment initial shears of the dam foundation soil on the upstream. The further from the toe weight, the more insignificant its effect is.

The result shows that toe weight can effectively augment initial stress of the foundation soil, especially significant on the dam axis on the upstream. The further from the toe weight, the more insignificant its effect is. Stress near the dam axis is greatest, basically the x-axis symmetry, diminishing along the direction of upstream and downstream.

5. Conclusion

Based on the analyses carried out, some helpful results are reached. Toe weight can effectively improve the stability of the clay core wall and coarse sand-gravel shell dam. The toe weight block length should be 0.45-0.55 times the length of the dam. The toe weight block height should be at least larger than 0.19 times the dam height. The larger is toe weight block height, the larger is the safety coefficient. But the toe weight block height should not be larger than 0.3 times the dam height. Additionally, toe weight can effectively augment initial stress of the foundation soil. The further from the toe weight block, the more insignificant its effect is. Stress near the dam axis is largest, basically the x-axis symmetry, diminishing along the direction of upstream and downstream.

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