Seepage control effect of a concrete face rockfill dam on a deep overburden foundation

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Abstract. This study addresses the seepage field characteristics of a concrete face rockfill dam (CFRD) built on a deep overburden foundation. The seepage barriers and anti-seepage effect for the dam and foundation are analysed using the finite element method (FEM). Based on the numerical analysis, it is concluded that the anti-seepage wall in the overburden foundation can achieve good anti-seepage effect. A relative depth ratio of 0.7 between the wall and overburden is suggested when a suspended cut-off wall is used. The permeability of the overburden has a significant effect on the foundation seepage field.

1. Introduction

With the development of hydropower resources around the world, dam construction always involves complex geological conditions [1,2]. The deep overburden foundation is one typically complex geological condition, which characterised by looseness, lithology discontinuance, and complex genetic type [3]. To meet various special requirements, an increasing number of CFRDs have been built upon deep overburden foundations.

A series of technical problems arise when building dams upon deep overburden foundations; key challenges being leakage and seepage stability. A highly permeable overburden may cause leakage, slope instability, erosion of the foundation, and cracking of seepage barriers [4]. A horizontal impervious blanket and vertical cut-off wall are the main seepage barriers available for use in an overburden foundation, and the cut-off wall is found to be the most effective. The anti-seepage effectiveness of the cut-off wall is affected by its position, thickness, quantity, and depth [5,6]. Recently, engineers are adopting the suspended cut-off wall more often to deal with excessive depth of overburdens and restrictions in the construction level [7]. Brown and Bruggemann [8] concluded that a cut-off wall could achieve good anti-seepage effect by inserting the wall into a relatively impermeable layer. Maxwell et al. [9] argued that the cut-off wall could operate stably and reduce leakage when it penetrates more than 1 m into the aquitard. Most research results show that seepage control can be used reliably to determine the necessary penetration depth for the cut-off wall in deep overburden foundations. However, the research on seepage control effect of the CFRD on the deep overburden is relatively limited, so it is necessary to carry out further research.

In this paper, we first describe the geological conditions of a CFRD built on a deep overburden foundation. The seepage models we developed are based on the ADINA software. Using the FEM, we analyse the seepage control effect of the CFRD. We discuss the anti-seepage effect of the overburden foundation’s cut-off wall. In addition, the effects of overburden permeability on the foundation seepage field are discussed.
2. Miaojiaba CFRD

2.1. Miaojiaba project

The Miaojiaba CFRD was built on the Bailongjiang River in Wenxian City, Gansu Province, China (Figure 1), 18.0 km upstream from the Guantou dam and 31.5 km downstream from the Bikou hydropower station. The dam measures 111 m in height, with a crest of 348.20 m in length and 10.0 m in width. It has three generators in the downstream power station, and a total electric generating capacity of 240 MW. The construction of the dam began in 2009 and was completed in 2010.

2.2. Site condition

The dam is located in an alpine gorge region where the river bends sharply in a “V” shape. The site has a deep overburden 44–50 m thick. Figure 1(b) shows the geological conditions in a longitudinal section of the dam. The overburden, from bottom to top, may be classified into the following four groups: Q4a1-sand and gravel with block gravel layers, 5–10 m thick; Q4a2-sand and gravel (the major components of the overburden foundation), 12–15 m thick; Q4a3-stone, sand and gravel with gravel layers, 6–20 m thick; and Reservoir alluvium, 2–4 m thick.

3. Numerical model and parameters

3.1. FE mesh for seepage modelling

The overburden foundation consists of three layers (upper layer 20 m, middle layer 15 m, lower layer 15 m) in the seepage model. The FE mesh of the Miaojiaba dam’s seepage calculation is shown in Figure 2. The mesh consists of 67,185 spatial 8-node isoparametric elements and 73,184 nodes. The total water head and the downstream water head are applied to the surfaces beneath the water level. The ADINA software’s ADINA-T module is used to model the seepage field of the Miaojiaba dam. Analyses are based on steady-state conditions at normal water levels.

Figure 1. (a) Typical section and (b) geological cross section of the Miaojiaba dam

Figure 2. Three-dimensional FE mesh of the Miaojiaba dam for seepage calculation.
3.2. Input parameters

Hydraulic conductivity \((K)\) is derived from laboratory tests. To investigate the anti-seepage effect of the cut-off wall and analyse the effects of the overburden’s permeability on the seepage field, the hydraulic conductivity of the overburden are assumed to have different values in later parts of the research. The material parameters used in the seepage modelling are shown in Table 1.

| Materials         | \(K\) (m/s) | Materials          | \(K\) (m/s) | Allowable hydraulic slope |
|-------------------|-------------|--------------------|-------------|--------------------------|
| Slab              | \(1.0 \times 10^{-12}\) | Upper overburden  | \(1.7 \times 10^{-4}\) | 0.10 \~\~ 0.20          |
| Cushion zone      | \(1.5 \times 10^{-6}\) | Middle overburden | \(1.7 \times 10^{-4}\) | 0.20 \~\~ 0.40          |
| Main rockfill zone| \(3.2 \times 10^{-3}\) | Lower overburden  | \(1.4 \times 10^{-4}\) | 0.20 \~\~ 0.40          |
| Sub rockfill zone | \(1.9 \times 10^{-3}\) | Extruded curb     | \(1 \times 10^{-9}\)  | -                       |
| Transition zone   | \(2.1 \times 10^{-4}\) | Cut-off wall      | \(1 \times 10^{-9}\)  | -                       |
| Rock              | \(2.0 \times 10^{-7}\) | Bedrock           | \(2.0 \times 10^{-7}\) | -                       |

4. Results and discussions

4.1. Anti-seepage effect of the cut-off wall for the deep overburden foundation

The cut-off wall is always used to cut off the overburden\([8,9]\). Suspended cut-off walls are inserted to a satisfactory penetration depth. In this portion of our research, we study the depth of cut-off walls and the resulting anti-seepage effect. For the seepage model, the overburden is assumed to be 50 m and is divided into three layers. Three groups of isotropic hydraulic conductivity values are assumed in these layers. In the first group, the hydraulic conductivity of the upper, middle, and lower layers are assumed to be \(5.5 \times 10^{-4}\) m/s, \(5.0 \times 10^{-4}\) m/s, and \(4.6 \times 10^{-4}\) m/s, respectively, and in the second group are assumed to be \(6.0 \times 10^{-4}\) m/s, \(5.5 \times 10^{-4}\) m/s, and \(5.0 \times 10^{-4}\) m/s, respectively. In the third group, the overburden is assumed to have low permeability, with a hydraulic conductivity of \(5.0 \times 10^{-6}\) m/s. These variables are analysed with respect to the depth of the cut-off wall under steady-state conditions.

Figure 3 shows a head contour of \(x = 260\) m section of the dam. Because of the low permeability of the cut-off wall, the wall subtracted most of the head. The head contour is densest near the cut-off wall in the overburden, and it becomes sparser with distance from the wall. Because of the high head difference, the hydraulic gradient at the overburden under the wall is large. The large hydraulic gradient may cause seepage failure, especially when the suspended cut-off wall is used, most likely due to the presence of some residue under the wall, which can under low hydraulic gradient. The cut-off wall has a significant effect on reducing the saturation line. Similar results are obtained for the other two groups measuring hydraulic conductivity of the overburden.

![Figure 3. Total head (unit: %) at x =260 m cross section for the first group hydraulic conductivity.](image)

Referring to Figure 4, the cut-off wall can reduce the dam foundation seepage discharge, but it cannot obtain a significant reduction unless the wall inserts into the bedrock. The average reduction of the seepage discharge is \(0.223\) m³/s for every 5 m increase in the depth of the wall when the overburden has high permeability. When the wall is inserted into the bedrock, seepage discharge...
decreases by 99.81% compared to having no cut-off wall in the overburden. Results seem to indicate that the wall can achieve a more significant anti-seepage effect when the overburden has higher permeability. Even when there is no seepage barrier in the overburden foundation, foundation seepage discharge is very small when the overburden has low permeability. This shows that the overburden is no longer the main seepage channel of the dam when it has low permeability (i.e. $K < 1 \times 10^{-5}$ m/s).

Figure 4. Curve of dam foundation seepage discharge with the depth of the cut-off wall. Label 1, 2, 3 represent the three groups of hydraulic conductivity for the overburden, respectively.

Figure 5(a) shows that the cut-off wall can reduce the maximum hydraulic gradient at the escape point of the dam body and foundation, but it will not achieve good effect until the wall inserts into the bedrock. The hydraulic gradient at the toe of the dam is still larger, even when the overburden is cut off. The stability of the downstream toe and overburden is threatened when the overburden has high permeability. The results for the third groups’ overburden hydraulic conductivity shows no obvious change to the small hydraulic gradient values, further illustrating that the overburden is no longer the main seepage channel for the foundation.

Figure 5(b), the hydraulic gradient of the overburden under the cut-off wall shows first a decrease and then an increase. The hydraulic gradient reaches a minimum value when the wall has a depth of 35 m, and the relative depth ratio between the wall and the overburden is 0.7 at this time. Deepening the wall can cause a reduction in the seepage discharge, velocity, and hydraulic gradient in the overburden. Meanwhile, the seepage cross-section area in the overburden is also reduced, so the seepage gradient may increase when the wall reaches a certain depth. Some residue always exists under the cut-off wall, and this is detrimental to the stability of the fine particles in the overburden. The necessary penetration depth of the cut-off wall in the overburden can be determined by the
seepage stability in this area. When a suspended cut-off wall is used in the overburden, the suggested relative depth ratio between the cut-off wall and overburden is 0.7. The cut-off wall also undergoes a significant hydraulic gradient. So, strict requirements should be implemented under the design and construction of the cut-off wall.

4.2. The effect of permeability on the foundation seepage field
Natural overburden permeability is characterised by randomness, discontinuity and anisotropy[3]. Permeability directly affects leakage as well as the security and stability of the dam. Reasonable evaluation of permeability is vital so that treatment and anti-seepage measures can be taken for the overburden foundation.

The hydraulic conductivity of the overburden is assumed to be in the range of $1 \times 10^{-6} - 5 \times 10^{-4}$ m/s. Regarding the effect of permeability on the foundation seepage field, Figure 6 shows the curve of dam foundation seepage discharge in relation to the hydraulic conductivity of the overburden.

![Figure 6. Curve of foundation seepage discharge in relation to hydraulic conductivity of the overburden.](image)

As Figure 6 shows, the seepage discharge of the foundation increases with an increase in the hydraulic conductivity of the overburden. The hydraulic conductivity $K=1 \times 10^{-5}$ m/s could be regarded as the cut off value for the strength of the overburden permeability. The overburden is regarded as having low permeability when $K<1 \times 10^{-5}$ m/s. The curve shows obvious inflection point when $K=1 \times 10^{-5}$ m/s or so. When $K>1 \times 10^{-5}$ m/s, the seepage discharge shows a greater change. The curve indicates that when the overburden permeability is relatively higher ($K>1 \times 10^{-5}$ m/s), seepage discharge is relatively greater when the cut-off wall is not inserted into bedrock. The overburden permeability becomes the crucial factor affecting the seepage field in the dam foundation, and the overburden becomes the main seepage channel. Our results show that suitable anti-seepage measures for the foundation should be taken when the overburden has high permeability.

Naturally, the overburden always presents anisotropic permeability, even when having the degree ($K_y / K_z$) of 10 or more[3]. The horizontal hydraulic conductivity of the overburden is assumed to be $5 \times 10^{-4}$ m/s throughout. Vertical hydraulic conductivity was changed to model 1, 5, and 10 degrees of anisotropy. The result of these hydraulic elements is shown in Table 2. The depth of the cut-off wall is assumed to be 35 m in the seepage modelling.

The overburden permeability weakens as the degree of anisotropy increases. The foundation seepage discharge and hydraulic gradient at the toe of the dam decrease as the degree increases. The seepage discharge decreased by 21.75% when the overburden had an anisotropic permeability degree of 5, as compared to having isotropic permeability. The saturation line drops and the hydraulic gradient at the downstream overburden slightly reduces with an increase in the degree of anisotropy. In practical engineering, due to the scale effect and other factors, hydraulic conductivity regarding the anisotropy coefficient is uncertain. Meanwhile, differences in the hydraulic elements of the
overburden between isotropic and anisotropic permeability are not obvious for cut-off walls having greater depth. So, for the time being, anisotropic permeability of the overburden is ignored.

### Table 2 Hydraulic elements results

| $K_y / K_z$ | Foundation seepage discharge (m³/s) | Maximum hydraulic gradient |
|-------------|-------------------------------------|---------------------------|
|             |                                     | Toe of dam | Downstream overburden | Under the wall |
| 1           | 0.57                                | 0.213      | 0.021 | 2.89 |
| 5           | 0.446                               | 0.116      | 0.017 | 3.00 |
| 10          | 0.319                               | 0.085      | 0.013 | 3.12 |

5. Conclusions

The seepage field characteristics of a CFRD constructed on a deep overburden foundation are presented. Numerical analyses are conducted and the factors influencing the seepage behaviours of the dam and foundation are discussed. Based on this study, the following conclusions are drawn:

1) The necessary penetration depth of a suspended cut-off wall in the overburden foundation can be determined by its anti-seepage effect. The suggested relative depth ratio between the suspended wall and overburden is 0.7.

2) The hydraulic conductivity $K=1 \times 10^{-5}$ m/s can be regarded as the cut off value for the permeability strength of the overburden. The anisotropic permeability of the overburden has some effect on foundation seepage field, but for the time being, the anisotropic permeability of the overburden is always ignored.

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