An Analysis of Optimum Thickness of Inverted Filter Layer Made by Manufactured Sand

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Abstract. The soil stability problem caused by seepage is a hot issue in geotechnical engineering, which is widely existed in natural and artificial slope, embankment, earth-rock dam and other projects. The traditional seepage calculation only considers the saturated seepage, ignoring the unsaturated seepage, and in the design of the filter layer, the thickness of the filter layer is mainly determined by experience. This study, for above problems, finite element numerical simulation method was used to simulate different thickness of filter layer, and seepage analysis in the unsaturated zone was carried out and obtained that 0.8m was the optimal thickness of filter layer in the calculation example; due to the siphon effect of matric suction, water flow also exists in the unsaturated area, and the infiltration line is not the uppermost line in the flow network; when the free water is a little lower than the height of the corewall, it will increase the seepage flow on the corewall of the dam, intensify the seepage contact and erosion, cause damage to the dam body.

1. Introduction
The reserves of river sand and other natural sand are getting smaller, at the same time, as the petroleum price continues to rise, the transportation cost of natural sand increases, which is no longer suitable for long distance transportation, and the exploitation of natural sand also seriously damages the environment. Therefore, in the concrete industry, the use of manufactured sand to instead of river sand, has gradually become a development trend. At present, there are many researches on the application of manufactured sand in concrete in China, mainly focusing on the characteristics of manufactured sand in concrete. Although there are few researches on the application of artificial sand as filter material in dams, these researches mainly focus on production process and quality control. However, It is very important to use the manufactured sand as the filter layer in the core wall, the inclined wall, the bedding, the intercepting channel and the permeable layer of the dam shell and foundation, and it is the most effective measure to prevent the leakage of the dam.

The study of seepage is of great significance to water conservancy engineering, groundwater resource development, agricultural drainage irrigation and geotechnical engineering. Among them, there are many problems about seepage in water conservancy projects. For example, the soil flow and piping in the earth-rock dam, the seepage in the rock mass fissure and the contact flowing soil in the filter layer are also related to seepage. Moreover, the influence of water level change on the seepage field of the dam cannot be ignored. In the literature now, the finite element numerical simulation method is
mostly applied in the calculation of seepage, and mainly focuses on the seepage in the saturated zone [1]. The setting of filter layer plays a key role in seepage control, it can effectively control the seepage failure of soil. In recent years, the design of filter layer has been constantly garnered and improved. From the initial design principle of seepage control only focused on seepage prevention to current seepage control theory combines seepage prevention, drainage and filtration layer to achieve effective seepage control [2-3]. As for the design of the filter layer, the criteria proposed by Terzaghi fully considers the function of the filter layer. However, there are different opinions on the required thickness of the filter layer among the researchers, and most of the required thickness are determined according to the experience data of existing projects. Such issues about the thickness of filter layer will discussed in this study.

2. Saturated-unsaturated Seepage Theory

2.1. Basic Equation of Soil Water Movement

From 1852 to 1855, Darcy conducted a large number of permeability tests on saturated sand, and obtained famous Darcy’s law, that is the permeability rate was proportional to the hydraulic gradient.

\[ v = -K_s \frac{\partial h_w}{\partial y} \]  

(1)

Where, \( v \) is the permeability rate, \( K_s \) is saturated permeability coefficient, \( \frac{\partial h_w}{\partial y} \) is hydraulic gradient along the y direction.

Darcy's law is obtained by saturated sand test, but it also adapts to unsaturated soil. The difference is that in unsaturated soil, the permeability coefficient of soil is not a constant, but a function of soil water content or a function of matric suction [4-7].

In order to deduce the basic equation of water movement in soil, the conservation law and the Darcy's law are now combined, and the equation of unsaturated soil water movement are as follow:

\[ \frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left[ K_x(\theta) \frac{\partial \theta}{\partial x} \right] + \frac{\partial}{\partial y} \left[ K_y(\theta) \frac{\partial \theta}{\partial y} \right] + \frac{\partial}{\partial z} \left[ K_z(\theta) \frac{\partial \theta}{\partial z} \right] \]  

(2)

Where, \( \theta \) is total head, \( \phi = y + \varphi_m \), \( y \) is the gravitational potential, \( \varphi_m \) is the matrix potential; \( K_x \), \( K_y \) and \( K_z \) are the permeability coefficient along the \( x \), \( y \) and \( z \) direction; \( \theta \) is the volumetric water content.

In saturated soil, the pores are filled with water and the water content does not change, namely, \( \frac{\partial \theta}{\partial t} = 0 \). Therefore, the equation 2 can be rewritten as:

\[ \frac{\partial}{\partial x} \left[ K_x(\theta) \frac{\partial \phi}{\partial x} \right] + \frac{\partial}{\partial y} \left[ K_y(\theta) \frac{\partial \phi}{\partial y} \right] + \frac{\partial}{\partial z} \left[ K_z(\theta) \frac{\partial \phi}{\partial z} \right] = 0 \]  

(3)

2.2. Initial Conditions, Boundary Conditions, and Specific Solution Conditions

2.2.1. Initial Conditions and Boundary Conditions. Initial conditions:

\[ H(x,y,0) = \Phi(x,y,0) \]  

(4)

Boundary conditions. The boundary conditions generally include three categories:

First category: A given water head distribution \( \Gamma_1 \) on the boundary, or called water head boundary condition:

\[ H(x,y,0)|_{\Gamma_1} = y(x,y,t), t > 0 \]  

(5)

Second category: A given flow \( \Gamma_1 \) on the boundary, or called flow boundary condition.

\[ K \cdot \frac{\partial H(x,y,t)}{\partial n} |_{\Gamma_2} = q(x,y,z,t), t > 0 \]  

(6)

Third category: the head difference of aquifer boundary and the flow rate is a linear relationship [8].
2.2.2. Specific Solution Conditions. In the saturated unsaturated seepage, the specific solution condition is:

\[
\begin{align*}
\begin{cases}
 h(x,y,t) &= H_1(x,y,t), \quad (x,y) \in \Gamma_1 \\
 K_x \frac{\partial H}{\partial x} \cos(\bar{n}, x) + K_y \frac{\partial H}{\partial y} \cos(\bar{n}, x) &= q_n(x,y,z), \quad (x,y) \in \Gamma_2 \\
 h(x,y,t) &= z(x,y,t), \quad (x,y) \in \Gamma_3 \\
 h(x,y,t_0) &= H_0(x,y,t_0)
\end{cases}
\]

(7)

Where, \( \Gamma_1 \) is a given water head distribution, \( H_1 \) is boundary water head; \( \Gamma_2 \) is a known water flow, \( q_n \) is normal flow per unit time; \( \cos(\bar{n}, x) \) and \( \cos(\bar{n}, y) \) is the margin of the outer normal direction; \( \Gamma_3 \) is the seepage surface boundary, \( z \) is node coordinate of the seepage surface; \( H_0 \) is the water head at initial time.

3. The Design Principle of Inverted Filter Layer

The essential function of filter layer should be both prevention and discharge. The prevention means to prevent soil particles from being carried away by water flow, the discharge means the seepage water can be discharged beyond the dam. Namely, water drainage and soil filtration are the two functions of the inverted filter layer. On the one hand, the effect of water drainage determines the minimum particle size of the filter; on the other hand, the effect of soil filtration determines the maximum particle size of the filter layer. So that the particle size range is selected by the two principles.

3.1. The Principle of Water Drainage of Inverted Filter Layer

The permeability coefficient of soil determines the drainage capacity. The larger the permeability coefficient is, the stronger the drainage capacity will be, which means that the water pressure relief effect will be better. The Terzaghi’s drainage principle can be expressed by the magnitude of the coefficient of permeability:

\[
\frac{k_f}{k_p} \geq 4 \sim 16
\]

(8)

Where, \( k_f \) is the permeability coefficient of inverted filter layer, \( k_p \) is the permeability coefficient of the protected soil.

According to equation 8, select an allowed permeability coefficient of the inverted filter layer, the seepage pressure in the filter layer will disappear [9-10].

3.2. The Principle of Soil Filtration

\[
D_0 \leq \alpha d_k
\]

(9)

Where, \( D_0 \) is the average pore diameter of the filter layer, \( d_k \) is controlled particle size, which effects the seepage failure, \( \alpha \) is the arching coefficient.

Equation 9 indicates when the pore diameter of the filter layer is smaller than the controlled particle size of the protected soil layer, the geometric stability can be achieved.

4. The Study of Engineering Case

A dam clay corewall is 58.5 m high, 7 m wide at the top and 269.25 m at the bottom. The slope of the dam is 1:2. Its central wall is 54 m high, 6m wide and the slope ratio is 1:0.2. An inverted filter layer is set downstream of the corewall. The filter layer is mainly made of manufactured sand, and the slope ratio is same with the corewall, both 1:0.2. At the same time, a 62 m wide horizontal drainage ridge is arranged downstream of the dam. The upstream level of the dam is 54m, like shown in figure 1. Pore pressure is assumed to be same with atmospheric pressure, and the matric suction value is equal to pore water pressure, which can be expressed by the head of pore water pressure. The base of the dam is selected as the datum. In addition, the saturated permeability coefficients of the dam body, the corewall and the inverted filter layer are \(1.0 \times 10^{-6} \text{ m/s}, 1.0 \times 10^{-8} \text{ m/s} \) and \(1.0 \times 10^{-7} \text{ m/s} \) respectively.
4.1. Model Establishment and Mesh Generation

By using above given dimensions, a geometric model is established in the finite element software. A CPE4P element, namely a 4-node quadrilateral, bilinear displacement and pore pressure plane strain element was used in the calculation model. In this example, 381 meshes were generated at the filter layer and corewall. For detail information, the green portion represent the dam body, the blue portion represents the clay core, and the red portion represents the filter layer.

![Model and mesh diagram.](image)

The parameters of the three materials in the case are shown in the table below.

**Table 1. Material property parameters of dam soil.**

| Soil layer         | Young's Modulus (kPa) | Poisson's ratio | Density (t · m⁻³) | Coefficient of permeability (m · s⁻¹) |
|--------------------|-----------------------|-----------------|-------------------|-------------------------------------|
| Dam body           | 100000                | 0.2             | 2.0               | 1.0 × 10⁻⁶                          |
| Corewall           | 50000                 | 0.3             | 1.8               | 1.0 × 10⁻⁸                          |
| Inverted filter layer | 20000               | 0.3             | 2.4               | 1.0 × 10⁻⁷                          |

4.2. Boundary Condition

The selection of boundary conditions mainly includes the following: displacement boundary, pore pressure boundary and flow boundary [12]. For displacement boundary condition: the DOFs (Degree of Freedom) of all dam body regions are constrained. For pore pressure and flow rate boundary condition: the upstream boundary water head value is known as the water head boundary, and the pore water pressure on the boundary is specified to change linearly with the height. The stream can flow out of the interface of the downstream boundary and the horizontal drainage ridge at the bottom, where the pore pressure is 0.

4.3. Results Analysis

For comparative analysis, the thickness of the filter layer in this paper was 0.6 m, 0.7 m, 0.8 m, 0.9 m, 1.0 m, 1.1 m, and 1.2 m, respectively. According to saturated seepage flow network analysis, it is assumed that the infiltration line is the uppermost flow line, and water will not pass through this line, all flow beneath it. But in saturated-unsaturated condition, above assumption are incorrect. In the saturated-unsaturated condition, the water flow can pass through the infiltration line to the upper unsaturated zone, producing capillary force and negative pore pressure. That is, seepage exists in both saturated and unsaturated regions. Since the seepage velocity of water in soil is generally slow and its kinetic energy can be ignored, so the main determining factor of water movement in soil is its potential energy, while for general unsaturated soil, it is the gravitational potential and matrix potential. Therefore, the relative magnitude of the two potential energies determines the height of water flow in the unsaturated region [11].

4.3.1. The Infiltration Line. By comparing figure 2 to figure 6, when the thickness of the filter layer is different, it can be seen from the comparison of the height of the infiltration line that with the gradual increase of the thickness of the filter layer, the height of the infiltration line gradually decreases. However, when the thickness reaches 0.8m, the height of the infiltration line hardly changes. On the
opposite, when the thickness of the filter is 0.6 m, the infiltration line is at the highest. Detail information shown in follow figure.

Figure 2. The location map of the infiltration line at 0.6m.  

Figure 3. The location map of the infiltration line at 0.7m.  

Figure 4. The location map of the infiltration line at 0.8m.  

Figure 5. The location map of the infiltration line at 0.9m.  

Figure 6. The location map of the infiltration line at 1.0m.  

Figure 7. Curve of height of escape point with thickness.  

Collect the height of the infiltration line respects of the thickness of the filter layer, and detail shows in figure 7. It can be seen from figure 7 that the thickness of filter layer has a certain effect on the height of infiltration line. By increasing the thickness of filter layer, the height of infiltration line will fall, beneficial to the safety and stability of the dam. Another feature is when the thickness of filter layer reaches 0.8 m, the height of infiltration line decreases obviously, and after that, the change is slight. Considering the situ conditions and the elevation of the escape point, it is suggested that 0.8 m is the optimal thickness of the filter layer in this example, which can not only meet the basic functional requirements of the filter layer, but also achieve the economy purpose of material saving.

4.3.2. The Velocity Vector. The velocity vector near the upstream, the centre and the toe of the dam are plotted in figure 8(a), figure 8(b) and figure 8(c) respectively. It can be concluded from the velocity vector diagrams that the flow direction of water in most areas of the dam body is approximately parallel to the infiltration line. At the upstream of the dam, the stream is not within the infiltration line, but continues through the infiltration line into the upper unsaturated zone; at the central portion of the dam, the flows approximately parallel to the infiltration line; at the toe of the dam, water in the saturated zone continuously flows cross the infiltration line into the unsaturated zone.
Figure 8. Velocity vector: (a) at the upstream face of the dam, (b) at the central part of the dam, and (c) at the toe of the dam.

The seepage appears in unsaturated zone in the figure above is mainly due to the suction and hydraulic gradient in the soil, that is, water flow is affected by matrix potential and gravitational potential. When the free water is slightly lower than the height of the corewall, the flow through the unsaturated area will be relatively large because the suction effect. Under the action of matric suction, a large amount of water flows upward into the unsaturated zone and bypass the corewall with little permeability, that is, matric suction produces siphon effect. At the same time, in the saturated zone, only a small amount of water directly through the corewall. When the siphon effect occurs, the scour of water on the top of the corewall will be more significant, which makes the soil of the corewall become loose, and its particles will be gradually carried away due to the scour effect of water, so that the cracks inside the corewall will seriously propagate and pose a threat to the safety of the dam.

5. Conclusion

Based on the saturated-unsaturated seepage theory and the design criteria of the filter layer, the finite element software was used for numerical simulation calculation, and the following conclusions were drawn:

1) In the clay corewall dam, the infiltration line gradually decreases as the thickness of the filter layer increases. When the thickness of the filter layer reaches 0.8 m, the height of infiltration line hardly changes. So that 0.8 m is the optimal thickness in this calculation case, which can not only meet the basic functional requirements of the filter layer, but also achieve the economy purpose of material saving.

2) Due to the siphon effect of matric suction, a certain water flow exists in the unsaturated area above the infiltration line.

3) When the free water level is slightly lower than the height of the corewall, the water flow increases, thus exacerbating the seepage contact and scour, which poses a certain threat to the safety of the dam.
Acknowledgments
Funding projects: Project funded by the basic scientific research operating expenses of Northwest Minzu University (No.31920190168); Sponsored by Ningxia water conservancy and hydropower engineering bureau co. LTD (No. NGJKY002)

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