Research Article

Research on Progressive Stabilization Filter System of Silt Foundation around Tube Well

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To obtain the applicable filter layer range of the silt sand around the dewatering well of a ship lock renovation project in Nanjing, several existing classic filter layer criteria are analyzed, and the concept of a progressively stable filter system is put forward accordingly. The self-designed horizontal percolation filter is used to carry out the silt filter test, and the filter effect of these graded filter materials on the test silt filter is studied, and the mechanism of the progressively stable filter system is described. Tests show that when the ratio of the filter material to the characteristic particle size of the silt soil falls within the range of 4.3–7.7, the system maintains a stable percolation state. Through the particle tests of the base soil and the filter material after filtering, it is found that an effective filter system is that the filter layer induces soil’s self-filtration, and they work together. No matter what filter material criterion is used to design the filter, as long as the gradual and stable filtration mechanism is formed in the filtration process, stable filtration can be ensured. The research on the progressively stable filter system will help to determine the gradation range of the filter material more reasonably in the engineering design, reduce the failure probability of the filter layer, and provide a certain reference for the design of the filter layer in similar projects in the future.

1. Introduction

At present, there are still general contradictions in drainage and soil preservation in the construction of tube well drainage [1]. There are many dual foundation structures in the river that face sedimentary zone of the middle and lower reaches of the Yangtze River. When excavation and precipitation of foundation pits are carried out on it, the overlying impermeable layer blocks the flow of water, which produces a large head difference with the underlying permeable layer. During precipitation, a three-dimensional seepage effect is formed around the tube well. Under the action of a large hydraulic gradient around the well, a large amount of soil particles is easily lost, which leads to the occurrence of integral seepage failure of the foundation structure, which seriously threatens the safety of the project.

Reverse filtration is the first step to control seepage, and it is the most effective method for the prevention and treatment of seepage deformation at the outlet [2]. The application of the filter layer can intercept quicksand, prevent a large amount of sand loss, and control the development of seepage damage at the same time. At present, in the construction of the project, most of the reverse filtration around the tube well is wire wrapping, net wrapping, gravel filling, or directly filtering the tube well [3–6]. The above-mentioned filtering methods are easily trapped in the dilemma of clogging and soil erosion.

This article aims to design a scientifically applicable filter material. The filter layer considers the requirements of both
soil preservation and drainage and makes use of the excavated sand and gravel soil as much as possible. It does not only meet the construction requirements of dewatering wells but also ensures the construction. It can effectively shorten the construction period and greatly save the construction cost.

To solve the technical problems such as the difficulty of accurate design of the filter material around the tube well in the actual project, this paper relies on the expansion and renovation project of a ship lock in Nanjing, based on the systematic study of the filter system around the well. In this paper, the suitable filter layer types and particle size ranges around the dewatering well are obtained through research to optimize the filter layer design process and form a filter layer design method and criteria suitable for the dewatering well.

2. The Concept of Progressively Stable Filter Criterion

2.1. The Proposal of a Progressive Filter System. Terzaghi [7] put forward the famous Terzaghi filter design criteria in 1922:

\[
\begin{align*}
D_{15} &\leq 4 \sim 5, \\
D_{15} &> 4 \sim 5.
\end{align*}
\] (1)

In the formula, the content of soil particles smaller than a certain size is 15% corresponding to the particle size on the particle analysis test curve, and the content of soil particles smaller than a certain particle size is 15% and 85% on the protected soil particle analysis test curve corresponding to the particle size.

It can be seen from formula (1) that the design guidelines of the Terzaghi filter layer are based on the protection of 85% of the corresponding particle size particles in the foundation soil as the design basis of the filter particle size upper soil protection and 15% as the lower drainage design. Figures 1 and 2 show the arrangement of particles when the filter material with a diameter of D15 meets the Terzaghi criterion.

Terzaghi criterion sets the characteristic particle size of the soil based on the content of the protected soil particles and designs the filter layer based on the characteristic particle size of the protected soil. This criterion has universal applicability and is one of the common guidelines for material design.

In the following years, scholars developed and proposed a variety of classic filter media design criteria based on the Tersa-based filter layer guidelines. Compared with the Tersa-based filter layer guidelines, the later-derived several classic filter layer design guidelines are based on the particle size of the filter media. The selection of the scope has been broadened. The follow-up research reached the theoretical point of view on the design of the filter layer, that is, the Terzaghi filter criterion is biased towards safety or is called conservative. The study found that in the process of filtering, there is a phenomenon of complementary filtering between the filter material particles and the protected soil particles, that is, the design of the filter material induces the filter material and the base soil to form a natural filter layer to block the soil particles. The progressive stabilization filter system proposed in this paper is a natural filter layer induced by the designed filter material, which can be illustrated in Figure 3.

The progressive filter system guarantees the stability of the penetration of the soil and the filter layer. The stabilized filter system can be divided into three areas, as shown in Figure 3. Zone I is the gradual change zone of the soil particles. According to the micro-mechanism of the Terzaghi filter criterion, under the action of water flow, some particles below d85 will enter the filter material in the protected soil, some of the fine particles of the base soil will be lost, and the skeleton particles will be sorted. The base soil layer has a certain self-filtration effect, which can prevent the loss of fine particles with a small content. This area forms an effective self-filtration to protect the fine particles that cannot be protected by the filter material from

![Figure 1](image1.png) The loosest arrangement of particles when the filter material with a diameter of D15 meets the Terzaghi criterion.

![Figure 2](image2.png) The densest arrangement of particles when the filter material with a diameter of D15 meets the Terzaghi criterion.

![Figure 3](image3.png) Schematic diagram of progressive filtration system.
further loss. A complementary graded filter layer is formed in zone II. Under the action of water flow, the protected soil enters the filter layer. Part of the base soil particles is retained and filled in the pores of the filter material. Finally, the protected soil particles are filled in the entire zone II filter layer in a diminishing manner, and the two are redistributed to form the new filter layer which prevents the entry of finer particles in the protected soil. Zone III is the stable permeable area of seepage flow. This area is composed of graded filter media and a small number of soil particles. The hydraulic gradient of this area is small, and it has good permeability. It not only further prevents the loss of fine particles in zone II but also ensures stable drainage around the well. During seepage, the soil in zone II filters the water and soil in zone I, and the soil in zone III filters the water and soil in zone II. This forms a gradual filtration structure that protects from the inner to the outer layer. The formation of this structure makes the infiltration tend to be stable.

The progressive filter layer cannot be directly used as the design value in the filter layer design, but it has a very important influence on the mechanism of the filter system and the stable seepage and filter state, which helps to control the particle migration law in the filter layer system. It is understood that this influencing factor should be considered in the design of the filter layer, especially the filter layer with high requirements for seepage.

3. Materials and Methods

3.1. Basic Physical and Mechanical Indicators. All the test soils in this paper are taken from the foundation soil of the Nanjing section of the Yangtze River. The tested foundation soil is silty sand, which is yellowish-brown after natural air drying, as shown in Figure 4. The basic physical and mechanical indexes of the sandy soil are analyzed through routine indoor tests. The result is shown in Table 1.

<table>
<thead>
<tr>
<th>Soil sample</th>
<th>Moisture content (%)</th>
<th>Density (g/cm³)</th>
<th>Proportion</th>
<th>Quick cut index</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wet</td>
<td>Dry</td>
<td></td>
<td>c_q (kPa)</td>
</tr>
<tr>
<td>Sand</td>
<td>30.7</td>
<td>1.81</td>
<td>1.38</td>
<td>2.67</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>37.7</td>
</tr>
</tbody>
</table>

3.2. Particle Test of Soil. The particle gradation and particle size structure of the soil are some of the important parameters for seepage control. The particle analysis test method specified in the standard for geotechnical test methods (GB/t50123-1999) is used to test the particle distribution of the test soil. The particle analysis results are shown in Figure 5, which provides a reliable calculation basis for the design of seepage control filter material.
Some important parameters are obtained from the silt particle distribution curve as follows: $d_{10} = 0.052\, \text{mm}$, $d_{30} = 0.11\, \text{mm}$, $d_{60} = 0.18\, \text{mm}$, uneven coefficient $Cu = 3.46$, and curvature coefficient $Cc = 1.29$.

3.3. Test Device. The self-designed horizontal permeation reverse filtration test device is used to carry out the reverse filtration test of the graded filter material. The schematic diagram of the device is shown in Figure 6. The water inlet device uses a height-adjustable overflow bucket to control the water head, and a 300-mesh filter screen is fixed at the water outlet to intercept the protected soil particles flowing out of the test instrument, to calculate the amount of sand that flows out after the seepage is completed.

3.4. Test Plan. In this paper, according to the characteristic particle size of the protected soil and according to four typical domestic and foreign filter media criteria, combined with actual working conditions, a total of 6 filter media with different gradations are designed. These 6 filters are shown in Figure 7, and their size distribution curve is given in Figure 8.

Among them, the upper envelope and lower envelope filter materials of Terzaghi are prepared according to the filter media criterion of formula (1). According to the upper and lower critical conditions of the public (1) Terzaghi filter material criterion, two kinds of filter materials with smaller particle size and larger size were prepared, respectively, hereinafter referred to as the upper and lower filter media of Terzaghi.

According to the actual hydrogeological conditions of the project, the anti-seepage test reduction project carried out was scaled to the laboratory’s self-designed variable-head level anti-seepage test device on the same scale, to restore the most realistic seepage field effect at the project site.

After setting the filter layer parameters, the test can be carried out according to the following test steps.

The first step is to load samples according to dry density. To prevent soil samples from being mixed, three hard thin plates are used to separate the soil sample areas, and samples are loaded in layers according to the area. After the sample is loaded, let it stand for 5–10 minutes.

The second step is to seal. After clay filling, the cover plate is inserted and further fixed with a steel plate and bolt.

In the third step, the sample is saturated. The water head saturation of the sample is carried out three times. The water head is controlled at 1/3 height, 2/3 height, and full height of the sample for saturation. The duration of each head height is 30 minutes.
Table 2: Critical hydraulic gradient of different graded filters.

<table>
<thead>
<tr>
<th>Serial number</th>
<th>Filter material</th>
<th>0–2 cm from the interface</th>
<th>2–4 cm from the interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>U.S. water and soil conservation agency filter media</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>Terzaghi upper covered wire filter material</td>
<td>2</td>
<td>4.2</td>
</tr>
<tr>
<td>3</td>
<td>Terzaghi undercover filter material</td>
<td>1.5</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>Water Research Institute filter material</td>
<td>0.8</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>Witt filter</td>
<td>0.8</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>Outsourcing coarse particle filter</td>
<td>0.8</td>
<td>2</td>
</tr>
</tbody>
</table>

Figure 10: Silt loss amount after filtration with the Terzaghi upper envelope filter. (a) Contrast curve of silt loss at 0–2 cm of interface. (b) Contrast curve of silt loss at 2–4 cm of interface.

Figure 11: Silty sand influx after filtration with the Terzaghi upper envelope filter. (a) The silt inflow curve at 0–2 cm of the interface. (b) The silt inflow curve at 2–4 cm of the interface.
The fourth step is to change the height of the water head to test. The water head height is raised sequentially from low to high, and the water heads of each level are continuously infiltrated for 48 hours and then raised to the water head height corresponding to the next level of the hydraulic gradient.

In the fifth step, after the filtration is completed, the test samples are disassembled, and the silt and filter materials are layered for particle analysis test research. Starting from the boundary between the protected sample and the filter material, the protected soil and filter material are divided into three groups of 0–2 cm, 2–4 cm, and 4–8 cm for sampling and fractionation.

### 4. Test Results and Analysis

#### 4.1. Seepage Velocity Changes with Hydraulic Gradient

It can be seen from Figure 9 that for any gradation filter material,
the seepage velocity increases with the increase of the hydraulic gradient; under the same hydraulic gradient, the larger the particle size of the filter material, the greater the seepage velocity. However, the seepage velocity of the 1st material and 2nd material is always at a low level. However, the seepage velocity of the 5th and 6th filter media had increased rapidly. These indicate that the particles of 1st and 2nd filter media are always in a relatively dense state and the intergranular pore channels are small. On the contrary, the pore channels are relatively open and the grains are slightly loose. Taking into account the effects of both drainage and soil conservation, it can be determined that 3rd and 4th have the best filter effect.

According to Darcy’s law: \[ v = k i \], the penetration rate of the test silt has a linear relationship with the hydraulic gradient, but it is found from the figure that under each gradation filter material, the seepage velocity has two obvious fluctuations as the hydraulic gradient rises. The characteristicsof the two fluctuations of the seepage velocity of the graded filter material under different hydraulic gradients confirm the formation process of the 1.1 progressive reverse filtration system: in the initial stage of seepage, due to the initial force, some small particles migrate. The intergranular pore diameter in the densely packed area of fine particles has changed greatly, forming the first seepage velocity fluctuation. Subsequently, under the continuous action of hydraulic power, the fine particles migrate rapidly, and the pore size between the protected soil layer and the filter material changes after a certain amount of accumulation, and the particles are redistributed. The size of the pores between the particles has changed greatly compared with the previous one, and the second obvious fluctuation occurs. After that, the seepage velocity increases approximately linearly.

### 4.2. Experimental Study on the Critical Hydraulic Gradient of Filter Media

Table 2 shows that the larger the particle size of the filter material, the lower the initial critical hydraulic gradient, indicating that the particles of the protected soil are easier to start. The critical hydraulic gradient appears to increase first and then decrease, indicating that when the filter material particle size gradation is at the two critical values of wider and narrower, the water head that the silt filter system can resist is at a lower value. Only when the filter material gradation is in a certain particle size range can the foundation soil be better protected against hydraulic erosion. Comparing the filtering effect of 1st to 6th filter media, it can be found that, except for the 6th filter material, the critical hydraulic gradient of silt soil under the back filtration of the other five graded filter media is all above 4. These filter materials can better resist the occurrence of seepage deformation and have obvious protective effects on silt soil. Among them, 3rd and 4th filter materials have the most significant ability to resist seepage damage.

### 4.3. Grading Test of Silt and Filter Media after the Test

To explore the evolution mechanism of the progressively stable filter system, the silt sand and filter media after the test were particle analyzed layer-by-layer. Taking the interface of the soil layer as the center and extending to both sides, the silt sand and filter media are taken at a distance of 0–2 cm from the interface, and then the silt and filter material are taken at a distance of 2–4 cm from the interface. The particle analysis test was carried out on the protected soil sample, and the filter material soil sample was taken out after the test. The particle scoring curve was extended according to the particle scoring curve extension method given by Zhou and Jia [8]. The method is as follows: fix the overlapping part of the particle analysis curve before and after the filter test, and these fixed parts can be regarded as the skeleton particles with the same content in the sample. Then, stretch the particle curve before the test in an equal proportion along the y-axis of the coordinate axis according to the particle curve of the soil sample after the test. Fitting the particle curves of large particles with constant mass together, the

<table>
<thead>
<tr>
<th>Serial number</th>
<th>Filter material</th>
<th>0–2 cm from the interface (%)</th>
<th>2–4 cm from the interface (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>U.S. water and soil conservation agency filter media</td>
<td>1.1</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>Terzaghi upper covered wire filter material</td>
<td>1.25</td>
<td>0.7</td>
</tr>
<tr>
<td>3</td>
<td>Terzaghi undercover filter material</td>
<td>3.2</td>
<td>1.45</td>
</tr>
<tr>
<td>4</td>
<td>Water Research Institute filter material</td>
<td>4.65</td>
<td>2.2</td>
</tr>
<tr>
<td>5</td>
<td>Witt filter</td>
<td>5.78</td>
<td>2.6</td>
</tr>
<tr>
<td>6</td>
<td>Outsourcing coarse particle filter</td>
<td>12.4</td>
<td>6.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Serial number</th>
<th>Filter material</th>
<th>0–2 cm from the interface (%)</th>
<th>2–4 cm from the interface (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>U.S. water and soil conservation agency filter media</td>
<td>1.23</td>
<td>0.21</td>
</tr>
<tr>
<td>2</td>
<td>Terzaghi upper covered wire filter material</td>
<td>1.52</td>
<td>0.3</td>
</tr>
<tr>
<td>3</td>
<td>Terzaghi undercover filter material</td>
<td>3.65</td>
<td>0.84</td>
</tr>
<tr>
<td>4</td>
<td>Water Research Institute filter material</td>
<td>4.66</td>
<td>1.53</td>
</tr>
<tr>
<td>5</td>
<td>Witt filter</td>
<td>5.03</td>
<td>2.69</td>
</tr>
<tr>
<td>6</td>
<td>Outsourcing coarse particle filter</td>
<td>7.15</td>
<td>5.28</td>
</tr>
</tbody>
</table>
position where the two curves start to diverge can be regarded as the upper limit of the small particles that can move with the water flow.

The loss of silty particles can be obtained by calculating the different part of the particle curve before and after the test. Based on this, the loss of silty particles and the content distribution of the silty particles flowing into the filter layer are calculated.

Due to limited space, only the test results of the upper and lower envelope filter materials of the Terzaghi filter media guidelines are given. The results are shown in Figures 10–13, and the results of the remaining filter materials are given in Table 3.

The soil retention and drainage effects of each filter material can be obtained from the results of the particle test: 1st and 2nd filter materials can strictly control the loss of silt sand. Their filter layer near the interface (0–2 cm) can intercept nearly 80% of the lost sand. This makes the soil at the front end of the filter layer become dense, so it can withstand higher water pressure, but due to the continuous reduction of the pores of the filter layer, the filter system is also prone to clogging and damage. The 5th and 6th filters will cause lots of waste of foundation soil. The results of this test are consistent with the results of the hydraulic gradient test, and both show the advantages of 3rd and 4th filter media in filtering silt.

From Tables 3 and 4, there is a greater lost amount of particles in the silty soil layer close to the filter material. Similarly, the amount of silty sand retained in the filter material layer closer to the base soil is also greater. Due to the difference in pores, in principle, the size of the intergranular pores of the two types of soils is the same, which can better maintain the stability of the particles. When the pores of the particles increase significantly, the smaller particles will be transported, and it is easy to move under the action of force. Combining the filter material particle curve to obtain the filter material layer that achieves effective reverse filtration, its particle distribution state is consistent with the assumption in 1.1. After filter, the above-mentioned progressively changing particle distribution state appears, that is, near the interface, it is a denser silt-original filter material mixed filter layer area. The pores of the filter layer extending outward become more and more open. The entire filter layer presents a gradual gradation, and the filter layer structure changes gradually from tight to loose. The important reason for the failure of the 1st and 6th filters is that they did not form an effective progressive filter layer combination of protected soil particles and filter layer particles in the process of filtering.

5. Conclusion

In this study, the filter tests of silt under six different filter material criteria were carried out to research the progressively stable filter system. The following conclusions were drawn.

It can be obtained from the inverse filtration test results that the 2nd to 5th filter media can guarantee the stable seepage of the silt sand used in the test. Among them, the filter media of IWHR and Terzaghi had the best filtering effect. The grading filter material prepared according to the critical conditions of the lower envelope curve of the Terzaghi benchmark has a better silt filtering effect than the upper envelope curve.

When the ratio of the characteristic particle size of the filter material to the silt soil falls within the range of 4.3–7.7, the system maintains an excellent percolation state. At this time, the hydraulic gradient i that the sand can resist is in the range of 1.5–5.

The formation process of the progressively stable reverse filtration system is the migration process of particles, which is the result of the coupling effect of mutual filtration and self-filtration between the base soil and the filter material. Regardless of the size of the filter material particles, if the pore channels between the particles can ensure that an effective progressive filter system is formed with the soil particles in the filter process, it can protect the soil particles from abnormal loss and ensure the stability of the filter system.

In the test, the 5th Witt filter material has a larger particle size, and its gradation conforms to the gradual and stable filter mechanism. Under the action of this filter material, the precipitation process is smoother, and the soil loss does not exceed the critical value. In the project, the reasonable application of a wide range of filter materials not only effectively reduces the blockage around the well but also achieves a natural balance between soil conservation and water permeability. The rationality here means that its gradation can induce the formation of a progressively stable filter structure.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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