Study on the Factors Affecting the Design of Deep Backfill Foundation Pit and the Factors Affecting Soil Construction Disturbance

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Abstract. Water is an indirect construction disturbance factor, which has important influence on the stability evaluation and analysis of foundation pit slope engineering. The study is mainly aimed at the deep backfill, the mechanical parameters are not uniform, and the effect of water on its mechanical parameters is great. The mechanical parameters of the backfill under different moisture content were measured by static triaxial shear test. The results show that the cohesion, internal friction angle and shear strength of the backfill are attenuated with the raise of the water content, the cohesion and internal friction angle of the attenuation law showed a linear gentle trend, and the shear strength of the decay trend gradually slowed down. The simulation results show that the mechanical parameters of backfill are reduced with the increasing number of saturation-dehydration cycles. The first degree of decay is the most significant, and finally tends to a certain value. The connection between the deterioration coefficient and the cycles follows the negative exponential function, and the mathematical expression of water deterioration was obtained finally. The study analyzes the damage mechanism of water in the construction disturbance, which has some theoretical support for the stability evaluation and disaster mitigation of the foundation pit.

1. Introduction

Problems of soil filling is commonly seen in areas of Hunan Province, where most areas are low hills, thus often involves many situations of soil cut and fill. Newly filled soil is getting deeper, and the slope safety and stability has become a big concern during the foundation construction. This problem could not only affect the safety of the project itself, but also jeopardize the surrounding environment[1]. In recent years, the construction underground has been facing the problem of slope instability. This is largely due to construction disturbance, which weakens the soil quality[2] and brings even worse influence on deep newly filled soil. Among the factors that influence project safety, water is the most active one. When water acts on the soil, its physical and mechanical properties worsen, thus threaten the project’s long-term stability[3-5].

The influence of water-induced deterioration on the stability of deep backfill foundation pit mainly reflects in water’s mechanical effect and its weakening effect on soil mass. Currently, a large number of scholars have conducted relative researches on water-induced deterioration effect. For instance, Pryco[6](1995) mainly analyzed the dry-wet cycle’s influence on the mechanical parameter strength of shale through experiments, the research of Chinese scholars on water influence on the performance of rock-soil mass extends to the research and analysis of soil mass (expansive soil); Zeng Sheng[7] et al.(2009) used red sandstone near a highway under construction in Hunan province to simulate the dry-wet cycle process in the nature by means of dry-saturation, and carried out tests on the shear
strength; Jiang Yongdong[8] et al. (2011) discussed that the mechanical parameters of the rock reduced with the increase of dry-wet cycles and the deformation increased, and meanwhile the mechanical parameters and the number of saturation-water loss cycle-index presented a logarithmic function relationship, and Ni Weida[9] et al. (2013) quantitatively described the degradation process of rock-soil mass on the bank slope of reservoir under the action of dynamic seepage field by defining the dry-wet cycle degradation coefficient and long-term saturation degradation coefficient, and meanwhile they considered the water-induced degradation effect in the time-varying stability analysis of the bank slope of reservoir. At present, regarding the support of foundation pit and side slope with newly filled soil, Niu Jiandong et al. have developed related patents such as double-liquid grouting and steel pipe soil nail[10-11], which have a good application effect on site. However, the buckling failure of the filled soil under the action of water is an urgent scientific issue to study. With regard to the understanding of the dry-wet cycle degradation, experts have conducted experimental researches on different types of rock and soil mass; Yang Heping[12] et al. (2005) adopted the method of direct shear test to analyze the shear strength of expansive soil, showing that the \(c\) value and \(\varphi\) value of expansive soil decreased the most under the first "water-saturation and air-drying"; Yao Huayan[13] et al. (2010) conducted dry and wet cycle tests on red sandstone, showing that the degree of rock mass weakening is the most obvious at the first time of full-water and water-loss process, and the weakening degree gradually declines under the action of circulation; Deng Huafeng[14] et al. (2012) conducted a geotechnical study on water-saturation and water-loss of sandstone, and the study showed that with the increase of dry-wet cycles, the porosity of the rock mass steadily increased and the damage degree increased; Liu Xinrong[15] et al. (2013) studied the weakening effect under the action of water and rock, introduced the explanation of chemical action to the weakening mechanism of rock and soil mass, and concluded the pattern that the shear strength of sandstone decreases gradually with the increase of saturation-water loss number; Zhou Cuining[16] et al. (2005) concluded the change rule of mechanical parameters of soft soil under long-term saturation state through uniaxial compressive test, shear test and split tensile test, indicating that with time increase, the mechanical parameter index goes down exponentially. Guo Fuli[17] et al showed that the softening effect of saturated water was due to water entering the pores, which weakened the connection of soil particles, and water, as a solvent, dissolved some of the hydrophilic components. Liu Xinrong[18] et al. studied the variation pattern of the shear strength of sandstone under the dry-wet cycle. This paper selects backfilled soil as the research object, and studies the degradation effect of water on deep backfilled soil during construction disturbance by simulating its static triaxial shear test under different moisture content and direct shear test under different dry-wet cycle.

2. Experimental material and method

2.1. Basic characteristics of soil sample

The soil samples were taken from plot No.4, Yangguang 100 Guoji Xingcheng, Yuelu District, Changsha city. The filled soil selected for experiment is artificial fill. Backfilled soil is complex in nature, such as containing a large amount of impurities and uneven mechanical parameters. By filtering out impurities with large particle size, the backfilled soil was remolded to obtain sample with relatively average mechanical properties. Take 1 kg soil sample out and test out its natural mechanical parameters, namely its moisture content though drying method, its density though cutting-ring method and its liquid-plastic limit though combination method. See table 1 for the index of the remolded soil sample.

| Moisture content/% | Density (/g/cm$^3$) | Plastic limit/% | Liquid limit/% | Plasticity index |
|-------------------|---------------------|-----------------|----------------|-----------------|
| 21.11             | 1.54                | 32.4            | 17.7           | 14.8            |
2.2. experiment program

2.2.1. The shear test on remolded backfilled soil

1) Soil sample preparation: The dry density was controlled as a constant value (1.65g/cm³ was used in this experiment) to prepare remolding backfill soil with different moisture content (10%, 15%, 20% and 25%). Spray pot is used to add water layer by layer to keep the uniformity of moisture content, and then the prepared soil sample is sealed and left for one nychthemeron (24 hours).

2) Shear test: A static triaxial unconsolidated and undrained test was used in the shear test. Four test blocks were prepared for each group of moisture content test. The shear rate was controlled at 0.5%/min, and the confining pressure was set at 100, 200, 300kPa for the test.

2.2.2. Dry-wet cycle test of backfill soil

1) Soil sample preparation: Since the natural moisture content of backfilled soil is 21.11%, the moisture content of remolded soil is configured as 20% in order to better simulate the natural state. The dry density was maintained at 1.65g/cm³ during sample preparation, and the required soil was poured into two layers of ring knives. The test block should be prepared as soon as possible to prevent the air-drying of the test soil, and the prepared soil samples should be put into the container to seal, so as to prevent the change of moisture content.

Simulation of water-saturation and water-loss process: the tests were divided into five groups, and dry-wet cycle tests of 0, 1, 2, 3, 5 were conducted respectively. Firstly, the sample is freely immersed in water; then, put the samples into a drying oven at low temperature (≤40℃) for air-blast drying. The soaking time was controlled at about 8h, and the low-temperature air-blast drying time was kept at about 12h, which was counted as a dry-wet cycle. As the test soil sample is silty clay, which is easy to soften and deform when immersed in water, the soaking time is controlled at about 8h, and the low-temperature blast drying time is kept at about 12h. In order to ensure that the test is not affected by moisture factor, the moisture contents after cycles of 1, 2, 3 and 5 are first measured during the 0 dry-wet cycling process, after which, a group of soil samples are prepared based on the tested moisture contents to carry out the 0 dry-wet cycle test.

2) Quick shear test on Backfilled soil: According to the engineering practice, loads of 100, 200, 300, and 400kPa were applied to the sample, and the shear rate was controlled at 0.8mm/min.

3. Experiment result and analysis

3.1. Shear test on remolded backfilled soil

Through the sample axial deformation reading Δh₁ (1/100mm) and the measuring force loop reading R₁ (0.01mm), the axial strain ε₁(%) and the principal stress difference σ₁ – σ₃(kPa) can be calculated as follows:

\[ \varepsilon_1 = \frac{\Delta h_1}{h_0} \times 100 \]  
\[ \sigma_1 - \sigma_3 = \frac{C R}{A_a} \times 10 \]

Above, \( h_0 \) is the original height of the sample, \( C \) is the coefficient of measuring force ring (kg/0.01mm), \( A_a \) is the correction area, and its value is below: \( A_a = \frac{A_o}{1 - \varepsilon_1} \).

The principal stress difference \( \sigma_1 - \sigma_3 \) at each point was used as the ordinate and the axial strain \( \varepsilon_1 \) as the abscissa. Take the peak value in the figure as the failure point. If there is no obvious peak value, take the principal stress difference value when axial strain is 15% as the failure point; take \( \frac{\sigma_1 + \sigma_3}{2} \) as the center and \( \frac{\sigma_1 - \sigma_3}{2} \) as the radius of the stress circle at the time of failure, so that the stress envelope was drawn, and we could get the cohesion as well as internal friction angle. The results are revealed in Table 2, and the relation curves of moisture content with cohesion as well as internal friction angle of backfill were drawn respectively (see Figure 1).
Table 2. Mechanical properties of backfill under different moisture content

| Moisture content/ % | Cohesion /kpa | Internal friction angle /° |
|---------------------|---------------|---------------------------|
| 10                  | 171.608       | 25.569                    |
| 15                  | 88.423        | 19.308                    |
| 20                  | 20.393        | 13.338                    |
| 25                  | 6.889         | 6.519                     |

Figure 1. The cohesion of backfill soil and the curve of internal friction angle and moisture content

We can see from Figure 1 that when the water content increases, the cohesive force of backfilled soil decreases. When the moisture content is at 10%~20%, the cohesive force shows an obvious linear attenuation trend when the moisture content increases, while when the moisture content is over 20%, the cohesion declines slowly and finally tends to a certain value. Meanwhile, we can see that when the moisture content is at 10%~25%, the value of internal friction angle shows an obvious linear attenuation trend when the moisture content increases. However, due to the limited number of test groups, the experimental data for moisture content above 25% cannot be obtained. According to the research results from a large number of scholars at home and abroad, the internal friction angle eventually tends to a certain residual value.

The shear strength of backfill soil is set as $\frac{\sigma_{1}-\sigma_{3}}{2}$, which is half of the maximum stress difference. If there is no maximum stress difference, the stress difference when the axial strain is 15% is chosen. According to different confining pressures, the shear strength of backfill under different moisture content is drawn in the same coordinate system to obtain the relationship between the shear strength and moisture content of backfill under different confining pressures. The results are shown in Table 3, and the relationship curve between the shear strength and moisture content under different confining pressures is drawn (see Figure 2).

Table 3. Connection between the shear strength and moisture content under different confining pressures

| Moisture content/ % | Shear strength/KPa under different confining pressures/KPa |
|---------------------|-----------------------------------------------------------|
|                     | 100 | 200 | 300 | 400 |
| 10                  | 367.91 | 423.69 | 467.29 | 610.86 |
| 15                  | 174.55 | 222.85 | 272.66 | 322.59 |
| 20                  | 50.64 | 98.21 | 109.62 | 145.78 |
| 25                  | 20.21 | 35.34 | 43.23 | 60.22 |
As shown in Figure 2, with the increase of moisture content, the shear strength under different confining pressures showed a decreasing trend, and its trend gradually slowed down with the increase of water content. With the increase of confining pressure, the shear strength of backfill increased. When the moisture content is below the plastic limit moisture content, the shear strength has the most obvious attenuation trend with the increase of moisture content. It can be seen that with the increase of moisture content, the solidification cohesion between soil particles declines rapidly.

### 3.2. Backfill dry-wet cycle test program

According to the stress-strain curve determined by the direct shear test, the shear strength of backfill under different loads is shown in Table 4.

| Number of cycle | Direct shear test result under different load/kPa |
|-----------------|--------------------------------------------------|
|                 | 100     | 200     | 300     | 400     |
| 0               | 73.34   | 120.12  | 145.86  | 184.44  |
| 1               | 69.24   | 99.75   | 140.77  | 168.25  |
| 2               | 62.15   | 104.72  | 126.49  | 160.96  |
| 3               | 59.16   | 99.93   | 119.94  | 152.65  |
| 5               | 54.52   | 94.86   | 114.37  | 146.51  |

According to Coulomb's theorem formula:

\[\tau = \sigma \cdot \tan \phi + c\]  \hspace{1cm} (3)

After processing the data in Table 4, the shear strength parameters of backfill as shown in Table 5 were obtained, and the relation curves of backfill dry-wet cycle number with cohesion and internal friction angle were respectively drawn (see Figure 3).

| Number of cycle | Fitting a straight line |
|-----------------|-------------------------|
|                 | y = 0.359x + 41.128(R^2 = 0.9886) |
|                 | y = 0.338x + 34.992(R^2 = 0.9946) |
|                 | y = 0.3182x + 34.03(R^2 = 0.9859) |
|                 | y = 0.305x + 32.8(R^2 = 0.9843) |
|                 | y = 0.2955x + 28.695(R^2 = 0.9836) |

| tan\(\phi\) | C/KPa | \(\phi/(^\circ)\) |
|-------------|-------|------------------|

Figure 2. Relation curve between the shear strength and moisture content under different confining pressures
We can see from Figure 3 that, in the first time of cycle, the attenuation degree of cohesion is the most obvious, while with the increase of the number of cycles, the cohesion gradually decreases but the trend gradually slows down, and finally reaches a residual value. Meantime, we can also see that the internal friction Angle is in line with the linear attenuation trend at the 0, 1 and 2 cycles, and the attenuation gradually decreases after 3 cycles, and finally tends to a certain value.

3.2.1. The mathematical expression value of the backfill cohesive force and the dry and wet cycles

The water-induced degradation coefficient of cohesion $c$ is defined as $\lambda(n)$, whose specific expression is:

$$\lambda(n) = \frac{c_n}{c_0}$$

(4)

In this expression, $c_n$ represents the cohesive force of rock mass after the NTH weakening, and $c_0$ is the initial cohesive force. The mathematical expression of the degradation coefficient of cohesion can come down to the following negative exponential form:

$$\lambda(n) = \frac{c_n}{c_0} = \alpha + (1 - \alpha)\exp(-an)$$

(5)

In this expression, $\alpha$ represents the final residual value (that is: $\alpha = \lim_{n \to \infty} (\lambda(n))$) after saturation-water loss of rock and soil mass; $a$ is a test parameter. The data in Figure 3 were processed with the degradation coefficient and fitted in the form of negative exponent, and the results were shown in Figure 4. According to Matlab solution results, $\alpha=0.6741$, $a=0.4238$, $R^2=0.9419$. In this test, the specific mathematical expression of the cohesion degradation coefficient of backfill soil is as follows:

$$\lambda(n)=0.6741+0.3259\exp(-0.4238n)$$

(6)
3.2.2. The mathematical expression of internal friction angle of backfill and the dry and wet cycles

Same as 2.2.1, $\mu(n)$ is defined as the degradation coefficient of the tangent value for the internal friction angle, whose specific expression is shown in the following formula:

$$\mu(n) = \frac{\tan \theta_n}{\tan \theta_0}$$  \hspace{1cm} (7)

Similarly, the mathematical expression of the degradation coefficient (n) of the tangent value for the internal friction angle can be summarized as:

$$\mu(n) = \frac{\tan \theta_n}{\tan \theta_0} = \beta + (1 - \beta) \exp(-bn)$$  \hspace{1cm} (8)

In this expression, $\beta$ represents the final residual value (that is: $\beta = \lim_{n \to \infty} (\mu(n))$ after saturation-water loss of rock and soil mass; $\beta$ is a test parameter. The test data in Figure 3 were processed by cftool toolbox to obtain the fitting curve in Figure 5. According to Matlab solution result, $\beta = 0.7857, b=0.3894, R^2=0.9758$. In this test, the specific mathematical expression of the cohesion degradation coefficient of backfill soil is as follows:

$$\mu(n) = 0.7857 + 0.2143 \exp(-0.3894n)$$  \hspace{1cm} (9)

Therefore, the overall degradation expression can be shown as:

$$\tau(n) = \sigma(n)[0.283 + 0.076\exp(-0.3894n)] + 13.38\exp(-0.4238n) + 27.8$$  \hspace{1cm} (10)

4. Conclusion

This paper studied the degradation effect of water on deep backfilled soil during construction disturbance by simulating its static triaxial shear test under different moisture content and direct shear test under different dry-wet cycles, which can play a certain role in stability evaluation and disaster mitigation of foundation pit engineering, and the preliminary conclusions are as follows:

(1) The cohesive force, internal friction angle and shear strength of backfilled soil all decline with the increase of water content. The difference of the three is that the first two would enter the linear attenuation at early stage and then the trend would slow down and gradually tends to a certain value, while the third one’s weakening trend gradually slows down instead of entering linear phase.
(2) The mechanical parameters of backfill reduced with the increase of dry-wet cycle times. At the first cycle, the attenuation degree of cohesive force was most obvious. With the increase of the cycles, the cohesive force still decreased but the amplitude gradually slowed down, and finally reached a residual value. When the internal friction angle is at 0, 1 and 2 cycles, it conforms to the linear attenuation trend. The attenuation gradually decreases after 3 cycles, and finally tends to a certain value.

(3) The cohesive force, the deterioration coefficient of internal friction angle and cycles are all in accordance with the functional relation of negative exponent. Through experiments, the specific parameters and expressions can be fitted respectively, after which, the overall degradation expression can be obtained.

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