Analysis of Deformation Characteristics of Expansive Soil Embankment under Extreme Atmospheric Action

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Abstract. By setting extreme boundary conditions, the working behaviour of expansive soil embankment under atmospheric action is analyzed. The embankment is subjected to continuous rainstorm for 6 days after 3 months evaporation under hot weather. On the basis of fracture description, the deformation process considering infiltration is calculated. The deformation of embankment treated with lime-soil and without lime-soil is compared, and the influence of different water levels is taken into account. The results show that expansive soil embankment will produce large deformation in evaporation and rainfall environment. When expansive soil embankment is treated with lime-soil enclosure, the deformation becomes small. This treating method can effectively reduce the influence of extreme environment, and ensure the deformation of embankment stably.

1. Introduction

Expansive soil is a kind of unsaturated soil with special properties. The water content has a great influence on its strength and deformation characteristics. It tends to have high strength at low water content, after exposure to water, the volume expands rapidly and the strength is significantly reduced. This change in strength is mainly caused by changes in the physical properties of the pore water-air interface. The commonly used matrix suction ($u_a-u_w$) of unsaturated soil mechanics describes this physical and mechanical property [1-4], and the change in matric suction is due to capillary phenomenon and is closely related to water content. For expansive soil slopes, the evaporation effect causes the development of soil fractures as an important prerequisite for catastrophic slopes [5-6]. As the number and extent of dry and wet cycles caused by atmospheric evaporation and rainfall increase, the expansive soil creates crisscross fractures that destroy the integrity of the soil. The soil becomes loose and the strength is reduced. The fracture network, on the other hand, provides a good channel for water evaporation and rainwater infiltration, and promotes the influence of the atmosphere on the soil to the deep. With the rapid development of the regional economy and the acceleration of urbanization, a large number of expansive soil slopes were created during the construction of roads, railways and water conservancy facilities in expansive soil areas. Because expansive soil is very sensitive to environmental changes, rapid changes in meteorological conditions can easily lead to deterioration of expansive soil properties, which in turn induces catastrophic slopes [7-10].

Based on the above considerations, based on the soil parameters considering the long-term performance of the expansive soil embankment under the action of the atmosphere, the numerical
simulation method is used to analyze the deformation characteristics of the expansive soil embankment under extreme atmospheric action.

2. Overview of the Project
The total length of a highway in Henan is about 90 kilometers. The terrain is stepped and sloped from northwest to southeast. The four types of landforms are divided into low hilly area, mountainous accumulation area, denuded ridge area and alluvial plain area. unit. The low hilly area and the piedmont accumulation area are the expansive soil distribution sections, and the soil sample is weak to medium expansive soil according to the expansion index.

When the subgrade height H>1.52m, the roadbed 80cm deep is filled with non-expansive soil or weakly expansive soil mixed with 7% lime-soil. If a packing with large permeability coefficient (>10⁻⁵ cm/s) is used, the lower part of the road bed 30cm should be modified with cement or lime to prevent the influence of upper water seepage on the core part.

- The treated base is filled with 7% lime to improve the weak expansive soil, and the upper and lower embankment cores are filled with weak expansive soil. The thickness of each layer is not more than 30cm, and the crushed water content is at the optimum moisture content. Within +3.0%, after rolling it over, spread a 3.0% lime dose (rolling forming thickness 5cm) to prevent rainwater from penetrating during construction and prevent water from collapsing at the edges.
- 2.5m on both sides of the embankment slope is filled with weak expansive soil mixed with 7.0% lime to prevent the surface of the embankment slope from being affected by the dry-wet cycle in the depth of 1.6m, and the expected effect of the edge treatment is achieved.
- For the rainy-day drainage considerations and taking into account the settlement of the embankment section, the bottom shape of the embankment is generally presented, and the cross slope of the embankment is appropriately increased to 3.5% to 4.0%, and the slope is drained to prevent the slope from being washed.

The cross section of the expansive soil edging embankment is shown in Figure 1.

![Figure 1. The cross section of the expansive soil edging embankment](image)

3. Calculate initial conditions and calculation parameters

3.1 Calculate initial conditions
Initial conditions for embankment calculation: It is assumed that the initial pore water pressure of the soil is hydrostatically distributed according to the groundwater level, and the soil temperature is 25°C.

Prior to rainfall, expansive soil slopes often experience different evaporation processes, resulting in different surface fractures. When analyzing the influence of surface fracture distribution caused by different evaporation processes on the deformation of expansive soil embankment after rainfall, different equivalent fracture spacings is used to describe the distribution of surface fractures, thus reflecting different degrees of atmospheric evaporation. Due to the poor expansion and contraction of the lime-soil, the shrinkage of the soil is close to the undisturbed soil, so the distribution of the crack mainly exists in the undisturbed soil and the soil. According to the calculation of relevant data, the
atmospheric depth of the expansive soil is about 1.6m.

3.2 Calculation parameter

3.2.1 Indoor test soil sample calculation parameters. Considering the long-term performance of the expansive soil embankment under the action of the atmosphere, the selected expansive soil strength parameter is the residual strength value after the dry-wet cycle. The deformation and permeability parameters are the parameters after the dry-wet cycle. The specific values are shown in Table 1.

The unsaturated permeability parameters of the soil are predicted and calculated according to the saturated permeability coefficient and the soil water characteristic curve after the soil wet and dry cycle.

Table 1. Strength parameter, deformation parameter and permeability parameter

| Soil type                        | Cohesive force /kPa | Friction angle $\Phi_0$ | $\Phi_{B0}$ | Compression modulus $E_{1-2}$ /MPa | Permeability coefficient /m·s$^{-1}$ |
|----------------------------------|----------------------|-------------------------|-------------|-----------------------------------|-------------------------------------|
| Undisturbed soil in unweathered area | 27                   | 16                      | 8           | 8                                 | 1.06E-06                            |
| Undisturbed soil in weathered area   | 9                    | 7                       | 4           | 4                                 | 5.41E-06                            |
| Compacted soil in zone 90         | 11                   | 8                       | 4           | 3                                 | 1.43E-07                            |
| Compacted soil in zone 93         | 12                   | 8                       | 4           | 3                                 | 6.10E-08                            |
| Compacted soil in zone 96         | 16                   | 9                       | 5           | 3                                 | 1.14E-08                            |
| Compacted lime-soil in zone 90    | 22                   | 16                      | 8           | 12                                | 2.22E-05                            |
| Compacted lime-soil in zone 93    | 23                   | 17                      | 9           | 15                                | 1.75E-05                            |
| Compacted lime-soil in zone 96    | 28                   | 19                      | 10          | 39                                | 3.17E-06                            |

3.2.2 Description of the expansive soil fracture. This paper intends to use the method based on fracture description to carry out the relevant simulation calculation of rainfall infiltration [11], and the calculation model of rainwater infiltration in fractured soil is shown in Figure 2.

Field tests show that the fracture rate and water content of expansive soil have a good linear relationship. The linear regression relationship between fracture rate and water content is as shown in formula (1):

$$P_i = -0.0191w_i + 1.0285$$  \hspace{1cm} (1)

The fracture distribution calculated in the field test is substituted into in terms of the two-dimensional form, as shown in Figure 3. According to the results of field test observation, the average width of the original crack under long-term evaporation is 0.005 m, and the relationship between the surface soil moisture content and the crack spacings is shown in Figure 4. It can be seen that the higher the water content, the larger the crack spacing.
limit, the volume change of the soil that continues to evaporate is small, which indicates that the crack width of the soil at the shrinkage limit moisture content can be described as the maximum width of the crack, combined with the formula (1) And the results of the indoor shrinkage test, the fracture rate and the crack spacing under the shrinkage limit water content of the expansive soil are shown in Table 2.

Table 2. Fracture ratio and spacing under shrinkage-limited water content

| Soil type    | Gravity Moisture Content of Surface Soil % | Fracture ratio % | Soil fracture spacing m |
|--------------|------------------------------------------|------------------|------------------------|
| Expansive    | 10.47                                    | 0.83             | 0.6                    |

3.2.3 Car load. In addition to bearing the weight of the soil, the roadbed is also subjected to the driving load. At the time of checking, the soil of equivalent height is calculated together with the sliding soil. According to the "Technical Standards for Highway Engineering" (JTJ01-88), the vehicle load is calculated: q = 19 kPa, taken as 20 kPa.

3.2.4 Meteorological parameters. Considering the meteorological characteristics of the project area in the past 10 years, the calculations set continuous evaporation in June, July and August, and set the bad weather data of rainfall as shown in Table 3. After continuous evaporation, the embankment suffered continuous rainy weather for 6 days.

Table 3. Meteorological Data of Rainfall Process

| Date   | Temperature /°C | Relative humidity /% | Mean wind speed /m/s | Total rainfall/mm | Rainfall onset time/h | Rainfall end time/h | Net radiation (MJ/m²/day) | Potential evaporation /mm |
|--------|-----------------|----------------------|----------------------|-------------------|----------------------|---------------------|--------------------------|--------------------------|
| 5/9    | 32.94           | 23.61                | 99.99                | 64.92             | 0.73                 | 98.4                | 19                       | 11.31                    | 4.10                     |
| 6/9    | 33.03           | 23.47                | 99.99                | 65.03             | 0.39                 | 54.6                | 18                       | 8.96                     | 3.42                     |
| 7/9    | 33.35           | 24.98                | 99.99                | 68.41             | 0.48                 | 51.2                | 21                       | 10.74                    | 3.64                     |
| 8/9    | 31.17           | 25.06                | 99.99                | 84.07             | 0.74                 | 74.2                | 22                       | 7.40                     | 0.39                     |
| 9/9    | 31.22           | 22.90                | 99.99                | 83.46             | 0.84                 | 71.8                | 24                       | 8.20                     | 1.56                     |
| 10/9   | 24.22           | 22.71                | 99.99                | 99.99             | 0.36                 | 54.8                | 24                       | 2.64                     | 0.05                     |

4. Calculation results and analysis

Taking an embankment with a fill height of 4m as an example, the analysis is carried out. The basic dimensions, boundary conditions and load distribution of the model are shown in Figure 5. The initial water pressure distribution is set according to the hydrostatic pressure. The groundwater level of 0.5m and 2.0m is analyzed.

Figure 4. Relation between Fracture Spacing and Gravity Water Content

4.1 Continuous evaporation calculation results

After three months evaporation, with or without lime-soil treatment, the pore water pressure
distribution of the embankment is shown in Figure 6-7, and the embankment deformation after evaporation is shown in Figure 8-9. The maximum suction in the surface soil is shown in Table 4.

![Figure 6. Distribution of pore water pressure of soil embankment](image)

![Figure 7. Distribution of pore water pressure of lime-soil embankment](image)

![Figure 8. Deformation of soil embankment](image)

![Figure 9. Deformation of lime-soil embankment](image)

| Groundwater level /m | Extremum of matrix suction on soil surface /kPa |
|----------------------|-----------------------------------------------|
| Soil embankment      |                                               |
| 0.5                  | -24349.7                                       |
| 2                    | -25381.4                                       |
| Lime-soil embankment |                                               |
| 0.5                  | -24400                                         |
| 2                    | -25400.5                                       |

4.2 Continuous rainfall calculation results

After continuous rainfall, with or without lime-soil treatment, the pore water pressure distribution of the embankment is shown in Figure 10-11, and the embankment deformation is shown in Figure 12-13.
4.3 Analysis of calculation results

4.3.1 Analysis of continuous evaporation calculation results. It can be seen from the calculation results after three months evaporation, that the groundwater level has been reduced. The embankment with an initial water level of 0.5 m has a water level reduction greater than the initial water level of 2.0 m, and the groundwater in the embankment range. The reduction in position is much smaller than in the natural ground area, and the groundwater level in the embankment area is higher than the natural ground area. The migration of moisture in the embankment area, part of which migrates through the contact area between the embankment and the atmosphere, and the other part migrates naturally to the sides. The continuous evaporation process gradually reduces the water content in the embankment, and the absolute value of the negative pore water pressure increases continuously. It can be seen from the contour map that the negative pore water pressure of the soil in the 50cm surface varies greatly. The extreme value of the negative pore water pressure on the surface of the soil is shown in the table, and both are in the shrinkage limit moisture content. After the embankment is continuously evaporated, the subgrade will settle. It can be seen from the contour map that the extreme point of the embankment deformation is mainly in the shoulder area.

After continuous evaporation, the settlement of subgrade is shown in Figure 14 (a). The maximum settlement and differential settlement values of subgrade are shown in Table 5. It can be seen that the maximum deformation occurs in the shoulder area. The value of the soil embankment is much larger than that of lime-soil embankment. The maximum settlement under both working conditions exceeds 0.04m, and the differential settlement reaches 0.03m, which exceeds the permissible value of the specification (JTG D30-2004) for post-construction settlement.

| Calculation condition | Initial water level /m | Maximum Settlement /m | Differential settlement value /m |
|-----------------------|------------------------|------------------------|---------------------------------|
| Soil embankment Evaporation | 0.5 | -0.047 | 0.028 |
| Soil embankment Evaporation | 2 | -0.049 | 0.032 |
### 4.3.2 Analysis of continuous rainfall calculation results

All in all, after the 4.0m embankment is treated by lime-soil, the settlement and differential settlement of the subgrade under continuous evaporation are greatly reduced, and meet the requirements of the specification.

After continuous evaporation, continuous rainfall will cause the groundwater level of the natural ground to rise rapidly. Because of the existence of fractures in the soil embankment, the correlation between the change of water pressure in the shallow soil and the fracture is strong, and the water infiltration process of the lime-soil embankment. It is mainly related to the permeability of the ash-covered ash. After comparison, the change of the water level in the embankment area lags behind the change of the groundwater level in the natural ground area, and the change of the water quantity in the embankment slope area is affected by the rainfall and the road surface water. The effects of the atmosphere are more dramatic.

After continuous rainfall, the soil subgrade and the lime-soil subgrade are relatively initial, and the settlement is shown in Figure 14 (b). The maximum settlement and differential settlement of the subgrade are shown in Table 6. It can be seen that the maximum deformation of the subgrade occurs in the shoulder area, showing a bulging trend. The maximum settlement and differential settlement of the soil subgrade are much larger than the lime-soil subgrade. When the initial water level is low, the same rainfall conditions, the maximum deformation of the roadbed is higher than the initial water level.

The extreme values of the relative deformation of the subgrade before and after rainfall are shown in Table 7. It can be seen that the rainfall process after continuous evaporation makes the embankment show a large deformation process, while the lime-soil embankment has a strong ability to resist such dramatic changes in the atmosphere.

![Figure 14. Distribution of Subgrade Settlement](image)

| Calculation condition | Initial water level /m | Maximum Settlement /m | Differential settlement value /m |
|-----------------------|------------------------|-----------------------|---------------------------------|
| Soil embankment       | Rainfall               | 0.5                   | +0.0049                         | 0.0076                          |
|                       | 2                      |                       | +0.0084                         | 0.011                           |
| Lime-soil embankment  | Rainfall               | 0.5                   | -0.0014                         | 0.0017                          |
|                       | 2                      |                       | +0.0027                         | 0.0025                          |

![Table 6. Comparisons of Subgrade Settlement](image)
Table 7. Relative deformation of subgrade before and after rainfall

| Calculation condition         | Initial water level /m | Maximum Settlement /m |
|-------------------------------|------------------------|-----------------------|
| Soil embankment               | 0.5                    | 0.052                 |
|                               | 2                      | 0.057                 |
| Lime-soil embankment          | 0.5                    | 0.0073                |
|                               | 2                      | 0.011                 |

5. Conclusion
By setting the atmospheric environment of continuous evaporation and continuous rainfall, the deformation characteristics of the expansive soil ash soil embankment and the soil embankment are compared and analyzed for different groundwater levels without considering the pavement structure. The conclusions are as follows.

- The evaporation effect will cause the embankment to settle, and the extreme value occurs in the shoulder area. Under the same external conditions, the deformation of the embankment with low initial groundwater level is greater than embankment with a high groundwater level.

- The infiltration of continuous rainfall will induce the embankment to undergo uplift deformation, and the extreme value occurs in the shoulder area. Under the same external conditions, the embankment with low initial groundwater level is more deformed than the embankment with high groundwater level.

- The expansive soil embankment will produce large deformation in the evaporation and rainfall environment, and the settlement and differential settlement value of the subgrade will be large. After the embankment height reaches 4.0m, the extreme settlement of the subgrade will exceed 0.004m, the maximum. The value reaches 0.008m, and the relative deformation maximum value before and after rainfall is close to 0.06 m. It can be seen that the expansive soil embankment cannot be used in long-term use, especially in the case of severe meteorological conditions, ensuring that the subgrade deformation meets the required value of post-construction settlement.

- When the expansive soil embankment is treated by lime-filled edging, the deformation of the embankment in the evaporation and rainfall environment is small, the deformation of the subgrade is smaller than about 0.003m, and the maximum relative deformation before and after rainfall is about 0.01m. Far less than the soil embankment, the subgrade settlement values are in the safe range. It can be seen that the expansive soil embankment adopts the treatment method of lime-soil edging, which can effectively resist the influence of severe meteorological environment on the expansive soil embankment and ensure the long-term stability of the roadbed deformation.

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