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Numerical study on loess slope failure induced by rainfall infiltration based on the finite difference method

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Abstract: Due to its own structural characteristics, such as multi porosity, low density and water sensitivity, loess disasters occur continuously, and rainfall is the main factor causing the loess slope damage. Loess slope failures induced by rainfall infiltration occur frequently, due to its special characteristics such as multi porosity, low density and water sensitivity. Taking a secondary railway slope in Xinzhou City as a reference, a model is built to carry out the rainfall test of loess slope. The influence of rainfall intensity, slope angle and slope height on slope stability is studied in detail. The results of numerical simulation and field experiments show that when the rainfall lasts for 300 minutes, the soil pressure at the toe of the first grade slope changes suddenly, the horizontal stress is the largest, and the slope is damaged. Under the condition of constant rainfall intensity, with the increase of slope angle and height, slope landslides are more likely to occur.

1. Introduction

Loess is a kind of silty soil with special material composition. Loess area is widely distributed in China. Due to the characteristics of loess itself, such as humidity sensitivity and large aperture, loess slope is easy to be damaged after rainfall infiltration. Loess landslide is one of the main forms of slope damage. With the continuous development of national infrastructure, the public facilities such as roads and railways built on the loess slope are increasing, landslide disaster will bring huge loss. Therefore, the research on the loess landslide damage is of great significance.

At present, the impact of rainfall on loess landslides is studied from three aspects, including Theoretical Analysis, Test and Stability Analysis. The earliest research abroad began in 1856 when Darcy used sand to simulate porous media to monitor the sand flowing through a cylindrical container. The famous Darcy's law was obtained[1]. Richards[2] extended Darcy's law to unsaturated seepage theory on the basis of experiment and theoretical calculation. In recent years, some progress has been made in the stability analysis, and the problems related to the calculation of slope stability by using numerical analysis method are gradually mature, mainly including: Finite Element Calculation and Analysis Method[3], discrete element calculation and analysis method[4], finite difference calculation and analysis method[5], etc. FLAC3D, based on the finite difference method, can effectively simulate the process of discontinuous and large deformation landslide, and it is more and more widely used in slope stability analysis.

However, FLAC3D still has limitations in the process of seepage calculation. In order to solve the unsaturated seepage problem of FLAC3D software, scholars have adopted different methods to improve the calculation method of FLAC3D unsaturated deep flow. In this paper, based on the theory of unsaturated soil, the second development of FLAC3D software seepage module and displacement calculation module simulate various working conditions of the actual project. Finally, the stress, negative pore pressure and displacement are verified by rainfall test of loess slope in laboratory.

2. Numerical simulation of rainfall on Loess Slope

2.1. Model building

The supporting project is a section of railway in Shenchi County, Shaanxi Province, which is located in the position of deep cutting, and the loess slopes on both sides are collapsible loess. The upper layer of the slope body is Q3 loess and the lower layer is Q2 loess. The study slope is a secondary slope. The height of the first grade is 15m, the slope angle is 42°, the height of the second grade is 10.5m, and the slope angle is 28°. According to the field investigation and reference data, the model parameter settings are shown in Table 1. In order to ensure that the simulation process is basically consistent with the actual rainfall induced slope failure process, the simulation process strictly controls the slope boundary conditions, constitutive relationship, rainfall realization process and calculation process. The limiting conditions of the boundary conditions of the cross-sectional model are that no displacement limiting measures are taken at the positions of the top and the hypotenuse, and the remaining boundary portions limit the vertical displacement of the boundary. The simulated slope is determined to be a secondary slope, and the Mohr-Coulomb model is used. The first grade slope is 15.6m high with a slope angle of 42°, the second grade slope is 10.5m high with a slope angle of 28°. The calculation model is set as shown in Fig. 1.

Table 1: Model paremeter settings

Loess type	Volume water content (%)	Density (g/cm^3)	Elastic Modulus (Pa)	Porosity	Saturation permeability coefficient (m/s)	Internal friction angle (°)	Cohesion (kPa)	Poisson's ratio
Q2	20	1 530	2×10^6	0.5	4.5×10^{-10}	26	20.6	0.4
Q3	20	1 450	2×10^6	0.5	4.5×10^{-10}	24	19.9	0.4

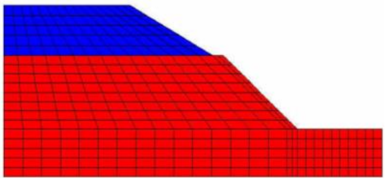


Figure 1: Calculation Model of loess slope

According to the data from the National Meteorological Administration, the rainfall in the study area in recent years is divided into light rain (5mm/24h), moderate rain (17mm/24h), heavy rain (37mm/24h), heavy rain (75mm/24h), heavy rain (175mm/24h) and extra heavy rain (400mm/24h).

The mean value of each case is taken to calculate the surface infiltration flux. (The average value of each case is used to calculate, the surface seepage flux is calculated by rainfall)The upper slope is 28 °, the lower slope is 42 °, and the permeate flux is obtained by calculation, the calculation results are shown in Table 2. The saturated permeability coefficient of loess is 4.5×10-6 m/s, which is close to the permeability coefficient of loess in the case of heavy rain. In order to study the failure law of loess slope under different rainfall conditions, the light rain, heavy rain and heavy rain are selected for research.

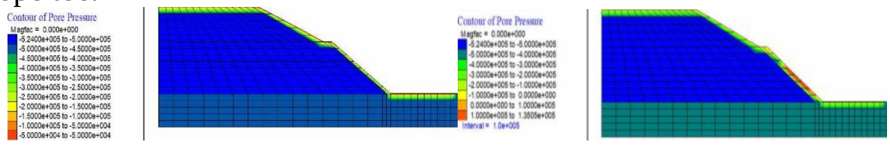
Table 2: Rainfall parameters

Grade of precipitation	5mm/24h	17mm/24h	37mm/24h	75mm/24h	175mm/24h	400mm/24h
Infiltration value of slope top surface(m/s)	5.78×10^{-8}	1.97×10^{-7}	4.28×10^{-7}	8.68×10^{-7}	2.03×10^{-6}	4.63×10^{-6}
Infiltration value of secondary grade slope(m/s)	5.09×10^{-8}	1.74×10^{-7}	3.77×10^{-7}	7.65×10^{-7}	1.79×10^{-6}	4.08×10^{-6}
Infiltration value of first grade slope(m/s)	4.28×10^{-8}	1.46×10^{-7}	3.17×10^{-7}	6.43×10^{-7}	1.50×10^{-6}	3.43×10^{-6}

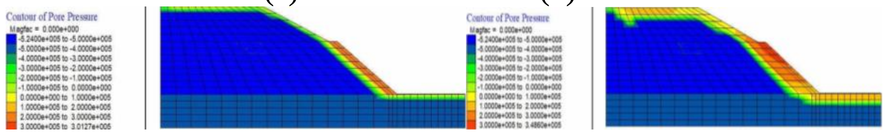
2.2. Analysis of simulation results

2.2.1. Comparison of damage under different strength

Comparing the negative pore pressure of light rain (5 mm / 24 h), heavy rain (37 mm / h) and heavy rain (400 mm / 24 h), as shown in Fig.2 (because of the limited space, only the simulation results of heavy rain are shown), it can be concluded that when the rainfall time is the same, the difference of rainwater infiltration depth with the rainfall intensity is very small, and with the increase of rainfall time, the difference of infiltration depth gradually decreases. From the slope to the location of the wet front, the negative pore pressure changes more with the increase of rainfall intensity. Because there is a fixed function relationship between negative pore pressure and water content, it can reflect the distribution of water content. The condition of slope transient saturation is that the rainfall intensity is greater than the infiltration velocity, and when the rainfall intensity is very small, there will be no large-scale saturation zone on the surface. The infiltration depth is the largest at the slope toe.



(a) 1 h (b)10h

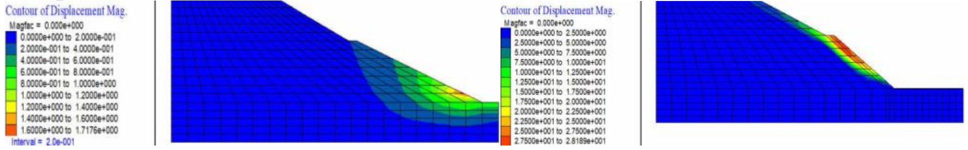


(c) 40h (d) 4d

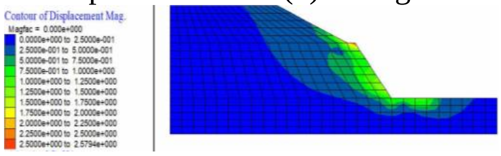
Figure 2: Variation of pore pressure

2.2.2. Influence of slope angle change on slope stability during rainfall

To study the influence of the angle change of the first grade slope on the slope stability, the calculation model is set to take the secondary grade slope angle as 28 ° and keep unchanged, the first-grade slope angles are 24 °, 42 ° and 57 ° respectively. Fig. 3 shows the initial failure of slope under the rainfall intensity of 37mm/24 h. When the first-grade slope angle is 24 °, it only affects the vicinity of the slope toe; when the first-grade slope angle is 57 °, it greatly affects the first and second grade slopes.



(a) First grade slope toe 24 ° (b) First grade slope toe 42 °

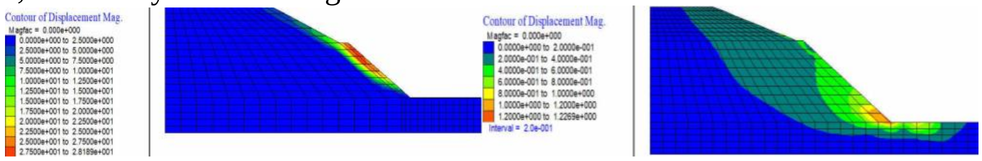


(c) First grade slope toe 57 °

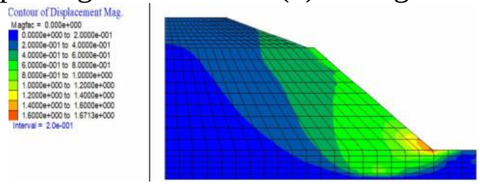
Figure 3: Relationship between the first grade slope angle and the failure form

2.2.3. Influence of slope height change on slope stability during rainfall

To study the influence of the change of the height of the first-grade slope on the stability of the slope. The calculation model is set to take the height of the secondary grade slope as 10.5m and keep unchanged. The first-grade slope are 15.6m, 25.6m and 35.6m respectively for comparative study. Fig.4 shows the initial failure of the slope under the rainfall intensity of 37mm/24h. When the first-grade slope height is 15.6m, the failure starts from the outer layer, and the entire slope position is exfoliated toward the inner layer; When the first grade slope height is 35.6m, after the position of the first-level slope toe is destroyed, the failure extends to the inner part, the upper part loses support, eventually lead to a large landslide.



(a) First-grade slope height 15.6 m (b) First-grade slope height 25.6m



(c) First-grade slope height 35.6m

Figure 4: Relationship between the first-grade slope height and the failure form

3. Rainfall simulation test of loess slope

3.1. Model building

In order to further reveal the catastrophic law of loess slope under the condition of rainfall infiltration and verify the correctness of numerical simulation, the rainfall simulation test of loess slope is carried out. The test soil sample shall be sampled from the appropriate location of the railway section, and covered with waterproof cloth during transportation. Select the soil samples suitable for the actual situation to pile up the test model in the model test box, which is 2m long, 1m wide and 2m high. In order to prevent rainwater from flowing out of the gap, a layer of plastic cloth shall be laid before loess filling. The numerical parameters of the slope toe of the built test model should be consistent with the numerical simulation, and be reduced in a certain proportion. The filling height of the first grade slope model is 0.8m, the slope is 41°; the filling height of the secondary grade slope model is 0.55m, and the slope is 28 °. The completed test model is shown in Fig. 5.

The accumulated slope in the indoor rainfall test is remolded soil, and the matric suction cannot reflect the actual slope situation of the railway section. The pore water pressure sensor is used to verify the initial change time and general trend of negative pore water pressure. In remolded soil, it is mainly the change of fluid pressure. Pore gas pressure is basically equal to atmospheric pressure. Both of them are related to the change of fluid pressure in the pore. Both of them increase with the rainfall. The pore water pressure sensor can be used to verify the general trend of matrix suction and the initial change time. The pore water pressure sensor number is 311-316, with a range of 1-10 kPa; the earth pressure sensor number is 301-305, with a range of 0-10 kPa. The Loess model and sensor layout are shown in Fig. 6.

Figure 5: Slope layout

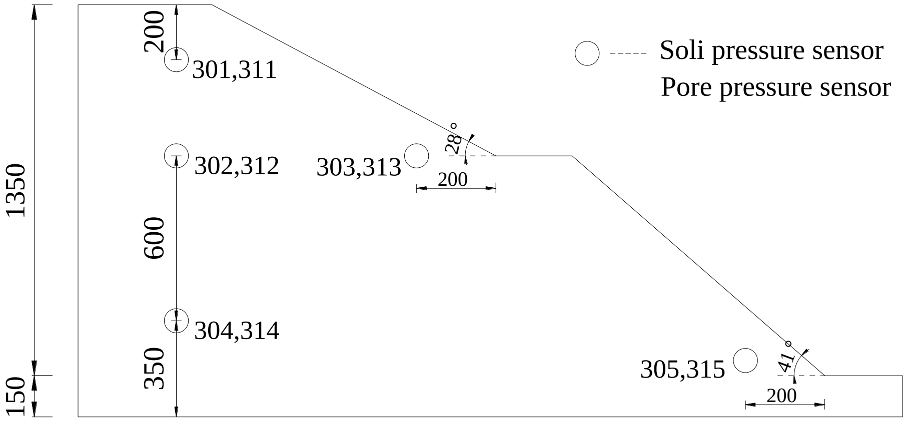
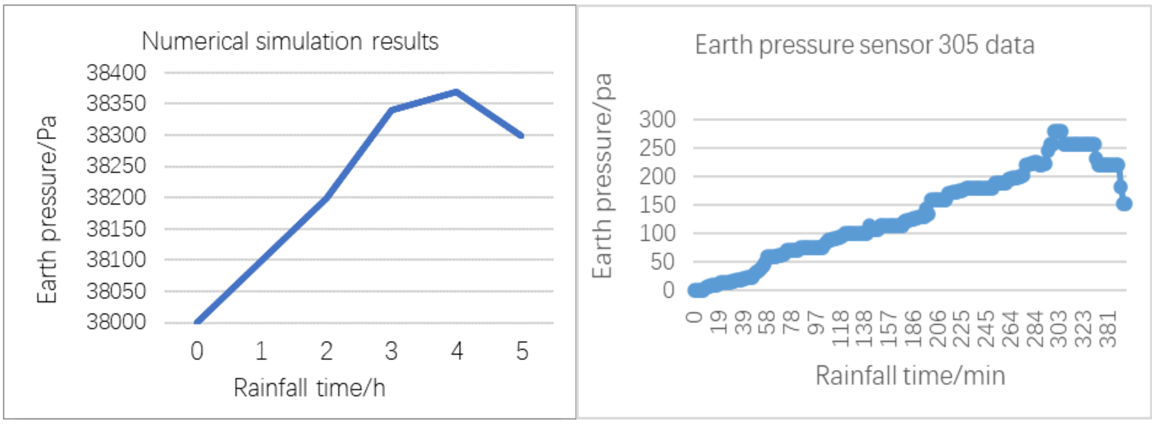


Figure 6: Instrument layout (unit: mm)

3.2. Comparison of test and numerical simulation data

3.2.1. Comparison of earth pressure sensor data

With the progress of rainfall, the pressure at this location gradually increases, while with the increase of water content, the shear strength of the soil at this location gradually decreases. After 300 min, the stress decreases, limited to space. Only in the case of heavy rainfall (400 mm/24 h), the horizontal pressure of soil pressure sensor 305 at the toe of the first grade slope changes with the rainfall time, as shown in Fig. 7. The results show that the depth of the sensor is shallow because of the error, and the shear strength of the surface soil is smaller than the gravity of the slope due to the increase of the water content, which leads to the sliding. The corresponding position of numerical simulation is relatively deep, and the test results are basically consistent with the trend of simulation results.



(a) Test results (b) Numerical simulation results

Figure 7: Change of 305 value of earth pressure sensor with time

3.2.2 Data comparison of pore pressure sensor

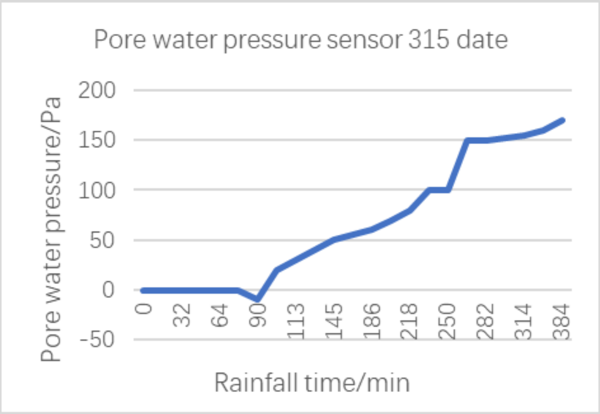


Figure 8: Numerical simulation results

Before the beginning of rainfall, all pore pressure values in the test are set to the initial value of 0, both of which increase with the rainfall, and the initial change time and general trend are compared with the numerical simulation results. The numerical simulation data of negative pore water pressure at the same location and depth of the pore water pressure sensor 311-315 are shown in Fig. 8. Limited to space, it only shows the change of 315 value of pore pressure sensor at the toe of first grade slope with rainfall (400mm/24h) time under the condition of severe rainstorm, as shown in Fig. 9. The increase of pore water pressure began at 88 min, which indicated that the wetting front reached this position at 88 min, and then the pore water pressure gradually increased. Through comparison, it can be concluded that the initial change time and trend of pore pressure sensor 311, 313 and 315 values are consistent, the negative pore pressure at three locations is basically consistent at 5 hours, and the simulation results are consistent with the test results.

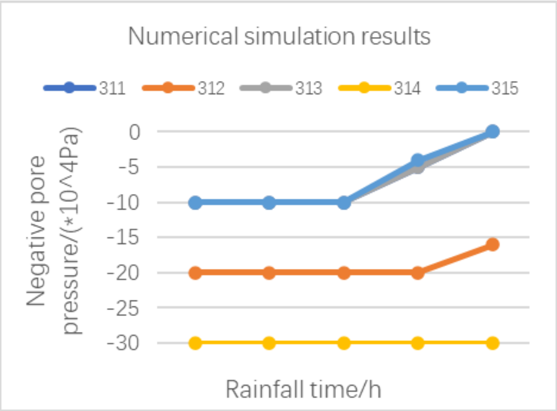
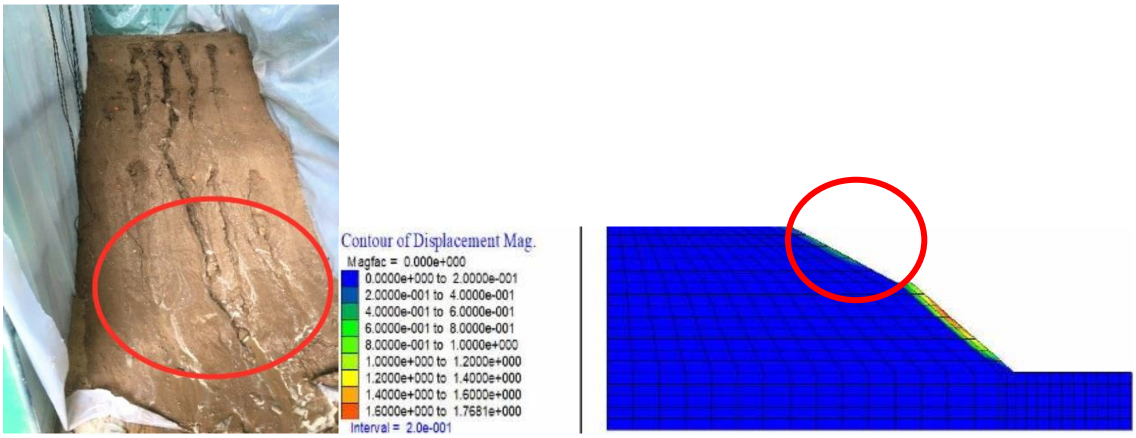


Figure 9: Pore water pressure sensor 311 value

3.2.3 Comparison of failure results

In the case of 400mm/24h rainfall, both the numerical simulation and the test failure time are about 5 hours, and the damage location is shown in Fig. 10. The failure position of rainfall test is marked in 10(a), which is on the surface of first grade slope; the failure position of numerical simulation is marked in 10(b), which is also on the surface of first grade slope. The test results are consistent with the failure mode and failure location of numerical simulation, which shows that the numerical simulation is in line with the actual situation.



(a)Test results (b) Numerical simulation results

Figure 10: Comparison between experimental and numerical simulation failure

4. Conclusion

(1) With the increase of rainfall intensity, the infiltration depth is larger, but the increase range is very small. With the increase of rainfall duration, the difference of infiltration depth of different intensities is decreasing. When the rainfall intensity is greater than the saturated infiltration speed of loess, the infiltration depth is almost not affected by the rainfall intensity because the infiltration speed is constant. The greater the rainfall intensity is, the greater the rainfall infiltration is, but with the increase of depth, the rainwater infiltration capacity will gradually weaken; the greater the rainfall intensity is, the greater the change value of negative pore pressure from the slope surface to the wet front position is, indicating that the higher the rainfall intensity is, the higher the surface water content is; when the rainfall intensity is very small, there is no saturated area on the slope surface.

(2) Under different rainfall, slope angle and slope height, the horizontal stress at the slope toe is the maximum position of the whole slope, and it is also the maximum position of the horizontal displacement. The maximum vertical displacement is at the top of the slope, and the position of the slope toe is the most dangerous position. In a certain range, the greater the rainfall intensity is, the greater the stress increases. The greater the depth is, the greater the upper load is, and the greater the horizontal stress will be. Therefore, the position of the first grade slope toe is the most dangerous position, and the change of water content in this position is also large.

(3) In a certain range, with the increase of the slope angle, the rainwater infiltration depth at the slope location gradually decreases. Because of the large load on the upper part, the position of the first grade slope toe is the position with the maximum horizontal stress of the whole slope. The first slope toe is the most vulnerable part, and the secondary slope toe has little effect on the overall stability. With the increase of the first grade slope angle, the stress at the toe of the slope will increase, so the earlier the failure occurs, the larger the influence range, and the more likely the displacement will change abruptly.

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