Study on Moisture Migration Characteristics in Ancient City Wall Ruins

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Abstract. Aimed at the failure of ancient city wall ruins induced by heavy rainfall, the numerical model of the typical wall section of Zheng Han ancient city wall ruins is generalized. Based on the software of ABAQUS, the variation regularity of pore water pressure, saturation and seepage velocity in ancient city wall ruins under the influence of different rainfall elements and structure characteristics is discussed. The results show that the dynamic process of pore water pressure in the wall (the rate of change and the range) is directly proportional to the unit rainfall intensity. Under the same rainfall intensity, the pore water pressure on the wall surface with larger initial substrate suction increased faster than the wall surface with smaller initial substrate suction. Within the depth range of rainfall influence, the rate of water infiltration into the interior of the wall body decrease from the wall surface to the depth of the wall. At the same section of the wall, the growth rate of saturation at the platform is significantly higher than that in the wall region with larger slope angle; with the increase of saturation, the growth rate slows down.

1. Introduction
Heavy rainfall is one of the principal causes of slope instability, occurring during or after a period of rainfall. The ancient city wall is similar to the slope, and it is also exposed to the risk of rainfall-induced instability. The destruction of the city wall will pose a serious threat to the protection and inheritance of human cultural heritage [1].

Unsaturated soil is a complicated three-phase soil, and the infiltration of rainwater inside the wall is a dynamic process [2]. During the rainfall period, rainwater seeps into the wall, especially when the soil layer on the surface of the wall is loose, the rainfall infiltration is more obvious. The infiltration of rainwater lead to the increase of water content of the wall and the decrease of matrix suction. Depending on the theory of unsaturated shear strength of soil, the decrease of matrix suction will lead to the continuous reduction of the shear strength of the potential sliding surface of the wall, resulting in the instability of the city wall [3]. In recent years, many scholars have studied the process of water movement in the aerated zone of soil, and have achieved fruitful results. Li X.G et al. [4] studied the collapse sliding failure of the excavation slope of joint type less under the action of seepage in different rainfall intensity. Zhang S.R et al. [5] combined with strength reduction technique to calculate slope stability under transient seepage. Shi Z.M et al. [6] proposed an analysis method for considering the stability of multi-layer unsaturated soil slopes under rainfall infiltration; Zhao J.G et al. [7] carried out a tracking test to study the deformation mechanism of the filling slope under precipitation-evaporation cycle, and then analyzed its evolution law and genetic mechanism. Wu C.F et al. [8] used the theory of
unsaturated soil mechanics to consider the time and space effects of water transport on slope stability under rainfall.

It can be observed that many researchers have systematically studied the mechanism of water migration and stability changes in slopes and embankments under rainfall, among which the two factors of rainfall intensity and rainfall duration are the most abundant. The city wall has noticeable differences compared with the slope and the embankment. The city wall has a larger infiltration surface and multi-platform, slope angle and other structural features, as showed in Figure 1. These structural features caused by natural disasters and man-made damage have an important impact on the infiltration rate and infiltration volume, resulting in extremely uneven water transport in various areas of the city wall, and the saturation is greatly different, and the collapse of the city walls is often extend from these weak areas. The above-mentioned multi-factor coupling of rainfall infiltration is more complicated and of more research significance.

![Figure 1. Rainfall infiltration surface of slope, embankment and city wall](image)

Based on the investigation of the ruins of Zhenghan's ancient city wall in Xinzheng City, Henan Province, this paper generalizes the typical wall model and the software of ABAQUS was applied to study the variation of pore water pressure, seepage velocity vector field and saturation caused by the unique structural characteristics of ancient city wall ruins under different rainfall factors. The research can provide a basis for revealing the mechanism of rainfall induced wall instability.

2. Water transport equation

In the analysis of the seepage field of the urban wall under rainfall conditions, the water migration caused by rainfall infiltration can be generalized into the transient unsaturated seepage field on the wall section, which follows the Darcy law and the conservation law of mass[9].

2.1 Transient unsaturated seepage

The partial differential equation of rainfall infiltration in two-dimensional unit:

$$\frac{\partial}{\partial x} \left( k_x(h_m) \frac{\partial h_m}{\partial x} \right) + \frac{\partial}{\partial z} \left( k_z(h_m) \left( \frac{\partial h_m}{\partial z} + 1 \right) \right) = \frac{\partial \theta}{\partial t} \tag{1}$$

Where $\theta$=volumetric water content; an item attached in the z-coordinate direction is caused by the position head

2.2 Description of the soil water characteristic curve and permeability coefficient curve

In the numerical calculation of saturated and unsaturated seepage, the permeability coefficient of the ancient city wall is related to the saturation and the pore water pressure. The soil-water characteristic curve refers to the relationship between soil volumetric water content and pore water pressure, which is an important tool to describe the relationship between unsaturated soil strength and permeability coefficient. The permeability coefficient curve refers to the relationship between the permeability coefficient and the pore water pressure [10-12]. The relationship between soil-water characteristic curve and permeability coefficient is reflected in the function of hydraulic parameters.

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[ \frac{1}{1 + (a \psi)^m} \right]^n \tag{2}$$

$$K_\theta = K_s \left( \frac{\theta - \theta_r}{\theta_s - \theta_r} \right)^{0.5} \left\{ 1 - \left[ 1 - \left( \frac{\theta - \theta_r}{\theta_s - \theta_r} \right)^{1/n} \right]^m \right\}^2 \tag{3}$$

Where $\theta_r$=residual moisture content; $\theta_s$=saturated moisture content; $K_s$=saturated permeability coefficient; $a$, $m$, $n$=corresponding parameters of the soil water characteristic curve; $\psi$=matrix suction.
3. Models, parameters and schemes

3.1 Models

According to the research on the slope model, the size of the boundary range has a great influence on the finite element calculation, especially the seepage field calculation [13]. Therefore, distance from the slope foot to the model boundary is taken as twice the height of the city wall, and the total height is not less than 2 times the height of the wall.

![Finite element calculation model](image)

The model presented in figure 2 is a typical section of the northern wall section. The number of calculated grid cells is 1904 and the number of nodes is 2015. Due to the huge model area, feature points and feature path are selected to quantify the variation of pore water pressure and seepage rate inside the city wall. Among them, the feature path I is drawn from the highest point of the wall along the vertical direction to the bottom of the model. The heights of the feature points A, B, C, and D from the surface are 14m, 9.05m, 5.77m, and 3.96m, respectively; The feature points E, F, and G are located in the surface soil layer of the wall at different slope angles (71.7°, 25.7°, 0°) on the left side of the model.

3.2 Calculation parameters and initial conditions

According to the Test Methods of soils for Highway Engineering (JTG E40-2007), the average saturated permeability coefficient of the wall is $5 \times 10^{-6}$ m/s. The soil-water characteristic curve of the soil was obtained by the Van-Genuchten model fitting, as showed in Fig. 3. The soil permeability coefficient was obtained by fitting the Van-Genuchten permeability coefficient model. The result is shown in Fig. 4.

Initial conditions: Groundwater is located 10m below the surface of the earth. Figure 5 shows the variation of initial pore water pressure with height on path I.

Boundary conditions: the rainfall intensity is converted into the surface flow boundary applied to the surface of the model wall. When the rainfall intensity is less than or equal to the permeability coefficient of the soil, the flow boundary is set according to the rainfall; When the rainfall intensity is greater than the permeability coefficient of the soil, the flow boundary is set by the saturation permeability coefficient.

![Soil water characteristic curve](image)

![Permeability function curve](image)

![Distribution of initial pore water pressure](image)

3.3 Calculation scheme

Under the influence of the city wall surface, it is necessary to study the law of water migration under the influence of different rainfall factors. According to the rainfall intensity and rainfall duration, the three rainfall schemes shown in Table 1 are set to simulate the rainfall infiltration process of the city wall.
Table 1 Rainfall intensity distribution and parameter design

| Saturated permeability coefficient/ \( k_s \) | Rainfall intensity | Rainfall duration |
|-----------------------------------------------|--------------------|------------------|
| (m/s)                                          | (m/s)              | (h)              |
| Scheme 1                                       | 0.05ks             | 96               |
| Scheme 2                                       | 5×10^{-6}          | 0.1ks            | 96               |
| Scheme 3                                       | 0.2ks              |                  | 96               |

4. Calculation results and analysis

4.1 Pore water pressure

The stability of the city wall under rainfall is affected by many factors. One of the important factors is the decrease of matrix suction or even the formation of positive pore water pressure, which leads to the decrease of effective stress of the city wall soil. In view of this, the variation of pore water pressure at the feature points under different rainfall schemes is simulated, and the results are shown in Fig. 6.

Figure 6 Variation of pore water pressure with time at A~D feature point

Feature points A, B, C and D are located at different heights of the wall section and are affected by groundwater differently. After 96 hours of rainfall, the matrix suction at point A decreased the most. The analysis shows that the larger the initial matrix suction, the smaller the permeability coefficient and the larger infiltration surface on both sides of the city wall, the rapid infiltration at the feature point where the initial matrix suction is larger, and the pore water pressure changes significantly. Secondly, matric suction on the surface decreases with the duration of rainfall, even reaching 0 kPa in saturation.

With the increase of rainfall intensity, infiltration and seepage rate increase obviously, and the matric suction decreases more in the same rainfall duration.

4.2 Velocity vector field

The variation of the flow velocity of each node on the path I with the infiltration depth of rainwater about the three schemes is shown in Fig. 7.

Figure 7 Seepage velocity at different heights

Analysis of the three schemes shows that within a certain depth range, the seepage velocity grows with the increase of rainfall duration. Under any rainfall intensity, the infiltration rate of rainwater is constantly supplemented, and the surface infiltration rate is higher than the infiltration rate of the wetting
front. As a result, the rainwater does not seep over the wetting front and accumulates gradually, resulting in the surface soil to basically close to saturation. In addition, by comparing the seepage rate of the surface layer under different schemes, it can be seen that the seepage rate of the surface layer increases obviously with the increase of rainfall intensity. This indicates that rainfall intensity can also determine the infiltration rate and infiltration amount of the surface soil to a certain extent.

4.3 Infiltration depth
Defining the depth range of the wall section affected by rainfall infiltration is the precondition for determining the increase value of the downward sliding force above the sliding surface of the wall. Figure 8 is based on scenario 2, analyzing the variation of saturation with depth on path I, and can visually see the depth of rainfall infiltration under different rainfall durations.

![Figure 8 Variation of saturation with depth](image)

As can be seen from the Fig. 8, the variation of saturation along the depth is consistent at any time. Due to the influence of rainfall infiltration, the saturation of surface soil increased. With the increase of depth, the saturation gradually became smaller. After the corresponding rainfall duration, the variation curve of saturation with depth coincides with the initial saturation curve after exceeding a certain depth, and the corresponding depth at this coincidence is the influence depth of rainfall infiltration. The longer the rainfall lasts, the greater the depth range of rainfall infiltration.

Within the influence depth of rainfall infiltration, rainfall will increase the weight of soil and the sliding force of sliding surface, which is very unfavorable to the strength of soil and the stability of city wall. The variation of the influence of rainfall infiltration in the scheme II with the change of rainfall duration is shown in Table 2.

| Duration of rainfall/(h) | 0  | 12 | 24 | 48 | 72 | 96 |
|-------------------------|----|----|----|----|----|----|
| Influence depth value/(m) | 0  | 3.4 | 4.7 | 7.6 | 13.9 | 16.4 |

4.4 Slope angle and platform
From the model in Figure 2, the left side of the city wall presents different steps from top to bottom, and the stepped structure (platforms and slopes with different dip angles) will affect the process of rainfall infiltration, and affect the changes of pore water pressure and saturation in the main area of the city wall. Table 3 shows the angle between the surface of the wall where the feature points E, F, and G are located and the surface (positive in the counterclockwise direction). Figure 9 shows the variation of the saturation of each feature point with the rainfall duration when the rainfall intensity is 0.2 k, m/s.

| Feature point | Slope angle/° | Vertical distance from the wall surface/(m) |
|---------------|---------------|-------------------------------------------|
| E             | 71.7          |                                           |
| F             | 25.7          | 0.5                                       |
| G             | 0(platform)   |                                           |
As can be seen from Fig. 9, during the rainfall period, the saturation at each feature point increases with the increase of the rain duration. The saturation of the characteristic point G (at the platform) is always greater than the other two feature points E, F, where the saturation of the feature point E (slope angle =71.7°) is the smallest. The saturation of the feature point G begins to change after the rainfall of 1.1 h, and the growth rate is high. The saturation of the feature points E and F increased significantly after 10.34 and 1.45h, respectively, and the growth rate of the E point decreased significantly. The reason shows that during the rainfall period, more rainwater will be collected at the platform of the city wall, the infiltration rate is larger, and the response time affected by the rainfall is also the shortest. However, the infiltration rate and the infiltration amount decrease with the increase of the slope angle.

The structural characteristics of the city wall (platforms and slopes with different dip angles) are important factors affecting the rainfall infiltration of the city wall. The impact of rainfall on the platform of the city wall is large, resulting in uneven water transport in various areas of the wall.

5. conclusion

(1) The large infiltration surface of the city wall makes the water migration in the wall complex and variable. Under the same rainfall intensity, the rate of pore water pressure rise in the surface wall of the city wall increases monotonously with the initial matrix suction.

(2) The water transport rate in the city wall body gradually decreases from the surface layer to the deep layer, but the decreasing extent is related to the depth of the city wall.

(3) Under the same rainfall conditions, the saturation of the surface soil at the wall platform is always greater than that at the place with larger slope angle. In the early stage of rainfall, the growth rate of saturation at the platform of the same wall profile is significantly higher than that in the area with larger inclination angle. Instability mechanism is easily triggered on potential sliding surfaces with uneven water movement and obvious difference in saturation in the main wall area. Therefore, in the renovation of the ancient city wall sites, the drainage at the city wall platform should be paid enough attention.

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