Effects of Rainwater Infiltration in Low Impact Development Facilities on Adjacent Municipal Roads in Collapsible Loess

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Abstract

The effective and reasonable construction of the low impact development (LID) facilities in loess area depend on the functionality of typical LID facilities and the safety of surrounding structures in areas. A full-scale field test on rainwater concentrated infiltration of bioretentions in a collapsible loess site was conducted in this study. The water content and deformation law of the site were analyzed, and the water movement law of the rainwater-concentrated infiltration at bioretention facilities in the loess site was determined. The site settlements were calculated as per the wetting deformation curve and infiltration depths were calculated on an improved infiltration depth model tailored to the loess area. The rainwater infiltration rules of different bioretention structural forms are different in the collapsible loess field. The diffusion rate of the retaining wall type in loess decreases over time, while that on a sloping type does not. Within the same infiltration time, the retaining wall has a stronger influence on the site than the sloping type. When the water is concentrated in the site, its influence on the subgrade settlement is small (generally less than 1.5 mm) enough to satisfy the relevant engineering requirements. A modified Green-Ampt model based on assumed loess saturated unsaturated stratification can be used to predict the infiltration depth of facility water at the site. The adverse effects of water infiltration related to stagnant bioretentions can be mitigated by adjusting the initial water content and saturated water content at the loess site.

1. INTRODUCTION

Waterlogging has become an increasingly common occurrence in recent years alongside climate-change-induced weather extremes and aggressive urbanization. Waterlogged structures and roads can severely negatively impact surrounding communities. Low impact development (LID) facilities are widely used in the United States, the United Kingdom, China, and other countries as an effective means of urban stormwater control and hydrological cycling (Dietz, 2007; Pyke et al., 2011; Ahiablame and Shakya, 2016; Jia et al., 2016; Hu et al., 2017; Wu et al., 2018a; Li et al., 2019b). Rainfall distribution is not uniform and evaporation exceeds rainfall in collapsible loess areas of China, where LID facilities should be designed not only to reduce the peak rainfall and minimize rainwater pollutants but also to promote regional rainwater circulation and effective utilization.

Collapsible loess, a water-sensitive type of soil with a sub-stable structure, is widely distributed throughout the world (Shroder et al., 2011; Chen et al., 2018; Lian et al., 2020). Loess soil readily disintegrates under the action of rainfall and irrigation, which can cause nearby structures (e.g., buildings, municipal roads) to crack and even to collapse. Slope instability, landslides, and other geological disasters are frequently reported in loess areas (Kozubal and Steshenko, 2015; Wu et al., 2017; Yates et al., 2018; Assadi-Langroudi, 2019). It is crucial to effectively understand the seepage law and moistening deformation of the infiltration rainwater of LID facilities in loess areas to ensure the safety of the facilities and surrounding structures.

LID facilities mainly include permeable pavement, green roofs, and bioretentions. Previous studies on LID facilities have mainly centered on peak reduction design, non-point source pollution risk reduction, and portfolio management (Ahiablame and Engel, 2012; Tang et al., 2016; Eckart et al., 2017; Ma et al., 2017; Winston et al., 2018; Yekkalar et al., 2018; Chen et al., 2019; Hou et al., 2019a; Sohn et al., 2019). There has been little research to date on risk prevention or rainwater detention control measures in loess area LID facilities. Academics and professionals agree that the LID facilities in collapsible loess areas must be specially equipped for safety; this may include shallow and small-scale designs and full paving with impermeable membranes at the bottom of underground facilities (Zhang, 2016; Si et al., 2018).

Wang et al. (2019) and Deng et al. (2020) studied the impact of rainwater on loess sites in cases of impervious membrane leakage to develop a construction optimization scheme. Their work has assisted in designing LID facilities in collapsible loess areas. However, the overall anti-seepage measures still have some drawbacks as the factors that further reduce the rainwater retention time and the total amount of infiltration and storage in the underlying surface of the facilities can cause the detention function ineffective. Rainwater infiltration and soil strength and deformation laws can be used to identify the controllable critical range of rainwater infiltration in the construction of LID facilities in loess areas. The numerical simulation Geo Studio has been used to analyze the seepage field and displacement field of different bioretention facilities in collapsible loess areas (Chai et al., 2019; Liang et al., 2020) and ultimately to optimize the length of underground bioretentions in various loess areas. The function of LID facilities in the loess area can be ensured using the methods described above. However, as a unique unsaturated soil, the infiltration mechanism of collapsible loess is not yet fully understood. The infiltration of loess is affected by initial water content, temperature, and pore characteristics (Wang et al., 2010; Haeri et al., 2012; Li and Li, 2017; Shao et al., 2018; Li et al., 2019a; Zhang et al., 2019). These characteristics are difficult to simulate numerically because the parameters and the calculation model of water movement law cannot effectively reflect water movement through loess; besides, the infiltration boundary conditions are unrealistic. Compared with the numerical simulation, the field test study can obtain the actual infiltration law of water in Loess more accurately.

Many previous researchers have investigated the law of water infiltration in loess. The depth of water infiltration is limited in collapsible loess sites if diversion measures are not taken. The influence of concentrated infiltration in loess areas on water content is more intense than that in natural rainfall infiltration areas (Tu et al., 2009; Huang et al., 2011; Min et al., 2017; Wu et al., 2018b; Hou et al., 2019a, 2020). However, previous studies have centered on the water infiltration law of single-layer collapsible loess. The structures of LID facilities vary but are mainly composed of replacement fill and gravel layers. LID facilities are also often arranged around municipal roads or buildings, which makes these sites vulnerable to the initial stress field of the subgrade. The law of water infiltration in a single loess site does not accurately represent changes in the seepage field and deformation field of the site after water infiltrates the facility.

A typical LID facility construction project in the loess area of Shaanxi Province, China, was taken as the engineering background for this study. Previous optimization results regarding the length of the anti-seepage membrane at the bottom of a typical bioretention, also a $Q_3{}^{eol}$ collapsible loess site was used to selected a full-scale rainwater infiltration test of bioretention facilities near municipal roads under the worst-case rainfall intensity. The law of water infiltration was determined accordingly. Consolidation compression test data was used to calculate the wetting settlement of the site. The applicability of the modified Green-Ampt model in predicting the infiltration depth of LID facilities in the loess area was verified as discussed in detail below.

2. MATERIALS AND METHODS

2.1 Typical Application Environment of LID Facilities in Loess Areas

Bioretentions are usually located in the separation zone between motorized and non-motorized lanes. The typical application environment of bioretention facilities in a loess area is shown in Fig. 1. The site under analysis here is a Class I non-gravity collapsible loess site.

[Insert Figure 1]

Bioretentions in loess areas are mainly transport type and retention type. The primary function of the transfer type bioretention is to transfer runoff rainwater from the upper part of the facility. The retention type bioretention may be a retaining wall with L-shaped concrete retaining wall poured on both sides (referred to from here on as “Biorentinion I”) or a slope on the side of the structure (“Biorention II”), both of which have the same filling materials. The bottom is paved with 35 cm thick gravel (particle size 30-50 mm), and then with 5 cm thick gravel (particle size 5-15 mm), then the top is filled with replacement fill to the proper proportions. The specific structure is shown in Fig. 2. The main function of a retention type bioretention is to absorb and transport rainwater, so the retention bioretention has a more significant impact on the foundation field than the transfer type bioretention. Thus, the influence of rainwater infiltration through retention type bioretentions was the focus of this study.

[Insert Figure 2]

The Xixian New Area in Shaanxi was taken here as an example. It has the highest intensity of LID facility construction in collapsible loess areas in China. The average annual precipitation is 485.22 mm. Within the last 25 years, the maximum annual rainfall was 897.80 mm, in 2003, and the annual minimum rainfall was 302.20 mm, in 1997. The annual difference is 595.60 mm. The precipitation distribution in a given year is uneven and the monthly average evaporation is greater than the rainfall. Cloudy conditions and rainstorms prevail in summer and autumn months. The average monthly rainfall and evaporation in 2018 are shown in Fig. 3.

[Insert Figure 3]

2.2 Immersion Test of Typical Bioretentions in Loess Area

2.2.1 Test Site

The test site is located in Chang’an District, Xi’an, Shaanxi Province, China. It is 25 m × 12 m in size. According to the Chinese code, the collapsibility coefficient of the site loess is 0.0810, which belongs to medium collapsible loess. Other essential parameters of the site are shown in Table 1. The hydrological conditions of the site are similar to the engineering background.

[Insert Table 1]

2.2.2 Testing System

The experimental setup mainly consists of a bioretention facility system, water supply system, and test system. The site layout is shown in Fig. 4. As shown in Fig. 4(a), the bioretention facility system consists of a 14-m long bioretention facility belt with three typical bioretention facilities and a 14 m × 3.5 m simulated municipal road with compacted loess as the subgrade. The water supply system consists of a reservoir (5 m × 3 m × 1 m), a measuring weir, and a return channel. The water in the reservoir was pumped to the measuring weir as necessary during the experiment. An open channel was set at the end of the bioretention facility belt to form a flow loop with the reservoir.

The test system is mainly composed of a test I moisture sensor section, a test II moisture sensor section, a test III moisture sensor section, and a data collector. The moisture sensor is a CS635 (Campbell Co., USA), and its measurement accuracy is +- 1%. The sensor was embedded by digging an exploratory well. The influence of water infiltration on the vertical water content of the site is usually less than 2 m (Hou et al., 2019b), so a total of 12 soil moisture sensors were arranged at depths of 1.5 m, 2 m, 2.5 m, and 3 m. The sensor positions in the test 1 section are shown as an example in Fig. 4(b). The data collector model is TDS-602 and its fastest sampling speed is 0.02 s.

[Insert Figure 4]

2.2.3 Test Conditions

The test process is shown in Fig. 5. The allowable ponding height of the bioretention facility is 20 cm; rainwater with ponding height greater than 20 cm is discharged through the overflow facility. The designed ponding time in this case is 24 h. The worst-case rainfall conditions were simulated with a constant water head of 20 cm for 24 h to observe the changes in water content at the site. An impervious membrane was placed at the bottom of each facility according to Liang et al.'s method (2020). The specific parameters of the test are listed in Table 2.

[Insert Figure 5]

[Insert Table 2]

3. WATER INFILTRATION LAW

3.1 Variation of Water Content with Respect to Time

The variation of water content with respect to time at different depths under bioretention facilities is presented in Fig. 6.

[Insert Figure 6]

In the process of concentrated infiltration of rainwater through facilities, the volume water content curve at M and N positions at the bottom of facilities in the loess site progresses through three stages: initial stability (I), rapid growth (II), and slow growth (III). The duration of stage I increases with depth. That is, the duration of stage I at 2 m is longer than that at 1.5 m. In stage II, the water content decreases as infiltration depth increases; it takes more than 1.5 m to reach a stable water content at 2 m depth. In stage III, the maximum stable water content decreases as depth increases. The stable water content at 1.5 m, 2 m, and 2.5 m decreases in turn because the porosity of soil decreases as depth increases, thus the saturated water content of the soil and the stable water content both reduced.

At the bottom of the roadbed, the soil volume water content fluctuates only slightly as the water immersion time increases. The soil moisture content was basically +- 2% of the initial moisture content throughout the experiment. Under the test conditions, the water infiltration of facilities exerted little influence on the seepage field of the subgrade.

Further, at the same depth in the retaining wall type facilities, changes in water content at 0.5 m on the left side of the bottom center were less intense than at 0.5 m on the right side. There was no significant difference in the sloping type facilities. It is possible that the construction of retaining wall facilities significantly influences the foundation, which then affects the law of water permeability there.

At the same depth, the rapid growth period of Bioretention I was shorter than that of Bioretention II. The water infiltration of Bioretention I affected the foundation water content within a shorter amount of time as well. When the depth was 2.5 m, the water content of Bioretention I increased from 17% to 32% over 1.5 hours, while that of Bioretention II risen from 17% to 31% over 3.5 hours. The time also gradually increased with the infiltration depth, which can be attributed to the structure of the facility. Bioretention I stores more water than Bioretention II, so it has a larger seepage height. The water content of the site also changed more rapidly in Bioretention I than in Bioretention II.

As water infiltrated the site, the soil became saturated once the saturation of soil exceeded 85%. According to the relationship between saturation and volumetric water content (Wu et al., 2018b), the average saturated volumetric water content of the site is 46%. After 24 h of infiltration time, the maximum water content of the soil was 39.8% $<$ 46%. The centralized infiltration process of the facility in the loess field is unsaturated. Huang et al. (2015) obtained similar experimental results.

3.2 Variation of Water Content in Different Sections

The water profiles in different sections of Bioretention I and II from the center of the structure outward changed with time, as shown in Fig. 7.

[Insert Figure 7]

As shown in Fig. 7(a), the initial water content of each water profile in the loess site was different. The maximum and minimum water content values were 18.8% and 13.4% respectively. The initial water content at 2.5 m was the largest. This may be due to the changes in soil density during the backfill compaction process of the horizontal hole containing the sensor, which created different water content levels.

At the section about 0.5 m from the centerline of the facility, the water curves were scattered at the beginning of the infiltration process and grew close to each other after 4 h. After this point, the water content of the site increased rapidly with further infiltration time until the water content of each position became stable. The maximum water content in the whole process was 39.8%.

The subgrade is located at 2 m and 3m to the left of the facility centerline, where the water content did not change significantly with different infiltration depths at different time points. That is, the water infiltration at the bottom of the facility had little effect on the water content of the subgrade within 24 h. Further, as shown in Fig. 7(b), the initial water content was similar in each water profile except for Section B. The maximum and minimum initial water content in Section B was 20.9% and 14.2%, respectively. This may be attributable to uneven backfill compaction of the exploration wells after the sensors were embedded.

The wetting front of the profile at 0.5 m to the left and right of the facility center line gradually decreased with time. When the infiltration time was 24 h, the maximum water content was about 40% at 1.5 m and 2 m. The curves at 2 m and 3.5 m to the left of the facility centerline were approximately coincident, that is, the water content at these sections tended to be stable throughout the infiltration time. The infiltration appears to have little effect on the water content at this section.

As shown in Figs. 7(a) and 7(b), the water infiltration in the retention type of bioretention mainly affects the bottom of the facility. For the water profile at the bottom of the facility, in the bottom of Bioretention I, the wetting front gradually tended toward stability rather than decreasing with time, while the wetting front under Bioretention II moved downward with time.

3.3 Influence Range of Water Infiltration in Bioretention Facilities

A water content map of the loess site was drawn based on data gathered at different positions at different time points during the water infiltration process (Fig. 8).

[Insert Figure 8]

In Bioretention I, 4 h into the process of infiltration, the vertical diffusion velocity of water in the site was greater than that in the horizontal direction. The shape of the soil infiltration range was slender and pear-like. With an increase of infiltration time, the horizontal diffusion of the soil accelerated and the vertical diffusion decelerated until finally becoming stable. In Bioretention II, the infiltration range in the initial stage has a round, flat pear shape. The pear shape was gradually elongated as the infiltration progressed because the vertical diffusion significantly increased over the horizontal diffusion before becoming progressively stable.

In the initial stage of infiltration, water moving through Bioretention I significantly influenced the site's water content. After about 4 h of infiltration, the influence range was smaller in Bioretention II than in Bioretention I. The wetting front was located at the position where the water content increased by 3%, so in Bioretention I, the wetting front diffused to 1.5 m away from the centerline of the facility in the horizontal direction at a depth more than 2.54 m. In Bioretention II, the diffusion range was 2 m in the vertical direction and 1.5 m in the radial direction. The water infiltration range increased over time and was more intense in Bioretention II than elsewhere in the site. When the infiltration time reached 24 h, the horizontal infiltration effect was 3 m within Bioretention II, which was 1.75 m greater than that in Bioretention I.

4. MOISTENING DEFORMATION OF LOESS SITE

The effects of water infiltration through facilities on foundation deformation were further examined based on the change law of water content at the collapsible loess site and the wetting deformation curve of the soil layer.

4.1 Loess Moistening Deformation Calculation Method

Consolidation compression tests of undisturbed soil samples in typical loess site with different water contents under 200kPa load conditions were carried out, and the curve was fitted as shown in Fig. 9.

[Insert Figure 9]

The moistening deformation curve was fitted using Eq. (2):

(2)

where y is the vertical deformation of the 20-mm thick soil layer in mm and ϑ is the moisture content.

At the position of P_{i} (i=0,1,2…4), the initial water content was ϑ_{i0} and the initial vertical deformation was y_{i0} . At the time$t$, the water content and vertical deformation atP_{i} were ϑ_{t0} andy_{it}, respectively. The moistening deformation calculation diagram is given in Fig. 10.

[Insert Figure 10]

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The wetting compression of soil at $P_{\mathrm{i}}$is:

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(3)

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The wetting compression of soil

at time t of $P_{i\ \text{-}1}$ can be obtained using the same formula. The wetting compression of the soil layer with a thickness of h_i between$P_{i\ \text{-}1}$ andP_i is expressed as:

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(4)

Therefore, the moistening deformation Z at the time t ofP_{i} is:

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(5)

4.2 Moistening Deformation Law

The water content values of different facilities at different times in the immersion process were substituted into Eqs. (3) and (4). The moistening deformation of each position was calculated at different time points and a contour map of humidifying deformation of the loess site was obtained accordingly, as shown in Fig. 11.

[Insert Figure 11]

As shown in Fig. 11(a), in the initial stage of water infiltration, the maximum deformation was 3.5 mm away from the bottom of the facility at 0.35 m. By 6 h, the maximum deformation of the bottom of the facility increased to about 10.5 mm due to the rapid increase in water content, which was three times larger than that at 2 h. By 24 h, the water content and deformation of the bottom of the facility had both stabilized. There was deformation under the subgrade at that time but only by about 0.5 mm, which is far less than the specification for subgrade deformation. The water infiltration in Bioretention I, to this effect, did not impact the road safety around the facilities.

As shown in Fig. 11 (b), after 2 h of infiltration, the settlement at the bottom of the facility was about 1.5 mm. After 6 h, the deformation at the bottom of the facility reached 10.5 mm, which is seven times larger than that at 2 h. Once the water content was stable, the maximum deformation at the bottom of the facility reached 15 mm, which is 1.4 times larger than that at 6 h. The settlement of the site increased slowly with the gradual stabilization of the water content. After 24 h, the settlement of the subgrade was less than 1.5 mm, which is below the relevant specification. Again, it appears that water infiltration had little influence on the subgrade.

Water infiltration through biorentention facilities appears to have influence on the subgrade. The influence range of Bioretention II on the subgrade was smaller than that of Bioretention I in this experiment. This phenomenon is possibly attributable to the structural form of the facilities and the disturbance degree to the site during their construction processes.

5. PREDICTION MODEL OF WATER INFILTRATION DEPTH

Under the assumption of saturated-unsaturated stratification in the process of loess infiltration, a modified Green-Ampt (MGAM) model (Wen et al., 2020) was established to calculate the water infiltration depth in the loess area at different points in time (Fig. 12).

[Insert Figure 12]

According to the MGAM model, during the infiltration process, the cumulative infiltration I can be expressed as:

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(6)

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. (7)

So,

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. (8)

If

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(9)

then,

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(10)

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. (11)

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When t is very small, L_1 is negligible but

is not. Thus,

The infiltration depth L is:

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. (12)

In the above equations, ϑ_s is the saturated water content, ϑ_i is the initial water content,$\Delta\vartheta = \vartheta_s$-$\vartheta_i$ is the increase in water content, ?$_s$ is the saturated permeability coefficient (cm/min), K is the unsaturated permeability coefficient (cm/min), s_f is matric suction and H is the height of surface water accumulation (cm).

The model was used to predict the depth of water infiltration through bioretentions in loess. And this is an unsaturated infiltration process; it is difficult to obtain the unsaturated permeability directly. During the test, the cumulative infiltration I at different times$t$ was as shown in Fig. 13. The correlation between t and$I$

based on relevant soil parameters is expressed in Eq. (13). The average infiltration rate S was determined to be 1.698 according to Eq. (13).

[Insert Figure 13]

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(13)

Eq. (14) can be used to estimate the average unsaturated permeability coefficient of the test section:

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(14)

Besides, the relationship between s_{f} and Scan be showed with Eq. (15):

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(15)

The facilities concentrate rainwater, which increases the depth of soil moisture infiltration (Tu et al., 2009; Wu et al., 2018b). The adjustment coefficient $a = 1.20$ was taken to modify the infiltration depth values of the MGAM model. At t , the water infiltration depth L_{BIO}(cm) in the facilities can be calculated as follows:

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(16)

where L_{MGAM} is the infiltration depth calculated based on the MGAM model.

The hydraulic model parameters and infiltration depth values are listed in Table 3.

[Insert Table 3]

The average relative error was 10.41%, which indicates that the modified MGAM model effectively reflects the water infiltration depth of the loess area at different times within the bioretention facilities. The water infiltration depth of the facility increased as the initial water content at the site increased. The infiltration depth of water in the facility decreased as the saturated water content of the site increased. To prevent any adverse impact caused by the bioretention facilities to the loess foundation, compaction and other foundation treatment methods can be used to adjust the saturated water content at the site so as to control the influence range of rainwater infiltration.

6. CONCLUSION

In order to ensure the functionality of typical LID facilities and the safety of the surrounding buildings and roads in collapsible loess areas, a full-scale field test on water infiltration in typical stagnant bioretention facilities was carried out. The water content and moistening deformation law of the site during the process of rainwater infiltration were comprehensively analyzed. The conclusions of this work can be summarized as follows.

(1) As rainwater infiltrates the stagnant bioretentions in the loess area, the infiltration effect first increases and then tends toward stability. The influence range of rainwater varies with the type of facility. The retaining wall type affects the site more intensely at the initial stage of infiltration, while the sloping type has a more significant impact on the site at the later stage of infiltration.

(2) Water infiltration mainly affects the bottom of the facilities but has little effect on the subgrade. The subgrade deformation specification was met at the test site. The deformation under the subgrade of the retaining wall type facility was 0.5 mm and exerted a greater impact on the subgrade deformation than the sloping type facility. When the bioretentions are constructed near a municipal road, sloping infiltration facilities should be given priority.

(3) The modified Green-Ampt model accurately reflects infiltration rainwater law in the collapsible loess field under bioretentions. The model's average infiltration depth error is about 10%.

(4) The adverse effect of water infiltration in the retention type bioretention can be mitigated by adjusting the initial water content and saturated water content in the loess area.

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