Mechanical properties of re-packed reinforced Earth embankment during service stage

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ABSTRACT
Problems of large settlements and uneven settlements on the road always happen during service stage. Reinforced embankments can reduce these problems. But currently the study on the mechanical properties of reinforced embankments during service stage are so few, and lack of measured data. This study uses numerical simulation and on-site measured data analysis to set up a geogrid creep damage model and traffic load model. Based on the analysis of the mechanical properties of reinforced embankment under the conditions of new test section and widening test section, the influence laws of traffic load amplitude, frequency and driving interval on reinforced embankment are obtained. When the traffic load amplitude is 2q₀, there is little difference in settlement between the two test sections; but the settlement ratio gets the maximum value of 0.028 mm/d when the amplitude is 2q₀. When the traffic load frequency increases from 1 Hz to 4 Hz, the embankment settlement is in the sudden settlement stage, and the settlement is almost stable after 4 Hz. When the driving interval is greater than 4 s, the rebound value and rebound time are almost stable.

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Re-packed reinforced soil; traffic load; long-term performance; mechanical properties

1. Introduction
Disaster investigation shows that the embankment will produce deformation and settlement under the repeated action of soil weight, environmental factors, and traffic loads, which affects road stability and safety directly, as shown in Figures 1 and Figures 2 (Feiyu
2007). Figure 1 shows the local settlement disease of the filled embankment during the service stage, and the disease is located on the side of the road near the canal. Figure 2 is a schematic diagram of road cracking caused by a traffic flow of 30,000 vehicles/day for 1 year. Reinforcement can prevent from uneven settlement of embankment, which get widely attention in road engineering.

Reinforced earth structure, due to its light weight, low cost, and strong foundation adaptability, has been widely used in the support structure of road, water transport, water conservancy, railway and other civil engineering projects and the reinforcement of embankments. The geocell (Vinay Kumar and Saride 2016) applied to the granular foundation layer shows a relatively better improvement, reducing the permanent deformation of the granular foundation and increasing the percentage of elastic deformation (MehrpaZhoh, Tafreshi, and Mirzababaei 2019). Placing a layer of 0.3 m thick reinforced material in the non-woven geotextile (Yu et al. 2019) and compacting the soil at 97% significantly reduces the penetration force of the CBR piston at all target repeated load levels. Compared with the non-geogrid solution, it is applied to the track structure under pressure (Correia and Zornberg 2018), and the geogrid solution reduces the settlement of the structure. The mechanical extensometer attached to geogrid is used to check the elastic and permanent components of displacement caused by geogrid (Bergado and Teerawattanasuk 2007), and the results show that the existence of geogrid in asphalt cover will lead to lateral restraint mechanism. Two full-scale test embankments (Narani et al. 2020), i.e., steel grating embankment (long embankment) with a length-to-size ratio of 3.0 and hexagonal network reinforced embankment, are used with the same constitutive model and characteristics of foundation soil as those of previous researchers. The experimental results show that 2D and 3D numerical analysis should be regarded as important factors that may affect the numerical simulation results, which are consistent with the current settlement prediction using Skempton-Bjerrum correction.

There are many existing reinforcement methods, but few use turn-up geogrids to reinforce embankments. Adding different content of waste tire textile fiber (WTTF) to the sand to carry out repeated load triaxial test (Xiaoyong and Jing 2016), the results show that adding fiber will increase the permanent strain. The use of geogrid as a flexible reinforcement material (Fattah, Zabar, and Hassan 2016) can effectively improve the mechanical performance of the widened roadbed. The test results of using ordinary stone pillars and closed stone pillars as reinforcement materials show that (Sakleshpur et al. 2019), the column wrapped with geogrids is the most effective to improve the bearing ratio of the reinforced soil.

A series of studies on the mechanical properties of reinforced embankments have also been carried out. Through direct shear test (Tingle 2019), the open area and bonding strength of the geogrid are important factors that affect the shear strength response of the soil–aggregate interface. Through dynamic centrifugal model tests, three types, namely large stone cages, drainage reinforced piles and ground anchors with pressure plates, have been obtained. The reinforcement effect is good. The correlation between the influencing factors and the vertical stress-settlement response of the underground soil pile-embankment system was established through parameter research (Rui et al. 2020). Through the numerical simulation of the embankment model (Fattah, Mohammed, and Hassan 2016), it was found that the bearing capacity increased by 13% and 23%, respectively, when the geogrid layer was embedded at the interface and 0–1 h. For soft soil embankments reinforced with ordinary stone pillars, as the load increases, the settlement value will decrease, which means the ultimate bearing capacity increases (Al-Taie, Al-Kalali, and Fattah 2019). By studying the engineering performance (CBR) of different types of soil subgrades reinforced by geogrids (Rajesh, Saja, and Chakravarti 2016), the results show that the influence of plasticity and fineness (%) and the effect of geogrids on improving the performance of immersed CBR, while in the absence of the grid, this performance is very poor. In general, the research focuses on static loads, and there
is a lack of research on reinforced structures under traffic loads.

For the reinforced embankment under traffic load, the following studies are made. The finite element method is used to carry out implicit dynamic analysis of reinforced soil subgrade under traffic load, and based on the calculation of cumulative plastic deformation and analysis of influencing factors, it is revealed that reinforcement reduces the residual deformation of subgrade soil (Shichuan and Jianming 2011). The results show that dynamic the deviator stress is one of the important factors that cause the residual deformation of the roadbed. The greater the stiffness of the geogrid, the more significant the reduction of the dynamic deviator stress. The finite element analysis program is used to predict the soil-soil interaction under vehicle load (Shuwang, Xinqiang, and Run 2004), and it is concluded that the geogrid placed at the bottom of the base layer can effectively reduce the cumulative plastic deformation caused by the periodic load of the vehicle. Through 7 sets of large-scale

| Measuring point | Symbol | Test items          |
|-----------------|--------|---------------------|
| S1              | ⬤      | Settlement          |
| S2              | ⬤      | Grid strain         |
| S3              | ⬤      | Earth pressure      |
| S4              | ⬤      | Horizontal shift    |

**Table 1.** Test item test table.

![Figure 3. Schematic diagram of the test plan of the test section.](image)

**Figure 3.** Schematic diagram of the test plan of the test section.

![Figure 4. Site map of the test section.](image)

**Figure 4.** Site map of the test section.
laboratory tests, the settlement and dynamic response characteristics of shallow square feet on geogrid-reinforced sand under cyclic loading were studied (Wang et al. 2018), and it was found that if the reinforcement is too shallow, the depth of the first layer of reinforcement is in the case of 0.3B, the rupture of the geogrid may occur under cyclic loading. Based on the soil model, a numerical study on the cyclic load response of the strip foundation supported by the geosynthetic material filled embankment was carried out (Alam, Gnanendran, and Lo 2018), and a reasonable and good agreement was obtained between the experimental observation and the numerical prediction. Through dynamic triaxial test and numerical simulation analysis (Wei et al. 2016), the dynamic characteristics and deformation behavior of soil and reinforced soil under cyclic loading are studied, and the mechanical properties and application of geosynthetic reinforced soil are studied. There are many studies on the mechanical properties of reinforced embankments under traffic loads, but there are few studies on turn-up reinforced embankments, and there is a lack of experimental data on long-term performance during service stage.

So, the study on the mechanical properties of the reinforced earth embankment under the traffic load, combining with the long-term actual measured data was conducted. Comparing the new built test section and widened test section, the influence of traffic load on the settlement of reinforced embankment is predicted. The study has great theoretical and practical significance in rational economic design of reinforced embankments and the guarantee of long-term performance.

### 2. Field testing plan

The connection section of a new construction highway in Yunnan Province of China was selected as the site test section. To further research the mechanical properties of the back-packed reinforced earth embankment under traffic load, a corresponding number of sensors were placed at fitting locations in the reinforced earth embankment to record the settlement,
grid strain, earth pressure and horizontal displacement. The location and number of sensors are shown in Figure 3.

The test items corresponding to the test points in the schematic diagram of the test plan of the test section are shown in Table 1.

The two test sections include 100 m long widened reinforced embankment and 100 m long new reinforced embankment, as shown in Figure 4. After the size of the embankment to be built and the location and quantity of the corresponding test equipment are determined, the embankment in the test section is built. First, the foundation surface needs to reach the compaction standard. Second, lay the first layer of geogrid. Third, lay the filler on the geogrid. When filling, you need to follow the rule of “first fill the two sides, then fill the middle”. After the filler is laid and compacted according to the rule, the next layer of grille can be laid. The on-site rolling diagram is shown on the right side of the Figure 4 and the geogrid return chart is shown in the lower left corner of the Figure 4. The use of grass seed bags on the roadbed slope can temporarily fix and protect the slope. Sensors need to be arranged in the test section, then the corresponding sensors are tied to the geogrid at the specified location. The sensor arrangement is shown in in the upper left corner.

The physical parameters of backfill soil are shown in Table 2.

3. Results and analysis
3.1. Diffusion coefficient

After the embankment construction in the test section is completed, the mechanical properties of the reinforced embankment under traffic load can be tested. At the same time, the reinforced embankment between the new test section and the widened test section are compared.

In order to measure the diffusion effect of geosynthetics on load, a diffusion coefficient $k$ is quoted in the literature (Gongxin et al. 2005). In this paper, let $K$ represent the diffusion coefficient which describes the diffusion effect of geosynthetics on load:

$$ K = \frac{s_1}{s_2} $$

Where $s_1$ – Daily accumulated road center settlement under traffic load;

$s_0$ – Daily accumulated road edge settlement under traffic load;

$K$ – The diffusion coefficient of geosynthetics to the load.

Diffusion coefficient $K$ is the ratio of daily accumulated middle road settlement and daily accumulated edge road settlement measured by the sensor under long-term traffic load. The distribution of diffusion coefficient $K$ is shown in Figure 5. $K_1$ comes from new test section and $K_2$ comes from widened test section. It can be seen from Figure 5 that the diffusion coefficient value of the new test section and the expanded test section are both bigger than 1. As the time pass by, under the first 100 days’ traffic load, since the road is a new road, the settlement of subgrade is increasing every day and the subgrade is gradually compacted, settlement basically showing an upward trend. Under the second 100 days’ traffic load, the settlement of subgrade is basically stable.

It is worth noting that in the range of 200–250 days of traffic load, there is a phase that does not match the previous rules. After 250 days of traffic load, the diffusion coefficient tends to be stable again. It can be seen from the investigation that the sudden change time interval in the curve corresponds to local August, which is rain season. There are many times of heavy rainfall. The increase of soil moisture, the decrease of porosity and accumulated sub-grade settlement make the diffusion coefficient change suddenly. After the rain season pass away, the moisture in the soil decreases and the porosity increases. Under traffic load, the compression coefficient will increase, resulting in the rising section of the sudden change section. Subsequently, the diffusion coefficient tends to be stable again.

Figure 6 describes the distribution of earth pressure along the embankment height after returning to the bag. S1–S3 come from new test section, and S4–S6 come from widened test section. The study records the distribution of earth pressure along the embankment height at six locations of the test section. Generally speaking, the distribution law of earth pressure along the embankment height of each panel is the same. The earth pressure distribution law is: big in the middle and small in the end. That is to say, the

![Figure 6. Distribution of earth pressure along the wall (embankment) height after returning to the bag.](image-url)
earth pressure at the top and bottom of the embankment is relatively small, while the earth pressure in the middle of the embankment is relatively large. The result is basically the same as the conclusion of Salman, F. A., Fattah, M. Y. and others (Salman et al. 2011). They estimate the earth pressure distribution generated behind a 20 m high retaining wall by the finite element method and compared with that obtained from classical earth pressure theories. The shape of the pressure distribution obtained by Dubrova’s method has a parabolic shape and its maximum value appears at about one-third from the wall base.

Figure 7. Strain curves of expanded test section and new test section.

Figure 8. Settlement curve and settlement rate curve.
Comparing Figures 5 and Figures 6, the diffusion effect of the new test section is better than that of the geosynthetics in the widened test section, which can make the load more evenly distributed in the embankment and improve the stability and safety of the embankment.

3.2. Grid strain curve

The grid strain-Time curve of the widened test section and the new test section is Figure 7. Strain sensors are set at each layer of geogrid. The top, middle and bottom of geogrid strain curves are selected as representatives for analysis and comparison. Sequence 1 is the strain curve of middle geogrid. Sequence 2 is the strain curve of top geogrid. Sequence 3 is the strain curve of bottom geogrid. Compared with the grid strain curves of the widening test section and the new test section, it can be seen that the grid strain curves can be divided into four stages: the rising stage, the stable stage, the mutation stage (heavy rainfall induced) and the restable stage. However, the difference between the two test sections is that under the same traffic load, when the strain curve of the middle grid tends to be stable, the strain of the geogrid in the widened test section reaches 2.25%, while the strain of the geogrid in the new test section reaches 1.6%. Similarly, when the top and bottom grids tend to be stable, the grid strain of the widened test section is also greater than that of the new test section. And with heavy rainfall, the mutation value of the new test section is smaller than that of the widened test section.

It can be seen from Figure 7 that with the completion and opening of the road in the test section, under the long-term reciprocating action of traffic load, the grid strain develops continuously in the first 40 days, forming the rising trend in the first stage. After a period of load, the grid strain reaches a stable value. Under the ideal condition of the test section, the grid strain tends to be stable, forming a stable curve in the second stage. As the third stage corresponds to the local August of the test section, it has suffered heavy rainfall for many times, resulting in the increase of soil moisture in the embankment, the grid retraction, reducing the grid strain. After the end of heavy rainfall, the water content in the embankment decreases, and the grid strain increases, forming the catastrophe curve of the third stage. Subsequently, the strain curve of the grid tends to be stable again.

Comparing the curves above, it can be seen that the strain of the grid increases gradually as the time pass by. One to three months after construction, the strain of the grid tends to be stable and reaches the maximum value. Under the same conditions, the grid strain curve of the embankment of the new test section is more stable, so the stability of the embankment of the new test section is better than that of the widened test section embankment, which is less affected by the weather.

3.3. Settlement-time curve and settlement rate-time curve

According to the test data, the settlement curve and settlement rate curve can be obtained, as shown in Figure 8. In Figure 8, S1 is a new test section and S2 is a widened test section. It can be seen from Figure 8, the accumulated settlement of the new test section is bigger than that of the widened test section, but the settlement trend is basically the same. After 350 days of traffic load, the total settlement of the new test section and the widened test section reaches 11.5 mm and 10.5 mm. However, for the settlement rate curve, the settlement rate of the newly built test section is about 0.3 mm/d in the initial stage, while that of the widened test section is about 0.1 mm/d. The settlement rate of the newly built test section is 3 times of that of the widened test section. After 50 days, the settlement rate curve of the two sections is relatively close. After the long-term action of traffic load, if the subgrade is compacted certainly, the subgrade will not continue to settle. When the settlement increment can be ignored, the settlement rate is close to 0.

From Figure 8, in the period of 200–250 days in Figure 9, there is a sudden change in the settlement rate, which coincides with the appearance of the third stage mentioned in Section 3.2.

Figure 9. Distribution of grid tension with horizontal distance.

Figure 10. Creep damage model of geogrid.
3.4. Grid tension-horizontal distance curve

Figure 9 shows the distribution of grid tension with horizontal distance. In Figure 9, S1–S5 comes from new test section, and S6–S9 comes from widened test section. Under the traffic load, the maximum grid tension occurs at 2 m from the center of pavement. In the two test sections, the grid stress along the horizontal distance is distributed in the range of 0 to 2 meters from the road center-line. The farther away from the road center-line, the bigger the grid stress is. In the range of two to four meters away from the road center-line, the grid stress is almost stable with the increase of distance. In the range of four to six meters away from the road center-line, the farther away from the road center-line, the smaller the grid stress is. The distribution rule of grid stress with horizontal distance can be divided into three stages, the rising stage (0–2 m), the gentle stage (2–4 m) and the falling stage (4–6 m). Since the horizontal length of the geogrid laid in the widening test section is limited by the size of the widened embankment, S6–S9 in Figure 9 show the tensile force of the grid on the length of the geogrid that can be laid at different heights in the widening section.

4. Numerical analysis model considering traffic load

4.1. Creep damage model of geogrid

The four-parameter creep model is composed of Kelvin model, elastic element and plastic element, as shown in Figure 10. The plastic element is used to measure the plastic strain of geogrid, and a tensile modulus is used to obtain the strain (Guangqin et al. 2019).

As a viscoelastic model of geogrid creep, the constitutive relation is

$$\sigma = \sigma_0 + \sigma_1 \dot{\varepsilon} + \sigma_2 \ddot{\varepsilon}$$  \hspace{1cm} (2)

Where: $\sigma$ is stress, $\varepsilon$ is strain, $\dot{\varepsilon}$, $\ddot{\varepsilon}$, $\sigma_1$, $\sigma_2$ are the first and second derivative of stress and strain, respectively. $\sigma_1 = \frac{\eta}{E_1} \dot{\varepsilon}$, $\sigma_2 = \frac{\eta_1}{E_1} \ddot{\varepsilon}$, $\eta$, $E_1$ is the viscosity of the clay pot and the elastic modulus of the spring in Kelvin model. $E_0$ is the tensile modulus of plastic element in series with Kelvin model. $E_0$ is the elastic modulus of the spring in series with Kelvin model and plastic element, which is determined by fitting the creep test data curve.

The stress $\sigma = \Delta(t) \cdot \sigma_0$ (t is creep time) is substituted into constitutive Equation (2). Where, $\sigma_0 = 4.3 \text{MPa}$ is the constant stress initially applied in the creep test, also known as the nominal stress in the case of no damage. By using Laplace transform and its inversion, the creep strain of geogrid under the condition of no damage is

$$\varepsilon(t) = \frac{\sigma_0}{E_0} + \frac{\sigma_0}{E_1} \frac{1 - \exp \left( -\frac{E_1}{\eta_1} t \right)}{1}$$  \hspace{1cm} (3)

According to the damage mechanics, Rabotnov proposed that the damage factor was

$$D = A - \frac{A}{A}$$  \hspace{1cm} (4)

Where, A is initial cross section before loading and is effective bearing area.

The effective stress $\bar{\sigma}$ of material under load is

$$\bar{\sigma} = \frac{F}{A} = \frac{\sigma_0}{1 - D}$$  \hspace{1cm} (5)

Where, F is external load applied by creep test.

When using coupling damage mechanics to study the creep deformation of geogrid, the change rate of kanchanov creep damage factor is obtained by Norton formula

$$D = a a^n (1 - D)^{-n}$$  \hspace{1cm} (6)

Where, $a$, $n$ are damage parameters of materials.

The damage time threshold of creep is obtained from Equation (6)

$$t_s = \left[ a (1 + n) a^n \right]^{-n}$$  \hspace{1cm} (7)
According to formula 6 and 7, the evolution rule of damage factor $D$ is

$$D = 1 - 1 - \frac{t^{\frac{1}{m}}}{\tau} = 1 - [1 - \alpha(1 + n)\sigma^m t^{\frac{1}{m}}]$$

(8)

According to Lemaitre’s strain equivalent principle, it can be concluded that the damaged geogrid’s deformation can be calculated by the effective stress of the geogrid itself. For any material in damage state and non-destructive state, the constitutive relation is the same. So, the constitutive relation of damaged material can be obtained by the nominal stress of non-destructive material. Only the nominal stress in non-destructive state is replaced by the effective stress. By substituting Equation (8) into Equation (5) and the calculation results into Equation (3), the viscoelastic plastic constitutive equation of creep damage of geogrid under constant stress can be obtained as follows.

$$\varepsilon(t) = \frac{\sigma_0}{E_0} + \frac{\sigma_0}{E_1} + \frac{\sigma_0}{E_2} \left[ 1 - \exp \left( -\frac{E_2}{E_1} t \right) \right]$$

(9)

The relevant data of geogrid used in the field test are determined by test (Figure 11) as shown in Table 3.

### 4.2. Traffic load model

Asymmetric half wave sinusoidal load ($q_u$) is designed to simulate the traffic load on the top of embankment. And $q_u$ acts on the road surface within 12 m of the top of the embankment, while the frequency $f$ is 0.1 Hz and the driving time interval is 4 seconds. The left amplitude load amplitude of the road $q_1$ is 50 kPa while the right amplitude load amplitude of road $q_2$ is 20 kPa, which is the basic working condition of asymmetric traffic load, as shown in Figure 12. The free boundary is used in the dynamic calculation to reduce the influence of boundary effect on the calculation results.

The changing law of traffic load $q_u$ with loading time is shown in formula 10 and Figure 13. The change
Comparing Figures 13 and Figures 7, it can be found that excluding the third stage of Figure 7, the change trends of the two figures are consistent. So, it shows that the numerical analysis model used in this study is correct.

5. Parametric analysis

5.1. Influence of traffic load amplitude

Design three different load amplitude working conditions, which are $q_0\cdot 2q_0, 3q_0$, respectively, as shown in Figure 14. The influence of traffic load amplitude on the mechanical properties of embankment is analyzed under three working conditions.

The influence of traffic load periodicity with different amplitude on the settlement and settlement speed of reinforced embankment pavement is shown in Figure 15. S1 comes from new test section, and S2 comes from widened test section. It can be seen from Figure 15 that the change rule of settlement and settlement rate of the new test section and the widened test section are similar. In the observation range, the settlement and settlement speed of the two conditions increase periodically with the number of load increases. The settlement both gradually reach the same maximum value and the settlement speed is close to 0. The vertical settlement is increasing with the load amplitude (Hamdi, Fattah, and Aswad 2020).

5.2. Influence of traffic load frequency

Increase the traffic load frequency from 1 Hz (Shaowen, Jun, and Ling 2014), and the influence of traffic load frequency on the settlement of reinforced embankment pavement is shown in Figure 16. In Figure 16, S1 comes from the widened test section, and S2 comes from the new test section. According to the experimental results curve, the greater the frequency of traffic load is, the shorter the time for pavement settlement to reach stability, the smaller the settlement when stable, and the smaller the rebound amplitude of settlement. The different location of traffic load also leads to the more differential settlement along the road surface. When the frequency of traffic load increases from 1 Hz to 4 Hz, the embankment settlement is in the sudden drop stage. When the frequency continues to increase after 4 Hz, the embankment settlement is very small, and the change amplitude with the frequency is also small.

5.3. Influence of traffic load headway

Take the interval $t$ of driving load as 2 s, 4 s, 6 s, 8 s, etc. And record the rebound amount and rebound time of embankment settlement under different intervals.
Figure 17 shows the relationship between rebound time, rebound amount and loading time of reinforced embankment under traffic load time interval. The data of new test section and widened test section are compared for research. It can be seen from Figure 17 that the longer the time interval between driving loads, the longer the gentle section in the curve is. With the increase of time interval, when the rebound experience time of embankment settlement is longer, the more sufficient the rebound is and the greater the rebound is. Finally, the settlement tends to be stable. When the time interval between driving loads is longer than the time required for the complete elastic rebound of the embankment, the rebound is the maximum elastic variable of the embankment. And then the settlement rebound will not change any more. The smaller the time interval of load, the more obvious the advantage of reinforced embankment are. According to literature 24, when the driving interval, $\Delta t$, is greater than 4 s, the effect of increasing the interval on the maximum road settlement is small. And the road rebound value and rebound time obtained this study are basically stable when the interval is greater than 4 s. This shows the correctness of the test results in this study.

6. Conclusion

This study reveals that the traffic load how to affect the mechanical properties of the reinforced earth embankment. Comparing long-term monitoring data between the new test section and the widened test section and combing with numerical analysis model, the rule of the amplitude, frequency and driving interval of the traffic load on the reinforced embankment is analyzed. The conclusions as following.

(1) According to the load diffusion coefficient diagram of geosynthetics in the embankment of new test section and widening test section, under the traffic load, the overall layout of geosynthetics are better than that of local layout, and the stress distribution is more uniform. According to the distribution of earth pressure along the embankment height after returning to the bag, the earth pressure reaches the maximum value at a position 2 m away from the bottom of the embankment, and the earth pressure gradually decreases from the middle of the embankment to the top and bottom.

(2) The strain curve of the grid in the middle part is larger than that of the top and bottom of the embankment. Under the traffic load, the settlement of the new test section and the widened test section is approximately the same, and the initial settlement speed of the new test section is bigger.

(3) The settlement of reinforced embankment develops approximately linearly with the change of load amplitude, but the settlement rate reaches the maximum value of 0.028 mm/n when the amplitude is $2q_0$. Under the two conditions, the pavement settlement decreases with the increase of load frequency. The larger the driving interval is, the smaller the pavement settlement is. When the driving interval is greater than 4 s, the rebound value and rebound time are almost stable. The smaller the driving interval is, the less time is required for the settlement rebound of embankment, and the more obvious the advantage of reinforced embankment are.

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