Durability-Aimed Design Criteria of Cement-Stabilized Loess Subgrade for Railway

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Abstract: The subgrade is the foundation of railway construction, so its strength and stability are very important to ensure the safety and stability of a train. Loess is widely distributed in northwestern China, and it must be stabilized before being used in railway subgrade construction because loess is sensitive to water. Railway subgrade withstands not only the train load but also repeated attacks from the environment and climate because it has to be exposed to natural environment after construction. Therefore, the strength of cement-stabilized loess deteriorates continuously because of the above factors. Taking account of long-term stability, the influences of load on the cement-stabilized loess as well as the strength reduction laws of cement-stabilized loess under wet–dry cycling and freeze–thaw cycling were analyzed in this study. Additionally, the respective reduction coefficients were obtained. Finally, the strength design criteria of cement-stabilized loess subgrade were put forward based on railway subgrade durability by analyzing the obtained reduction coefficients and the critical dynamic strength of railway subgrade.

Keywords: loess; strength; wet–dry cycling; freeze–thaw cycling; design criteria

1. Introduction

Loess has good strength and high compressive resistance, which has been widely used in the construction of railway subgrade. However, loess is sensitive to water, so it is prone to significant deformation and settlement after being immersed in water. Cement is usually used to improve the characteristics of loess [1–4]. Besides, innovative recycled materials such as plastic and glass have been used in railway substructure [5,6]. The strength of cement-stabilized loess gradually deteriorates under the action of wet–dry cycling, freeze–thaw cycling and repeated load because railway subgrade is exposed to the natural environment. Therefore, when designing the railway subgrade filling, the impact of environment and the train load on the subgrade should be considered to ensure the long-term strength, stability and durability of the subgrade.

At present, as for stabilized soil, many engineering departments use unconfined compressive strength $q_u$ as the strength index in China and other countries [7–9]. The actual experience of railway departments in China shows that it is safer to choose 7-day saturation strength as the strength of stabilized soil 10. As for the durability of subgrade, many countries refer to the loss rate of mass or strength after 12 times of wet–dry and freeze–thaw cycling, according to the ASTM (American Society for Testing Material). However, the loss rate of strength after only 5 times of wet–dry and freeze–thaw cycling is used to control the durability of subgrade in China [11], and long-term stability under influences of wet–dry and freeze–thaw cycling is less considered. The strength design criteria of stabilized soil of subgrade bottom and embankment below the subgrade of all grades of the
railway are shown in Error! Reference source not found., which is provided by “Code for Design of Railway Earth Structure” 12.

Table 1. The strength requirement of stabilized soil in China.

| The Grade of Railway | Design Speed (km/h) | 7-Day Unconfined Compressive Strength Saturated with Water (kPa) |
|----------------------|---------------------|---------------------------------------------------------------|
|                      |                     | Subgrade Bottom | Embankment below the Subgrade |
| Passenger and freight railway, Ballast track | 120, 160 | ≥350 (550) | ≥200 |
| Inter-city railway, Ballastless track | 200 | ≥350 (550) | ≥250 |
| High-speed railway, Heavy-haul railway | - | ≥350 (550) | ≥250 |

Note: The contents in brackets refer to the strength value of stabilized soil considering freeze–thaw cycling.

In this study, several inter-city railways in Shaanxi, China, were selected for testing. The first selected loess was not immersed in water with a compaction level of 90%. Its minimum unconfined compressive strength was 420 kPa, which is 1.20 times the required critical strength (350 kPa) of the subgrade bottom. The second selected 8 types of cement-stabilized loess were saturated with water with 90% compaction level and 3% cement dosage. Its minimum 7-day unconfined compressive strength was 514 kPa, which is 1.47 times the required critical strength of the subgrade bottom. It can be seen that the design criteria in Error! Reference source not found. cannot control the construction quality very well.

In fact, the design criteria of filling can be determined by Equation (1) based on strength control.

\[
[q_u] \geq \sigma_{dmax} \quad (1)
\]
\[
[q_u] \geq \sigma_{dmax} \quad (2)
\]

where

- \([q_u]\) is the strength considering the impact of the environment and train load on the subgrade filling, kPa;
- \(q_u\) is the strength without the impact of the environment and train load on the subgrade filling, kPa;
- \(\sigma_{dmax}\) is the maximum dynamic stress of subgrade, kPa;
- \(k_f\) is the fatigue reduction coefficient of the subgrade filling under repeated train load;
- \(\eta_G\) is the strength reduction coefficient of the subgrade filling under wet–dry cycling;
- \(\eta_D\) is the strength reduction coefficient of the subgrade filling under freeze–thaw cycling.

The strength design criterion \(q_u\) of subgrade filling can be obtained by substituting Equation (2) into Equation (1).

\[
q_u \geq \sigma_{dmax} / (k_f \cdot \eta_G \cdot \eta_D) \quad (3)
\]

Two aspects should be considered when determining the strength design criteria of subgrade filling for the railway. One is \(\sigma_{dmax}\), and the other is \(\eta_G\) and \(\eta_D\). For dynamic stress, Zhu et al. investigate dynamic compressive stress characteristics and related influencing factors in the permafrost site along Qinghai-Tibet Railway 13. Yao et al. presented a full vehicle-track-ground coupling model to evaluate the dynamic response of subgrade under high-speed trains 14. Wang et al. compared the dynamic responses of the earth structures constructed using stabilized cinders and traditional geomaterials 15. Ma et al. conducted the dynamic triaxial tests on cement- and lime-improved loess specimens to study the cyclic shear strain threshold and critical dynamic stress 16. Fang et al. established a new track-multilayer ground model to investigate railway subgrade dynamic responses...
induced by moving train load. Moreover, dynamic responses of high-speed railway and heavy-haul railway were studied by some scholars. In China, Ye et al. studied the subgrade design indices of improved soil and found that the cumulative deformation rate of stabilized soil was less than 0.5% when the strength of improved soil was 5 times the critical dynamic strength of filling. Based on theoretical calculation and field measurement data, the strength design criteria of filling can be 250 kPa of the top surface of the subgrade bottom and 125 kPa of embankment below the subgrade bottom when the design values of dynamic stress are 50 kPa and 25 kPa, respectively, and the actual design criteria are 416 kPa and 208 kPa because of the differences between field and laboratory, which is basically consistent with Error! Reference source not found.

As for train loads, Fahoum et al. studied the fatigue stability of cement-stabilized soil under a cyclic load of the train. Preteseille et al. pointed that the selection and design of filling are closely related to fatigue performance, which can avoid empirical errors. Lenior et al. studied the fatigue performance of fiber-cement-stabilized soil and found that the fatigue performance of cement-stabilized soil-doped fiber was improved.

As for environmental factors, the effects of wet–dry cycling and freeze–thaw cycling were studied. Yan et al. investigated the characteristics of unconfined compression strength and void distribution of lime-flyash loess by means of a series of experiments under freeze–thaw cycling or wet–dry cycling. Besides, Yan et al. studied the reduction law of the antierosion ability parameters of PP fiber-reinforced loess under wet–dry cycling and freeze–thaw cycling. Hu et al. established a compacted loess reduction model that comprehensively considers the influencing factors. Zhang et al. studied the influence of cement dosage and water content on the compressive strength of cement-stabilized soil under wet–dry cycling and found that cement dosage is the decisive factor to affect the durability of wet–dry resistance of cement-stabilized soil. Helson et al. studied the mass change of cement-stabilized soil under wet–dry cycling. Zhao et al. studied the shearing strength characteristics of cement-stabilized soil under freeze–thaw cycling.

In view of the required values being too low to be better used for engineering control due to defective consideration of strength reduction of cement-stabilized loess under wet–dry cycling, freeze–thaw cycling in current criteria in China, the strength design criteria of cement-stabilized loess combined the above factors were investigated in this study. Firstly, the strength reduction coefficients of cement-stabilized loess were calculated under train load, wet–dry cycling and freeze–thaw cycling. Additionally, the dynamic stress of the railway subgrade and the critical dynamic strength of filling were analyzed. After that, the values of each index in Equation (3) could be determined. Finally, the strength design criteria were presented after a comprehensive analysis.

### 2. Experimental Design

#### 2.1. Materials

##### 2.1.1. Loess

The physical properties of loess used in this study are shown in Error! Reference source not found. The loess was collected from the area where the Xi’an-Hancheng intercity railway is located. The appearance of the loess is bright yellow and loose. The type of the loess is silty clay, and the depth is about 3 m.

| Technical Indices | Particle Density (g/cm³) | Liquid Limit (%) | Plastic Limit (%) | Plasticity Index | Percentage Passing (%) of Sieve Sizes (mm) |
|-------------------|--------------------------|------------------|-------------------|-----------------|------------------------------------------|
| Test value        | 2.74                     | 26.4             | 15.7              | 10.7            | 2.47                                    |

Table 2. Physical properties of loess.
2.1.2. Cement

The technical properties of cement for performance tests are shown in [Error! Reference source not found.], which was P.O42.5 ordinary Portland cement.

| Technical Indices | Fineness (%) | Soundness | Ignition Loss (%) | Initial Setting Time (min) | Final Setting Time (min) |
|-------------------|-------------|-----------|-------------------|---------------------------|-------------------------|
| Testing standard  | ≤10         | Qualified | ≤5                | ≥45                       | ≤600                    |
| Test value        | 1.2         | Qualified | 1.02              | 265                       | 320                     |

2.2. Specimens Preparation

The optimum moisture content and the maximum dry density of cement-stabilized loess with each cement dosage were determined according to the heavy compaction test from the “Code for Soil Test of Railway Engineering” [53]. The specimens were prepared by static pressure method, and the prepared specimens were placed in a curing room with a temperature of 20 ± 2 °C and a humidity of 95% until 24 h before the specified curing time.

Different cement dosages were used to study the strength reduction coefficient of cement-stabilized loess influenced by wet–dry cycling, freeze–thaw cycling and load. The cement dosages were 2%, 3%, 4% and 6%, respectively. The influences of wet–dry cycling and freeze–thaw cycling on the strength of cement-stabilized loess were studied. Various compaction levels were conducted, which are 92%, 95% and 97%, respectively.

2.3. Test Methods

2.3.1. Fatigue Test

The fatigue test using the indirect tension method was chosen in this study. The mode was stress control, and the load was a sinusoidal wave. The cyclic characteristic coefficient $R$ (maximum and minimum stress ratio) was 0.1 [54], the 5 stress levels $S$ were 0.85, 0.80, 0.75, 0.70 and 0.65, and the load frequency was 4Hz. The material testing system (MTS-810) was used for the test, and the setup of the specimen is shown in Figure 1.

![Figure 1. The setup of specimen.](image)

2.3.2. Wet-Dry Cycling

The specimens were immersed in water at a temperature of 20 ± 2 °C for 24 h and divided into 2 groups. Specimens from the first group were tested according to the wet–dry cycling test method [55]. Then, the unconfined compressive strength of all specimens were tested according to the method of TB10102 [53]. The unconfined compressive strength without wet–dry cycling was denoted by $q_u$, and the unconfined compressive strength with $n$ times of wet–dry cycling was denoted by $q_c$. 
2.3.3. Freeze-Thaw Cycling

The freeze–thaw cycling was conducted according to T0858 of “Test Methods of Materials Stabilized with Inorganic Binders for Highway Engineering” [56]. The specimens were immersed in water at a temperature of 20 ± 2 °C for 24 h and divided into two groups. Specimens from the first group were performed \( n \) times of freeze–thaw cycling. Then, the unconfined compressive strength of all specimens was tested according to the method of TB 10102 [53]. The unconfined compressive strength without freeze–thaw cycling was denoted by \( q_u \), and the unconfined compressive strength with \( n \) times of freeze–thaw cycling was denoted by \( q_Du \).

3. Results and Discussion

3.1. Fatigue Performance of Cement-Stabilized Loess

The fatigue test results of cement-stabilized loess are shown in Error! Reference source not found.. According to previous studies, the Weibull distribution was used to analyze and process the above data [57]. The fatigue life \( N \) and the equivalent fatigue life \( \bar{N} (\bar{N} = N^{1/\beta}) \) of cement-stabilized loess obey a two-parameter Weibull distribution, and then the failure probability \( \rho \) is [58]:

\[
\rho = F(\bar{N}) = 1 - \exp\left[-(\bar{N}/t_0)^m\right], \quad N\geq1; \quad m, \ t_0 > 0
\]  

(4)

where

- \( m \) is shape parameter;
- \( t_0 \) is scale parameter.

Assuming that there is a fatigue limit of cement-stabilized loess, the fatigue equation should satisfy the following two boundary conditions:

- when \( S = 1, \ N = 1 \);
- when \( S = 0, \ N \to \infty \);

The above boundary conditions are properly relaxed to obtain a relatively reasonable fatigue equation, which is Equation (5).

\[
\lg N = m - n \lg S
\]  

(5)

where

- \( m \) and \( n \) are undetermined regression coefficients of the fatigue equation.

| Cement Dosage, \( P_s \) (%) | Compaction Level(%) | The Fatigue Life \( N \) of Cement-Stabilized Loess Specimens under the Following Stress Levels \( S \) (Time) |
|-----------------------------|---------------------|-------------------------------------------|
| 92%                         | 95%                 | 97%                                      |
| 0.80                        | 239 568 1326 4825 8143 | 416 1645 4060 9061 19,320 |
| 0.75                        | 344 782 2072 6843 11,629 | 688 3098 7345 16,453 34,396 |
| 0.70                        | 656 996 2945 8848 14,401 | 935 4552 8840 23,697 46,005 |
| 0.65                        | 897 1453 4177 10,268 19,955 | 1210 6009 11,285 32,078 54,720 |
| 0.60                        | 1121 1882 5584 12,851 26,785 | 1720 7946 13,865 42,153 72,153 |
| 0.65                        | 578 3177 6835 13,645 51,421 | 896 4945 9275 22,787 76,553 |
| 0.60                        | 1427 6362 12,951 30,597 85,648 | |
According to Equation (4) and Equation (5), the data in Error! Reference source not found. were analyzed to obtain the fatigue prediction equation of cement-stabilized loess with a 5% failure probability. The results are shown in Error! Reference source not found. as follows:

Table 5. Prediction equation regression coefficient of fatigue life $N$ of cement-stabilized loess.

| $P_s$(%) | 3 | 4 | 6 | Average |
|---|---|---|---|---|
| 92% | 0.571 | 0.780 | 0.823 | 1.125 | 0.890 | 0.591 | 0.679 | 0.883 | 0.823 |
| 95% | 14.393 | 17.253 | 14.543 | 15.368 | 18.426 | 17.864 | 19.806 | 19.666 | 16.776 |
| 97% | 0.9662 | 0.9706 | 0.9378 | 0.9356 | 0.9378 | 0.9268 | 0.9663 | 0.9540 | 0.9542 |

According to a 95% confidence level, the regression coefficient of the fatigue equation of cement-stabilized loess was calculated, which is shown in Equation (6) and Equation (7).

$$m_{0.95} = \bar{m} - 1.645S$$

$$n_{0.95} = \bar{n} - 1.645S$$

(6) (7)
where \( \bar{m} \) and \( \bar{n} \) are the average of undetermined regression coefficients of the fatigue equation; \( S \) is the criteria deviation.

The fatigue reduction coefficient is used to represent the strength reduction characteristics of specimens after repeated load. According to the above research, the fatigue reduction coefficient \( k_f \) of cement-stabilized loess could be expressed as:

\[
k_f = \sqrt[10]{\frac{m}{n}}
\]

where

\( N_e \) is the accumulated times of axle load within the design life.

It was assumed that railway capacity is saturated, the daily running capacity of trains is 90, and the number of accumulated daily axle load is 2880 59,60. Then, the cumulative number of axle loads in the design life \( N_e \) is \( 1.05 \times 10^8 \) times. The fatigue reduction coefficient \( k_f \) of cement-stabilized loess is 0.262 when \( m = 0.95, n = 0.95 \) and \( N_e \) are substituted into Equation (8). This result is overall consistent with the principle that the critical strength of improved soil is 5 times the dynamic stress [25]. Therefore, the fatigue reduction factor \( k_f \) of cement-stabilized loess is 0.26 in this study.

3.2. Strength Reduction under Wet-Dry Cycling

The 28-day compressive strength test results of cement-stabilized loess under wet–dry cycling are shown in Table 6. The wet–dry reduction coefficient is used to represent the reduction characteristics of compressive strength of specimens after wet–dry cycling, which was calculated according to Equation (9). The greater the wet–dry reduction coefficient, the smaller the strength reduction of stabilized loess after wet–dry cycling.

\[
\eta_G = \frac{q_G}{q_u}
\]

where

\( \eta_G \) is the strength reduction coefficient under wet–dry cycling;
\( q_G \) is the compressive strength of specimens after \( N \) times of wet–dry cycling;
\( q_u \) is the compressive strength of specimens before wet–dry cycling.
Assuming that there is a strength reduction coefficient equation for cement-stabilized loess under wet–dry cycling, and it is satisfied the following three boundary conditions:

\[
\text{when } N = 0, \quad \eta_{GN} = \eta_{G0}
\]

\[
\text{when } N = \infty, \quad \eta_{GN} = \eta_{G\infty}
\]

\[
\eta_{G0} > \eta_{G\infty}
\]

where

\(N\) is the time of wet–dry cycling of cement-stabilized loess;

\(\eta_{GN}\) is the strength reduction coefficient of cement-stabilized loess after \(N\) times of wet–dry cycling;

\(\eta_{G0}\) is the strength reduction coefficient of cement-stabilized loess before wet–dry cycling, which is equal to 1;

\(\eta_{G\infty}\) is the limit of strength reduction coefficient of cement-stabilized loess under wet–dry cycling.

According to the above boundary conditions, the strength reduction coefficient equation of cement-stabilized loess after wet–dry cycling was established:

\[
\eta_{GN} = \eta_{G\infty} - (\eta_{G\infty} - 1)/(\xi \cdot N^2 + 1)
\]

(10)

where

\(\xi\) is the regression parameter of equation.

The strength reduction coefficient equations of cement-stabilized loess after wet–dry cycling were obtained by fitting with Equation (10), which are shown in Error! Reference source not found.. As can be seen from Error! Reference source not found., the strength reduction of cement-stabilized loess gradually increases with the increase of the number of wet–dry cycling, and the reduction coefficient is stable between 0.41 and 0.48 after more than 15 times of wet–dry cycling. According to the most unfavorable conditions, the reduction coefficient of cement-stabilized loess under wet–dry cycling is 0.4.
3.3. Strength Reduction under Freeze-Thaw Cycling

The compressive strength test results of cement-stabilized loess under freeze–thaw cycling are shown in Error! Reference source not found. The specimens with 2% of dosage became loose after 10 freeze–thaw cycles, so these data were not recorded. The freeze-thaw reduction coefficient is used to represent the reduction characteristics of compressive strength of specimens after freeze–thaw cycling, which was calculated according to Equation (11). The greater the freeze-thaw reduction coefficient, the smaller the strength reduction of stabilized loess after freeze–thaw cycling.

$$\eta_D = \frac{q_{Du}}{q_u}$$  \hspace{1cm} (11)

where

- $\eta_D$ is the strength reduction coefficient under freeze–thaw cycling;
- $q_{Du}$ is the compressive strength of specimens after $N$ times of freeze–thaw cycling;
- $q_u$ is the compressive strength of specimens before freeze–thaw cycling.

| Cement Dosage, $P_s$ (%) | Compaction Level (K) | 0 | 1 | 3 | 5 | 7 | 9 | 12 | 15 | 20 |
|--------------------------|----------------------|---|---|---|---|---|---|----|----|----|
| 2                        | 92%                  | 1.03 | 0.71 | 0.61 | 0.46 | 0.31 | 0.24 | - | - | - |
|                          | 95%                  | 1.34 | 0.96 | 0.81 | 0.62 | 0.43 | 0.29 | - | - | - |
|                          | 97%                  | 1.65 | 1.22 | 1.01 | 0.80 | 0.57 | 0.39 | - | - | - |
| 3                        | 92%                  | 1.30 | 0.95 | 0.81 | 0.64 | 0.49 | 0.42 | 0.39 | 0.37 | 0.37 |
|                          | 95%                  | 1.60 | 1.19 | 1.04 | 0.81 | 0.71 | 0.64 | 0.60 | 0.58 | 0.57 |
|                          | 97%                  | 2.03 | 1.53 | 1.32 | 1.05 | 0.93 | 0.84 | 0.78 | 0.75 | 0.75 |
| 4                        | 92%                  | 1.49 | 1.13 | 0.98 | 0.76 | 0.64 | 0.58 | 0.53 | 0.52 | 0.52 |
|                          | 95%                  | 1.90 | 1.44 | 1.28 | 1.02 | 0.90 | 0.83 | 0.77 | 0.75 | 0.74 |
|                          | 97%                  | 2.26 | 1.76 | 1.55 | 1.30 | 1.11 | 1.02 | 0.96 | 0.93 | 0.93 |
| 6                        | 92%                  | 2.03 | 1.56 | 1.37 | 1.05 | 0.91 | 0.83 | 0.76 | 0.74 | 0.74 |
|                          | 95%                  | 2.44 | 1.89 | 1.61 | 1.32 | 1.16 | 1.05 | 0.99 | 0.98 | 0.98 |
|                          | 97%                  | 2.80 | 2.18 | 1.87 | 1.59 | 1.38 | 1.23 | 1.16 | 1.14 | 1.14 |

Table 7. The 28-day compressive strength test results of cement-stabilized loess under freeze–thaw cycling.
The strength reduction coefficient equation of cement-stabilized loess after freeze–thaw cycling is established with the same method in Section 3.3.2.

$$\eta_{DN} = \eta_{D\infty} - \frac{(\eta_{D\infty} - 1)(\xi \cdot N^2 + 1)}{12}$$  \hspace{1cm} (12)

where

- $\eta_{DN}$ is the strength reduction coefficient of cement-stabilized loess after $N$ times of freeze–thaw cycling;
- $\eta_{D\infty}$ is the limit of strength reduction coefficient of cement-stabilized loess under freeze–thaw cycling;
- $N$ is the time of freeze–thaw cycling of cement-stabilized loess;
- $\xi$ is the regression parameter of the equation.

The strength reduction coefficient equations of cement-stabilized loess after freeze–thaw cycling was obtained by fitting with Equation (12), which are shown in Error! Reference source not found. As can be seen from Error! Reference source not found., the strength reduction of cement-stabilized loess gradually increases with the increase of the number of freeze–thaw cycles, and the reduction coefficient is stable between 0.33 and 0.40 after more than 12 times of freeze–thaw cycling.

![Figure 3](image-url)

**Figure 3.** The relationship between $\eta_{D}$ and $N$. (Note: a, b, and c were used to distinguish the three pictures.)

The average permafrost depth in Xi’an, Chengcheng and Hancheng, China, is 45 cm, 29.6 cm and 19 cm, respectively, during 28 years, and the extreme depth of permafrost in northwestern China can reach more than 80 cm [61,62]. Therefore, the reduction coefficient of the freeze–thaw cycling is 0.3 according to the most unfavorable conditions.
4. The Design Criteria Aiming at Subgrade Durability

4.1. Determination of Dynamic Stress

The strength control method is usually used to determine the thickness of the railway subgrade bed and material strength, which is the maximum dynamic stress $\sigma_{d_{\text{max}}}$ transferred to filling through the subgrade bed under the train load must be less than the allowable strength of filling.

As for measured values of dynamic stress, there is a belief that the dynamic response of the existing railway subgrade was 35.0–86.0 kPa in China 63. In addition, the dynamic stress of some specific test sections of the railway was specially tested by some Chinese scholars 27,31,64–67. The study showed that the dynamic stress of subgrade surface does not change significantly with train speed but increases with the increase of axle load 68. As for the calculated value of dynamic stress, the formula of the maximum dynamic stress $\sigma_{\text{d_{max}}}$ of subgrade surface was given in “Code for Design of Intercity Railway” 69 and “Code for Design of High Speed Railway” 70. In addition to the criteria, some scholars calculated the dynamic stress by finite element simulation 31,32. It was found that the calculated values are in good agreement with the measured values. It can verify the possibility of finite element analysis. The measured and theoretical data showed that the dynamic stress of the subgrade decreases rapidly with depth 26–36. As for the reduction law of dynamic stress along the depth, it can be known that the calculated value of dynamic stress of subgrade is generally greater than the measured value according to the above research results. Based on the existing research results, it was determined that the dynamic stress of the subgrade bottom is 20–50 kPa, and the dynamic stress of embankment below the subgrade bottom is 10–25 kPa under a certain guaranteed rate.

As for the critical dynamic strength of filling, when the critical dynamic strength of subgrade filling is less than the dynamic stress generated by the dynamic train load, the soil structure will be destabilized, and the deformation will increase rapidly. However, when the situation is opposite, the soil is gradually compacted by load, and the increment of strain decreases gradually. If the load reaches a certain time, the soil density reaches a certain degree. Therefore, the actual dynamic stress is less than the critical dynamic strength, and the dynamic stress of the subgrade bed is stable for a long time. It was found that the minimum value of dynamic strength is 30 kPa even for the fine-grain soil, which is sensitive to water 27,71,72. Additionally, the calculated method of the critical dynamic strength $[\sigma_d]$ using foundation coefficient $K_{30}$ or critical static strength $[\sigma_0]$ was obtained 32 by analyzing the field data of subgrade of Da-Qin Line, which is shown in Equation (13) and Error! Reference source not found. It can be seen that the calculated value is basically consistent with the measured value. According to the respective requirements of $K_{30}$ for the filling at the subgrade bottom and the embankment below the subgrade bottom in “Code for Design of Railway Earth Structure” 12, the critical dynamic strength of filling at the subgrade bottom and the embankment below the subgrade bottom is, respectively, 147 kPa and 104 kPa.

$$[\sigma_d] = 0.45[\sigma_0] = 1.08K_{30} + 6.75$$ (13)

| The Type of Data            | $K_{30}$ (MPa/m) | 90  | 110 | 130 | 150 | 170 | 190 |
|-----------------------------|------------------|-----|-----|-----|-----|-----|-----|
| The calculated value        | $[\sigma_0]$ (kPa) | 231 | 279 | 327 | 375 | 425 | 471 |
| The calculated value        | $[\sigma_d]$ (kPa) | 104 | 126 | 147 | 169 | 190 | 212 |
| The measured value          | $[\sigma_d]$ (kPa) | 118 | 134 | 150 | 166 | 182 | 199 |

The above analysis shows that the critical dynamic strength of subgrade filling is greater than the dynamic stress transferred to subgrade by the dynamic load. If the strength reduction coefficient of subgrade filling is determined, the dynamic stress in the subgrade structure layers needs to be determined. As is known, the dynamic stress of the
subgrade bottom and embankment below the subgrade bottom is not fixed. According to the most unfavorable condition, the dynamic stress of subgrade bottom or the embankment top below the subgrade was taken to determine the strength criteria design of each layer filling: the dynamic stress $\sigma_{dmax}$ of the subgrade bottom is 50 kPa, and the dynamic stress of embankment below the subgrade is 25 kPa.

4.2. The Design Criteria

The filling strength design criteria of cement-stabilized loess could be obtained by substituting $k_f$, $\eta_G$, $\eta_D$ and $\sigma_{dmax}$ into Equation (3):

The filling strength of subgrade bottom $\geq \frac{50}{0.26 \times 0.4 \times 0.3} = 1602$ kPa

The filling strength of embankment below the subgrade $\geq \frac{20}{0.2 \times 0.4 \times 0.3} = 801$ kPa

The strength of cement-stabilized loess increases with age. 7-day strength is about 0.6 times the critical strength, while 90-day strength is about 0.9 times the critical strength [73,74]. There are at least 3 months between the completion of constructing subgrade and the beginning of train operation, so 90-day strength is too long to be used as the design index because it is not convenient for engineering application. The 7-day strength is usually used as the design index in the project. Therefore, the 7-day strength design criterion was determined combined with the relationship between the strength and age of stabilized soil:

$$q_u = \left(0.6 \times q_u\right) / 0.9 = \frac{2}{3} q_u$$

(14)

According to Equation (14), 7-day strength design criteria of cement-stabilized loess filling could be preliminarily obtained:

The filling strength of subgrade bottom $\geq 1602 \text{ kPa} \times \frac{2}{3} = 1068$ kPa

The filling strength of the embankment below the subgrade $\geq 801 \text{ kPa} \times \frac{2}{3} = 534$ kPa

Therefore, 7-day strength design criteria based on durability are presented, as shown in Error! Reference source not found.

Table 9. The strength design criteria of cement-stabilized loess.

| The Grade of Railway                  | 7-Day Unconfined Compressive Strength Saturated with Water (kPa) |
|--------------------------------------|---------------------------------------------------------------|
|                                      | Subgrade Bottom | Embankment Below the Subgrade                                 |
| Passenger and freight railway,       | $\geq 1100$     | $\geq 550$                                                    |
| Inter-city railway                   |                 |                                                              |
| High-speed railway,                  |                 |                                                              |
| Heavy-haul railway                   |                 |                                                              |

5. Conclusions

(1) The effects of cement dosage and compaction level on the fatigue characteristics of cement-stabilized loess were investigated in this study. Taking into account the most unfavorable conditions, the strength fatigue reduction coefficient of 0.26 was obtained.

(2) The effect of wet–dry cycling on the strength reduction of cement-stabilized loess was investigated in this study. The results show that the strength decreases continuously with the increase of the time of wet–dry cycling, and the strength became to be stable after 15 times. Taking into account the most unfavorable conditions, the strength reduction coefficient of cement-stabilized loess under wet–dry cycling of 0.40 was obtained.

(3) The effect of freeze–thaw cycling on the strength reduction of cement-stabilized loess was investigated in this study. The results show that the strength decreases continuously with the increase of the time of freeze–thaw cycling, and the strength became to be stable after 12 times. Taking into account the most unfavorable conditions, the
strength reduction coefficient of cement-stabilized loess under freeze–thaw cycling of 0.30 was obtained.

(4) The dynamic stress level of the railway subgrade was analyzed in this study. Moreover, it was obtained that the dynamic stress $\sigma_{d\text{max}}$ of subgrade bottom is 50 kPa, and the dynamic stress $\sigma_{d\text{max}}$ of the embankment below the subgrade is 25 kPa.

(5) The 7-day strength design criteria were presented based on durability: 7-day unconfined compressive strength of cement-stabilized loess saturated with water of the subgrade bottom should be higher than 1100 kPa, and 7-day unconfined compressive strength of cement-stabilized loess saturated with water of embankment below the subgrade should be higher than 550 kPa.

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