Analysis on the critical dynamic stress and accumulated deformation characteristic of coarse-grained soil filling for subgrade under cyclic loading

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Abstract

In recent years, with the progress of science and technology and the constant updating of technology, the development level of various railway transportation industries is gradually improving. As the key structure of railway routes, subgrade has made outstanding contribution to railway transportation engineering. As the core layer of subgrade, coarse-grained soil filling is directly subjected to repeated application of various trains. With the development of industry, the railway transportation industry is growing with the carrying capacity of subgrade also increasing. Subjected to repeated load of various trains, the structure of coarse-grained soil structure for subgrade gradually changes, which hinders the running of trains and the stability of subgrade structure. Based on this, this paper first analyzes relevant theories to cyclic loading and then studies the critical dynamic stress and accumulated deformation characteristic of coarse-grained soil filling for subgrade under cyclic loading in detail in the hope of providing theoretical reference basis for the adjustment and design of relevant railway engineering.

Key words: Cyclic Loading, Subgrade, Coarse-Grained Soil Filling, Dynamic Stress.

1. RESEARCH BACKGROUND

1.1 Literature overview

Compare with normal subgrade fillings, coarse-grained soil filling can carry greater weight. In order to further explore the intensity and deformation characteristic of coarse-grained soil filling for subgrade, a series of experiments are adopted to study the influence of confining pressure, pressure, water content and other factors on the deformation of coarse-grained soil filling for subgrade. The results show that the increased confining pressure can increase the stability of the coarse-grained soil, which may serve as the main criteria to determine coarse-grained soil filling (Leng et al., 2016). As the core layer in railway subgrade, coarse-grained soil filling is subjected to the repeated application of different loads to give rise to different deformation effects occur, which directly determine the stability of coarse-grained soil filling. At present, the carrying capacity of coarse-grained soil filling in railway subgrade is gradually reducing under the repeated application of trains (Zhou et al., 2014). Since coarse-grained soil filling is located at the surface layer of subgrade to be crushed by train, the critical dynamic stress of trains has a direct impact on the deflection of the subgrade. It is of great significance to systematically study factors affecting coarse-grained soil filling by triaxial test method to improve the carrying capacity of coarse-grained soil filling (Leng et al., 2015). The traffic frequency on subgrade is mainly affected by train speed. Generally, the higher the train speed is, the greater the traffic frequency will be. Since the long-term performance subgrade is still unknow to some extent in practical research, studying the long-term dynamic performance under different traffic frequencies is of great importance to prolong the service life of subgrade (Cai et al., 2017). Meanwhile, analyze the impact of the water content above subgrade, dynamic level and compaction coefficient on the plasticity and deformability of solid powder soil for subgrade through triaxial experiments. The results show that the deformability of the subgrade increases with the increasing water content above subgrade and the increasing pressure intensity above it (Xiao, 2010).

1.2 Research purpose

At present, coarse-grained soil filling is widely used in the subgrade of heavily loaded railway. Critical expressions
of the dynamic behavior of coarse-grained soil filling under different dynamic stresses can be obtained by making coarse-grained soil filling samples with different water content for triaxial experiments and analyzing the plastic strain capacity of the subgrade filled with coarse-grained soil, so as to establish a plastic model for coarse-grained soil filling in the hope of improving the stability of subgrade (Mei et al, 2017). According to the existing dynamic characteristic experiments, the long-term settlement formula of railway subgrade can be established by analyzing and comparing accumulated deformation models established, which is used for analyzing the axle weight, speed and axle load times of trains and monitoring the train speed above the subgrade. (Xiao et al, 2010). To study the settlement performance of soft clay under long-term cyclic loading, plastic structure models of soft clay under different cyclic loading conditions can be established, which greatly promotes the long-term settlement capacity of soft clay, (Li and Huang, 2007). By studying the impact of speed, lower limit stress and upper limit stress on major emission characteristics of sandstone under cyclic loading, it is found that different cyclic loading effects cause different damage to the sandstone (Xu et al, 2008). At present, the deformation characteristic under different cyclic loading effects of some special materials such as red-bed mudstone can be studied through a series of dynamic triaxial experiments. According to the results, the accumulated deformation characteristics of the materials vary regularly with the changing times of cyclic loading on condition that it does not exceed the dynamic critical value of the materials. Then the accumulated deformation characteristics of different materials can be obtained (Kong and Jiang, 2012). Therefore, it is of great importance to study the critical dynamic stress and accumulated deformation characteristic of coarse-grained soil filling for subgrade under cyclic loading in this paper.

2. RELEVANT THEORY ANALYSIS OF CYCLIC LOADING EFFECTS

So far, elastic-plastic models and viscoelastic models are mainly used to study deformation characteristics under cyclic loading. Generally, new elastic models can be formed by describing some ideal elastic elements, the viscoelastic models of which can be divided into linear models and nonlinear models. Viscoelastic models under cyclic loading can be used to calculate the permanent deformation of related objects. But it can only reasonably calculate the shear stress, acceleration and shear strain of soil mass, ignoring the factor for object deformation under dynamic stress. Therefore, it fails to analyze the accumulated deformation characteristic and study the stress deformation path for soil mass in detail. Therefore, a model proposed under cyclic loading is to be improved by considering some factors affecting the deformation and the materials in the deformation process as basic variables to measure deformation reasons of the model. The method does not traditionally adopt confirmed yield surface to calculate the deformation rule of the material to avoid some complicated steps in calculating the yield surface. In this context, dynamic elastic-plastic models are widely used to calculate the deformation characteristic of materials for it can visually reflect deformation characteristics of soil mass. Under cyclic loading, this paper introduces a new element to establish a multi-yield surface model to verify the rationality of accumulated deformation characteristic of the model. The basic representation model is shown below:

\[ f^{(m)} = \frac{3}{2} [S_{ij} - e_{ij}^{(m)}][S_{ij} - e_{ij}^{(m)}] + \beta^{(m)} - [k^{(m)}]^2 \]  

(1)

In the formula above, \( S_{ij} \) mainly represents the stress strain of the yield surface, \( e_{ij}^{(m)} \) and \( \beta^{(m)} \) the central coordinates of the yield surface, \( k^{(m)} \) the size of the yield surface and \( c \) the ratio between the long axis and the short axis of the ellipse of the yield surface. Generally, yield surface can be in a variety of shapes, of which elliptical yield surface is often use, for its mathematical model is simple, convenient and verifiable in a relatively short time. Therefore, this paper selects elliptical yield surface as the main research object for the yield surface model. Since the stress path of yield surface under cyclic loading moves along relevant trajectory, the net water pressure on the soil surface will not result in yield surface deformation. Therefore, net water pressure can be excluded from consideration in establishing yield surface function, then the model below can be derived;

\[ f^{(m)} = \frac{3}{2} [S_{ij} - e_{ij}^{(m)}][S_{ij} - e_{ij}^{(m)}] - [k^{(m)}]^2 \]  

(2)

Assume there are m stress points on the yield surface, then the stress increment model of the yield surface can be obtained as follows;
\[ d\alpha_{ij} = \frac{ds_{ij}}{2G} + \frac{3}{2H_m} \frac{S_{ij} - e_{ij}^{(m)}}{[k^{(m)}]^2} - [S_{ij} - e_{ij}^{(m)}]ds_{ij} \]  

(3)

where \( \alpha_{ij} \) mainly represents the shear strain increment of the yield surface and \( G \) the elastic shear modulus of the yield surface, besides the above variables explained. At this point, if the yield surface moves again, the following three different results will can obtained:

where the compatibility condition 0:

\[ d\mu = \frac{(\partial \sigma_{ij}^{(m)}/\partial \sigma_{ij}) d\sigma_{ij}}{(\partial \sigma_{ij}^{(m)}/\partial \sigma_{ij})[\sigma_{ij}^{(m+1)} - \sigma_{ij}^{(m)}]} \]  

(4)

Where the compatible condition is small:

\[ d\mu = \frac{3/2[S_{ij} - e_{ij}^{(m)}]ds_{ij} - k^{(m)} dk^{(m)}}{k^{(m+1)}k^{(m)} - \frac{3}{2}[S_{ij} - e_{ij}^{(m+1)}][S_{ij} - e_{ij}^{(m)}]} \]  

(5)

After the above conditions are determined, it is necessary to modify the yield surface established, and then build a multi-yield surface model as follows:

\[ dE_i = \frac{ds_i}{3G} + \frac{1}{3} \left( \frac{2G - H_m}{H_m} \right) S_i - e_i^{(m)} \sum_{i=1}^{3} [S_i - e_i^{(m)}] ds_i \]  

(6)

\[ de_i^{(m)} = \frac{d\mu}{k^{(m)}} \left( k^{(m+1)}[S_i - e_i^{(m)}] - k^{(m)}[S_i - e_i^{(m+1)}] \right) \]  

(7)

\[ d\mu = \frac{\sum_{i=1}^{3} [S_i - e_i^{(m)}] ds_i - k^{(m)} dk^{(m)}}{k^{(m+1)}k^{(m)} - \sum_{i=1}^{3} [S_i - e_i^{(m+1)}][S_i - e_i^{(m)}]} \]  

(8)

In the model established above, \( H_m \) is the shear modulus of the multi-yield surface and \( S_i, S_2, S_j \) the stress space established in the multi-yield surface model. This model is widely applied in analyzing critical dynamic stress and accumulated deformation characteristic of materials under cyclic loading for its variable setting and calculation method are simple and the plane strain experiment is very convenient.

3. ANALYSIS ON THE CRITICAL DYNAMIC STRESS AND ACCUMULATED DEFORMATION CHARACTERISTIC OF COARSE-GRAINED SOIL FILLING FOR SUBGRADE UNDER CYCLIC LOADING

3.1 Test process and calculation

To test and analyze the critical dynamic stress and accumulated deformation characteristic of coarse-grained soil filling for subgrade, certain experimental samples were extracted in the test area by five-point sampling method. After measuring their pore water pressures, the effective critical dynamic stress of coarse-grained soil filler for subgrade was be obtained according to the following formula.

\[ \sigma_{ij} = \sigma_{ij} - u_{ij} \]  

(9)
\[ \sigma_{3f}' = \sigma_{3f} - u_f \]  

(10)

In the formula above, \( \sigma \) mainly represents the principal stress of the sample taken and \( u_f \) the pore water pressure of the sample. The specific loading situation is shown in Figure 1.

As shown in Figure 1, conduct a continuous loading experiment for the samples. Shear the samples After the samples were completely solidified, shear the samples to analyze the critical dynamic stress and accumulated deformation characteristic of coarse-grained soil filling for subgrade. It is necessary to analyze the materials by comparison according to the above model. Select appropriate materials, allocate standard sample, make the strain curve for the experiment and draw a curve with high shear strength according to the corresponding criterion to obtain the axial deformation model. The axial strain value is calculated in the formula below;

\[ \varepsilon_1 = \Delta h_1 / h_0 \]  

(11)

In the formula above, \( h_0 \) mainly represents the height of the sample before being sheared and \( \Delta h_1 \) the height change of the sample during the shearing process. The area and stress difference of the samples can be calculated after the axial deformation values are obtained. The detailed calculation formula is as follows;

\[ A_u = A_0 / (1 - 0.01 \delta_1) \]  

(12)

\[ \sigma_i - \sigma_3 = R / A_u \]  

(13)

In the formula above, \( A_0 \) mainly represents the original area measured of the sample before the test, \( A_u \) the area measured of the sample after being corrected and \( R \) the strain force reading obtained from certain measurement and calculation processes for the sample.

### 3.2 Test result study

Three sets of samples were tested in the experiment with a static triaxial experiment for each sample respectively to mainly analyze the critical dynamic stress and accumulated deformation characteristic of the coarse-grained soil filling for subgrade. With respect to the critical dynamic stress of coarse-grained soil filling for subgrade, there may be three situations in the experiment, as shown in Table 1. First, when the strain force was small, its strain curve almost tended to be a straight line. When the confining pressure increased, the strain force of the samples taken continued to increase to form a nonlinear growth curve. It was found after a certain period of observation that the curve increased over time with some peaks gradually, which are not obvious. This curve is a softening curve. Second, when the strain force was also small, the strain force of the samples taken would increase with the increasing straight line with the sample models kept consistent. The strain force curve presented a nonlinear growth trend. Third, the pressure above the soil increased gradually under cyclic loading and the confining pressure around the coarse soil filling also increased. At this point, the coagulability between soil grains was not largely damaged if the soil deformation was not too severe. It can be learnt that the coarse-grained soil
filling is still at a stage with certain elasticity with stable structure. After that, apply more pressure to the samples, then the strain and consequent axial strain force of the samples also increased. At this point, corresponding movement occurred between soil blocks inside the coarse-grained soil filling sample taken. In case the displacement becomes excessive, the cementing force of the coarse-grained soil filling will be directly damaged, which result in a test curve of non-linear characteristic for the critical dynamic stress of the coarse-grained soil filling sample. Therefore, the strain force of coarse-grained soil filling of the samples presents nonlinear change with the increasing external pressure under certain test conditions, and the whole soil structure will be damaged in severe cases.

| Table 1 Table of Critical Dynamic Stress Test of Coarse-Grained Soil Filling Samples |
|---------------------------------|---------------------------------|-------------------------------|------------------|
| State of coarse-grained soil filling sample | State of critical dynamic stress | Adhesive force of soil mass | Curve characteristic |
| Softening state | -0.1% | High | Non-linear |
| Coagulation state with partial softening | -0.1% | High | Non-linear |
| Coagulation state | 0.5% | Good | Non-linear |
| Loose state | 1.0% | Poor | Non-linear |

With respect to the accumulated result of the coarse-grained soil filling sample for subgrade, it is found by analyzing the accumulated deformation curve of the sample that the accumulated deformation of the coarse-grained soil filling sample for subgrade presents two characteristics in the whole test process. On one hand, in case the total strain force of the coarse-grained soil filling for subgrade is constant, the coagulability will increase slightly with the accumulated deformation force increasing accordingly. On the other hand, in case the total strain force of the coarse-grained soil filling for subgrade is increasing, the coagulability will decrease gradually with the accumulated deformation force decreasing. Since the anti-shear ability inside the soil decrease sharply, the samples of coarse-grained soil filling for subgrade presents a loose state visually. Therefore, the accumulated deformation of the coarse-grained soil filling samples for subgrade may present two phenomena, one with little change, and the other with significant change, which directly result in damage to the coarse-grained soil filling sample for subgrade. Therefore, relevant personnel should set corresponding description according to the characteristics of coarse grained soil filling for subgrade to ensure the stability of the whole subgrade structure.

4. CONCLUSION

By analyzing relevant theories of cyclic loading effects, the critical dynamic stress and accumulated deformation characteristic of coarse-grained soil filling for subgrade are studied with high reference value for relevant railway transportation departments. It has effectively solved a series of problems existing in the construction and design of heavy-loaded railway and changed the design concept of railway engineering in many ways, making railway loading and superimposed effect gradually obvious. It also brings highly potential prospect to applying coarse-grained soil filling to railway engineering to effectively improve accumulated deformation in relevant railway engineering as well as the carrying capacity of railway subgrade.

REFERENCES


