Review Article

A Short Review on the Dynamic Characteristics of Geogrid-Reinforced Soil Retaining Walls under Cyclic Loading

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The internal force and the form of reinforced soil wall used in high-speed railway change due to the static loads of self-gravity and rail system and dynamic load of train travelling. As a kind of flexible retaining structure, the study of the dynamic characteristics of reinforced retaining walls is of great significance for its engineering application and structural analysis. In this article, recent advances in using various research methods on the dynamic characteristics of reinforced retaining walls are reviewed. Through a series of experimental studies and numerical analysis, the research progress of dynamic characteristics of reinforced retaining walls is summarized. The advantages, disadvantages, and application of various test methods are analyzed. Finally, laboratory model tests are expounded based on previous research achievements, and prospects are proposed on the development of dynamic characteristics of reinforced retaining walls.

1. Introduction

Reinforced soil technology was first invented by French engineer Henri Vidal since 1958. Schematic diagram of the geogrid-reinforced soil retaining wall is presented in Figure 1.

It has been developed rapidly with its excellent characteristics. Reinforced retaining walls have increasing applications in the civil engineering field, especially in railway engineering. This is because of their antivibration performance, cost-effectiveness, and convenient construction. As the foundation of the railway embankment, the reinforced retaining walls not only bear the superstructure loads of the railway line but also bear the cyclic loads caused by wheel movement.

Layering geogrid in soil can strengthen the integrity of the retaining walls and form a stable structure. The reinforced material and the soil are interbedded to produce friction, which limits the lateral deformation of the soil. It is equivalent to imposing a transverse constraint on the soil, increasing the integrity of the soil, improving the shear strength, and reducing the soil pressure and uneven settlement.

Figure 2 shows the warp knitted polyester geogrid, glass fiber geogrid, bidirectional plastic geogrid, and steel-plastic geogrid, which are extensively used in reinforced retaining walls. The present review focuses on the extensive use of bidirectional plastic geogrid as a stable, inert, eco-friendly material used in geogrid-reinforced soil retaining walls with highly improved mechanical properties.

The dynamic characteristics of reinforced retaining walls under train cyclic loading, such as dynamic stress, dynamic displacement, horizontal acceleration, vertical acceleration, and residual deformation, will lead to the deterioration of railway line operation conditions. Excessive dynamic stress of reinforced retaining walls will cause embankment elastic deformation, accumulated settlement, and stress relaxation of reinforcement, and so on, which results in the change of track geometry and seriously affects the railway transport capacity.

In addition, the action of vibration load is very complex, which varies with different amplitude, frequency, and duration of action. The interface form and interaction mechanism of reinforced soil under train moving loads are complex. At present, none of the reviewers have reviewed in this field, which restricts the application of reinforced soil technology in engineering. Therefore, it is essential to
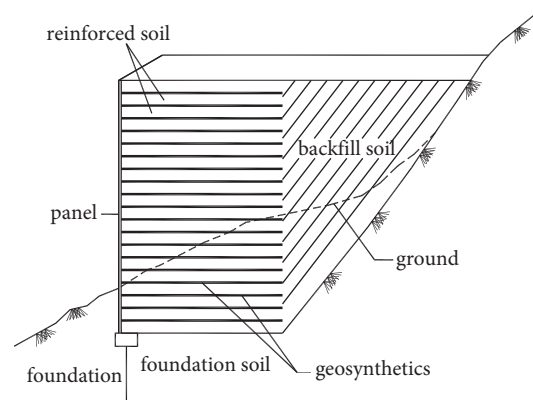
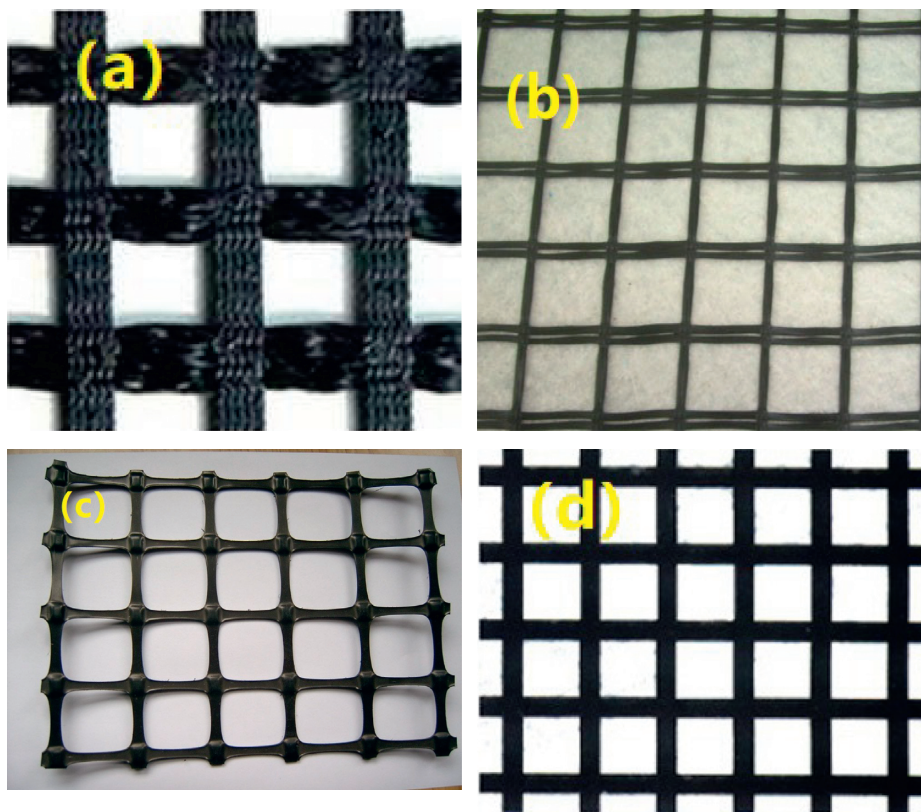FIGURE 1: Schematic diagram of geogrid-reinforced soil retaining wall.

FIGURE 2: Geogrids: (a) warp knitted polyester geogrid, (b) glass fiber geogrid, (c) bidirectional plastic geogrid, and (d) steel-plastic geogrid.

analyze and study the dynamic characteristics of reinforced retaining walls for ensuring the safety of reinforced soil structure and improving the extensive application of reinforced soil technology.

In general, there are two main methods to study this kind of problem: one is the laboratory model test, which studies the dynamic characteristics of reinforced retaining walls through dynamic triaxial test, resonant column test, large-scale shaking table model test, or geotechnical centrifugal model test. The other is the numerical analysis, which uses the excitation force function to simulate the vertical dynamic loads of the train and studies the dynamic characteristics of geogrid-reinforced soil retaining walls.

Based on previous research achievements, the experimental research methods of dynamic characteristics of reinforced retaining walls are summarized. Laboratory model tests of reinforced retaining walls are expounded, and suggestions for further researches are put forward.

2. Study of Dynamic Characteristics of Reinforced Retaining Walls

2.1. In Situ Tests. In situ test studies on the dynamic characteristics of reinforced retaining walls started in the 1980s, which is the most direct method to obtain first-hand

data. Through the analysis of the experimental data, the dynamic characteristics of the railway embankment were obtained.

Japanese scholar Sunaga et al. conducted the in situ tests of dynamic stress and settlement on the railway embankment [1]. German scholar Göbel et al. [2] found that it can improve the bearing capacity of the embankment protection layer and decrease the settlement of embankment by reinforcement. The stress fields of reinforced retaining walls in different types of vehicles were studied with in situ tests by Italy National Rail Corp. The earliest in situ tests of reinforced retaining walls in China were conducted by the Ministry of Railway.

Cai and Huang [3] analyzed the test data of longitudinal dynamics of a heavy haul train of DaQin railway. The findings suggest that even if the dynamic stress is small, with the increase of repetition, it still causes large deformation, even destruction. Thus, the number of cyclic loadings is an important factor which can influence the dynamic characteristics of reinforced soil structure. In addition, some scholars have studied the dynamic characteristics of the reinforced soil structure at different train speeds. Sun et al. [4] carried out dynamic tests on reinforced retaining walls on 3 cross section profiles in DK 243 + 400~DK 243 + 900, and the results showed that the change rate of embankment dynamic stress with speed and axle weight of train is less than that of the conventional railway.

Wang et al. [5] investigated the notion that train moving loads have little influence on the horizontal soil pressure, vertical soil pressure, and tensile deformation. Nie et al. [6] investigated that the embankment dynamic stress increases linearly as train speed increases. The results proved that the dynamic stress of the reinforced retaining walls is gradually increasing with increasing train speed, so the dynamic characteristics of the embankment are emphasized in the design.

Benjamin et al. [7] built eight prototype geotextile-reinforced soil structures to analyze their characteristics. The in situ monitoring program involved the measurement of vertical and horizontal displacements within the reinforced soil mass, as well as face displacements. Indraratna et al. [8] carried out in situ tests on an instrumented track in Australia. The geocomposite is effective for reducing the vertical and lateral strains of the ballast with obvious implications for improved track stability and reduced maintenance costs.

Researchers have also shown that in situ tests were conducted by capturing the deformation and strain upon embedding the apparatus in different cross sections of embankment. These apparatuses include soil pressure box, displacement gauge, pressure sensor, and displacement sensor. By this method, the dynamic stress and dynamic strain of reinforced retaining walls which are subjected to high-frequency loads are obtained, and the stress and deformation of the wall panel are accurately measured. However, this method is restricted by site conditions and funding. In addition, the dynamic characteristics are influenced by many factors, such as retaining walls, structure form, axle load, train speed, backfill properties, and reinforcement mechanical properties.

The boundary of in situ test is difficult to control, and it is difficult to observe the evolution process of deformation and failure inside the rock and soil mass, which limits the research on the mechanical mechanism of rock and soil materials.

Therefore, it cannot be easily determined with in situ tests. And a fact needs to be noticed that most in situ tests will last for a long time. Therefore, this method has some limitations.

2.2. Numerical Simulation. Numerical simulation is an effective means to study the interaction of various elements of reinforced retaining walls. It could help provide a better understanding of the dynamic response characteristics of reinforced retaining walls, which has been valued by scholars.

Ling et al. [9] studied the influence of combined horizontal and vertical seismic accelerations on the stability and displacement of reinforced retaining walls. The results showed that the effect of vertical acceleration should be considered in the design when the horizontal seismic coefficient exceeds 0.2. Kerry Rowe and Skinner [10] simulated an 8 m tall geosynthetics-reinforced soil wall constructed with a layered foundation stratum by two-dimensional finite element method. It is found that the foundation accumulative settlement can significantly increase the displacement of the wall surface, wall bottom, and the strain of reinforcement and increase the vertical stress at the toe of the wall. Chen et al. [11] studied the settlement, horizontal displacement, geogrid strain, and stability of a reinforced soil wall with soft clay by using a three-dimensional seepage-coupled finite element modeling (Z_Soil3D). Compared with 2D FEM, 3D FEM can more deliberately simulate the elements of geosynthetics, soil, and their interface and consequently capture the bulging of the reinforced soil wall facing during step loading.

Leshchinsky and Ling [12] studied the assumption that geocell is effective in improving the characteristics of ballasted foundations for a wide range of geocell stiffnesses, embankment stiffnesses, and ballast strength. Geng et al. [13] constructed the track-embankment model by using FLAC^{3D}. The results showed that the attenuation law of dynamic stress along the depth of the embankment is rarely affected by the speed, and with the increase of embedding depth of geogrid, the vertical stress of the embankment first decreases and then increases. Jiang et al. [14] studied the GRR wall with secondary reinforcement resulting in smaller facing deflections and maximum strain in the primary reinforcement layers. The results indicated that secondary reinforcement could provide clear benefits in improving the performance of GRR walls.

Many scholars have studied the numerical model of the reinforced retaining wall by using finite element software. The working principle, seismic mechanism, dynamic characteristics, and related parameters of geogrid-reinforced retaining wall are deeply studied, and the theoretical level is continuously improved. However, there are still some problems in the practical application of reinforced retaining

walls, such as the stability analysis under seismic action, stability coefficient, and the synergy between soil and retaining wall, which needs further discussion.

2.3. Model Tests. In the study of dynamic characteristics of reinforced retaining walls, the accuracy of in situ test and numerical simulation is often limited by the complex characteristics of civil engineering materials [15–17]. By contrast, the model test and laboratory tests can reflect the dynamic characteristics and settlement development law, which is an important means to study the interaction of high-speed railway track-embankment system and accumulative settlement.

Model test is an important method to study the dynamic characteristics of reinforced soil structures. The model test study is divided into two main categories: shaking table model test and centrifugal model tests. Model tests are conducted to simulate the dynamic effect in shaking table tests or centrifugal reduced-scale model tests, large-scale model tests, and full-scale model tests. The shaking table model tests are performed in different proportion models. The mechanical properties of the reinforced retaining walls were studied by inputting various signals of simulation dynamic loads. Shaking table of Tongji University is shown in Figure 3.

In recent years, the shaking table model tests have been carried out by several researches. Sakaguchi [18] conducted shaking table model tests on 1.5 m (height) reinforced retaining walls and studied the effects of compaction degree of backfill, the length and number of reinforcements, and the type of reinforcement on the dynamic characteristics of reinforced retaining walls.

Yang et al. [19] suggested that both the acceleration and the displacement average value of the walls are related to the wall height. The acceleration of the walls may be in the vertical or horizontal direction. Magdi and Richard [20] studied the seismic performance of reduced-scale geogrid-reinforced retaining walls constructed with different toe boundary conditions, facing panel configurations and re-inforcement layouts through a series of dynamic shaking table experiments. Ling et al. [21] conducted an experimental study. Three large-scale 2.8 m tall modular block geosynthetics-reinforced retaining walls were subjected to shaking by the Kobe earthquake motion. The test results showed that the walls deformed very little with negligible horizontal acceleration amplification when subjected to the first shaking load. Huang et al. [22] performed model tests on the deformation of geogrid-reinforced retaining walls, which simulate cyclic loading by MTS universal material testing machine.

Li et al. [23] designed a container with 3.0 m (length) ∗ 0.85 m (width) ∗ 2.0 m (height) as a large reinforced gabion retaining wall model, and its dynamic characteristics are investigated with the red sandstone filler through the input sine waves with different ampli-tudes and frequencies of the incentive. The results indi-cated that there was no obvious damage in the internal and external walls after 2 million times of cyclic loading,

FIGURE 3: Shaking table of Tongji University.

and the structural stability was good. When the vibration frequency reaches 10 Hz, the vertical and horizontal ac-celeration and displacement characteristics of the retaining walls are changed greatly.

Zhu et al. [24] studied that, compared with the netted reinforced retaining wall, the packaged one has smaller deformation by using large-scale shaking table tests. For the selection of the reinforced retaining wall in earthquake-resistance protection zone, especially the buildings in high earthquake intensity regions, the packaged reinforced soil wall is an optimal choice. Model designs of the shaking table tests are shown in Figure 4.

Liu et al. [25] obtained acceleration, earth pressure, accumulative settlement, and reinforced tensile strain under different amplitudes and frequencies through a number of shaking table tests. The findings indicated that the accel-eration characteristics and soil pressure on the top floor are maximum, and the tensile strain is affected by the loading amplitude and less affected by frequency. Komak Panah et al. [26] performed a series of tensile and pullout tests on 0.8 m tall reduced-scale models constructed in a rigid container to determine the best reinforcement material and reinforce-ment length. They found that the displacement of the retaining walls can be reduced by reinforcement, and the mechanical properties can be enhanced. If the length of the bottom band is decreased, the length of the upper band is not increased, and the displacement of the retaining wall is increased by 1.2~7 times.

As previously described, the shaking table model test can be used by most of the researchers, due to its repeatability and operability. However, the scale of the experiments is large, and it is important to deal with the similar relationship and boundary conditions of the model. Han et al. [27] studied the notion that piles have been installed inside GRR walls to support bridge abutments and sound barrier walls. A pile in a GRR wall at a larger distance away from the back of the wall facing could carry more lateral load than that at a closer distance.

Chen and Bian [28] from Zhejiang University designed a high-precision and full-scale high-speed railway subgrade dynamic test system. It can truly reflect the dynamic re-sponse and accumulated deformation of railway track subgrade system under cyclic loading. A full-scale high-speed railway dynamic testing facility is shown in Figure 5.
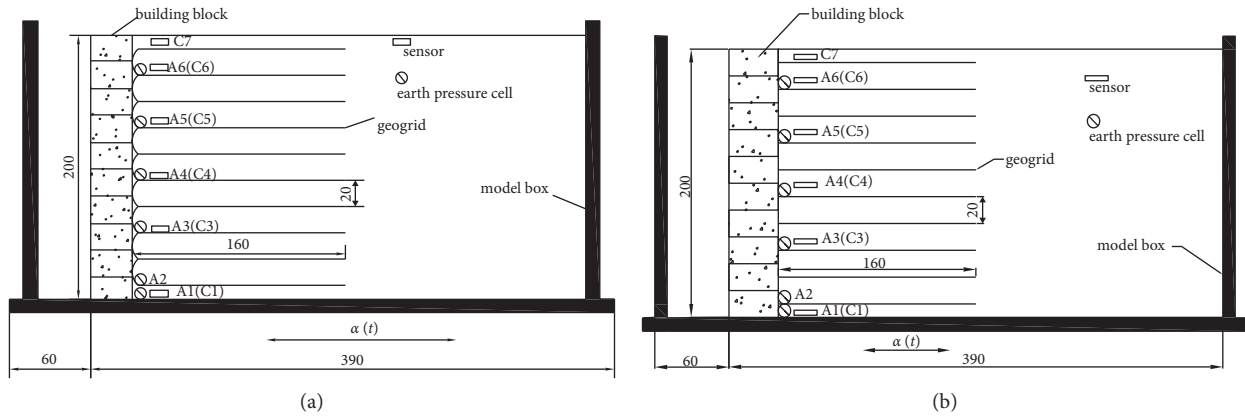
(a)

(b)

FIGURE 4: Model design of shaking table test: (a) netted reinforced soil wall; (b) packaged reinforced soil wall.
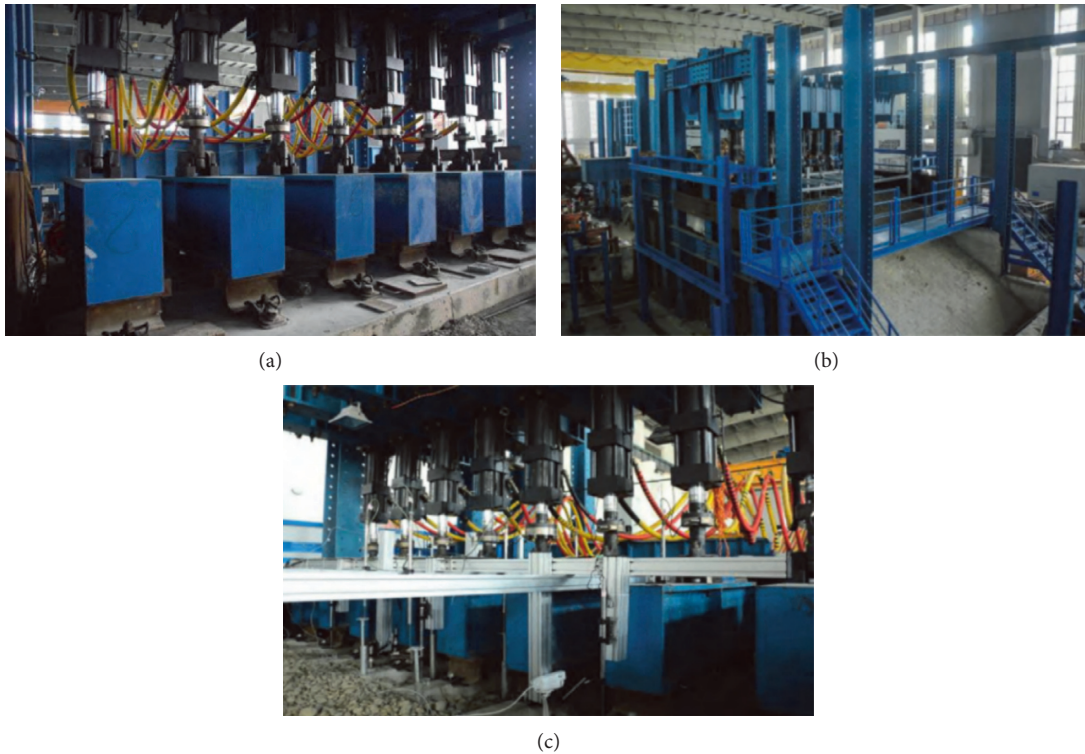

(a)

(b)

(c)

FIGURE 5: Full-scale high-speed railway dynamic testing facility in Zhejiang University: (a) train running loading device; (b) track-embankment-foundation full-scale model; (c) monitoring and testing system.

Through the field data of Beijing-Tianjin intercity railway and Wuhan-Guangzhou high-speed railway, the reliability and test accuracy of the test device are verified. Based on this device, a series of experimental studies are carried out on the dynamic response of ballastless track and the influence of the change of groundwater level on the long-term service performance of the subgrade.

Based on four large-scale model tests and relevant literature, the magnitude, forms, and evolution modes of horizontal displacement of tiered geosynthetics-reinforced retaining walls are investigated by Yang et al. [29]. The study has shown that the maximum horizontal displacement of retaining walls appears at the top of each retaining wall and the displacement decreases with increasing step width.

Another kind of model test is the geotechnical centrifugal model test. The method can be traced back to 1869; Phillips was the first to put forward the centrifugal model. According to the equilibrium differential equation of the elastic body, the similarity relation between the prototype and the model is deduced. When the gravity is the main factor in the equilibrium force factor, it can be used to increase the gravity of the model.

Supergravity centrifugal model test can provide a test environment for settlement deformation of deep soft soil

foundation and pile reinforced embankment under cyclic loading, which is one of the most powerful means to promote long-term accumulation of high-speed railway embankment. Geotechnical centrifuge model is presented in Figure 6.

The principle of the centrifuge model is that the model is set in a centrifuge under a high gravity acceleration field, to compensate for self-weight loss due to small-scale models. Paying attention to the stress level makes the simulation of geotechnical structure with self-weight as the main load more effective [30]. Then Sharma and Bolton [31] performed centrifugal model tests to investigate the effect of reinforcement on soft soil embankment and measure the tensile stress of geogrid. The results showed that the friction increased due to the increase of the depth of soft soil. Guo et al. [32] conducted centrifugal model tests to study geotextile-reinforced soft foundation and proposed antianalysis method through test data. Ren et al. [33] studied that the wall displacement and reinforcement strain at the naturally dry and saturated states are larger than those at the unsaturated state, meaning that suction does have an enhancement effect on the seismic performance of geogrid-reinforced retaining walls.

In recent years, shaking table model test and geotechnical centrifugal model test are used to study the dynamic characteristics of structures under high-frequency cyclic loading and to study the seismic characteristics of geotechnical and structure, and they are one of the main research means of earthquake engineering. At present, the modernization of test means and large scale of test object are the development trend of model tests, but the effectiveness of testing is reduced due to the boundary problem of the model.

The design of similarity relation is one of the key problems in the model test. It is difficult for the model tests to fully satisfy the similarity law of all physical quantities. In addition, there are still some problems to be discussed about the initial boundary conditions of the energetic state and the time-dependent deformation and failure process of the rock mass.

2.4. Laboratory Tests. The dynamic triaxial tests are the most conventional laboratory method to obtain the deformation and strength properties of soils. In general, laboratory tests were carried out by a dynamic triaxial apparatus, which can test the deformation under varying cyclic dynamic loading, including the liquefaction resistance of saturated sand.

There are many kinds of dynamic triaxial apparatus, including soil dynamic triaxial apparatus, high pressure triaxial apparatus, large triaxial apparatus, and unsaturated soil triaxial apparatus. The manufacture of the dynamic triaxial apparatus is not yet finalized in the design, but in general, these apparatuses have the same performance. Research institutions design the apparatus according to different research contents by themselves, respectively. The United States developed a variety of impingement vibration triaxial apparatus with different control loading rates in 1948. China Water Conservancy and Hydropower Research Institute developed one-way vibration triaxial apparatus in 1959.

Figure 6: Geotechnical centrifuge model.

Large-scale dynamic triaxial apparatus was designed and developed by academician Kong Xianjing's team of Anti-Seismic Research Institute of Dalian University of Technology. Figure 7 presents a detailed sketch and picture of the apparatus [34].

The main components of the dynamic triaxial apparatus include the pressure chamber, excitation equipment, and measuring equipment. According to the control mode, the instrument is divided into two types, stress control and strain control, respectively. According to the way of cyclic tests, there are unidirectional cyclic tests and bidirectional cyclic tests. According to the test methods, there are unidirectional vibration tests and bidirectional vibration tests. Pressure chamber is required to have high strength and stiffness and excellent watertight and to be as easy as possible to disassemble and install. The excitation system is set in the axial of the instrument for providing different vibration loading types.

There are three wave types which could be adopted in the test. Figure 8 presents the impact type, periodic type, and arbitrary type of cyclic loading.

Sketch of the wave shape of cyclic loading is shown in Figure 9. σ_{max} and σ_{min} represent the maximum stress and the minimum stress of cyclic loading, respectively; $\Delta\sigma$ is the amplitude load, $\Delta\sigma = \Delta_{max} - \Delta_{min}$; T is the cyclic of vibration; f is the frequency, $f = 1/T$.

The vibration frequency varies from 0.1 Hz to 10 Hz. Some even may be greater because of the test purpose. The stress, deformation, and pore water pressure of the sample are automatically monitored and acquired by the measuring system. The simulated dynamic principal stress is applied to the sample in the dynamic triaxial test, and the dynamic characteristics of the reinforced soil structure can be determined. The cyclic load is characterized by the dynamic stress amplitude and cyclic load action.

Magdi and Richard [35] studied that the vertical acceleration, horizontal acceleration, and vertical displacement of geogrid-reinforced retaining wall increase with the increase of wall height. However, the increase trend of horizontal
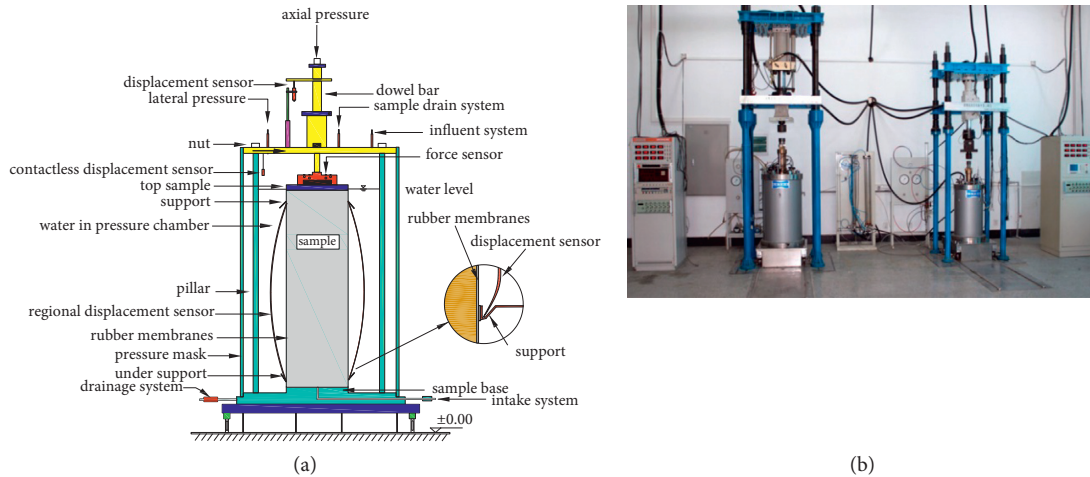
(a)

(b)

Figure 7: Sketch and picture of the dynamic triaxial apparatus: (a) a sketch of the dynamic triaxial apparatus; (b) the cyclic triaxial apparatus.

rectangular wave
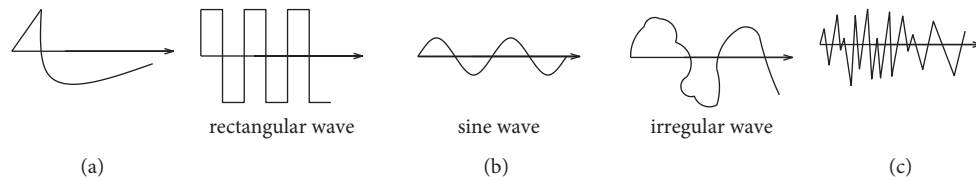
sine wave

irregular wave

(a)

(b)

(c)

Figure 8: Schematic diagram of dynamic load waveform: (a) impact type; (b) periodic type; (c) arbitrary type.

displacement was not obvious. Raju and Fannin [36] analyzed the notion that the interface coefficient of the soil is too conservative. Xie et al. [37] studied the mechanical behavior of the composite material through varying the number of geonet layers, confining pressure, and different dynamic stress in GDS high dynamic triaxial testing system. GDS high dynamic triaxial testing system is shown in Figure 10.

Lackenby et al. [38] conducted a series of high-frequency cyclic triaxial tests to examine the effects of confining pressure and deviator stress magnitude on ballast deformation and degradation. A loading frequency of 20 Hz was utilized to simulate high-speed trains. Cyclic loading continued for 500000 cycles or until the vertical deformation reached about 25% axial strain. The results showed that, for each deviator stress considered, the optimum range of confining pressure varied from 15 to 65 kPa such that the degradation is minimized. Naeini and Gholampoor [39] recently carried out a series of triaxial tests to investigate the mechanical characteristics of the geotextile-reinforced sand. The findings indicated that the axial modulus can be improved by reinforcement and increasing confining pressure and can reduce dry sand ductility for all dry sand mixed with different silt content.

Researchers have also shown the influence factors and variation law of the strength and deformation characteristics of reinforced soil, which can provide dynamic parameters for the design and stability of reinforced retaining walls [40–43].
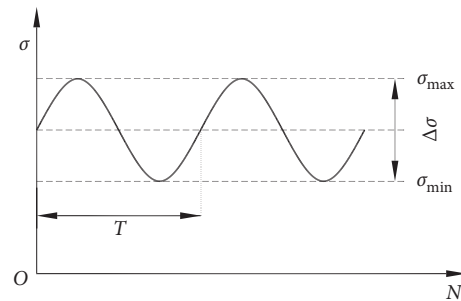

Figure 9: Sketch of wave shape of cyclic loading.

Figure 10: GDS high dynamic triaxial testing system.

The main factors that affect the dynamic characteristics are dynamic stress amplitude, confining pressure, vibration frequency, number of layers, and so on. It is important to focus on the selection of dynamic stress amplitude and the setting of frequency and confining pressure in the experiment, which make the results as close as possible to the actual situation. Moreover, the interaction characteristics of the reinforced soil interface under high-frequency cyclic loading are very complex and are worth more discussion.

In practical applications, geogrid-reinforced retaining walls are prone to damage under traffic cyclic loading. In this process, the additional stress and principal stress axis of the pure shear state of the soil will rotate, which is difficult to measure in practical engineering. Cyclic simple shear test can simulate the stress state of soil under various conditions such as earthquake and traffic load in the laboratory and determine the damping ratio and the dynamic shear modulus of the soil units. It can be used to study the strength, mechanical properties, dilatancy, and deformation characteristics of reinforced soil under actual load conditions and provide certain theoretical guidance for practical engineering [44–48].

3. Discussion

Many authors in the past have discussed the dynamic characteristics of geogrid-reinforced soil retaining walls under a uniformly distributed traffic load. The research will provide abundant experimental data for the verification of reasonable calculation models and numerical analysis methods. In this review, various test methods and their applications in dynamic characteristics of reinforced retaining walls are summarized, and the research status is introduced.

Among the three experimental methods, first-hand monitoring data can be obtained through in situ tests. However, it is important to note that in situ tests have certain restrictions and are difficult to work out due to many influence factors, field conditions, and financial constraints. Therefore, some researchers performed three triaxial tests in the laboratory. The instrument can be controlled easily, but it is limited by the standard of instrument. In most of the tests, simulated materials are chosen to replace the actual materials, so the test results are influenced. The most widely used test method is the model test, which is a good way to study the dynamic characteristics of reinforced soil structures. The model test needs strict similarity between the model and prototype to attain accurate test results. Clearly, the design and production of the model are the most important factors in model tests.

Most previous investigations have focused on the influence factors in cyclic loading conditions, such as confining pressure, dynamic stress amplitude, consolidation ration, reinforcement layers, and frequency. Furthermore, the rules of deformation, speed, acceleration, and stress of reinforced retaining walls under high-frequency cyclic loading have been studied through calculating the dynamic elastic modulus, damping ratio, and dynamic shear modulus. The results of previous research have indicated that the frequency of loading has no effect on the dynamic elasticity modulus (or shear modulus) and that only the damping ration decreases with increasing frequency. These studies provided calculation parameters and references for the design of reinforced retaining walls.

4. Conclusions

In this review, the research on the use of bidirectional plastic geogrid as a reinforcement material for reinforced retaining walls has shown that the advantages, disadvantages, and application of various study methods are analyzed. To assist the beginner to understand, the dynamic characteristics have also been discussed in terms of the influence factors and variation law:

(1) The authors thought that it is necessary to calculate the dynamic strength and accumulative settlement of reinforced retaining walls and predict the fatigue life of the structure, which is the important basis for the design of reinforced structure.

(2) Though there are few review papers available on geogrid-reinforced retaining walls, they are focused on the main influencing parameters governing the dynamic characteristics of reinforced retaining walls from experimental studies and numerical analysis, but none of the reviewers have reviewed the interaction between reinforcement and soil under dynamic loads, and the reasonable design has not been accepted. Here, we have attempted to show the latest study trends in geogrid-reinforced soil retaining walls with a detailed analysis of the abovementioned properties.

(3) Still, the authors feel that further studies are required to study the influence of other parameters such as length, spacing, and stiffness of the geogrids on the dynamic characteristics of the geogrid-reinforced retaining walls.

(4) Also, due to the variety of backfill and reinforcement, a uniform standard testing apparatus and testing methods to study the dynamic characteristics of reinforced retaining walls have not been established. Thus, optimizing the testing apparatus and building a unified standard are necessary.

Conflicts of Interest

The author declares no conflicts of interest.

Acknowledgments

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