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Research Article

An evaluation of vertical dynamic stress attenuation for compacted coarse-grained soils

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ABSTRACT

Coarse-grained soil (CGS), as a filler with the characteristics of high bearing capacity but difficult compaction for embankment construction, requires an appropriate thickness of a single compaction layer according to the influence depth of vertical dynamic stress. This paper used a numerical analysis using PFC2D following a scale model test with different particle gradations of compacted CGS fillers by adopting a modified PFWD. The results show that the influence depth is about 50 cm under the maximum impact stress of 0.066 MPa if defined the depth as the maximum stress attenuation to 20%. The compacted CGS filler with dense particle gradation and high strength has a rapid attenuation on vertical dynamic stress. Meanwhile, with the increase of stone content (P5, particle size ≥5 mm), the vertical dynamic stress of compacted CGS is attenuated exponentially. The maximum particle size also affects the attenuation of vertical dynamic stress, which needs further research. The findings support the development of non-destructive devices to inspect the compactness of subgrade construction rapidly.

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1. INTRODUCTION

With the rapid development of highway engineering and increasing environmental protection requirements, the coarse-grained soil (CGS) with a mixture of soil and gravel particles has enormous potential for being widely used in highway subgrade construction due to the high bearing capacity. However, the compaction of CGS fillers is quite tricky, which needs to confirm an appropriate thickness of the compacted layer [1]. As the soil fillers, the particle composition of CGS is essentially a vital factor in influencing the mechanical properties of compacted soil layers. Generally, the methods to study the influence mechanism of coarse-grained particle content on macroscopic and mesoscopic properties of CGS fillers are usually using the discrete element method (DEM) and large-scale direct shear test (DST) or both. The previous research compared physical tests, and numerical simulation indicated that the gra-

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(a) 0-2 mm


(b) 2-20 mm


(c) 20-60 mm

Figure 1. Three classifications of the CGS sample.

dation characteristics of CGS filler, such as controlling the optimal coarse-grained content, significantly influence the compaction behaviors [2, 3]. Therefore, several related research findings, including the gradation equation, were put forward to quantitatively express the influence of gradation on the mechanical behaviors of CGS fillers [4–6].

Meanwhile, the fine particles are the factors to influence the soil type, which further affects the mechanical performances of CGS [7, 8]. Moreover, the influence of particle gradation on volume deformation is related to dilatancy. The critical reason is that the particle composition of CGS fillers is the main factor determining the shear strength [9, 10]. Additionally, the test study on controlling the seepage failure gradient of CGS with different particle gradations indicated that the failure gradient of CGS with more coarse-grained components usually occurred later than that of the gradation with more fine-grained components. Meanwhile, the type of infiltration failure of CGS fillers reflects the internal structural stability of soil particles under specific particle composition and compactness degree [11]. Furthermore, the methods to estimate the deformation modulus of compacted CGS fillers were also developed [12, 13]. For the influence of the stiffness modulus, both the maximum dry density (MDD) and the optimum moisture content (OMC) were proved as the main factors by the portable falling weight deflectometer (PFWD), which is also currently and widely used in rapidly estimating the modulus of the structure intergradation of pavement or roadbed [14–18].

However, the current research for CGS fillers mainly refers to the conventional static features such as the MDD, compressive shear strength, and impermeability, while rarely from the perspective of dynamic response. For the soil subgrade, the previous research on the dynamic stress attenuation with different resilience modulus of compacted fillers under axial loads showed that the greater the modulus, the faster the dynamic stress attenuates [19]. The mechanical properties of CGS fillers, as a complex mesostructure, are essentially influenced by various factors. Under dynamic loads, the particles of CGS filler often occur microscopic behaviors such as straight movement, rotation, and even breakage. In practice, however, it is difficult to study its mesoscopic mechanical properties directly due to various restrictions of different conditions. Hence, using DEM, typically the program known as the particle flow code (PFC), is convenient to simulate the mechanical behavior of CGS fillers in terms of different particle interactions [20].

Therefore, the first objective for subgrade construction applying CGS fillers is to confirm an appropriate thickness of a single compaction layer by considering soil particle interaction behavior. From the application of PFWD, it is adequate to test the integration of pavement compaction. The thickness of a single CGS soil compacting layer also strongly correlates with the vertical attenuation of dynamic stress induced by non-destructive devices while not more significant efforts by compactor roller. Accordingly, this paper presents a test and numerical evaluation of dynamic stress attenuation for the compacted CGS fillers with different particle gradations using a modified PFWD tester.

2. MATERIALS AND METHODS

2.1. Test Materials

The CGS filler is an inhomogeneous mixture of earth and stone in the natural state. The soil sample of disintegrated granite in this research was from Chizhou City of Anhui Province in China. The CBR values of all samples meet the required values according to the highway earthwork specification (>14.3%). Meanwhile, the MDD and the optimal moisture content of CGS are 2.119 g/cm^3 and 7.6%, respectively. During the geotechnical sampling, the compaction work is between 2677.2 and 2687.0 kJ/m^3, according to the specification. Specifically, in this research, the CGS soil samples were divided into three categories in terms of particle size, fine particles (0–2 mm), medium particles (2–20 mm), and coarse particles (20–60 mm). The soil sample classification is processed in Figure 1a–c.

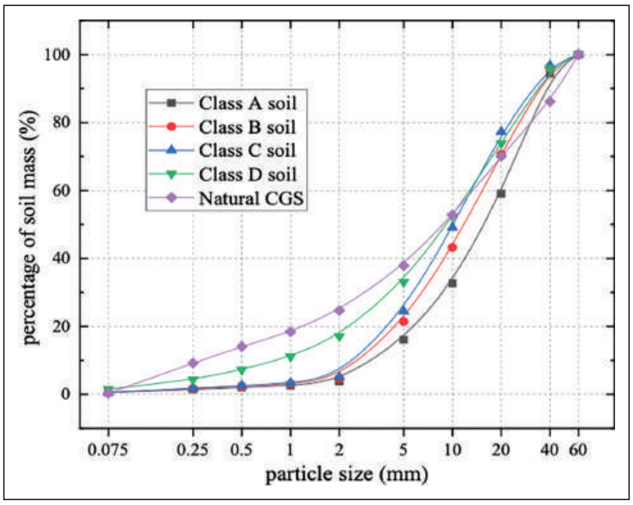

Figure 2. Gradation curves of test soil samples.

Table 1. Particle composition parameters

Soil types	Class A	Class B	Class C	Class D	Natural CGS
d10/mm	3.63	2.955	2.752	0.918	0.291
d30/mm	9.86	6.971	6.125	4.925	3.211
d60/mm	20.53	19.545	16.812	13.540	14.201
C_u	5.65	6.615	6.109	14.748	48.849
C_c	1.31	0.841	0.811	1.951	2.498

According to the particle filling theory, the sample soil materials are blended based on the proportion of the test soil samples and filled step by step until the original soil composition is recovered. Finally, we obtain five types of CGS with different particle gradations. Based on the soil classifications above, the original proportion of CGS particles with three ranges is *Fine* (0–2): *Medium* (2–20 mm): *Coarse* (20–60 mm) = 1:3.84:1.87 in the mass ratio by using sieve analysis. From this proportion, five test samples with different particle gradations are designed as, Class A = 1/3 *Medium*+3/3 *Coase*, Class B = 2/3 *Medium*+ 2/3 *Coase*, Class C = 3/3 *Medium*+3/3 *Coase*, Class D = 1/2 *Fine*+3/3 Medium+3/3 *Coase*, Natural CGS = 2/2 *Fine*+3/3 *Medium*+3/3 Coase. The gradations of the test CGS sample are shown in Figure 2. The parameters, including Cc and Cu of five particle compositions, are listed in Table 1.

2.2. Test Device and Principles

The test device used in this research, named dynamic, resilient modulus tester (DEM450) and shown in Figure 3, is modified based on the portable falling weight deflectometer (PFWD) [21]. The significant difference compared with PFWD is that the diameter of the loading plate base enlarged to 450 mm from 300 mm, and the mass of the

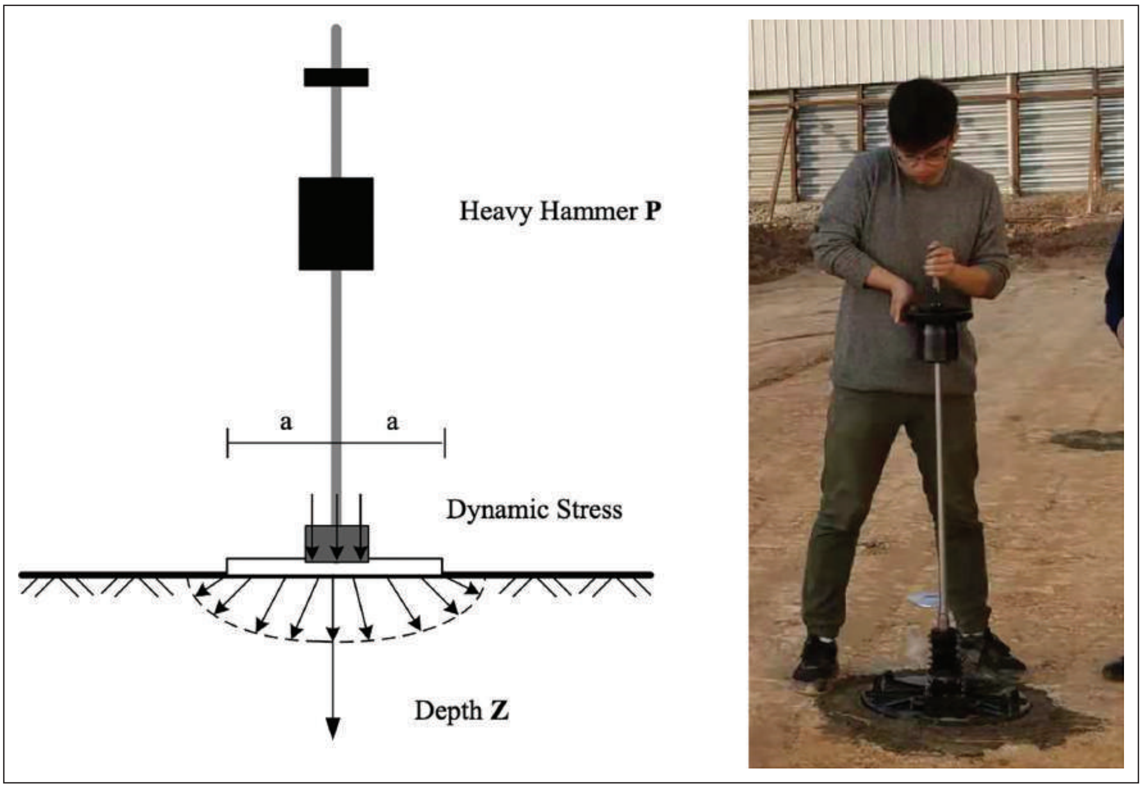

Figure 3. Dynamic, resilient modulus tester (DEM450).

drop hammer increased to 12 kg from 10 kg, which makes the acceptable size of the filler particle increased to 150 mm from 75 mm. Besides, the maximum stress is decreased to 0.066MPa from 0.1MPa due to the consistency of the initial tri-axle loading and the lightweight design. All modifications in DEM450 are for testing the soil filler with big size particles such as CGS.

The testing principle of DEM450 is the same as that of PFWD. Specifically, using a certain mass of the hammer, from a certain height with free fall, through the spring damping element and a particular area of the carrier plate to apply a specific size and time of action of the dynamic stress on the surface of compacted fillers, and then cause the surface to produce dynamic bending. By collecting the maximum impact force (N) and the corresponding resilient deformation (mm), then calculate the dynamic, resilient modulus (Ed) of the compacted soil layer. According to the correspondence between Ed and the degree of compaction (K), it is possible to use this modified device to check the compaction status of soil fillers. Especially this device is convenient for particular soils such as CGS fillers compared with the traditional sand cone method or others.

2.3. Test Methods

2.3.1 General Method

Using PFC2D, a DEM model was established to study the influence of three crucial factors of CGS fillers, namely, different particle gradation, the maximum particle size, and the stone content (P5, particle size ≥5 mm), on the dynamic stress attenuation of compacted CGS soil filler. After that, the numerical analysis results were verified by physical model tests in the laboratory. However, the scale model test needs to carry out firstly, using the impact loading on the top of compacted fillers in the layered stacked mold. In the test, an earth pressure cell is embedded at the bottom of the first compacted layer. The impact load is applied to the top to collect the dynamic strain values at locations with different depths of the structural layer. The dynamic stress values in the layer are obtained by converting the calibration coefficient and the formula of the applied strain sensor. The actual influence depth can be obtained by assuming 20% of the maximum stress value, as defined by the dynamic stress attenuation depth, which is consistent with the subgrade work zone under the standard axial load. The dynamic stress attenuation law of compacted CGS filers with different particle compositions under impact stress (0.066MPa) was studied using the scale model test in the laboratory. The test results can directly reflect the strength and mechanical properties of compacted CGS fillers from the dynamic response, providing a significant reference for the gradation selection of CGS filler in road subgrade construction. The objective of this research is to provide support for the research and development of rapid compaction quality control. Significantly, this research is also a theoretical basis for

Table 2. Mesoscopic parameters for DEM modeling

Project	Mesoscopic parameters	Symbol/unit	Values
Ball	Density	$\rho/kg{\cdot}m^3$	2500
	friction coefficient	f	0.7
	initial elastic modulus	E_c/Pa	2.5×10^7
	stiffness ratio	κ_n/κ_s	2.5
	Porosity	n	0.1
Ball-wall	normal stiffness	κ_n/Pa	2.5×10^6
	tangential stiffness	κ_s/Pa	2.5×10^6
Clump-ball	Density	$\rho/kg{\cdot}m^3$	3167
	contact stiffness	κ_n、κ_s/Pa	1×10^7

the feasibility of rapid inspection of CGS filler compactness and verifying whether the stress influencing depth meets the inspection requirements of highway construction.

2.3.2 Numerical Calculation

According to the rules of PFC, the number of particles generated in particle generation can reach hundreds of thousands if the actual gradation determines the value. For better efficiency, a reasonable simplification is essential in normal. Particles below 2 mm are replaced by related particles between 2 mm and 60 mm in equal amounts using a weighted average according to their mass proportion. After running the PFC program, according to the basic principles of dynamics, the initially generated overlapping particles repel each other and fill the whole space, finally forming the specified particle accumulation model. To simplify the analysis and improve the calculation efficiency, the size of the specimen model is 0.9 m long and 0.9 m wide.

In PFC2D, the voids in two-dimensional space differ from the actual voids in three-dimensional space and are slightly smaller than the latter numerically. Therefore, the voids in two and three dimensions need to transform quantitatively. Based on the assumption of particles with equal particle size and the principle of compactness modification, the formula for converting three-dimensional voids of particles to two-dimensional voids was proposed as follows [22].

$$\varepsilon_{3d} = 1-\xi(1-\varepsilon_{2d})^{\frac{3}{2}} \tag{1}$$

Where $\xi=\frac{\sqrt{2}}{\sqrt{\pi\sqrt{3}}}+D_r(\frac{2}{\sqrt{\pi\sqrt{3}}}-\frac{\sqrt{2}}{\sqrt{\pi\sqrt{3}}})$;

D_r is the relative compactness of the soil.

In this test, the relative compactness of CGS is 0.79, and the two-dimensional voids are 0.1. According to formula (1), the voids under three-dimensional condition is 0.31, which meets the compaction quality standard of this kind of filler. As there is no direct correspondence between parameters of the mesoscopic and the macroscopic scale of the actual soil particles, they have co-relation under natural conditions. Combined with relevant laboratory test data and repeated numerical simulation tests, the corresponding mesoscopic parameters affecting the macroscopic parameters and their relationship were determined. Accordingly, the mesoscopic parameters matching the macroscopic parameters of soil mass were listed in Table 2.

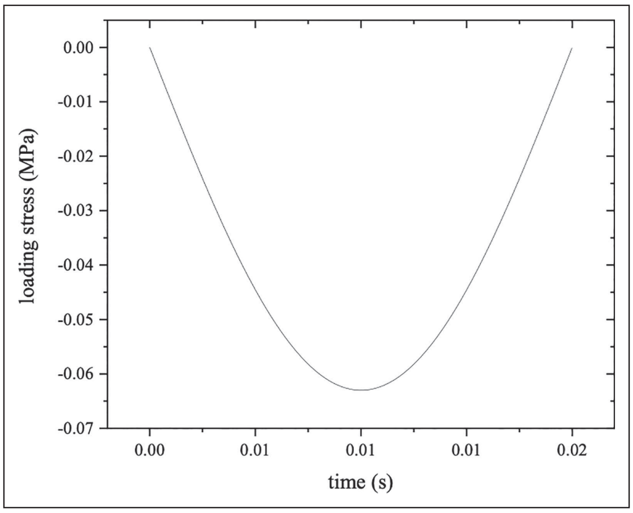

Figure 4. The time-history curve of semi-sinusoidal load.

The dynamic impact loading is in the form of semi-sinusoidal loads, and the maximum impact load and the bearing area determine the transient impact stress. According to the axial load in the standard test method of dynamic resilience modulus of subgrade soil specified in the highway subgrade design code [23], to study the dynamic properties and strength properties of compacted CGS filler subgrade, the semi-sinusoidal pulse load of 0.066MPa as the maximum axial preload in the dynamic triaxial test is selected for the transient impact stress on the bearing plate, with the standard action time of 18–20 ms. The time-history curve of the impact load stress is shown in Figure 5.

2.3.3. Scale Model Test

A physical model test was conducted in the laboratory to verify the reliability of the numerical modeling and the calculation results. Firstly, a specific size of layered and stacked mold was applied, and the categorized filler was added and compacted to the mold for the dynamic impact stress test. An earth pressure cell was pre-installed at the bottom of the first compacted soil layer to monitor the vertical dynamic stress transferred from the top of the model, as shown in Figure 5a. Three of the five fillers with different gradations mentioned above were selected for the test to verify the accuracy of the numerical simulation results. The loading model with and without molds and the loading process of the laboratory test are shown in Figures 5b and 4c, and 4d, respectively.

Figure 5. Dynamic, resilient test for compacted CGS fillers in laboratory. **(a)** Installation of earth pressure cell. **(b)** Parallel tests with molds. **(c)** Stacked models without mold. **(d)** Dynamic impact loading.

3. RESULTS AND DISCUSSION

3.1. Calculation Results

Since the PFC program cannot apply force directly to the wall, it must use particle loading conditions and fix the angular velocity of the clump in the horizontal direction to avoid horizontal displacement and rotation. The loading force of the clump is set for the loading of the numerical model. Taking CGS particles as an example, the force chain diagrams of its loading force diffusion process are shown in Figure 6 (left). The particle velocity vector diagrams under the corresponding loading force are shown in Figure 6 (right). The loading stress diffusion diagram and the corresponding particle velocity vector diagram show that the clump can load the DEM model effectively.

3.2. Effect of Stress Attenuation

3.2.1 Gradation Effect

Using the generation method and calibrated mesoscopic parameters model above, the PFC program generated the numerical model of particle flow of CGS with five different particle gradations and carried out the impact dynamic stress loading simulation test. The generated particle flow models are shown in Figure 7 (left). The stress distributions among the corresponding model particles are shown in Figure 7 (right). In Figure 7 (right), the dark part represents the compressive stress, distributed in chains on the geometric plane called the force chain. The force chain can intuitively show particles' properties, strength, and stress distribution. It was noticed that under the same conditions, as the particle gradation of soil samples is gradually better, the pressure chain is gradually increased, and the intercalation effect between particles is significant. Meanwhile, the distribution of the force chain is gradually uniform, and the transmission and distribution of forces also tend to be uniform.

The above numerical model loading method is used to load the test CGS filler. For example, the time-history curve of vertical dynamic stress response of the CGS filler embankment at different depths is shown in Figure 8. The time-history curve shows that the transfer of dynamic

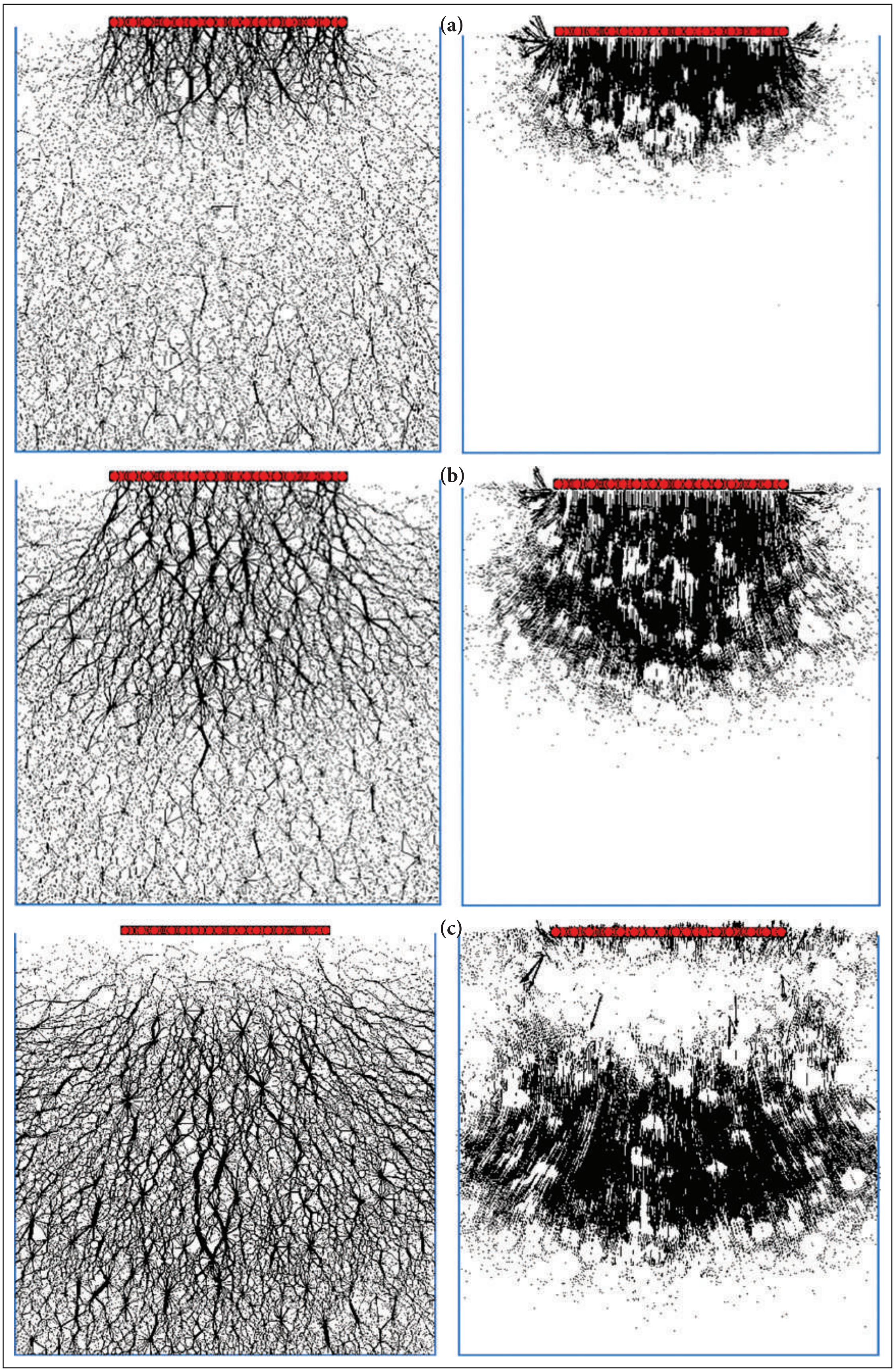

Figure 6. Dynamic loads and diffusion processing in three stages. **(a)** Initial loading. **(b)** During loading. **(c)** After loading.

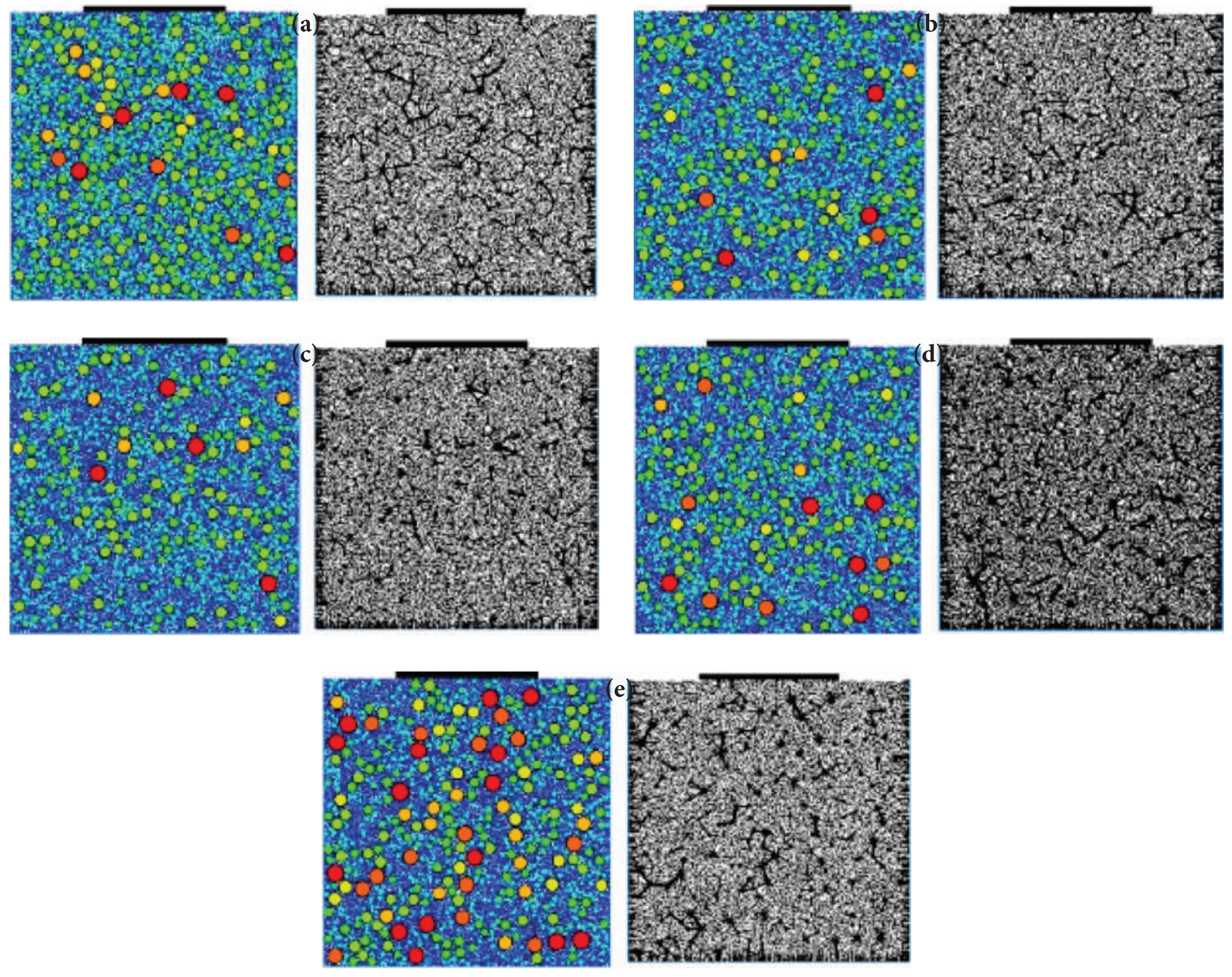

Figure 7. Different gradation models and force chains distribution among particles. **(a)** Class A. **(b)** Class B. **(c)** Class C. **(d)** Class D. **(e)** Natural CGS.

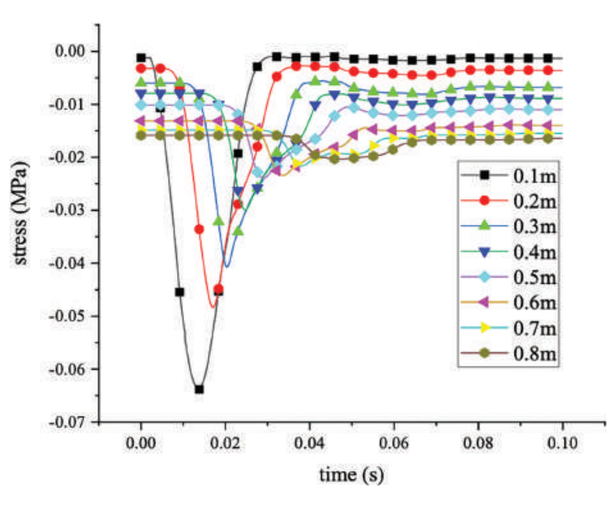

Figure 8. Time-history curves of dynamic stress at different depths.

stress delays along the depth direction. Under the action of semi-sinusoidal load, the emergence of stress peak is gradually delayed with the increase of depth. In addition, the dynamic stress of different depths under the loading of other groups of filler samples has similar regularity.

According to the numerical calculation results, the five test fillers' corresponding vertical dynamic stress curves are shown in Figure 9. The test results showed that the CGS filler gradation directly affected the transfer of dynamic stress in soil. The better the particle gradation of the filler, the greater the non-uniformity coefficient, the faster the attenuation of its vertical dynamic stress, and the more uniform the transmission of its stress. From Figure 9, the Natural CGS and Class D soil have a more significant attenuation rate of dynamic stress than the three others, which is caused by fine particles. For Natural CGS with complete gradation, the attenuated depth of vertical dynamic stress is about 50 cm. In other words, the single compaction thickness for CGS fillers is

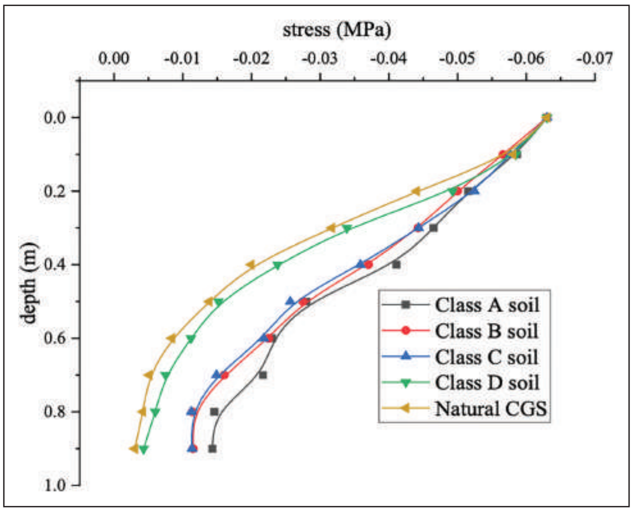

Figure 9. Vertical dynamic stress attenuation curves under different soil gradations.

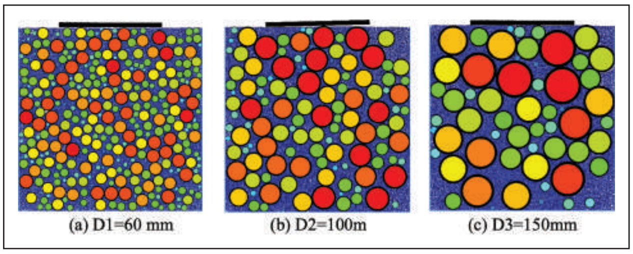
(a) D1=60 mm (b) D2=100m (c) D3=150mm

Figure 10. Models with different maximum particle size.

recommended to be less than 50 cm, which can match the influence depth of modified PFWD for quick compactness inspection.

3.2.2. Effect of the Maximum Particle Size

Taking the maximum particle size as a variable and considering the requirement of the maximum particle size of subgrade fillers for highway subgrade construction [24], set the two more maximum particle size variables of 100 mm and 150 mm to study the change of subgrade dynamic stress. The fillers to be simulated include two groups of particle size ranges and three gradations of soil samples with different maximum particle sizes, (2–5) mm+ (5–60) mm, (2–5) mm+(5–100) mm, and (2–5) mm+(5–150) mm. The numerical simulation randomly generated related particles in two groups of gradations, and the generated model is shown in Figure 10. The calculation results show the curve of vertical dynamic stress changing with depth in Figure 11. The results show that the maximum particle size of filler affects stress transmission and attenuation. However, with the increase in the maximum particle size of soil particles, the relationship between the stress attenuation and the maximum particle size is not apparent. Overall, the influence depth of vertical stress is above 48 cm under three maximum particle sizes.

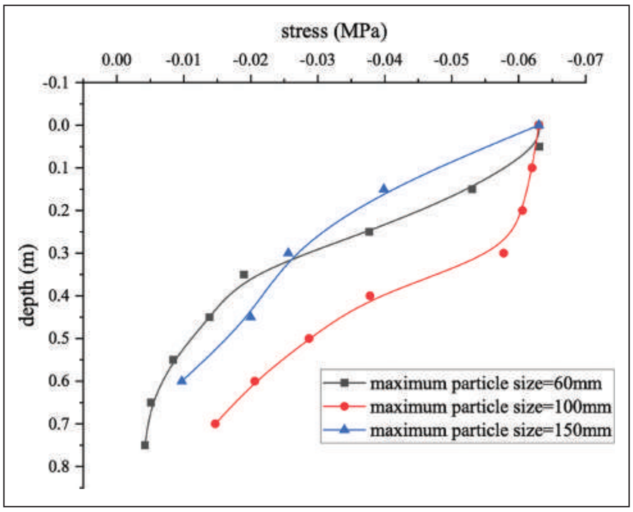

Figure 11. Dynamic stress attenuation curves with different maximum particle sizes.

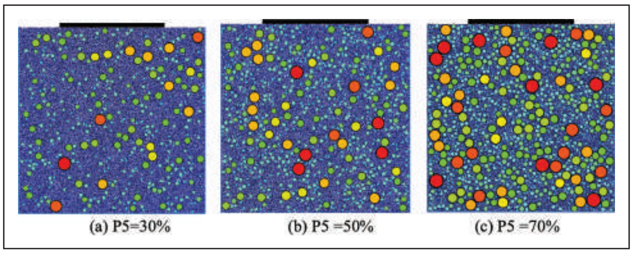
(a) P5=30% (b) P5 =50% (c) P5 =70%

Figure 12. DEM models with different stone contents.

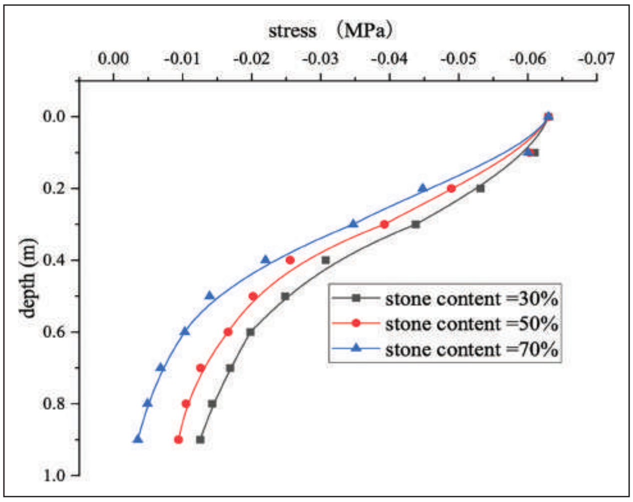

Figure 13. Stress attenuation with different stone contents.

3.2.3. Effect of Stone Content on Dynamic Stress Attenuation

In previous studies, they often took the particle size of 5 mm as the limit, and the particle size above 5 mm was defined as stone components, while the particle size below 5 mm as soil components. Therefore, P5 is a short expression for the stone content of the subgrade filler. With the

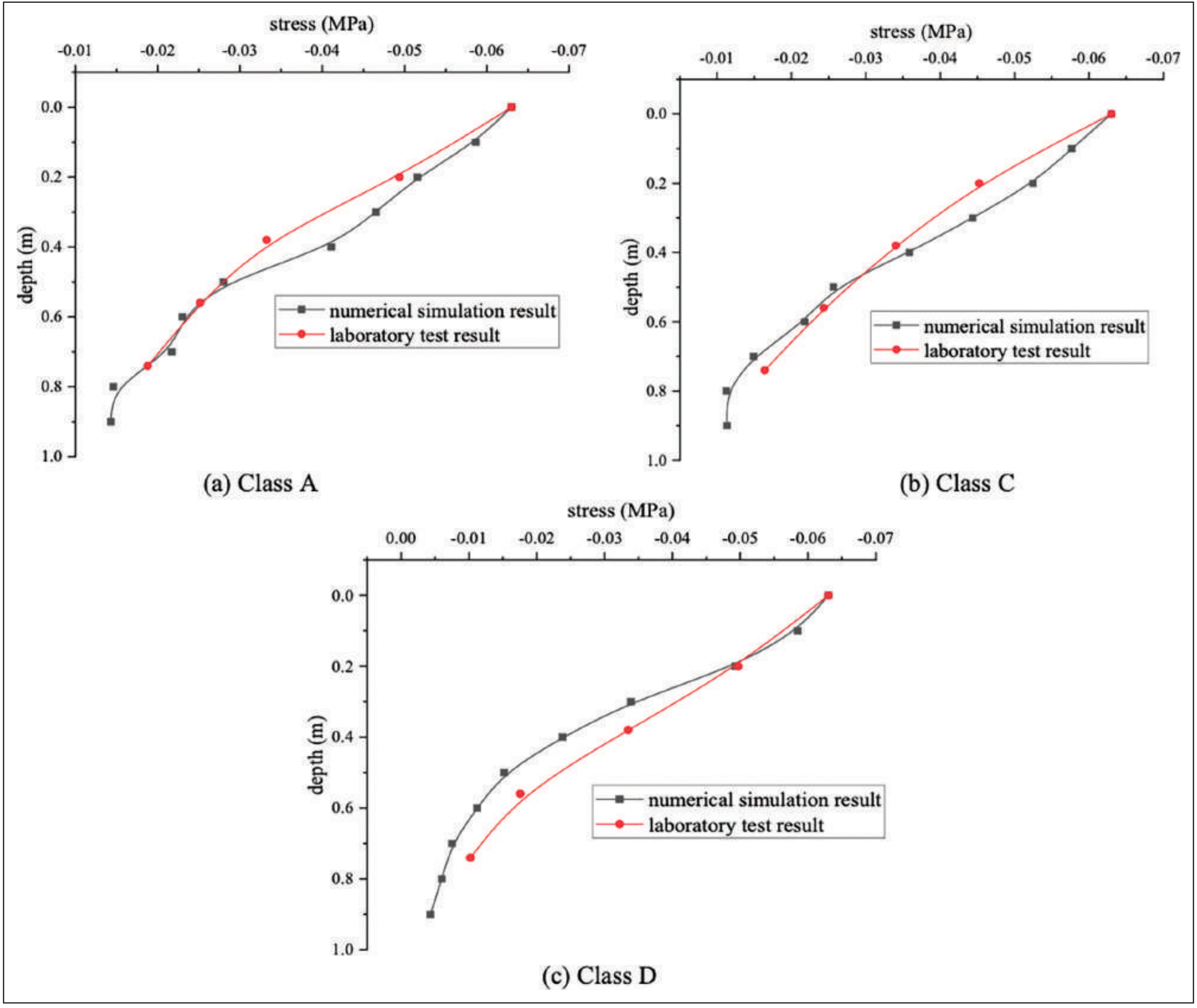

Figure 14. Comparison of results between laboratory tests and numerical simulations.

increase of P5, the structure of CGS is gradually changed from a dense-suspended structure (P5< 30%) to a skeleton-dense structure (30%<P5<70%), and finally to a skeleton-void structure (P5>70%) [25]. Taking P5 as the limit stone content of 30% and 70%, it generally showed that the CGS filler could not show the best mechanical properties when P5 is less than 30% or more than 70%. When the P5 is between them, its mechanical properties gradually increase with P5 increasing, and when the P5 is about 70%, the filler can achieve the best compaction characteristics in an excellent dense structure [26]. Based on this, this paper intends to take the limit stone content as the research variable, change the stone content in the PFC model, and analyze the change of subgrade dynamic stress under this condition. The simulated packing includes two particle size ranges, namely (2–5) mm+(5–60) mm. PFC program randomly generates related particles within the particle size range in two groups, and the generated model is shown in Figure 12.

The calculation results show the variation curve of vertical dynamic stress with the subgrade depth in Figure 13. The results show that P5 significantly influences the vertical dynamic stress attenuation. Accordingly, with the increase of P5, the overall trend of the transfer of dynamic stress in soil mass is that the stress attenuation accelerates with the increase of depth. Then the attenuation rate is sharp down, showing an exponential attenuation. Meanwhile, the rate of stress attenuation also increases with the increase of the P5. The minimum influence depth of dynamic stress is about 54 cm for the CGS filler with P5=70%, which means the attenuation effect is best.

3.3. Comparison between Laboratory tests and Numerical Analysis

According to the above laboratory tests, select the fillers with the same properties as the Class A, C, and D soils mentioned above for the impact dynamic stress loading test. Then, compare the numerical simulation results to verify the accuracy of the numerical simulation data. The corresponding vertical dynamic stress variation data is shown in Figure 14.

The test data shows that the numerical simulation results under the same conditions fit the scale model test results well. The vertical dynamic stress attenuates with the increase of depth. Therefore, using PFC to simulate the attenuation law and the influence depth of dynamic stress for CGS fillers is reasonable. However, according to the data curve, there is still a particular deviation between the data simulation and the model test. The possible reason for this difference is that particle gradation dramatically affects dynamic stress distribution. When generating the particles numerically, the simulation and the calculation efficiency must take into account, and the fine particles in the actual gradation are replaced, resulting in errors between the calculated gradation and the actual gradation, thus making the attenuation law of actual dynamic stress deviation.

4. CONCLUSIONS

(1) Particle gradation of coarse-grained soil (CGS) filler affects vertical dynamic stress attenuation of compacted subgrade. Under the same conditions, the better the filler gradation, the denser the filler, the higher its overall strength, the faster the vertical dynamic stress attenuation, and the more uniform the stress transfers will be. The minimum depth of dynamic stress under different gradations is about 50 cm.

(2) The maximum particle size of CGS filler affects the vertical dynamic stress transfer of the compacted subgrade. However, with the increase of the maximum particle size, the relationship between the vertical stress attenuation and the effect of the maximum particle size is insignificant. The influence depth of dynamic stress under the three maximum particle sizes is above 48 cm.

(3) The stone content (P5) of CGS filler significantly influences the dynamic stress attenuation of the compacted subgrade. In a specific range, with the increase of P5, the denser the soil structure, the faster the attenuation of vertical dynamic stress will be. The minimum influence depth of dynamic stress under three conditions of the P5 ranges is about 54 cm.

(4) The recommended thickness of a single compaction layer for CGS fillers is 50 cm when modified PFWD to inspect the compactness status rapidly. In this depth, it is reliable to build the relationship between the dynamic, resilient modulus from the modified PFWD and compactness degree from the conventional test method during subgrade fillers construction.

(5) The attenuation influenced by the comprehensive interaction of particle gradations, morphology, and crushing status needs further research. This research majorly focused on the gradation of CGS particles. However, the particles have random irregular shapes, and there is an "interlock" force besides friction between the particles. Besides, their size and shape affect the contact stress between particles. When the stress is significant, the particles will be crushed by extrusion, which will inevitably affect the attenuation of actual dynamic stress.

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DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

PEER-REVIEW

Externally peer-reviewed.

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