

Article

Three-Dimensional Discrete Element Analysis of Bearing Characteristics of Concrete-Cored Sand-Gravel Pile Composite Foundation under Cyclic Dynamic Load

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Abstract: Concrete-cored sand-gravel piles are a kind of composite pile formed by wrapping a concrete-cored pile with a sand-gravel shell, which has the advantages of both a rigid pile and bulk-material pile. The bearing characteristics of the concrete-cored sand-gravel pile composite foundation were investigated by establishing a three-dimensional discrete element numerical model for a cyclic dynamic loading test. The results show that the vertical stress of the core pile body fluctuates greatly at the beginning of loading, and the fluctuation amplitude decreases with the depth, and gradually tends to be stable in the middle and late stages, and the vertical-stress distribution is relatively uniform. The radial stress in the upper part of the core pile body fluctuates greatly, the fluctuation in the lower part is small, and the radial stress in each part of the core pile body gradually tends to be stable in the late-loading period. The radial stress factor of the core pile body reaches the stable speed with the foundation depth decreasing; the fluctuation amplitude of the pile-soil stress ratio decreases with the foundation depth and gradually tends to be stable with the increase in loading. The results of this study can provide a reference for the design and construction of a core sand pile composite foundation.

Keywords: composite foundation; concrete-cored sand-gravel pile; discrete element; bearing characteristics; cyclic dynamic load



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1. Introduction

A pile composite foundation is an effective means of weak foundation treatment, different pile types can cope with different types of natural foundations, and its construction is convenient and cost-effective; therefore, it has been widely used in the actual works of weak foundation treatment [1–6]. Cyclic dynamic loading is one of the main influencing factors of deformation produced by foundation soil. A concrete-cored sand-gravel pile composite foundation is a new type of foundation treatment technology, which is generally a composite pile formed by prefabricated concrete core piles and outsourced sand-gravel shells, and this composite pile combines the characteristics of the strong bearing capacity of rigid piles and strong drainage and consolidation capacity of discrete material piles; therefore, it has a good value for engineering applications [7,8].

In recent years, domestic and international scholars have conducted a number of studies on cyclic dynamic loads and concrete-cored sand-gravel pile composite foundations. Yin Feng et al. [9] analysed the influence mechanism of vehicle loading and dynamic loading on an X-shaped pile-net composite foundation by conducting dynamic characteristic model tests of an X-shaped pile-net composite foundation under different vehicle loads and dynamic loads. Niu Tingting et al. [10] established a large-scale meta-model of a

pile–net composite foundation under high-speed railway train loading and investigated the dynamic response characteristics of a pile–net composite foundation under high-speed railway train loading. He Jie et al. [11] conducted model tests on four composite piles with different cyclic load ratios and analysed the cumulative settlement, pile axial force distribution, pile end resistance, and lateral friction resistance of wedge-shaped strong-core hydraulic soil composite piles under cyclic loading. Li Tianbao et al. [12] carried out an indoor model test of a rigid-flexible, pile-bearing, reinforced bedding composite foundation and compared and analysed the bearing properties of a rigid-flexible pile and flexible pile-bearing reinforced bedding composite foundation under cyclic loading. Yuan et al. [13] carried out an indoor model test of a reinforced gravel pile composite foundation under multiple sets of traffic loads and analysed the effect of the cyclic loading ratio on the bearing properties of a reinforced gravel pile composite foundation. Zhu et al. [14,15] investigated the bearing characteristics of a pile–soil composite foundation under long-term cyclic loading by indoor dynamic modelling tests. Gao et al. [16] established a discrete element model of a geosynthetic wrapped gravel pile composite foundation, investigated the deformation characteristics and pile–soil stress ratio of piles under different pile lengths and pile diameters, and analysed the lateral deformation characteristics of piles under cyclic loading. Chen Junsheng et al. [17,18] conducted a comprehensive analysis of the consolidation deformation, pore pressure dissipation, pile–soil stress sharing, and bearing characteristics of a core-sand pile composite foundation through in situ observation and a test in the field. Guan et al. [19,20] analysed the load transfer mode and mechanism of core-sand piles and proved that the core-sand pile composite foundation has the advantages of small settlement difference, reliable quality, high bearing capacity, and good stability after the work. Chen et al. [21] established a three-dimensional force–water coupling numerical model of a core-sand pile supported embankment; explored the foundation settlement, superporous water pressure, load distribution between the soil and core-sand pile, and deformation law; and compared and analysed the results of in situ tests. Zhang et al. [22] proposed a plane strain conversion method for the analysis of the consolidation of composite foundations with core-sand piles and verified the validity of the method by comparing with the three-dimensional numerical simulation and the data from the embankment site to verify the validity of the method. Jin [23] derived the consolidation equation of a short-core core-sand pile reinforced composite foundation under time-dependent loading, solved it by the separated variable method, and verified the reasonableness of the solution.

The above studies mainly focus on the bearing performance of a concrete-cored sand–gravel pile composite foundation under static conditions and other composite foundations under cyclic dynamic loading, and the research means are mostly in situ tests, field experiments, and theoretical derivations, with less internal bearing mechanism and detailed analysis of a concrete-cored sand–gravel pile under cyclic dynamic loading. As an important part of a highway, the stability of the road base under long-term cyclic dynamic load is the foundation of a smooth and safe road structure. The application of a concrete-cored sand–gravel pile composite foundation in the design and construction of a highway roadbed, its design theory and method are not perfect, especially the bearing characteristics of a concrete-cored sand–gravel pile composite foundation under cyclic dynamic load, needs to be studied in depth. This paper establishes a numerical model of a concrete-cored sand–gravel pile composite foundation based on the discrete element analysis method, analyses the bearing characteristics of a concrete-cored sand–gravel pile single-pile composite foundation under cyclic dynamic loading, and reveals the internal bearing mechanism of the concrete-cored sand–gravel pile composite foundation from the perspective of micromechanics.

2. Parameter Calibration and Modelling

2.1. Parameter Calibration

2.1.1. Parameters of Soft Soil

The stress–strain curves of soft soil in a project were obtained by three sets of indoor triaxial compression tests with different peripheral pressures and then used to establish a

discrete element model for the triaxial compression test of soft soil. The numerical model adopts the same specimen size as the triaxial test, as shown in Figure 1. By constantly adjusting the detailed parameters, the numerical simulation and the stress–strain curve obtained from the indoor test basically coincide (see Figure 2), and the detailed parameters obtained from the calibration (see Tables 1 and 2) can effectively reflect the macroscopic mechanical properties of soft soil.

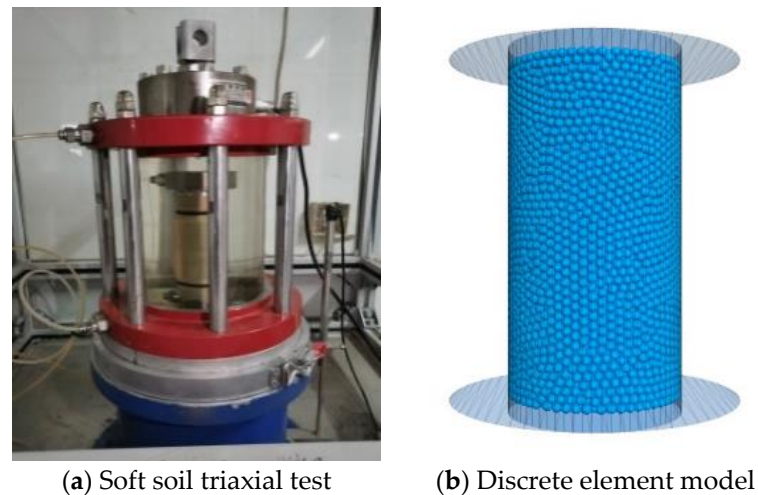


Figure 1. Triaxial testing and discrete element modelling of soft soils.

Table 1. Fine-scale parameters of soft soils.

Parameter	Soil
Particle density (kg/m^3)	2650
Particle normal stiffness (N/m)	4×10^4
Particle shear stiffness (N/m)	4×10^4
Contact bond normal strength (N)	3.2
Contact bond tangential strength (N)	3.2
Particle friction factor	0.25

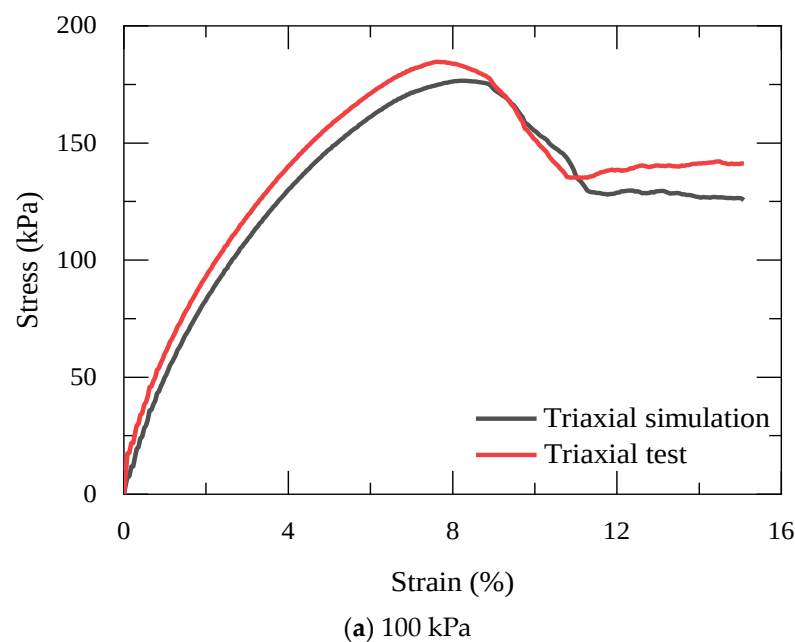
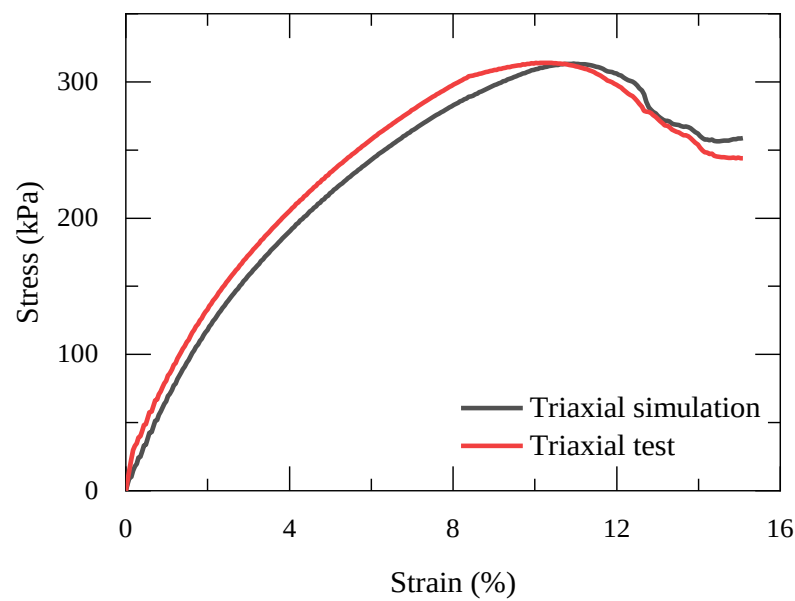
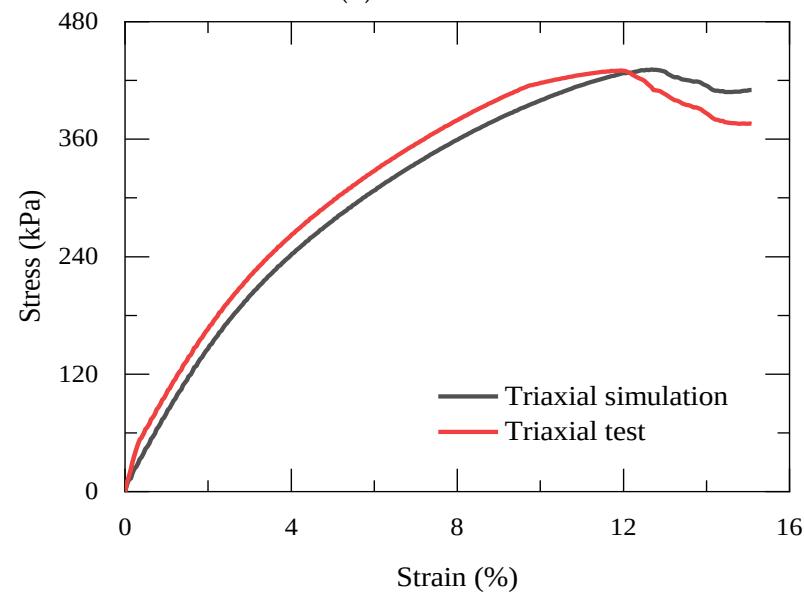


Figure 2. *Cont.*



(b) 200 kPa



(c) 300 kPa

Figure 2. Stress-strain curves of triaxial compression tests on soft soil under different perimeter pressures.**Table 2.** Contact strength of soft soil at different depths from top surface of pile soil.

Soil Horizon	Depth (mm)	Normal Strength (N)	Tangential Strength (N)
First floor	0–200	3.2	3.2
Second floor	200–400	3.4	3.4
Third floor	400–600	3.65	3.65
Fourth floor	600–800	3.95	3.95
Fifth floor	800–1000	4.2	4.2
Hard layer	1000–1500	4.5	4.5

2.1.2. Parameters of Sand–Gravel

Existing studies have shown that the discrete element simulation of the triaxial compression test of sand–gravel can calibrate its internal friction angle [18]. The numerical model of the sand–gravel triaxial compression test is established as shown in Figure 3,

and the discrete element simulation can obtain the stress–strain curve of the sand–gravel triaxial compression test under different peripheral pressures (see Figure 4). The internal friction angles of sand–gravel are 35.3° , 40.3° , and 48.8° [24] when the peripheral pressure is 20 kPa, 40 kPa, and 60 kPa, respectively (see Table 3).



Figure 3. DEM for triaxial testing of crushed stone.

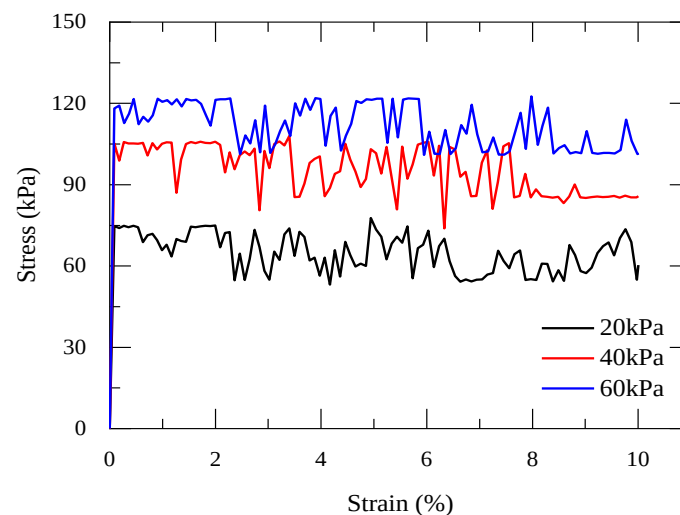


Figure 4. Stress-strain curves in gravel compression tests of crushed stone under different enclosure pressures.

Table 3. Fine view parameters of crushed stone.

Parameter	Sand–Gravel
Particle density (kg/m^3)	2500
Particle normal stiffness (N/m)	6×10^7
Particle shear stiffness (N/m)	1×10^7
Particle friction factor	0.8

This paper focuses on the calibration of the internal friction angle of sand–gravel. The angle of internal friction of sand–gravel can be calculated by the following formula:

$$\sin \varphi = q/p' \quad (1)$$

where φ is the angle of internal friction; q and p' are calculated by the following equation:

$$q = (\sigma'_1 - \sigma'_3)/2 \quad (2)$$

$$p' = (\sigma'_1 + \sigma'_3)/2 \quad (3)$$

where σ'_1 is the effective major principal stress and σ'_3 is the effective minor principal stress.

At the peripheral pressures of 20 kPa, 40 kPa, and 60 kPa, the internal friction angles of the sand–gravel were 35.7° , 40.8° , and 49.2° , which were calculated according to the formulae, and were very close to the calculated ones of 35.3° , 40.3° , and 48.8° in the existing discrete element simulation study, which indicated that the fine-scale parameters in Table 3 could respond to the macroscopic mechanical properties of the sand–gravel.

2.1.3. Parameters of Concrete

The concrete compressive strength curves were obtained from the indoor concrete specimen compression test (three sets of tests were averaged), and then, the discrete element model of the concrete specimen compression test was established. The numerical simulation is consistent with the specimen size of the test, as shown in Figure 5. The numerical simulation was basically fitted to the compressive strength curve of the indoor test by adjusting the fine-scale parameters (Figure 6), and the fine-scale parameters obtained from the calibration (Table 4) can effectively reflect the macro-mechanical properties of concrete.

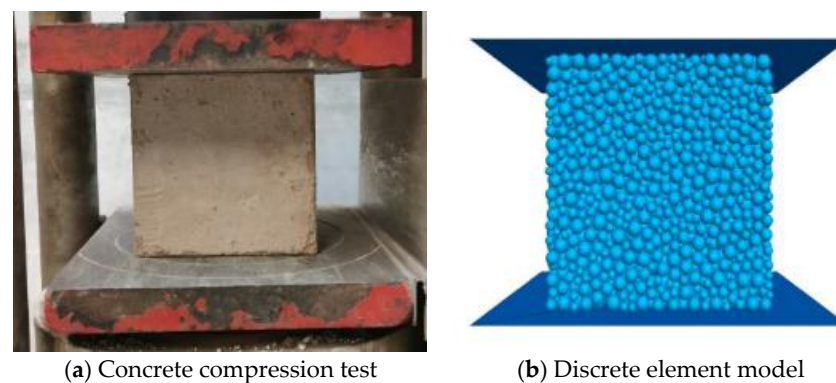


Figure 5. Concrete specimen compression testing and discrete element modelling.

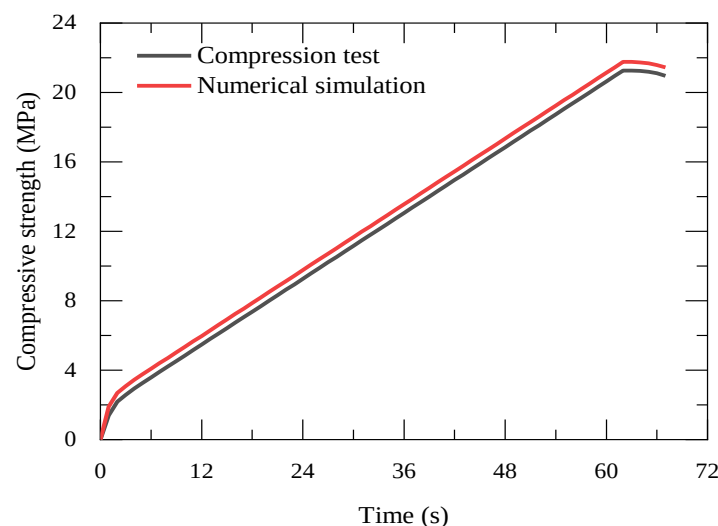


Figure 6. Compressive strength curve of concrete specimen.

Table 4. Microscopic parameters of concrete.

Parameter	Concrete
Particle density (kg/m^3)	2500
Elastic modulus (GPa)	10
Stiffness ratio	1.0
Parallel bond normal strength (N/m^3)	2.5×10^7
Parallel bond tangential strength (N/m^3)	1.7×10^7
Particle friction factor	0.5

2.2. Establishment of 3D Model

Firstly, equal volumes of soil were generated within a rectangular wall of 1200 mm in length and width and 1500 mm in height with soil particles of 18–20 mm in diameter, in which the burial depth of 0–1000 mm was a soft ground foundation and the burial depth of 1000–1500 mm was an underlying hard soil layer. The walls, which are the boundaries of the model, are rigid bodies whose displacements are fixed and cannot be deformed. While the contact bond model of the soil body is given, considering the influence of burial depth on the shear strength of clayey soil in a soft ground foundation, the contact bond strength in the fine view parameter is set to vary along the depth, the rest of the fine view parameters are the same as in Table 1, and the contact bond strengths of the clayey soil at different depths are shown in Table 2, which correspond to the different coloured soil layers in Figure 7.

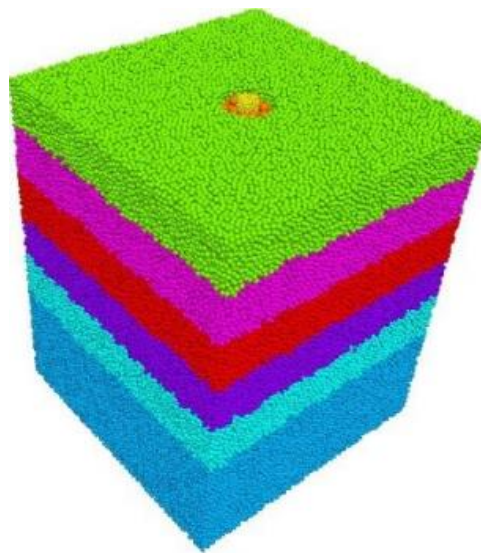


Figure 7. Discrete elemental modelling of concrete-cored sand–gravel pile composite foundations.

Then, the soil with a diameter of 200 mm at the centre of the model and a depth of 1000 mm was deleted. At the same time, to avoid excessive unbalanced contact forces between different particles, two upward-opening walls with diameters of 200 mm and 80 mm and heights of 1000 mm were generated as temporary boundaries between the sand and gravel shell and the concrete core pile. Between the two cylinders, 30–40 mm diameter gravel particles were generated, and a weak linear contact bond model was assigned to the gravel particle units to simulate the actual mechanical occlusion properties of the gravel corners, with the fine-scale parameters shown in Table 3. Concrete core piles with diameters of 5–10 mm were generated inside the 80 mm diameter cylindrical walls and given a linear parallel bond model with the detailed parameters shown in Table 4. The top wall and the two cylindrical walls of the model were deleted, and initial stress balancing was performed.

Finally, a clump with a side length of 560 mm and a thickness of 25 mm was generated on the top surface of the model as a loading plate. Cyclic dynamic loading was simulated using sinusoidal periodic loads of magnitude 5 ± 1 kN and frequency 5. At the same time, the corresponding parts of the model are arranged with measuring balls, through which the data (including pile stress, soil stress, etc.) presented in the analysis of the results are monitored.

3. Analysis of Simulation Results

3.1. Pile Stress Analysis

Normally, the pile body in the pile composite foundation will bear most of the load under vertical loading, and this is also the case for the concrete-cored sand–gravel composite foundation. As shown in Figure 8, the vertical stress of the core pile body fluctuates greatly

at the early loading stage, and the fluctuation amplitude decreases with the depth from the top surface of the pile soil. In the middle of loading, the peak value of vertical-stress fluctuation gradually decreased with loading time, and in the late-loading period, the vertical stresses at different depths from the top surface of the pile soil tended to be stable, and the magnitude of the values was in a relatively close state.

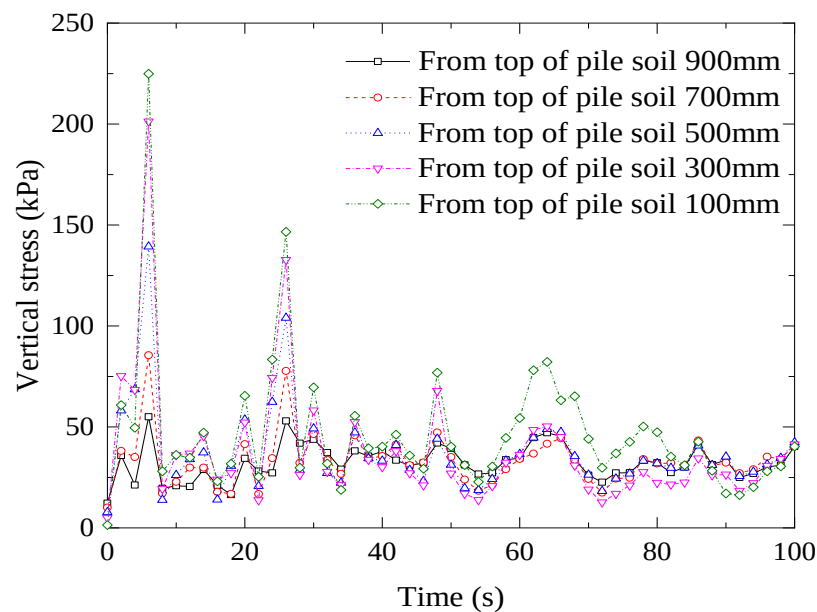


Figure 8. Vertical stress in concrete core.

Under the action of cyclic dynamic loading in the ordinary gravel pile composite foundation, the pile body is subjected to continuous compression and bulging deformation, and the vertical stress per unit area gradually decays [25]. Different from the ordinary gravel pile composite foundation, the concrete-cored sand–gravel composite foundation bears the main load in the early loading period, the vertical stress of the pile body rises greatly, and then, the vertical load is continuously transferred to the soil body around the pile through the lateral frictional resistance generated by the pile–soil interface so that the vertical stress of the pile body gradually tends to be stable and the distribution of stress is more uniform.

As shown in Figure 9, the radial stress of the core pile body at the early loading stage also had a large change. In the middle stage of loading, the radial stress in the upper part of the pile body still fluctuates greatly, and the radial stress in the middle and lower part of the pile body fluctuates less; the radial stress in the pile body at the distance of 300 mm from the top surface of the pile soil rises greatly, which is mainly due to the full play of the pile load bearing performance above the place, and the vertical load is rapidly transferred to the place. In the late-loading period, the radial stresses at different locations from the top surface of pile soil gradually tend to stabilise.

In the ordinary gravel pile composite foundation under cyclic dynamic loading, the pile body undergoes bulging deformation, and the soil body around the pile is continuously extruded by the gravel particles; due to the low strength of the soil body around the pile, the radial stress of the pile body no longer rises after the bearing capacity of the upper soil body reaches its limit, and there is no obvious change in the radial stress of the lower pile body [25]. Different from the ordinary gravel pile composite foundation, after the vertical load is transferred to the soil around the pile from the upper part of the pile body through the pile–soil interface, the radial stress in the lower part of the pile body still has a certain amplitude of fluctuation, which indicates that the lower part of the pile body can also bear part of the dynamic load and, therefore, has a better bearing capacity than that of the ordinary rubble pile composite foundation.

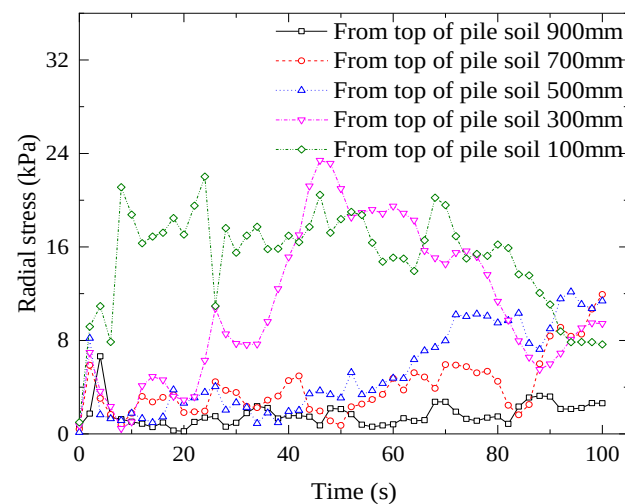


Figure 9. Radial stress in concrete core.

3.2. Analysis of Radial Stress Coefficient

The radial stress coefficient is an important parameter characterising the pile bearing capacity and can be determined from Equation (4):

$$k_{sp} = \frac{\sigma_v}{\sigma_r} \quad (4)$$

where k_{sp} is the radial stress coefficient; σ_v is the pile vertical stress; and σ_r is the pile radial stress.

The initial values of the radial stress coefficients at different depths from the top of the pile are of different sizes, and the change trends are also different. As can be observed in Figure 10, at 900 mm from the top of pile, the radial stress coefficient fluctuates greatly in the preloading period, and the fluctuation amplitude decreases gradually with time until it reaches a relatively stable state at the end of loading. At 700 mm and 500 mm from the top of the pile, the radial stress coefficient fluctuates greatly in the middle of the loading period and tends to be stable in the middle- and late-loading periods. At 300 mm and 100 mm from the top of the pile, after a certain amplitude fluctuation at the beginning of loading, a relatively stable state is reached quickly. It shows that the upper part of the pile can quickly transfer the vertical load to the soil around the pile, which makes the upper soil compacted and can provide a larger radial stress for the pile, while the lower soil provides a smaller radial stress; the speed of the pile radial stress coefficient to reach stability decreases with the depth.

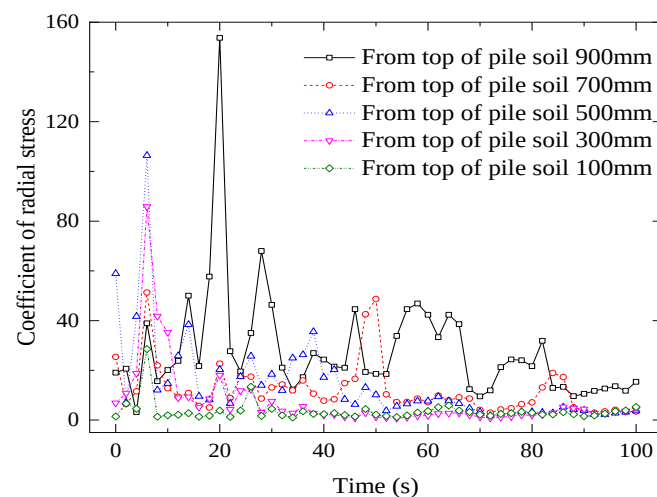


Figure 10. Radial stress factor of concrete core.

3.3. Analysis of the Coordination Number of Pile Particles

The coordination number refers to the number of coordination particles around the sphere particles, which can be analysed to measure the mobile behaviour and state of the sphere particles during the loading process; Figure 11 shows the change rule of the coordination number of the pile particles. From the figure, it can be observed that the coordination number shows different trends with loading time at different depths. At 900 mm from the top of the pile, the number of particles decreases and then increases; at 700 mm and 500 mm from the top of the pile, the number of particles is relatively stable; at 300 mm and 100 mm from the top of the pile, the number of particles is relatively stable in the early stage and then decreases slightly in the later stage. Normally, the particle coordination number of the core pile body at different depths has a small variation, and the values are close to each other, which indicates that there is a good contact between the particles of the pile body, the distribution of the particle contact is more uniform, and the integrity of the pile body is better.

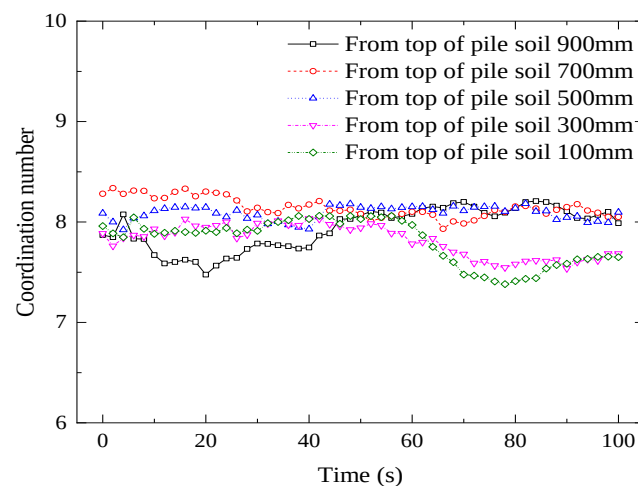


Figure 11. Particle coordination number of concrete core.

Figure 12 shows the contact force distribution of particles in different sections. As can be observed from the figure, under cyclic dynamic loading, along the whole pile length, partial detachment occurred between the sand–gravel particles and core pile particles, resulting in larger pores; the sand–gravel particles and soil particles always maintain good contact, indicating that cyclic dynamic loading will exacerbate the concentration of the vertical bearing of the core pile and the weakening of the vertical bearing of the sand shell, which is different from that of the core pile and the sand–gravel shell under the action of static force, which always maintains the effective contact and bears the vertical loading together.

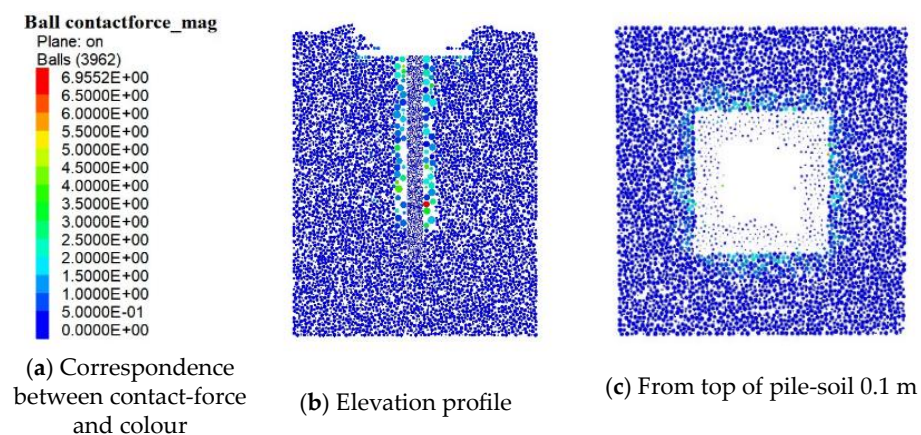


Figure 12. Cont.

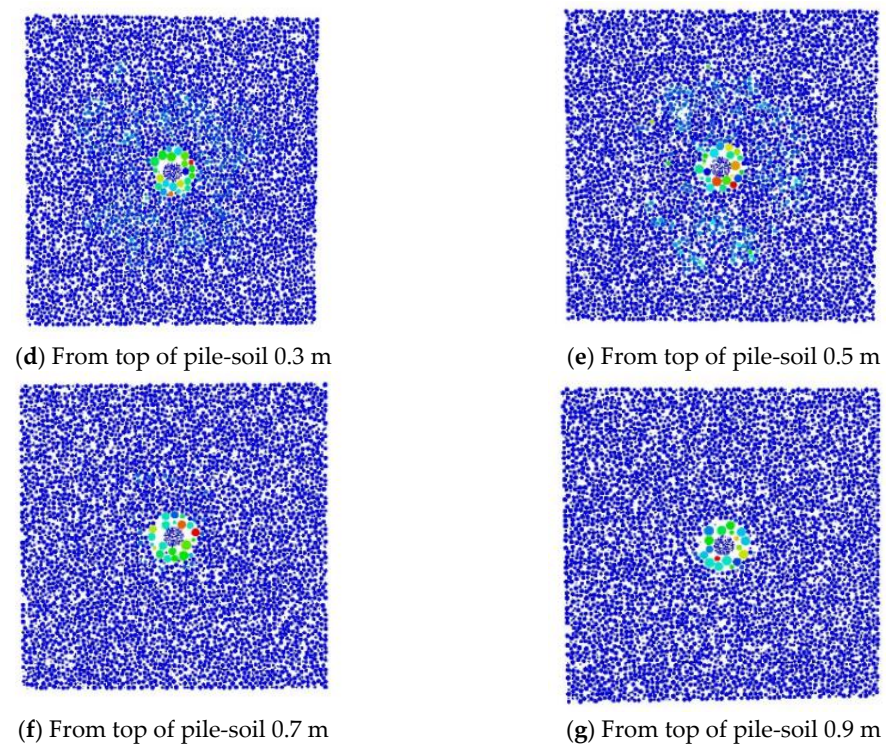
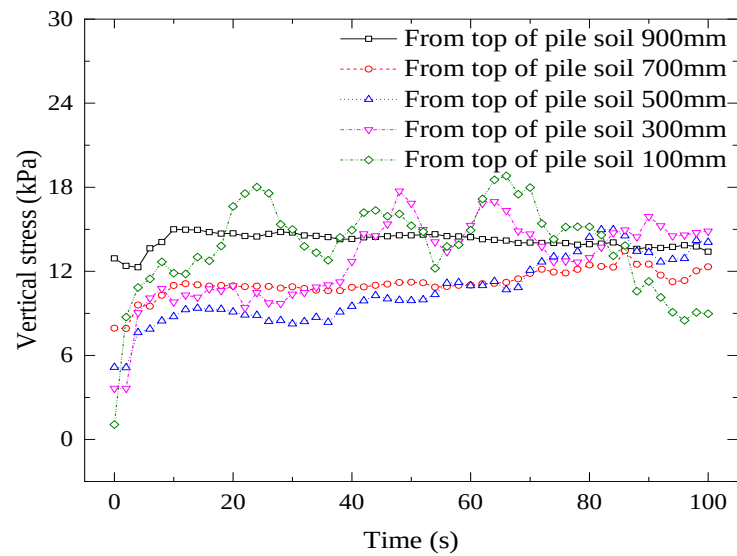


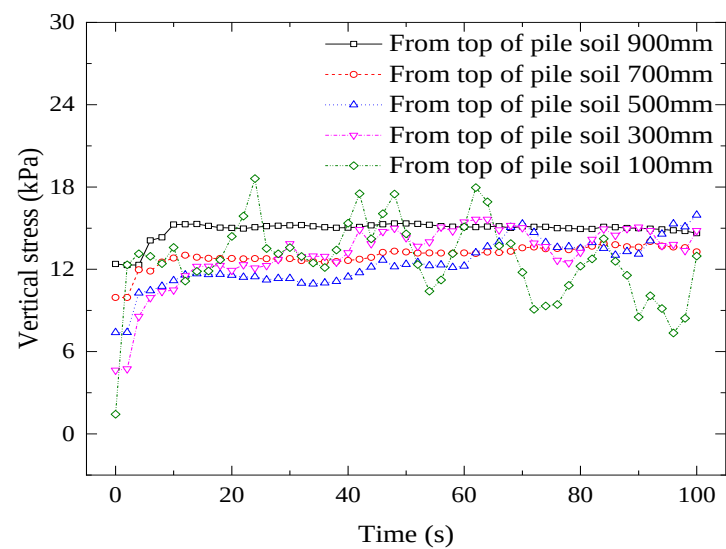
Figure 12. Particle contact force distribution for different cross-sections.

3.4. Stress Analysis of the Soil around the Pile

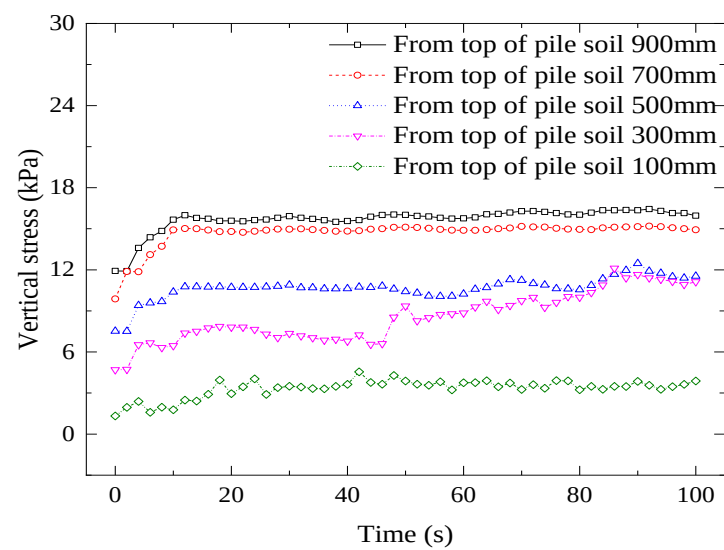
As shown in Figure 13, the change rule of peripile soil stress is different at different distances from the pile centre. From the centre of the pile at 0.15 m, from the top of the pile soil at different depths around the pile soil, vertical stress presents different trends: from the top of the pile soil at 900 mm and 700 mm, there is a pre-small rise in the middle that later becomes more stable; from the top of the pile soil at 500 mm, there is an overall upward trend but with a smaller amplitude; from the top of the pile soil at 300 mm, the pre-rise is more stable in the middle of the larger fluctuations that, later, gradually tend to be stable; from the top of the pile soil at 100 mm, there is an early large rise in the later large fluctuations, which, later, gradually decline; at 300 mm from the top surface of the pile soil, it is stable after rising in the early stage, it has a large fluctuation in the middle stage, and gradually tends to be stable in the later stage. At 0.25 m from the pile centre, 900 mm and 700 mm from the top surface of the pile soil, the vertical stress of the soil around the pile remains stable after a small rise in the early stage; at 500 mm and 300 mm from the top surface of the pile soil, the overall rise is maintained, but the rise is small; at 100 mm from the top surface of the pile soil, there is a large fluctuation after a large rise in the early stage. At 0.35 m from the pile centre, the vertical stress of the soil around the pile increases with the depth from the top surface of the pile soil, and there is an overall presentation of a small increase in the preloading period that gradually tends to be stable. After the composite foundation is subjected to the vertical load, the vertical load is rapidly transferred from the pile to the soil around the pile, the vertical stress of the soil body fluctuates, and the fluctuation amplitude decreases with the increase in the depth from the top surface of the model. At different distances from the centre of the pile, the soil vertical stresses vary with the depth from the top surface of the model, which is due to the fact that the soil is affected by the vertical load and the self-gravity stress at the same time, and with the increase in the distance from the centre of the pile, the soil that is affected by the vertical load gradually decreases, and the proportion of the self-gravity stress is gradually increased.



(a) Distance to pile centre 0.15 m



(b) Distance to pile centre 0.25 m



(c) Distance to pile centre 0.35 m

Figure 13. Vertical stresses in the soil around the pile.

As shown in Figure 14, the radial stress of the soil around the pile is in a relatively stable state at the position of 0.15 m from the pile centre and 900 mm from the top surface of the pile soil; it rises slightly at 700 mm from the top surface of the pile soil; 500 mm from the top surface of the soil produces a relatively large increase; at 300 mm from the top surface of the pile soil, the overall trend is increasing with a large fluctuation due to the bearing capacity of the upper soil body. It is due to the bearing performance of the upper soil body that the vertical load is rapidly transferred to this place after being sufficiently exerted; at 100 mm from the top surface of the pile, it is in a fluctuating state after a large rise in the early stage. At 0.25 m from the centre of the pile, the radial stress of the soil around the pile at 900 mm and 700 mm from the top surface of the pile is relatively stable; at 500 mm from the top surface of the pile, it shows a rising trend; at 300 mm from the top surface of the pile, it rises and fluctuates to a certain extent; and at 100 mm from the top surface of the pile, it has a relatively large fluctuation after a large increase in the previous period. At 0.35 m from the centre of the pile, the radial stress of the soil around the pile at 900 mm and 700 mm from the top surface of the pile is relatively stable; at 500 mm and 300 mm from the top surface of the pile, the radial stress shows a rising trend; at 100 mm from the top surface of the pile, the radial stress fluctuates with a certain magnitude after a large rise in the previous period. The fluctuation of radial stress decreases with the increase in the depth from the top surface of the model and decreases with the increase in the distance from the pile centre, indicating that the farther away from the load centre, the smaller the influence of the vertical load transmitted by the pile body.

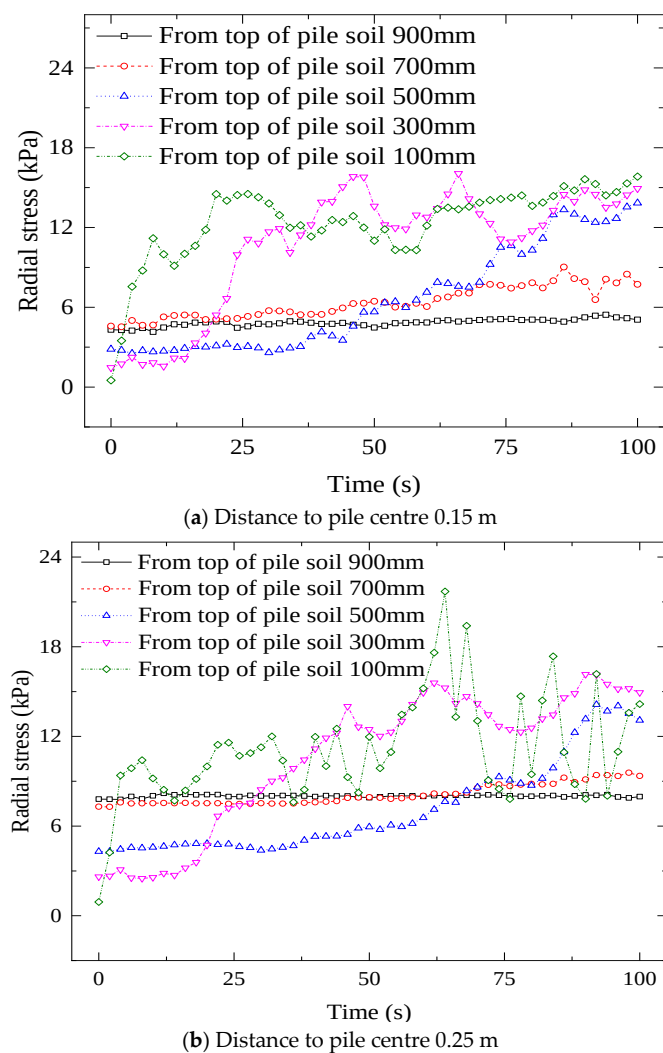


Figure 14. Cont.

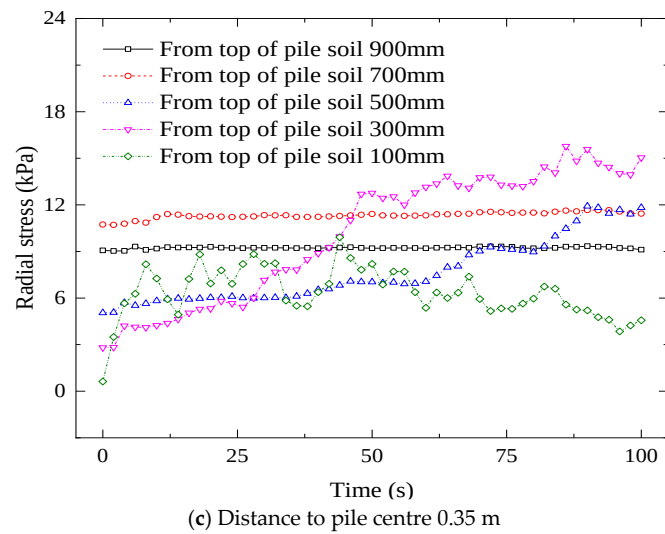


Figure 14. Radial stresses in the soil around the pile.

3.5. Analysis of Pile-Soil Stress Ratio

As shown in Figure 15, at 900 mm and 700 mm from the top surface of the pile soil, the pile-soil stress ratio is stable; at 500 mm and 300 mm from the top surface of the pile soil, the pile-soil stress ratio fluctuates slightly in the early stage and then becomes stable; at 100 mm from the top surface of the pile soil, the maximum value of the pile-soil stress ratio is more than 140; this is due to the fact that, after applying the load, the vertical stress fluctuation of the pile is large and that of the pile soil fluctuates less. This is due to the large fluctuation of vertical stress in the pile body and the small fluctuation of vertical stress in the soil surrounding the pile, which makes the pile-soil stress ratio fluctuate greatly in the early stage; then the vertical load is transferred to the soil surrounding the pile through the pile–soil interface, which makes the pile-soil stress ratio tend to be stable.

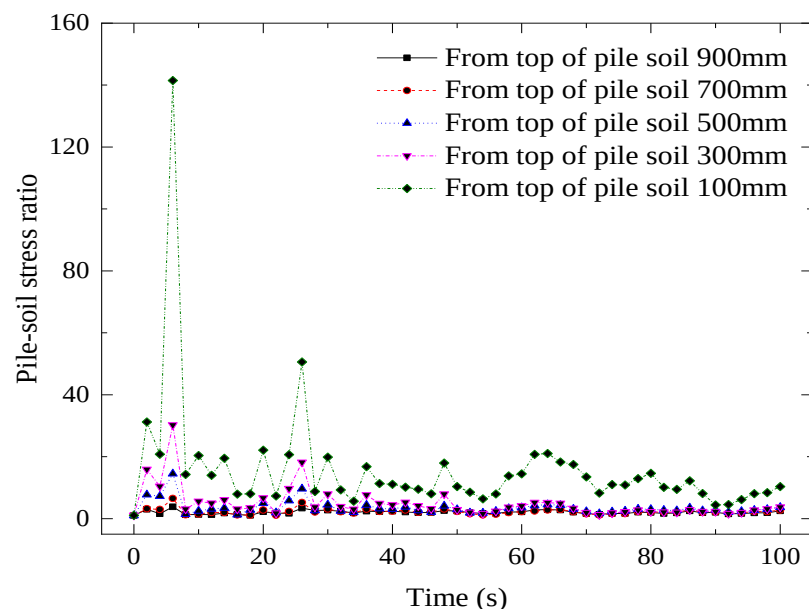


Figure 15. Pile-soil stress ratio.

4. Conclusions

This paper establishes a three-dimensional axisymmetric numerical model of a concrete-cored sand–gravel pile composite foundation based on the discrete element analysis method, discusses the bearing characteristics of a concrete-cored sand–gravel

pile composite foundation by analysing the changing rules of internal stress and particle movement of the pile body and soil body, and draws the following conclusions:

(1) Unlike the continuous attenuation of vertical stress in gravel piles, the pile body of a concrete-cored sand–gravel pile composite foundation has significant vertical-stress fluctuation at the early loading stage, with the fluctuation decreasing with depth and then tending to be stable and uniformly distributed at the later stage. The radial stress fluctuation in the upper part of the pile body is larger, while the lower part is smaller, and the overall radial stress is stable in the late-loading period.

(2) The rate at which the pile radial stress coefficient reaches stability decreases with foundation depth, and the magnitude of fluctuations in the pile-soil stress ratio decreases with foundation depth and gradually stabilises with increasing load.

(3) The small fluctuation and close value of the coordination number of particles in concrete-cored sand–gravel piles show that the contact between particles is close and uniformly distributed, which ensures the integrity of the pile body. Unlike static loading, where the core pile and gravel shell share the vertical load, cyclic dynamic loading leads to a concentration of the vertical bearing capacity of the concrete-cored sand–gravel pile and a weakening of the bearing capacity of the gravel shell.

Restricted by the scientific research conditions and my energy, the crushed stone in the discrete element model of this paper is simulated by sphere units, while the introduction of irregularly shaped rigid particle units, such as Clump or Rigid Block, to simulate graded crushed stone can obtain a closer match to the actual simulation results.

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