Research on the mechanism and testing technology of dynamic compaction of high-filled gravel soil roadbed

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Abstract. The dynamic compaction method is an important method for roadbed compaction treatment. Due to its simple procedure, quick construction speed, material saving, low cost, and excellent effect, it is an extremely important procedure in the roadbed construction with gravel soil. By analyzing the structure of the embankment, structural characteristics of the gravel fill and the the engineering stress characteristics of the subgrade in the mountainous area, the macroscopic and microscopic reinforcement mechanisms of the dynamic compaction is analyzed by using three waves transfer procedure. The results show that the various waves do positive to the gravel-filled foundation in the mountainous area. However, the way of contribution is different. The analysis should be focus on the effect of dynamic consolidation, which is the result of the synergistic action of three waves. Based on the Ping-zan highway project, the details of the test and the operating process have been introduced. Also, references for roadbed dynamic compaction reinforcement construction under similar conditions have been provided.

1. Introduction
Differential settlement of the embankment would appear in a short time after construction has completed, with weak bearing capacity or improper treatment to the foundation, which would affect the usage of the road or even reduce its service life time. Therefore, in the study of the strong construction technology of earth and rock filling in the high embankment of mountainous areas, especially the research on the reinforcement mechanism of such earth-rock mixed high-fill embankment is the most important[1-4]. Vallioppan et al.[5] applied the Fourier transform to study the vibration characteristics of vertical harmonic loads acting on the foundation surface, and obtained the frequency domain solution of two-dimensional dynamic consolidation. Mayne et al.[6-7] derived the dynamic stress response of ordinary soil under the action of dynamic compaction, the propagation of stress wave, the amount of sag and the contact stress of the hammer bottom. Sun et al.[8] tested the high-energy dynamic compaction test area. Liu et al.[9] studied the changes of permeability and density of gravel soil foundation before and after dynamic consolidation, and discussed the influence of dynamic consolidation on gravel soil structure. Guo et al.[10]analyzed the complex geographical
environment and the feasibility of using dynamic compaction method for foundation treatment on the basis of the foundation treatment project. Huang et al.[11] studied the mechanism of foundation settlement control and the selection of construction parameters and so on.

This paper uses wave theory to explain the dynamic compaction mechanism of gravel soil in mountainous areas. The purpose is to provide reference for the design and construction of dynamic compaction and play a positive role in the development of dynamic compaction theory.

2. Engineering characteristics of gravel soil subgrade

Rock powder, debris, gravel and block stone formed by blasting hill are the main foundation of gravel fill in mountainous area, large-sized boulders can’t be filled by small particles because their overhead effect. Therefore, the backfill gravel soil has not been treated in the initial stage, and its soil compressibility and permeability are large, bearing capacity is low, uneven settlement is obvious.

If the gravel soil is relatively compact, when the strength of the gravel block and the biting force between the gravel fills are lower than the impact force of the gravel fills, the gravel will break up and extrude from the compact soil, the voids between the particles will become larger, and the soil will become loose. So the tamping energy shouldn’t be too large, the opposite effect will be achieved if the tamping energy is too large. If the gravel soil is relatively loose, when the gravel body bears the appropriate impact force, because the compressibility of the soil particles is much smaller than the compressibility of the gas, the gas is discharged, the voids between the particles are reduced, the soil becomes compact, large gravels are crushed and compacted, and the soil reaches a more stable state.

3. Dynamic consolidation mechanism of gravel soil roadbed

3.1 Energy conversion process of dynamic compaction

The dynamic compaction method is to drop the heavy hammer freely from a certain height, in order to obtain larger ramming energy, so as to produce a great shock wave in the soil, overcome all kinds of resistance between the soil particles, make the loose fill compacted, so as to improve the bearing capacity of the foundation, reduce the settlement and achieve the effect of reinforcement. The transformation of energy in the whole process is as follows: (1) The initial tamping hammer is raised to a certain height, which is transformed from mechanical energy to gravitational potential energy. (2) During the free falling process of the rammer, the energy is transformed from gravitational potential energy to kinetic energy. (3) When the rammer touches the ground and impacts the ground, the kinetic energy generated by the rammer is transformed into the impact energy of the soil and accompanied by the generation of thermal energy and acoustic energy when the rammer impacts the ground. (4) When the rammer sinks in the soil, the impact energy produced by the rammer can be transformed into the vibration energy of each particle in the soil layer, and the soil vibrates.

In the process of transmission, the particle vibration caused by wave will collide, and energy loss will inevitably occur in the process of collision, which will lead to energy attenuation. Therefore, dynamic compaction can only reinforce the soil in a limited range in each compaction.

3.2 Macroscopic mechanism of dynamic consolidation

Vibration generated by impact in soil is transmitted downward in the form of vibration wave, which can be divided into two categories: body wave and surface wave. Body wave mainly includes longitudinal wave (P-wave) and shear wave (S-wave). Surface wave is a Rayleigh wave produced by the interference between longitudinal wave and shear wave, that is R wave. Among these three kinds of waves, the longitudinal wave has the fastest propagation speed, which dislocates the soil particles and compacts the foundation. The propagation velocity that next to it is shear wave, which also makes loose soil compact. Rayleigh wave propagation speed is the slowest, which compacting deep soil and loosening surface soil. The consolidation mode of dynamic compaction for soil is shown in Fig.1.
As can be seen from Fig.1, under dynamic compaction impact, I area is the loose area, II area is the strong compaction area, III area is the weak compaction area and IV area is the non-impact area. In the figure, A is the level influence area, B is the level effective reinforcement area, C is the effective reinforcement depth and D is the influence depth of dynamic compaction.

3.3 Microscopic mechanism of dynamic consolidation

Among the three kinds of waves, the fastest propagation speed is compression wave. The particle vibration caused by compression wave elongates to push-pull action. Compression wave compresses the fill through this action, so that the soil can achieve the effect of compaction and reinforcement. The whole compaction process can be seen from Fig.2.

As you can see from Fig.2, (a) shows the initial state of the movement of the upper filling particles under the action of compression waves; (b) shows that due to the relative movement of filling particles and their closeness to each other, the filling particles are closer to each other; (c) shows that after moving to the maximum displacement, the filling particles stop moving in opposite direction, which enlarges the position of filling particles; (d) shows that the relative positions of filling particles before and after moving are compared after being pushed and pulled by compression wave, the filling particles can’t move in the opposite direction with the initial amplitude; (e) shows that under the action of compression wave, an enlarged hollow zone will be formed; (f) shows that the bottom soil particles in the upper layer will sink and contact with the top soil particles in the lower layer, which will reduce the pore between filling particles, and finally the whole soil body achieves the reinforcement effect.

The propagation velocity that next to it is shear wave, which shearing the filling particles, making the filling shear dilatancy and shear contraction, compacting the lateral soil. From Fig.3, it can be seen that the shear wave force will loosen the compact filling particles. The volume of the filling particles will expand and the phenomenon of shear dilatation will be formed. When the gravel fill is loose, the
Shear forces will cause the loose filling particles to move tangentially, and the particles close to each other, thus making the loose gravel fill particles rearrange into a compact state, occurring shear shrinkage phenomenon, so that the soil tends to be compact, as shown in Fig. 4.

![Figure 3. Schematic diagram of compact fill with S-wave transverse action](image)

![Figure 4. Schematic diagram of loose fill with S-wave transverse action](image)

The slowest propagation speed is Rayleigh wave. Its particle motion mode is ellipse, which will roll over the filling particles, which will destroy the weak biting force between the gravel filling particles and make the filling loose. But with the deepening of the ramming pit depth, portions carried by Rayleigh waves, thus increasing the energy proportions carried by compression and shear waves. The self-weight stress of overburden soil increases, under the action of overlying stress and Rayleigh wave, the arrangement of irregular gravel fill will change regularly, and the compactness will be improved, so as to achieve the compaction effect. Therefore, Rayleigh wave can’t be said to be a harmful wave and has no compaction effect on dynamic consolidation of foundation in general. We should consider the synergistic effect of all kinds of waves from the whole process of consolidation.

In a word, all kinds of waves produced by dynamic compaction contribute to the reinforcement of gravel backfill foundation, but in different ways, even Rayleigh waves can play a compact role in backfill foundation to a certain extent.

4. Field testing technology of dynamic compaction

4.1 Engineering survey of test section

The main line of Ping-zan Expressway in Taihang Mountains of Hebei Province is 85.25 km long. The standard construction of two-way four-lane expressway is adopted, and the design speed is 120 km/h. Along the highway, there are many high fill embankment sections along the gully, steep valley slope, complex and changeable geology. The engineering geological characteristics of the test section mainly composed of amphibole gneiss, shallow granulite, amphibole and marble. The Archaean metamorphic rocks in this area are generally characterized by large thickness, varied lithofacies, and widespread granitic gneiss lithology. Granitic gneiss generally belong to hard rocks.

4.2 Test scheme of dynamic consolidation reinforcement

The height of the embankment slope in the test section is 15.1m. The compaction settlement difference method is used to control the rolling quality. The settlement difference between the last two times is not more than 5 mm. The area of dynamic compaction test area is about 10 m×12 m, the tapping energy is 2000 kN-m. The diameter and weight of the tamping hammer used by the dynamic compaction machinery are 1.6 m and 12.5 T. The north and south sides are empty, and the east and west sides are excavation sections. The test site is shown in Fig. 5. The field dynamic tamping machine is shown in Fig. 6.
4.3 Dynamic stress test arrangement
There are 40 earth pressure cell sensors in Ping-zan high-speed test, which need to be zeroed before the test. When the earth pressure box is buried, the buried position is first levelling, and then 10~15 cm thick fine sand is laid. The instrument is placed horizontally and then covered with 10~15 cm thick fine sand. It is necessary to compact the overlay to ensure that the instrument surface is in close contact with the overlay. The circuit of the instrument should be protected by PVC pipe, the connection should be fixed by tape, and then the fine sand is buried. The specific test process is shown in Fig.7.

5. Conclusion
(1) The tamping energy should be selected properly by the analyse of the engineering and mechanical characteristics for gravel, which shouldn’t be too large to endanger the stability of the embankment.
(2) Because of the different propagation direction, amplitude and speed, all kinds of waves have different effects on soil reinforcement.
(3) The compression wave can make loose soil become compact gradually. The volume of the filling soil contracts or expands caused by shear stress. Rayleigh wave can make surface filling loose,
but with the increase of the compaction pit depth and the self-weight stress of the overlying soil, the compactness of the soil will be improved, and the compaction effect will be achieved.

(4) Based on the project, the details of the test and the operating process have been introduced. Also, references for roadbed dynamic compaction reinforcement construction under similar conditions have been provided.

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