Effect of Tamping Energy on the Reinforcement of a High Embankment Filled with Soil-Rock

Licheng Hou¹, Guangqing Yang²,³, Jing Jin*⁴, Huali Lu⁵ and Ouyang Zhang¹

¹ The Third Construction Engineering Company Ltd., China Construction Second Engineering Bureau Ltd., Beijing, 100070, China
² School of Civil Engineering, Shijiazhuang Tiedao University, Shijiazhuang, Hebei, 050043, China
³ State Key Laboratory of Mechanical Behavior and System Safety of Traffic Engineering Structures, Shijiazhuang Tiedao University, Shijiazhuang, Hebei, 050043, China
⁴ School of Civil Engineering, Hebei University of Science and Technology, Shijiazhuang, Hebei, 050018, China
⁵ China State Construction Engineering Corp. Ltd, Beijing 100020, China

*Corresponding author’s e-mail: Jing Jin, jinjing@stdu.edu.cn

Abstract. Through dynamic compaction tests with tamping energies of 1500, 2000, and 2500 kN\(\cdot\)m of an embankment section in the PingShan–ZanHuang Expressway, the compression deformation behavior of the tamping settlement, soil deformation around the tamping rammer, consolidation depth, and dynamic stress of dynamic compaction were comprehensively tested. Comparative analyses of field data under three different tamping energies suggested that the optimal tamping energy, number of strikes, and vertical effective tamping depth for this embankment are 2000 kN\(\cdot\)m, six, and 5 m, respectively. The field test data proving that dynamic compaction has a significant effect on this embankment.

1. Introduction

Dynamic compaction involves raising a rammer to a certain height and then dropping it freely onto the ground. In this process, the rammer repeatedly rams the ground and impacts and vibrates the foundation, thus changing the physical properties, reducing the compressibility, and improving the bearing capacity of the soil. Engineering practice has proved that dynamic compaction is particularly effective in cohesionless soils, sand, and granular soils[1-3]. At present, the design and construction of dynamic compaction are mostly empirical or semi-empirical in nature and largely depend on the designers’ experience and judgment[4]. In general, owing to the complex geological conditions of a dynamic compaction construction site, the effectiveness of dynamic compaction is affected by the soil properties[5], groundwater level[6], and construction methods[7]. Further, the effect of dynamic compaction is determined by the tamper weight, dropping height, tamping point arrangement, and the interval between tamping points. Since modern dynamic compaction technology was first applied to foundation treatment in 1965, many researchers[8-11] have investigated the reinforcement effects of dynamic compaction on granular soils. Most of these studies[12] investigated the depth and effect of dynamic compaction. However, this formula causes some design and construction errors[13]. To
predict the reinforcement effect of dynamic compaction, Lo et al. [14] obtained a relationship between the tamping energy and the depth of dynamic compaction. However, this method was also empirical in nature, and it cannot be applied to a wider range of practical projects. Recently, many studies have conducted theoretical research and finite-element-based research on design parameters or numerical simulations to verify the effect of dynamic compaction [15-17].

In this study, for a high embankment filled with soil-rock in a typical section of the PingShan–ZanHuang Expressway in the Taihang Mountains of Hebei Province, China, dynamic compaction tests were conducted under three tamping energies of 1500, 2000, and 2500 kN·m along with relevant tests in terms of tamping settlement, ground heaves, compaction depth, and dynamic stress. The field tests should provide a reference for the design and construction of dynamic compaction for a high embankment in mountainous areas.

2. Engineering details of test section
The main line of the PingShan-ZanHuang Expressway (Shitaibei-Zanhuang Section of the Beijing–Kunming Expressway) in the Taihang Mountains of Hebei Province, China, is 85.25 km long. It was constructed as a standard two-way four-lane expressway, and the designed speed is 120 km/h. This highway features many high-fill embankment sections along gullies and steep valley slopes with complex and changeable geology. Test section K39+130-K39+150 consists of Archaean gneiss, comprising biotite plagioclase gneiss, amphibole gneiss, shallow granulite, amphibole, and marble, that is characterized by large thickness, varied lithofacies, and widespread granitic gneiss (a type of hard rock) lithology. Most granitic gneisses are hard rocks. Further, the embankment was filled with abandoned rocks produced by the excavation blasting of the cutting slope in adjacent sections. Test results of the particle gradation curve suggested that the filling gradation was poor. The maximum dry density of the filler is 2.21 g/cm³, and the optimum moisture content is 6.2%.

3. Test scheme for dynamic compaction
The height of the embankment slope in the test section was 15.1 m. To ensure a realistic compact quality, the consolidated settling rate was used to control the compact quality of the embankment. The settlement difference between the last two compactions was not more than 5 mm. To reduce the post-construction settlement and ensure the stability of the high embankment, a dynamic compaction was conducted for every 4 m of rolling compaction. Dynamic compaction tests were conducted along the Ping-Zan Expressway to study the dynamic compaction effect with different tamping energies.

Dynamic compaction tests were conducted in a 10 m × 12 m area. The rammer had a diameter of 1.6 m. The north and south sides of the high embankment were free faces, and the east and west sides were excavation sections. Fig. 1 shows the field test area. The tamping point is located 10 m to the left of the center of the embankment. Fig. 2 shows the dynamic tamping machine.

Field tests were performed with tamping energies of 1500, 2000, and 2500 kN·m. The tamping settlement, ground heaves, reinforcement depth, compaction depth, and dynamic stress of the
embankment under different tamping energies were measured to evaluate the optimal tamping energy, optimal tamping time, and effective reinforcement depth of the embankment.

4. Dynamic compaction test and analysis results

4.1 Formatting the title Tamping settlement

The tamping settlement of a single click (Fig. 3) is monitored on the spot, and the tamping settlement of cumulative clicks (Fig. 4) is calculated to determine the optimal number of tampings for dynamic compaction.

Fig. 3 shows that for tamping energies of 1500, 2000, and 2500 kN·m, the single tamping settlement reaches the maximum at the first tamping and then gradually decreases with an increase in the number of tampings. According to the Technical Specifications for Building Foundation Treatment, for tamping energy less than 4000 kN·m, the best number of tampings is that for which the average settlement of the last two tampings is less than 50 mm. The single tamping settlement of dynamic compaction is less than 50 mm after the 7th tamping for tamping energy of 1500 kN·m and after the 6th tamping for tamping energies of 2000 and 2500 kN·m. From the curves in Fig. 3, the tamping energy of 2000 kN·m with six tampings is considered appropriate for dynamic compaction.

In Fig. 4, the cumulative settlement increases with the number of tampings; however, the growth rate decreases gradually, indicating that the compactness of embankment filling effectively improves with an increase in the number of tampings. However, the increase in density tends to plateau as the number of tampings increases. Increasing the number of tampings is seen to enhance the reinforcement effect of dynamic compaction; however, this reinforcement effect gradually weakens with a larger number of tampings, and therefore, the number of tampings should be controlled within a reasonable range.

4.2 Ground heaves around tamping hammer

The ground heaves at different distances from the rammer center are measured during dynamic compaction. The experimental results indicate that each tamping click can cause a certain settlement of the soil; however, the settlement differs at different distances from the rammer center. Fig. 5 shows the relationship curve between the ground heaves and the distance from the rammer center for different numbers of tampings and different tamping energies.
Fig. 5 shows that the depth of the tamping pit increases with the number of tampings; however, the rate of increase gradually decreases. The tamping pit wall was basically formed during the sixth click, and it did not expand further with an increase in the number of tampings. For the same number of tampings, the depth of the tamping pit increases with the tamping energy.

With an increase in the number of tampings, the soil beneath the tamper becomes denser and the ground heaves simultaneously by lateral extrusion. However, the ground heave gradually decreases. The maximum uplift of the embankment surface is 1.5 m from the hammer center under tamping energy of 1500 kN·m, and the maximum heave is 0.12 m. Further, the maximum uplift of the embankment surface is 1.8 m from the hammer center under tamping energies of 2000 and 2500 kN·m, and the maximum heave is 0.2 m. At a certain level of tamping energy, the soil does not compact further and the ground heave continues to develop. It is important to note that the ground heave that occurs during dynamic compaction is unfavorable for the utilization of tamping energy, especially with high energy levels. We should focus on the ground uplift caused by dynamic compaction as it negatively impacts the construction project. Based on the deformation of the surrounding soil, a tamping energy of 2000 kN·m is considered optimal.

4.3 Depth of consolidation by compaction
The effective reinforcement depth of the embankment is an important parameter reflecting the effect of dynamic compaction, which is affected by factors such as the tamping energy, tamping point layout, and number of tampings. Some studies proposed calculation formulas that considered the impact
energy, hammer diameter, soil properties, and other factors; however, the actual reinforcement depth is often obtained through field tests. Although the term “effective reinforcement depth” has been used in relevant codes, it has not yet been defined clearly, and it is often judged based on designers’ experience or using test sections.

The effective reinforcement depth is determined by the dry density of the dynamic compacted soil. After the completion of tamping, the dry density of the embankment fillings at different depths is measured from the dynamic tamping surface, and dry density exceeding 2.0 g/cm³ is taken as the qualified standard of dynamic tamping. Fig. 6 shows the dry density at different depths. This figure indicates that the effective reinforcement depths for tamping energies of 1500, 2000, and 2500 kN·m are 4.0, 5.1, and 5.3 m, respectively. With an increase in tamping energy from 1500 to 2000 kN·m and from 2000 to 2500 kN·m, the effective strengthening depth increases by 27.5% and 3.9%, respectively. From these results, a tamping energy of 2000 kN·m is considered optimal for this project.

4.4 Dynamic stress of dynamic compaction

Dynamic stress data are collected using the dynamic earth pressure box during dynamic compaction, and the variation law of the dynamic stress along the depth is analyzed. Fig. 7 shows a curve of the dynamic stress along the depth range in the test section.

This figure indicates that for tamping energies of 1500, 2000, and 2500 kN·m, the dynamic stress 2.5 m below the rammer is 58.23, 63.33, and 66.75 kPa, respectively. When the tamping energy is increased from 1500 to 2500 kN·m, 1500 to 2000 kN·m, and 2000 to 2500 kN·m, the dynamic stress increases by 14.6%, 8.76%, and 5.46%, respectively. With an increase in the tamping energy, both the dynamic stress and the range of effective reinforcement depth increase. These results indicate that selecting a tamping energy of 2000 kN·m is more economical and reasonable for dynamic compaction.

6. Conclusion

The effect of dynamic compaction was analysed through field tests of the high embankment filled with soil-rock in the PingShan–ZanHuang Expressway mountainous area. The following conclusions can be drawn from this study.

During dynamic compaction, soil uplift occurs around the rammer owing to its impact energy, and the maximum amount of compaction settlement is generated during the first compaction. With an increasing number of compactions, the cumulative compaction settlement gradually increases; however, a single compaction settlement gradually decreases and becomes stable. Measurements surface compaction settlement under three tamping energies indicates that the optimum number of tampings is six. Further, the optimum compaction energy is 2000 kN·m. When using dynamic compaction for construction, there exists an optimum number of tampings. Upon exceeding this number, the effect of dynamic compaction reinforcement is not distinct. To reduce unnecessary waste,
construction should be performed with the optimum number of tampings. Dynamic compaction was successfully applied to the high embankment filled with soil-rock in the PingShan–ZanHuang Expressway.

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