# Study on the Influence of Low-energy Dynamic Compaction Near Land Area on Pile Foundation of High-piled Wharf

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**Abstract.** Aiming at the problem that the influence of dynamic compaction foundation treatment on pile foundations and the safe construction distance in the wharf land area are mostly dependent on experience and difficult to accurately predict, this paper takes a large deep-water high-piled wharf project in Peru, South America as the engineering background. Focusing on the demand for dynamic compaction treatment of backfilled foundation with mountain-excavated gravel soil in the rear land area, field dynamic compaction tests were carried out. The vibration responses and displacement variations of soil and steel pipe piles at different distances were mainly monitored, the vibration propagation law and the influence of soil compactness on vibration transmission were analyzed, and the influence degree of dynamic compaction on pile foundations was quantified. The results show that the bank slope and water area of the high-piled wharf form a natural vibration isolation trench. The pile vibration velocity induced by low-energy dynamic compaction beyond 15 m is within the allowable range of relevant codes. The vibration amplitude at the pile top is significantly lower than that of soil at the same distance, and low-energy dynamic compaction has a slight influence on pile displacement, which meets the engineering requirements.

**Keywords:** Ground improvement, dynamic compaction, vibration analysis, high-piled wharf, structural effect

## 1 Introduction

During wharf construction, dynamic compaction for land area foundation treatment will exert a certain influence on wharf structures. However, the impact of dynamic compaction on pile foundations and the corresponding safe distance are usually determined based on experience. Such an experience-based design and construction mode makes it difficult to accurately predict the effect of dynamic compaction vibration on wharf piles, and may easily lead to engineering problems such as excessive vibration and


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overlarge pile displacement. These problems not only affect construction progress, but also may leave long-term potential safety hazards. Especially for overseas port projects with tight schedules and complex construction conditions, pile installation and rear land area dynamic compaction often need to be carried out simultaneously, which further increases the difficulty of controlling the vibration impact on constructed piles. Therefore, it is urgent to clarify the propagation law of dynamic compaction vibration and its influence characteristics on pile foundations through field tests. Wang[1] analyzed the influence of dynamic compaction vibration on gravity wharf structures combined with field vibration monitoring. Huang[2] investigated the effect of dynamic compaction on existing buildings through field tests. Cheng[3] obtained the appropriate safe distance for adjacent bored piles based on field experiments. Yang[4] studied the vibration response of complex foundations with different hard crust thicknesses under dynamic compaction via field tests. Nevertheless, studies on the influence of rear land dynamic compaction on pile foundations of high-piled wharfs remain insufficient. Accordingly, taking a large deep-water high-piled wharf project in Peru, South America as the engineering background, this paper focuses on the dynamic compaction treatment of mountain-excavated gravel soil backfill in the rear land area. Field dynamic compaction tests are conducted to systematically monitor the vibration response and displacement variation of soils and wharf piles at different locations. The vibration propagation law and the effect of soil compactness on vibration transmission are analyzed, and the influence degree of dynamic compaction vibration on piles is quantified. Meanwhile, the foundation improvement effect of dynamic compaction is verified. The research results can not only provide a scientific basis for determining the safe distance and optimizing construction parameters for on-site dynamic compaction to ensure smooth project implementation, but also offer theoretical and engineering references for similar land area dynamic compaction projects of high-piled wharfs at home and abroad.

# 2 Project Overview

## 2.1 Project Description

The project is located at a large deep-water port project site in Peru, South America. The main structure of the wharf adopts the form of a high-piled wharf. The backfill of the rear land area uses gravel soil obtained by blasting and mountain excavation. To improve the bearing capacity and compactness of the backfilled foundation, the dynamic compaction method is proposed for foundation treatment in this area. Affected by the complex wind and wave conditions in the sea area where the project is located, conventional onshore construction methods cannot be adopted for pile foundation construction; instead, an offshore platform must be erected to conduct pile driving. Meanwhile, the progress of rear land backfilling is directly restricted by the construction progress of the main breakwater, resulting in relatively slow advancement of land reclamation. Given the tight overall construction schedule of the project, pile driving cannot be delayed until all dynamic compaction works of the rear land foundation are completed. Therefore, it is necessary to focus on studying the influence of vibration effects induced by dynamic compaction on the constructed wharf piles. Through field tests, the reasonable safe distance between dynamic compaction and wharf piles is determined to ensure that dynamic compaction will not exert significant adverse effects on the completed piles. This guarantees that the wharf piles can meet the design requirements and safety standards for subsequent construction after dynamic compaction, providing technical support for the smooth progress of the project.

## 2.2 Land Geological Conditions

The on-site foundation treatment area was backfilled with mountain-excavated gravel soil. The backfilled gravel soil is mainly composed of slate and sand obtained by blasting and mountain excavation, in which the intercalated slate is brownish yellow with poor rock mass quality and low mechanical strength. To determine the gradation characteristics of the backfilled gravel soil, representative samples of mountain-excavated gravel soil were selected for gradation tests. The test results are shown in Figure 1. It can be seen from the gradation curve that the particle gradation of the on-site mountain-excavated gravel is mainly distributed in Zone 1 of the applicable gradation curve for dynamic compaction. The particle gradation meets the applicable requirements for dynamic compaction, indicating that the foundation is suitable for treatment by the dynamic compaction method.

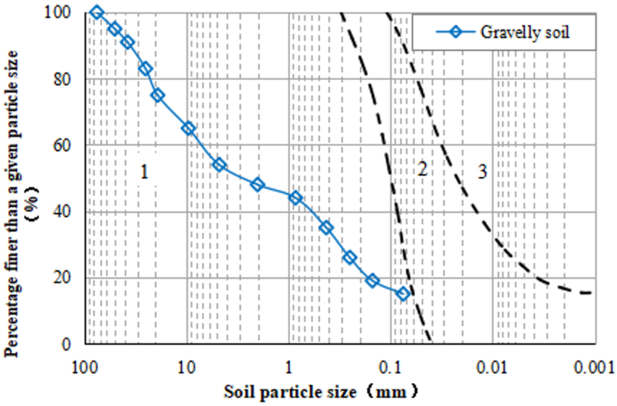


**Fig. 1.** Gradation curve of mountain-excavated gravel soil and applicability diagram for dynamic compaction[5]

## 2.3 Wharf Conditions

The wharf adopts a high-piled wharf structure, and all its pile foundations are steel pipe piles. According to the stress characteristics and layout requirements of the wharf, two specifications of steel pipe piles are designed. One row of steel pipe piles adjacent to the shore has a diameter of 1200 mm and wall thickness of 24 mm. Steel pipe piles in other areas have a diameter of 1016 mm and wall thickness of 20 mm, with a design length of approximately 40 m. Considering the influence of wind and waves in the sea area, pile driving is carried out by means of an offshore working platform. Pile installation accuracy is strictly controlled during construction, and steel pipe piles are driven to the design elevation. The pile bottoms are embedded into a very dense sand layer to meet the design requirements of bearing capacity, overturning resistance and sliding resistance, ensuring the stability of the main wharf structure.

# 3 Study on the Influence of Dynamic Compaction on High-piled Wharf Structure

## 3.1 Trial Area Scheme

The dynamic compaction test area is arranged on the rear land side of the high-piled wharf. The test area is designed to be 22.4 m × 22.4 m, with a total area of approximately 500 m². To reduce the adverse effects of dynamic compaction vibration on the adjacent constructed wharf piles, a heavy hammer with low drop height construction mode is adopted in this test. The tamping energy is 2000 kJ, with a hammer weight of 20 t, a drop height of 10 m, and a hammer diameter of 2.4 m., the cross-section layout of the test area is shown in Fig. 2.

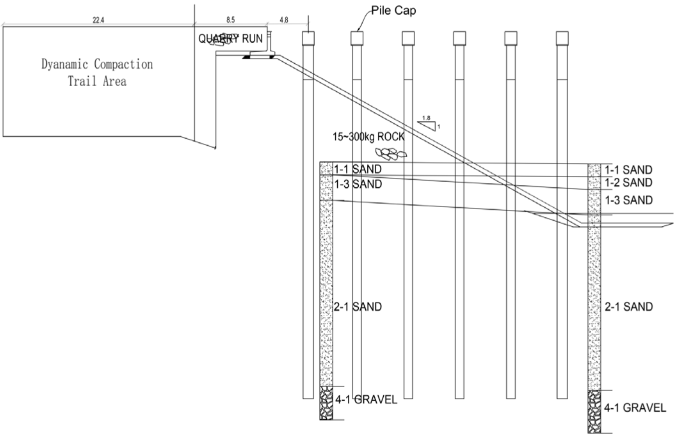


**Fig. 2.** Schematic cross-section of dynamic compaction test area and high-piled wharf layout

A total of 36 tamping points were arranged in the test area, and their plan layout is shown in Fig. 3. Tamping was carried out according to the numbered sequence of tamping points. The distance between the center of each tamping point and the pile foundation ranges from 14.8 m (minimum) to 35.9 m (maximum). To systematically investigate the influence law of dynamic compaction vibration, 6 key tamping points (Nos. 1, 2, 3, 34, 35, 36) were selected as major testing objects. During tamping, real-time monitoring was performed on the vibration response of soil and piles at different distances. A total of 5 soil vibration monitoring points (A, B, C, D, E) and 3 pile-cap vibration monitoring points (a, b, c) on the wharf were installed. The distribution law of dynamic compaction vibration with distance was analyzed. By comparing the vibration velocity between the pile-top cap and surrounding soil at the same horizontal distance, the influence characteristics of dynamic compaction vibration on pile foundations were clarified. Meanwhile, the test area was divided into upper and lower testing zones, which were constructed with tamping sequences from far to near and from near to far, respectively. By comparing test data of the two zones, the influence of soil density variation on dynamic compaction vibration propagation was studied. In addition, the overall displacement of pile foundations during the whole dynamic compaction process was monitored synchronously to quantify the influence degree of vibration on piles, providing an experimental basis for determining the safe distance of subsequent on-site dynamic compaction.

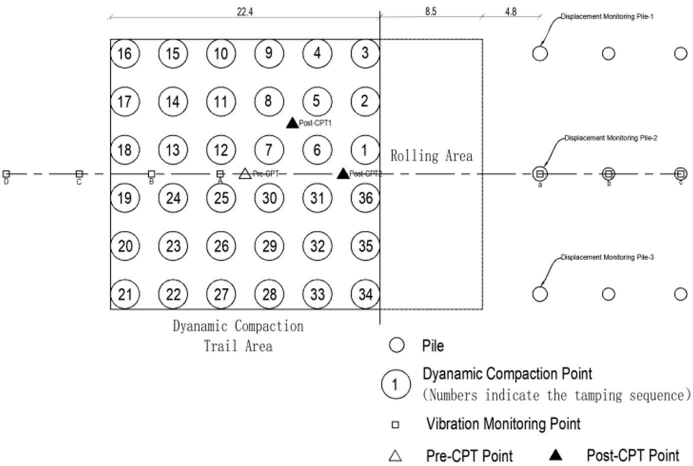


**Fig. 3.** Plan layout of the trial area

## 3.2 Analysis of Test Results

During dynamic compaction, the vibration energy generated by the falling hammer propagates in the backfilled gravel soil in the form of elastic waves, mainly including body waves (P-waves and S-waves) and surface waves[6]. As the dominant component of surface waves, Rayleigh waves (R-waves) propagate only along the ground surface and shallow strata, with concentrated energy and slow attenuation, making them the core factor affecting the vibration and displacement of adjacent wharf piles.To clarify the influence of dynamic compaction vibration on constructed steel pipe piles and the foundation improvement effect, a dynamic compaction test area of 22.4 m × 22.4 m was set up in the rear land area of the high-piled wharf. The test was carried out with a tamping energy of 2000 kJ using a heavy hammer with low drop height. A total of 36 tamping points were arranged, among which 6 key tamping points were selected to monitor the vibration responses of soil and piles at different distances. The test area was divided into two zones to compare the influence of soil compactness on vibration transmission under different tamping sequences. Meanwhile, the overall displacement at the pile caps was monitored, and the vibration velocities between pile caps and surrounding soil were compared. This study systematically investigates the propagation law of dynamic compaction vibration waves, as well as the characteristics and degree of dynamic compaction influence on pile foundations, providing a basis for subsequent result analysis and the determination of safe construction distance on site.

**Comparative Analysis of Vibration Results and Allowable Values.** The vibration velocity induced by dynamic compaction is not a constant value; it varies significantly with the actual tamping energy of each blow, the distance from the tamping center, and the compactness of the foundation soil. Even within the same soil layer, the measured vibration velocity changes continuously as the soil compactness evolves during repeated tamping operations. During the test, emphasis was placed on monitoring the vibration velocity and vibration frequency at point a (pile cap) of the wharf pile and point A (surrounding soil) at symmetrical positions during tamping at Nos. 1, 2, 3, 34, 35 and 36 tamping points. The distances from these tamping points to the measuring points are 15 m, 16 m and 18 m, respectively, so as to quantify the effect of dynamic compaction vibration on piles and soil. At present, no specific evaluation standard has been established worldwide for the influence of dynamic compaction on wharf structures. Therefore, this study refers to the relevant provisions on allowable vibration values of structures under dynamic compaction in German standard DIN 4510, Chinese standard GB 50868 and British standard BS 7385 to classify the influence level of dynamic compaction vibration on wharf piles and foundation soil. The cases with relatively high vibration velocity (vibration velocity ≥ 1 mm/s) were selected to analyze the influence of dynamic compaction vibration on piles and soil. The comparison is shown in Fig. 4.

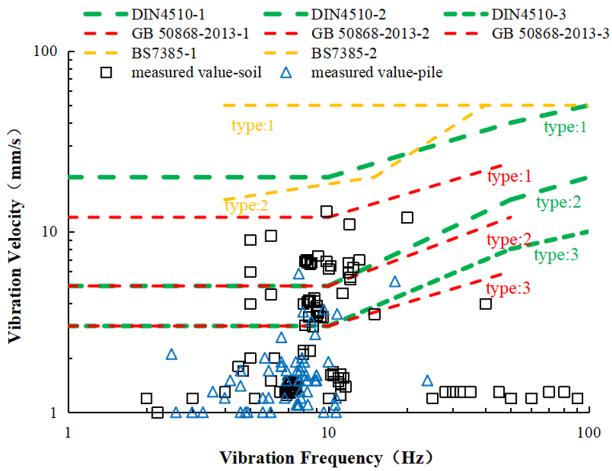


**Fig. 4.** Vibration frequency and velocity induced by dynamic compaction

According to the reference specifications, different countries define allowable vibration values for dynamic compaction according to the type of structure. Both Chinese and German standards classify allowable values into three grades: Grade 1 for industrial and public buildings, Grade 2 for residential buildings, and Grade 3 for vibration-sensitive buildings. The British standard only includes the first two grades and does not specify allowable values for vibration-sensitive buildings. In terms of numerical values, the Chinese standard provides the smallest allowable values, the German standard is moderate, and the British standard allows the largest values. Based on the comparative analysis between test data and code allowable values, the maximum soil vibration velocity induced by dynamic compaction beyond 15 m is less than 20 mm/s, and most values are below the Grade 1 allowable value of the German standard. The maximum pile vibration velocity is less than 10 mm/s, and most values are below the Grade 2 allowable values of various standards, indicating that the influence of dynamic compaction vibration on piles and soil is within a controllable range. Analysis of dynamic compaction vibration frequencies shows that the soil vibration frequency exhibits a concentration effect[8], mainly distributed in the range of 6–12 Hz. The vibration frequency at the pile cap is lower, mainly concentrated in 3–11 Hz. In addition, no high-frequency vibration component is observed in the pile area. The main reason is presumed as follows: the higher the frequency, the smaller the influence depth of Rayleigh waves (R-waves)[9]. The gap between the pile foundation and the bank slope forms a natural vibration isolation trench, which prevents high-frequency Rayleigh waves generated by dynamic compaction from propagating toward the wharf piles.

**Analysis of the Influence of Soil Compactness Along the Propagation Path on Dynamic Compaction Vibration.**
Since the vibration velocity induced by dynamic compaction is related to the relative compactness of the soil along the propagation path [7], the maximum vibration velocities at different distances during tamping of the first three tamping points (Nos. 1, 2, 3) and the last three tamping points (Nos. 34, 35, 36) in the test area were tested and compared. The influence of the compactness of the mountain-excavated gravel soil on vibration propagation is analyzed as shown in Fig. 5.

The test results show that the dynamic compaction reinforcement effect varies with distance mainly in the form of a negative power function [10]. The vibration velocities induced by tamping points 34, 35 and 36 are significantly higher than those of tamping points 1, 2 and 3, with the peak vibration velocity increasing by 7%–35%. The maximum increase of 35% occurs at the measuring point 15 m closest to the pile foundation. This indicates that the soil compactness along the vibration propagation path has a significant influence on the dynamic compaction vibration velocity [11]. Compared with loose mountain-excavated gravel soil, the measured vibration velocity is higher when vibration propagates in relatively compact gravel soil. The main mechanism is as follows: Loose mountain-excavated gravel soil has a large void ratio, few particle contacts, weak overall restraint and low equivalent shear modulus. During stress wave propagation, soil particles tend to slip, rotate and undergo large deformation. Energy is mainly dissipated by friction damping and soil structure reconstruction, resulting in more significant attenuation of vibration amplitude. In contrast, compact soil has higher stiffness and less wave attenuation, thus producing a higher vibration velocity.

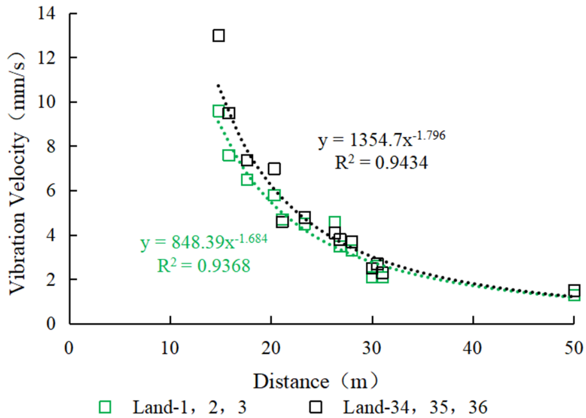


**Fig. 5.** Comparison of dynamic compaction vibration variation with distance at different tamping points

**Analysis of the Influence of Soil Compactness Along Propagation Path on Dynamic Compaction Vibration.**
he vibration velocities at the pile caps on the top of wharf piles induced by tamping Nos. 34, 35 and 36 (the last three tamping points close to the pile foundation with relatively high vibration velocities) were measured and compared with those on land. The results are shown in Fig. 6.

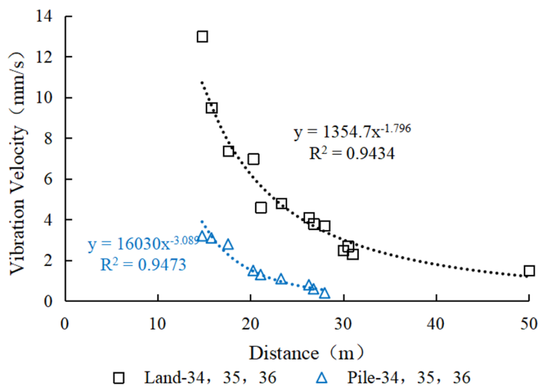


**Fig. 6.** Comparison of dynamic compaction vibration variation with distance in soil and at pile top

The test results show that the vibration amplitude of the pile caps at the top of the wharf piles under dynamic compaction is significantly lower than that of the onshore soil at the same distance, with the maximum vibration velocity reduced by 62%~89%. Moreover, the vibration velocity attenuates more significantly with the increase of propagation distance and intermediate water width. The main reason is that the bank slope and water area between the wharf piles and the dynamic compaction zone form a natural vibration isolation trench, which can significantly weaken the transmission of vibration waves to the pile structure and effectively reduce the adverse effect of dynamic compaction vibration on the wharf piles.

In the subsequent large-scale construction, active vibration isolation measures such as manually excavated vibration isolation trenches can be adopted to further control the vibration influence and ensure the safety of pile foundations.

**Analysis of the Influence of Dynamic Compaction on Wharf Displacement.** To quantify the displacement effect of dynamic compaction vibration on the wharf piles, repeated measurements were taken at the fixed prisms on the pile caps of the three piles near the shore before and after tamping at each tamping point, and the average values were adopted. The displacement characteristics of the pile tops were obtained through data processing, and the detailed deformation is shown in Fig. 7.

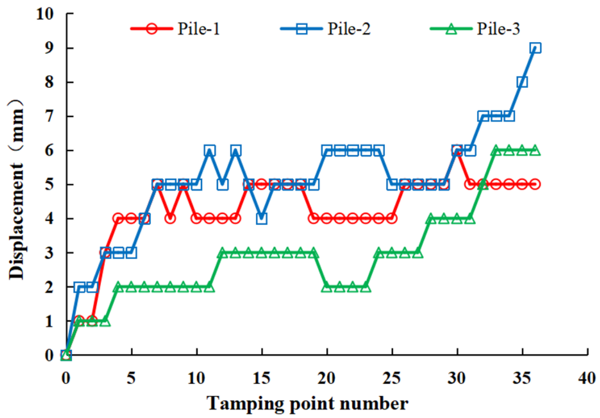


**Fig. 7.** Deformation of pile foundations at different positions

It can be seen from the measurement results that during dynamic compaction, certain displacements occur at the tops of the three piles near the shore. The displacement varies with the distance to the tamping points: the closer the tamping distance, the larger the pile-top displacement; the farther the tamping distance, the smaller the displacement. According to the final pile-top displacements after completion of the test area, Pile No. 2, closest to the test area, exhibits the maximum displacement of approximately 9 mm. The displacements of the other two piles are relatively small and similar, at 5 mm and 6 mm, respectively.

The pile-top displacements of all three piles meet the 20 mm limit required for subsequent construction and quality control. The 2000 kJ dynamic compaction has a minor influence on the pile-top displacement of the high-piled wharf at a distance of 15 m.

## 4 Conclusions

(1) Under the 2000 kJ energy level and heavy hammer with low drop height technology, both the vibration velocity and displacement of pile foundations beyond 15 m from the tamping points can meet the relevant requirements. Therefore, 15 m can be selected as the safe distance for dynamic compaction under this energy level.

(2) The water area and bank slope between the pile foundations and the land area can form a natural vibration isolation effect, which significantly weakens the propagation of high-frequency waves and reduces the vibration generated by dynamic compaction. During the dynamic compaction process, the vibration frequency of the pile foundations ranges from 3 to 11 Hz, with no obvious high-frequency components compared with the soil; at the same distance, the vibration velocity at the pile top is reduced by 62%–89% compared with the soil, showing a significant natural vibration isolation effect.

(3) The energy level of dynamic compaction has a significant impact on the generated vibration energy. The current research mainly focuses on low-energy dynamic compaction tests. Continuously increasing the energy level may have a certain impact on the pile foundations of the wharf structure, and the regular relationship between the dynamic compaction energy level and the safe distance needs further research.

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