Experimental Investigation on Dynamic Performance of Micro-Pile with Predrilled Oversize Hole on Shaking Table Test

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Abstract. For the situation of lacking research on micro-pile with predrilled oversize hole, the key part of semi-integral abutment bridge, the micro-pile-soil interaction shaking table test is carried out by considering the reaming pore diameter, depth, packing and other parameters in the end of the micro-pile to obtain the acceleration, pile moment, displacement and pile-system response frequency and other basic dynamic response and dynamic interaction law. Results show that: 1) the change of predrilled-hole parameters has litter effect on the dynamic properties of soil outside oversize hole; 2) The change of predrilled-hole parameters can cause the change of structural frequency, so led to the change of inertia force of pile head; 3) Inertial interaction has an important influence on the response of the upside part of pile and little influence in the downside part (lower than 15D). These conclusions will provide reference for dynamic response of interaction between pile with predrilled oversize hole and soil and make contribution to the practical application and designing of micro-pile with predrilled oversize hole.

Keywords. Bridge engineering, micro-pile with predrilled hole, parameters analysis, shaking table test, dynamic response

1. Introduction

Micro pile can effectively improve the seismic performance of seamless bridge with new semi integral abutment [1]. Under the seismic action, part of the seismic action of the bridge is transmitted to the micro pile by the connecting plate. Through the pile-soil interaction, part of the seismic energy is absorbed and dissipated by the soil around the pile, so as to reduce the damage of the seismic action to the bridge. At the same time, enlarging the hole at the top of the micro pile can improve the ability of the bridge to absorb longitudinal deformation in the normal service period.

Scholars at home and abroad have carried out many studies on the dynamic response characteristics of pile-soil. Xu Yanfei[2] simulated the shaking table test of pile group soil structure dynamic interaction by using the finite element software ANSYS, studied the dynamic responses of pile group soil system such as displacement time history, acceleration time history and pile internal force under earthquake, and considered that increasing the pile length is helpful to earthquake resistance. Sato [3] and Yang [4] carried out shaking table test of single pile in dry sand, focusing on the analysis of pile-soil dynamic interaction from the perspective of input seismic wave frequency and pile-soil system frequency. Wei Chunli [5] conducted five pile-soil-structure shaking table tests, processed the shaking table data with MATLAB, and analyzed the influence of inertial interaction and motion...
interaction on pile-soil dynamic interaction by using the method of frequency decomposition. Wang Jianhua[6] and others studied the dynamic response of micro aluminum pile in saturated sand through shaking table test, and mainly analyzed the pile bending moment and pore pressure at different depths during vibration. Zhang Zhongle[7] studied the shaking table test of micro pile group and single pile in dry sand, and mainly analyzed the acceleration time history, displacement time history and p-y hysteretic curve. Li Yurun[8] completed a large number of shaking table tests of micro aluminum piles in dry sand, and compared and analyzed the dynamic responses of pile shaft acceleration, pile-soil interaction force and pile shaft bending moment in pile-soil interaction. Fan

In conclusion, there are few studies on the dynamic response of micro pile-soil dynamic interaction under reaming. Therefore, this paper will further discuss its dynamic response under earthquake. The influence of reaming parameters on the dynamic response characteristics of micro pile foundation is revealed, which provides experimental and theoretical support for the reaming design technology of integral abutment bridge.

2. Shake Table Test

Test materials and equipment mainly include model soil, model pile, model box, reaming filler, measuring equipment and test equipment. The model soil is dry sand. The whole test adopts a single layer of soil. During the test, the dry sand is backfilled in layers (with a thickness of 20cm) into the model box, and the sand is compacted after each layer is paved. Physical and mechanical parameters of model soil are shown in table 1. At the same time, in order to avoid the influence of model pile body material and size effect on the test, the model pile is made as the actual pile, and its parameters are shown in table 2.

Table 1. Physical and mechanical parameters of model soil.

| Property                  | Value |
|---------------------------|-------|
| Compacton density $\rho$  | 1.601 |
| Relative compaction $D_r$ | 43    |
| Angle of internal friction $\phi$ | 31 |
| Void ratio $e$            | 0.663 |
| Coefficient of uniformity $C_u$ | 3.17 |

Table 2. Parameters of model pile.

| Property                  | Value |
|---------------------------|-------|
| cross section form diameter(mm) | 60    |
| wall thickness(mm)         | 4     |
| pile length(mm)            | 2300  |
| slenderness ratio          | 38    |
| density(kg/m$^3$)          | 7850  |
| material                   | Q235  |
| flexural rigidity(kN-m$^2$) | 58.20 |
| poisson ratio              | 0.3   |

Figure 1. Arrangement of micro-pile strain gauge unit (mm).

The size of model steel box is 2m (length) × 2m (width) × 2.1m (high). Channel steel is welded at the bottom of the box to reduce the relative sliding between the model soil and the bottom plate of the
steel box. In order to reduce the influence of reflected waves, reduce the restraint on the model soil and increase the softness of the side wall of the box, a layer of 100mm thick polystyrene foam board is lined on the inside surface of the steel box perpendicular to the ground motion. At the same time, in order to reduce the friction between the inner surface of the side wall parallel to the seismic direction of the steel box and the model soil, the inner surface of the side wall is pasted with polyvinyl chloride film and coated with lubricating oil. The test and measurement equipment mainly includes strain gauges and accelerometers. 24 reinforcement strain gauges, numbered A1 ~ A12 and B1 ~ B12, are symmetrically pasted along the depth direction of the pile at the edge of the outer wall of the steel pipe pile, as shown in Figure 1. At the same time, five accelerometers are arranged on the table and soil respectively, as shown in Figure 2(a). A medium is set at the top of the pile within a certain depth and width for reaming, and the soil around the pile is divided into internal and external parts. The compactness of the filler in the reaming is controlled to be less than that of the soil outside the reaming, so as to increase the deformation capacity and energy consumption capacity of the pile under lateral load. See Fig. 2 (b) for the local photos of reaming. In order to eliminate the boundary effect, when the ratio of soil lateral boundary value D to pile diameter D is greater than or equal to 6, the error caused by lateral boundary is very small and tends to be stable [9]; Previous studies have shown that [10], when the pile group spacing is greater than or equal to 10 times the pile diameter, it has little impact on the pile group effect. Therefore, the distance between the pile and the boundary is greater than 6D, and the pile spacing is greater than 10d. The test photos are shown in Figure 2C. In order to simulate the influence of pile top quality of micro pile in actual situation, a mass block is set at the pile top of model pile. Referring to reference [11], according to the weight of the actual approach slab, the weight of the pile top counterweight of a single micro pile is 56.4kg.

In addition, 2mm thick Q235 steel sleeve is selected as the reaming material, and the reaming filler is divided into loose sand and rubber particles. For loose sand, since the volume of reaming iron sleeve is known, its density is determined by controlling the quality of loose sand (its density is ρ= 1.48 g / cm³), so as to obtain the relative compactness of sand, and then obtain the sand compactness and mechanical parameters (internal friction angle) through the k-value curve [12] (figure. 3) φ= 29º, initial stiffness of sand k = 5000 kN / mm³). The recycled rubber particles produced by Hubei huayitong Rubber Co., Ltd. are extracted from pure radial steel tire, with particle size of 1.2 ~ 2.3 mm, shore a hardness of 68, elastic modulus of 10.6 MPa and density of 0.65 g / cm³.

In the test, 0.4g 5Hz sine wave was used to simulate 9-degree earthquake. Due to the limited test time and funds, Q235 steel pipe pile with 0.06m pile diameter and 4mm wall thickness was selected as the research object, the model soil was dry medium dense sand, and the loading waveform was representative load condition (0.4g sine wave). Considering the reaming hole diameter Shaking table test of pile-soil dynamic interaction of reaming depth and reaming backfill material. The reaming parameters are mainly changed during loading, and the loading scheme is shown in table 3.
(a) Test device for vibration table of Micro-Pile with enlarged hole.

(b) Detail structure of Micro-Pile with enlarged hole

(c) Solid Diagram of Micro-Pile Test

**Figure 2.** Micro-pile with predrilled oversize hole on shaking.

**Table 3.** Loading case (The quality of top of pile is 56.4kg).

| working condition | seismic wave | peak acceleration(g) | Expanding material | Expansion width(mm) | Hole Enlarging Depth(mm) |
|-------------------|--------------|------------------------|--------------------|----------------------|--------------------------|
| —                 | white noise  | —                      | —                  | —                    | —                        |
| 1                 | 5Hz sine wave| 0.4g                   | loose sand         | 180                  | 600                      |
| —                 | white noise  | —                      | loose sand         | 180                  | 600                      |
| 2                 | 5Hz sine wave| 0.4g                   | rubber             | 180                  | 600                      |
| —                 | white noise  | —                      | rubber             | 180                  | 600                      |
| 3                 | 5Hz sine wave| 0.4g                   | loose sand         | 180                  | 450                      |
| —                 | white noise  | —                      | loose sand         | 180                  | 450                      |
### Table 1
| Experiment | Stimulus | Material | Period (min) | Amplitude (g) |
|------------|----------|----------|--------------|---------------|
| 4          | 5Hz sine wave | rubber | 180 | 450 |
| —          | white noise | —       | 180 | 300 |
| 5          | 5Hz sine wave | loose sand | 180 | 300 |

![Figure 3](image.png)

**Figure 3.** Curve of K-value (1 - water, 2 – Under water).

### 3. Calculation Method of Relative Displacement of Pile Side

In the p-y curve, y refers to the displacement of the pile relative to the sand. In the analysis process, the displacement $y_{pile}$ of the pile is calculated separately according to the strain of the pile body, and then the displacement $y_{sand}$ of the sand is obtained according to the acceleration of the soil. Finally, the displacement y of the pile relative to the sand is obtained by subtracting the displacement of the sand from the displacement of the pile.

#### 3.1. Displacement of Pile

The curvature moment method is used to solve the pile side displacement [13]. According to the basic theory of material mechanics, the following equation can be obtained:

\[
EI \frac{d^2 y}{dx^2} = -M
\]  
(1)

\[
EI \frac{1}{\rho} \approx EI \frac{d^2 y}{d^2 x} = -M(x)
\]  
(2)

\[
EI \theta \approx EI \frac{d^3 y}{d^3 x} = -\int_0^x M(x)dx + C_1
\]  
(3)

\[
EIy = -\int_0^x dx \int_0^x M(x)dx + C_1x + C_2
\]  
(4)

Where: $EI$ — bending stiffness of beam; $\rho$ — radius of curvature of beam; $\theta$ — Inclination of beam; Bending moment of beam at $M(x) - x$.

When the beam is subjected to external load, the following expression can be obtained:
Thus, the moment area theory is obtained, that is, $\theta_{D/C} = \int_{C}^{D} \frac{M(x)}{EI} dx$ is equal to the area between $C$ and $D$ in the relationship between $M/\text{EI}$ of beam and pile length $X$.

According to the tangent lines of point $P$ and $P'$ on the curve, take a length of $dt$ line segments on the vertical line of point $C$, as shown in figure 4, and calculate the relative horizontal displacement $t_{C/D}$ of point $d$ relative to point $C$ in the vertical plane.

\[ d\theta = \frac{d^2 y}{dx^2} = -\frac{M(x)}{EI} \]

\[ \theta_d - \theta_C = \int_{C}^{D} \frac{M(x)}{EI} dx \]

The curvature area theory is obtained. $t_{C/D}$ is the tangent offset of point $d$ relative to point $C$, and $x_i$ is the distance between point $D$ and the integration unit. Assuming that the relative displacement between the pile bottom and the steel box is zero and has a certain initial inclination angle, the lateral displacement of the pile body is equal to the first-order moment of inertia of the area between points $C$ and $D$ on the curvature diagram relative to the calculation point. In the calculation of curvature area, linear interpolation method is used between nodes. The essence of this method is based on piecewise double integration and depends on the boundary conditions of the pile body. During the test, the pile bottom is consolidated with the steel box to meet the basic conditions of calculation requirements.

### 3.2. Displacement of Sand

In order to obtain the relative displacement $y$ of pile-soil, the displacement response of far-field soil
layer in the test needs to be calculated $y_{sand}$. Therefore, the acceleration time history recorded in the far-field soil layer is used to calculate the displacement time history of the excavated layer. Finally, the pile-soil relative displacement time history is obtained according to the pile displacement time history obtained by the curvature area method and the sand displacement time history.

4. Dynamic Response of Reamed Micro Pile Soil System

4.1. Fundamental Frequency Response of Reamed Micro Pile Soil System
Before the start of each working condition, input white noise with peak acceleration of 0.1g to measure the dynamic characteristics of pile-soil system. Based on the spectrum analysis of the acceleration data in the soil, the soil fundamental frequency can be obtained. It is found that the soil fundamental frequency is basically maintained at about 22 Hz, and changing the reaming parameters has little effect on the soil frequency. This is because the fundamental frequency of soil is mainly affected by compactness, and the compactness of sand is not greatly affected when loading and changing reaming parameters. This again shows that the dynamic performance of soil is relatively stable and the repeatability of the test is good.

4.2. Acceleration and Displacement Time History Curve of Mesa And Soil
During the test, 0.4g sine wave is selected to analyze the law of dynamic interaction between reamed micro pile and soil. Figure 5 shows the measured table acceleration and displacement time history curve under condition 5. It can be seen from figure 5 (a) that the table acceleration curve rapidly increases to the peak value of 0.4214g (basically close to 0.4g) at the initial stage of loading, remains constant during the loading process, and rapidly decreases to 0 at the later stage of loading. Similarly, it is obvious from figure 5 (b) that the table displacement curve increases rapidly to the peak value of 0.004 m at the initial stage of loading, and there is no sudden change in the curve during the loading process, indicating that the loading is relatively stable. Under other working conditions, the peak acceleration of the table is basically about 0.4 g, meeting the input requirements.

The law of soil acceleration and displacement under other working conditions is similar to that under working condition 5 (figure 6). Due to space limitation, this paper only gives the peak value and amplification factor of soil acceleration under various working conditions, as shown in table 5. It can be seen from table 5 that the soil acceleration from the pile bottom to the pile top shows an increasing trend, and the soil acceleration at 925mm and 1525mm is greater than the table acceleration, which indicates that the seismic response of the middle and upper layer of soil is large. According to the soil acceleration under different working conditions, the change of reaming parameters has little effect on the peak value of soil acceleration at the same height.

4.3. Time History Curve of Pile Top Acceleration and Displacement
Figure 7 shows the time history curve of pile top acceleration and displacement under condition 5. Limited to space, only the peak acceleration, peak displacement, amplification factor and the maximum inertial force obtained from the peak acceleration under various working conditions are given, as shown in Table 4. It can be seen from figure 7 that the variation law of pile top acceleration and displacement time history curve is also similar to that of table top acceleration and displacement time history curve, with peak acceleration of 1.0119g and peak displacement of 0.0079m. It can be seen from table 4 that the peak acceleration and peak displacement of the pile top are significantly greater than the peak acceleration and peak displacement of the table top. The amplification factor of the pile top is the largest compared with the acceleration amplification factor at other heights of the pile body, which is caused by the inertial force effect.
(a) Time history curve of table acceleration.  
(b) Table displacement time-history curve.

**Figure 5.** Time - history curves of acceleration and displacement for working condition 6.

(a) Time-history curve of soil acceleration at 925 mm from the bottom of soil  
(b) Time history curve of soil displacement at 925 mm from bottom of soil

(c) Time-history curve of soil acceleration at 1525mm from the bottom of soil  
(d) Time history curve of soil displacement at 1525mm from the bottom of soil

**Figure 6.** Time-history curves of soil acceleration and displacement under condition 5.
Table 4. Peak value of acceleration, amplification factor, inertia force and peak displacement of pile under all cases

| Working condition | Peak acceleration (m/s²) | Amplification coefficient | Inertia force (N) | Peak displacement (m) |
|-------------------|--------------------------|---------------------------|-------------------|-----------------------|
| 1                 | 1.1597g                  | 2.7945                    | 65.4044           | 0.0085                |
| 2                 | 1.6109g                  | 3.8363                    | 90.8518           | 0.0143                |
| 3                 | 1.0311g                  | 2.4620                    | 58.1530           | 0.0085                |
| 4                 | 1.5074g                  | 3.5814                    | 85.0184           | 0.0134                |
| 5                 | 1.0120g                  | 2.4014                    | 57.0734           | 0.0079                |
| 6                 | 1.3082g                  | 3.1935                    | 73.7798           | 0.0120                |
| 7                 | 0.9918g                  | 2.3893                    | 55.9373           | 0.0075                |
| 8                 | 1.2367g                  | 2.9829                    | 69.7524           | 0.0113                |
| 9                 | 0.9324g                  | 2.2323                    | 52.5890           | 0.0081                |
| 10                | 1.0107g                  | 2.3950                    | 57.0031           | 0.0104                |
| 11                | 0.8535g                  | 2.0444                    | 48.1386           | 0.0072                |

In addition, the inertia force exerted by the pile top after reaming is greater than that without reaming, indicating that reaming plays an amplifying role in the inertia force. When the reaming depth and hole diameter are unchanged, the inertia force is obviously less than that of rubber when the reaming material is loose sand; When the reaming material and hole diameter remain unchanged and the reaming depth increases, the inertial force increases; When the reaming material and depth remain unchanged and the reaming diameter increases from 2.5D to 4D, the inertial force increases first and then decreases. Because the loading conditions and pile top mass are the same, and the soil dynamic performance is also very stable according to the soil response frequency and acceleration response, the change of inertial force is the reaming parameter. The change of reaming parameters leads to the change of pile-soil system frequency, which leads to the change of inertial force.

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