

DYNAMIC LOADING TEST FOR PILE SUPPORTED TOWER CRANE IN SOFT CLAY

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SUMMARY

A self-supported tower crane, which is a type of cranes standing on the ground supported by a pile foundation, is widely spread due to a rush of constructions of higher residential buildings. Most of design cords for the tower cranes, however, have not sufficiently indicated the required performances for the foundation supporting the tower crane. Furthermore, as the tower cranes are coming into wide use, earthquakes causing a great deal of damage to the tower cranes will come to be a factor taken into account in the design code.

In this paper, a series of centrifugal shaking table tests was performed to investigate the dynamic characteristics of the tower crane supported by a pile foundation in soft clay. Two different weight conditions for the crane jib to accurately simulate practical situations were imposed. From the results of the tests, the dynamic behaviors of the tower crane and the influenced factors were discussed. In addition, it was concluded that the weight conditions for the crane jib give significant influence on the level of pile damage and might lead to different failure patterns of the tower crane.

INTRODUCTION

Tower cranes rising to hundreds of feet into the air like skyscrapers are common fixtures at any major construction sites to lift heavy and large building materials up and down. In Japan, a tower crane standing on the ground supported by a pile foundation is widely spread due to a rush of constructions of higher residential buildings in recent years. From the viewpoint of structural mechanics, the tower crane is one of unique structures as compared with the other common structures like buildings, which has a weight proportion of top-heavy and a slender figure. It means that the tower crane is susceptible to oscillating and

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overturning. Most of design cords for the tower crane, however, have not sufficiently indicated the required performances for the foundation supporting the tower crane. Furthermore, as tower cranes are coming into wide use, earthquakes causing a great deal of damage to the tower cranes will come to be a factor taken into account in the design code.

However, the designs of seismic resistance for any other structures can not be applied for the tower crane without careful consideration because of uniqueness of its vibration characteristics. In addition, there have been few studies to examine the dynamic characteristics of the tower crane.

The purpose of this study is to investigate the dynamic characteristics and the predicted failure patterns of tower cranes supported by a pile foundation. This paper describes the results of the dynamic centrifugal shaking table tests performed on a model tower crane supported by a pile foundation in soft clay.

EXPERIMENTAL SET UP

Centrifuge package

The centrifuge used in the tests was the National Institute of Industrial Safety (NIIS) Centrifuge (Toyosawa et al. 1994). The model setup used in this study is shown in Fig. 1. An aluminium model container with inner sizes of 450 mm in width, 150 mm in breadth, and 272 mm in height was used. The inner side of the container was coated with alumite to reduce wall friction. The front face of the container has a transparent window which enabled to observe the deformation of the model ground. Steel sheets with 0.5 mm thick were placed near both sides of the container to absorb stress waves from the side boundaries.

Model the tower crane and pile

In this study, a hammerhead type of tower crane, which has a simple figure relatively easy to grasp the seismic behaviors, was modeled as the superstructure of the model tower crane as shown in Fig. 2. Sizes and materials of the model tower crane were determined by considering the similarity rules for centrifuge modelling. Properties of the model tower crane are listed in Table 1. In this test, there were two cases of the tests set up with different weight conditions for crane jib to accurately simulate practical situations. One was the case of "Balance" which corresponded to the crane having no load, the other was "Unbalance" suspending the loads. In both cases, the total weights of the crane jibs were arranged to be the same.

In order to examine the natural frequencies of the model tower crane, a resonant search test was carried out at 1 g filed, which is a series of vibration tests with various frequencies and small amplitude. The dynamic response of the model tower crane was recorded by horizontal acceleration provided by the accelerometer located at upper part of the tower crane as shown in Fig. 2. Figure 3 shows the relationship between the amplifications and the frequency in the resonant search test. The amplifications of response peak accelerations (Acc-S2 / Input Acc) were calculated at each frequency. In the case of the balance condition, the first and second natural frequencies at which the peak of amplification occurs are 0.5 Hz and 1.6 Hz at prototype scale, respectively. On the other hand, in the case of the unbalance condition, the first and second natural frequencies are 0.5 Hz and 1.2 Hz at prototype scale, respectively.

The model substructure supporting tower crane consisted of an aluminium footing and 4 piles rigidly fixed to the footing. The pile spacing ratio s/d = 3.33 in the direction of shaking axis, and s/d = 4.00 in the transverse direction of shaking axis, as shown in Fig. 1. The model pile is approximately equivalent to a solid concrete pile with a diameter of 800 mm at prototype scale. Considering the similarity rules for centrifuge modelling, aluminum tubes with an outside diameter of 15 mm, a thickness of 1 mm, and a total length of 309 mm were used for the model piles. Properties of the model piles are listed in Table. 2. Strain gages were instrumented inside at 9 different levels to measure the bending moment distribution and 3 different levels to measure the axis forces for each pile. However, only 10 gauges for the bending

moment and 4 gauges for the axial force for the whole system were used in this study because of limitation of the data recorder used. It should be also noted that the model piles behaved elastically though real concrete piles might show non-linear response at large displacement.

Experimental procedures

Fujinomori clay was used for model clay layer in the tests. It is a well-characterized soil, which was reported for the project of research by Japan Geotechnical Society (1993). Their findings are shown in Table 3. Deaired slurry of the clay, which was prepared at 80 % water content, was first consolidated in a strong box on the laboratory floor under a pressure of 100 kPa. Prior to consolidation, rubber membranes smeared with silicon oil were placed at the inside walls of the container and the steel sheets to reduce wall friction. Then the model piles were driven into the soil in group configurations through a template to ensure location and verticality. The toe of the pile was in the condition of pin connection, which is allowed to freely rotate. Set all instrumentations, and apply centrifugal acceleration up to 50 g allowed for self-weight settlement of the soil. Then, after the excess pore pressure in the ground disappeared, a shaking table test was carried out. Two cases of different weight conditions for the crane jib were investigated in this test as mentioned above. All the results of the centrifuge tests are presented in terms of prototype scale, hereafter.

EXPERIMETAL RESULTS AND DISCUSSIONS

Resonant search test

A resonant search test in centrifuge was conducted only for the balance case to understand the dynamic responses of the whole system consisting of the super and the substructures, the ground at the relatively low amplitude levels. The dynamic responses of the model were measured by some accelerometers and strain gages to measure the bending moment distribution along the tower. The curves of the peak acceleration amplification are presented in Fig. 4 as the results of the accelerometers located at upper (Acc-S2) and lower part (Acc-S1) of the tower. In the upper part of the tower, the natural frequencies at which the peak amplifications occur are 1.6 Hz and 3.0 Hz within the range of frequency used in the test. The dominating frequency of 1.6 Hz was agreement with the second natural frequency of the model tower crane shown in Fig. 3. In the lower part of the tower, the dominating frequencies are 1.6 Hz and around 3.0 Hz, respectively. The relationships between the frequency and the bending moments of the tower divided by the input acceleration are shown in Fig. 5. In the result of the lower part of the tower, the first to the third dominating frequencies are found around 0.5 Hz, 1.6 Hz, and 2.7 Hz, respectively. On the other hand, the amplification at 0.5 Hz in the upper part of the tower is quite small in comparison with that of the lower part. It suggests that the bending moment in the upper part mainly comes from the vibration of the jib, while the bending moment in the lower part corresponds to the oscillation of the upper part of the tower, as shown in Fig. 4.

Shaking tests

Input acceleration

In this study, 30 sinusoidal waves with a frequency of 80 Hz (1.6 Hz at prototype scale), which approximated the second natural frequency of the system in the case of the balance condition, were applied. Typical time histories of the input sinusoidal waves are given in Fig. 6. This input wave is divided into three parts each of which consists of 10 sinusoidal waves. The peak accelerations for three parts of waves are 100 gal, 200 gal, and 400 gal at prototype scale, respectively. The reasons for applying the wave divided into three parts were to verify the influences of amplitude of input wave on the amplification of response acceleration and to examine the free vibration behavior during interval of each part and softening clay under the cyclic loading.

Acceleration response

Figure 7 shows the time histories of horizontal acceleration in both cases at all measurement points. Incidentally, in the case of the unbalance weight condition, Acc-G2 could not observe the motion because of the accelerometer breakdown. As for the response acceleration of the ground, the amplitude of acceleration decreased with decreasing the depth at each stage. The tendency was distinguished in Acc-G3 at the third stage because of the clay softening under cyclic loading. It should also be added that there were spiky waves observed in Acc-G3 in the balance weight condition at the third stage. This may be explained by the collision between the pile and the ground. In order to represent the attenuation behavior, the relationship between input acceleration with response acceleration at each measurement point was shown in Fig. 8. From the gradient of each loop, it was confirmed that the change of the response acceleration with initial amplitude during the second and the third stage was caused, whereas significant linear behavior was observed during the first stage. In addition, it is clear that the motion in the upper part of tower crane has 180 degrees of phase angle with other motion, which means out-of-phase response.

Comparisons of the dynamic characteristics between various weight conditions of crane jib

The time histories of the horizontal displacement of the footing in both cases are plotted in Fig. 9. As for the vertical axis in this figure, the positive side means the deformation in the direction of the main jib. Note that the point where the footing displacement was measured was 10 mm above the ground level. As shown clearly in the figure, in the case of the unbalance weight condition, inertial deformation took place in the middle of the second stage. At the end of shaking, the observed permanent horizontal displacement of footing was about 25 mm in the direction of the main jib which was heavy weight side. On the other hand, in the case of the balance weight condition, the horizontal displacement of the footing was nearly zero. For the results of horizontal displacement of the footing, it appears that not only kinematic forces resulting from cyclic ground displacement but also inertial forces from the superstructure may come to play important roles.

Figure 10 shows the comparisons of the axial forces observed at piles in both cases. In the vertical axis in this figure, the positive side means the compression of pile. In addition, Pile-1 is on the side of the main jib and Pile-2 on the side of the counterweight jib. In the case of the balance weight condition, the axial forces of Pile-1 changed in the opposite phase to the axial forces of Pile-2. It means that rocking motion occurred in the motion of the superstructure. Additionally, the axial force of Pile-2 was much larger than that of Pile-1 at the middle part of pile. In the unbalance weight condition, the axial forces recorded with Pile-1 and Pile-2 were the same phase. Thus, it can be thought that the response of the superstructure was dominated by sway motion. In comparison with the result of the balance weight condition, it is obvious that the maximum axial force at the pile head in the unbalance case is about twice as much as that in the balance case because of the overturning moment caused by the suspending load.

Figure 11 presents the time histories of bending moments at the locations of upper and lower part of the tower, together with the upper part acceleration. The results show that the bending moment of the lower part corresponds to the amplitude of the upper part acceleration. Therefore, compared with the unbalance case, in the balance case where the larger amplification occurred in the upper part of the crane, the bending moment became larger. Additionally, it could be said that there were negligible bending moment at the upper part of the crane in the unbalance case. Figure 12 shows the time histories of bending moments in both cases at all measurement points, together with the input acceleration. In the case of the unbalance condition, the magnitude of the bending moment of Pile-1 was larger than that of Pile-2 near the pile head (G. L. 0.675m), whereas the results reversed in the location of G.L. -1.975m. Figure 13 compares the bending moment at the pile head peaked in the seventh cycle are plotted in the balance and the unbalance weight condition at each stage. In the balance weight condition, it can be pointed out from the distributions that inertial forces from the superstructure mainly dominate. In such a case which the pile

head is heavily damaged, there may be great risk in tilting failure of tower crane. On the other hand, in the unbalance weight condition, it was thought that not only inertial forces but also kinematic forces, which derived from the relative displacement between the pile and the ground, may dominate. In this case, the pile will be damaged at the position of the middle part under the ground rather than at pile head. The results also provided that it is important to consider the dynamic interaction between the piles and the ground.

CONCLUSIONS

A series of centrifuge shaking table tests was performed to investigate the dynamic characteristics of the tower crane supported by a pile foundation in soft clay. The base motions consisted of sinusoidal waves at 1.6 Hz (prototype scale) frequency. Two different weight conditions of crane jib to accurately simulate practical situations were imposed. Major finding obtained from these tests are shown as follows;

1) The dynamic responses of the tower crane are influenced by the amplitude of the input motion, and the weight condition.

2) The bending moment caused at lower part of the tower, which may lead to tilting failure of tower crane, is proportional to the response acceleration at the crane jib.

3) The bending moment at pile is not necessarily equivalent to the input motion and the response acceleration and influenced by some factors including rocking and sway motion of the footing.

4) The weight conditions for the crane jib give significant influence on the level of pile damage and the bending moment distribution. These might lead to different failure patterns of the tower crane.

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(b) Outer view of model setup Figure 1 Experimental setup



Figure 2 Model the tower crane

	Prototype (m)	Model (mm)
Height of tower crane	30	60
Length of jib	30	60
Soil layer	12	24
Diameter of pile	0.75	1.5
Length of pile	13.5	27

Table 1 Properties of the model tower crane

Table 2 Properties of model pile

	Prototype	Centrifuge model
Material	Concrete	Aluminium
Diameter	0.8 m	15 mm
Wall thickness	Solid	1 mm
Pile length	13.5 m	27 mm
Young's modulus, E_p	245.0 3 10 ⁵ (kN/m ²)	702.7 3 10 ⁵ (kN/m ²)
Bending rigidity, $E_p I_p$	49.26 3 10 ⁴ (kNm ²)	76.543 10 ⁻³ (kNm ²)



Figure 3 The relationship between the amplification with frequency at upper part of tower crane

Property	
Particle density ρ_s (g/cm ³)	2.719
Maximum grain size (mm)	0.25
Mean particle diameter D ₅₀ (mm)	0.027
Liquid limit $w_{\rm L}$ (%)	62.7
Plastic limit $w_{\rm P}$ (%)	27.8
Plasticity index $I_{\rm P}$	34.9

Table3 Material properties of Fujinomori clay



(balance weight condition)

Figure 4 The acceleration amplitude vs. frequency Figure 5 The normalize bending moment of tower vs. frequency



Figure6 Typical time history of input wave under the shaking tests



Figure7 The time histories of response acceleration, together with the input acceleration



Figure-8 The relationship between input acceleration with response acceleration at each measurement point (balance weight condition)



Figure 9 The horizontal displacement response measured on footing



Figure 10 Time histories of axial forces of piles



Figure11 Time histories of bending moment of tower



Figure12 Time histories of bending moment of piles



(a) Balance weight condition

(b) Unbalance weight condition

Figure13 Distribution of bending moment along pile shaft