Effects of embedment on response of structures on spread foundation in centrifuge model tests



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SUMMARY

The objective of this study is to examine how the dynamic behavior of structures subjected to strong ground shaking relates to earth pressures acting on an embedded foundation. For this purpose, two series of centrifuge shaking table tests were performed, in which the height of the foundation embedment was varied. Each test model had two types of structures on spread foundations with different heights of the center of gravity. Test results lead to the following conclusions: 1) Structures have an ultimate value in overturning base moment. The ultimate overturning base moments are almost the same in high-rise buildings and low-rise buildings. 2) The ultimate values of the overturning base moment are smaller in the cases with shallow embedment than in the cases with deep embedment. 3) Earth pressure coefficient is larger in the cases with shallow embedment than in the cases with deep embedment. This is because the rotational stiffness is relatively small in the cases with shallow embedment, inducing a larger rotational angel of the foundation.

Keywords: Earth pressure, Spread foundation, Centrifuge model tests, Structural response

1. INTRODUCTION

Toward understanding the response of structures on spread foundations, the S-R model, in which sway-rocking motion of structures is taken into account, is widely used (Architectural Institute of Japan, 1998). In the S-R model, it is important to establish spring stiffness for sway and rocking motions during earthquakes. However, it is insufficient to investigate the effects of non-linear behavior of soil-structure systems on the sway and rocking motion, since experimental studies have been rare. To estimate the response of structures on spread foundations, Tamura et al. (2012) conducted centrifuge model tests with high-rise and low-rise buildings. It was described that the superstructure acceleration has a limit, depending on their ultimate overturning moment. In other words, the ultimate superstructure acceleration is related to bearing capacity of soil-foundation.

In Tamura's study, structure models did not have foundation embedment. The presence of foundation embedment might have affected the structure response as earth pressure acts on the embedded foundation. Regarding earth pressure, Mononobe (1924) and Okabe (1924) proposed formulas to estimate seismic earth pressures acting on walls. Ohara et al. (1985) and Fang et al. (1994) conducted tests with various wall movements, to estimate the ultimate earth pressure during earthquakes. Zhang et al. (1998) modified Mononobe-Okabe's formulas, in which the lateral displacement of walls is taken into account. Namely, the modified theory could present earth pressure under any lateral displacement between active status and passive status. The previous studies mainly targeted earth pressure acting on walls, but studies on earth pressure acting on foundations of structures have been rare (e.g. Tamura et al., 2010).

The objective of this study is to examine how the dynamic behavior of structures subjected to strong ground shaking relates to earth pressures acting on the embedded foundation. For this purpose, centrifuge shaking table tests with foundation-structure models were performed. This paper

describes the effects of foundation embedment on structural response.

2. CENTRIFUGE MODEL TESTS

To investigate the seismic behavior of structures on embedded spread foundations, centrifuge shaking table tests were conducted on two series. Fig. 1 shows soil-structure systems for two test series, which were constructed in a laminar shear box with dimensions of 800 mm x 1960 mm x 580 mm. Both the test systems had two structures with different heights of the center of gravity. The difference between the two test series was the thickness of foundation embedment. The thickness of embedment in series A was twice as large as that in series B. All the tests were performed at a centrifugal acceleration of 40 g. Hence the test models were on a scale of 1:40 in length.

To prepare sand deposits in the laminar shear box, Toyoura Sand ($e_{max} = 0.982$, $e_{min} = 0.604$) was used. Dry sand was air-pluviated and then compacted to the designated density (Dr = 90 %). The thickness of the sand deposit including the embedment was 543 mm in series A and 492 mm in series B, as shown in Fig. 1, corresponding to a prototype soil layer of 21.7 m and 19.7 m respectively. In the sand layer, two structures on spread foundations (Models N and L) were placed in each test series. Model N was a high-rise building and Model L was a low-rise building. Superstructures in series A and B were the same, but foundations in series A and B are different from each other. The foundations in series A had twice the height and weight as those in series B had. The weight of superstructure was about 9.5 kg in model scale and that of foundation was about 6.8 kg in series A and 3.0 kg in series B.

The soil-structure systems were instrumented with accelerometers and load cells, as shown in Fig. 1. To measure the kinematic force acting on embedded foundations, many load cells were installed in foundations, which provided data of earth pressure acting on foundations. In the shaking table tests, an artificial ground motion called Rinkai having a maximum acceleration adjusted to 1, 2, 4 and 7 m/s² in prototype unit was used as an input motion. Hereafter, tests are shown in two characters; the first one stands for test series (A or B) and the second one stands for the maximum input acceleration (1, 2, 4 or 7). Based on the centrifuge test results, seismic behavior of structures on embedded spread foundations are discussed in this paper. The observed test results discussed hereafter are those in prototype units with a scaling factor corresponding to 40 g.

3. TEST RESULTS AND DISCUSSIONS

3.1. Structure Response

Figs. 2 to 5 show time histories of accelerations of superstructures, the ground surface and the input motion and earth pressures acting on the left and right sides of foundations in four tests with the maximum input acceleration of 2 and 7 m/s² (Tests A2, A7, B2 and B7). In the cases with a smaller input acceleration (Tests A2 and B2), the maximum superstructure acceleration is almost the same between Models N and L in both series A and B (Figs. 2 and 3(a)(b)). In contrast, in the cases with a





larger input acceleration (Tests A7 and B7), the maximum superstructure acceleration is larger in Model L than in Model N in both series A and B (Figs. 4 and 5(a)(b)). With increase in the superstructure acceleration, the earth pressures on the right and left sides of foundations increase alternatively (Figs. 2-5(c)-(f)). This suggests that the increase in superstructure acceleration makes one side the passive side and the other side the active side. As expected, the earth pressure is larger in series A with deep embedment than in series B with shallow embedment, related with the surface area suffering earth pressure (Figs 2-5(c)-(f)).

To estimate the difference in superstructure accelerations, Figs. 6 and 7 show relations of the maximum superstructure acceleration versus the maximum input motion and the maximum ground surface acceleration. The maximum acceleration of superstructures is larger than those of the input





Figure 4. Time histories of major values in Test A7



Figure 5. Time histories of major values in Test B7

motion and the ground surface in the cases with a small input motion but is almost the same level as those of the input motion and the ground surface in the cases with large input motion. In both series, the superstructure acceleration is almost the same level between Models N and L in the cases with a small input motion but is lager in Model L than in Model N in the cases with a large input motion. In addition, the superstructure accelerations are larger in series A than in series B in the case with a small input motion. This trend is not shown in the cases with a large input motion. Fig. 8 shows amplitude ratios of superstructure accelerations with respect to the input motion in eight tests. With increasing input motion, the period, in which the amplitude ratio takes a peak, becomes large and its peak value becomes small. This suggests non-linearization of soil-structure systems causes the de-amplification of superstructure acceleration. The decrease in amplitude ratio is more significant in series B than in series A. This suggests that the height of the foundation embedment affects the superstructure response.

To investigate the difference in structural response between Models N and L in series A and B, the overturning moment from the structure acting on foundation base is calculated from the observed accelerations of superstructure and foundation. Fig. 9 shows the overturning base moment with the rotational angles of the foundation in four tests (Tests A2, A7, B2 and B7). The rotational angles are computed from the vertical acceleration recorded at the edge of the opposite sides of a foundation. The rotational angle of the foundation increases, with increasing overturning base moment. In the case with a small input motion, the relation between the two tends to be linear (Fig. 9(a)-(d)). In contrast, in the cases with a large input motion, the relations between the two show the S-shaped trend (Fig. 9(e)-(h)). Namely, the rotational angle increases with constant overturning base moment. This suggests that the overturning base moment has an ultimate value, as mentioned in the previous study (Tamura et al., 2012). Before overturning base moment reaches the ultimate value, the overturning base moment is larger in Model N than in Model L. This is because Model N has a larger rotational radius. Once the overturning moment reaches the ultimate value in Model L under a strong motion, an increase in superstructure acceleration of Model N is restrained, having its value





Figure 6. Superstructure acc. and input motion

Figure 7. Superstructure acc. and ground surface acc.



Figure 8. Amplitude ratio of superstructure acc. versus input motion

smaller than that of Model L. In addition, a comparison between series A and B shows that the ultimate value is likely to be larger in series A than in series B. This is because the kinematic force acting against the overturning base moment is larger in the test with deep embedment than in the tests with shallow embedment. This confirms that the bearing capacity of foundations is related to soil condition.

3.2 Earth Pressure Acting on Embedded Foundation

Fig. 10 shows relations of earth pressure with relative displacement between foundations and the ground surface in Tests A7 and B7. In Test A7, slope angles of the relations between the earth pressure and the relative displacement of Models N and L are different from each other. The earth



Figure 11. Relations of earth pressure with rotational angle of foundation



Figure 12. Relation of earth pressure coefficient with rotational angle of foundation

pressure of Model N is almost the same level as that in Model L, regardless of a small relative displacement of the foundation (Fig. 10(a)(b)). In contrast, in Test B7, the earth pressure and relative displacement are almost the same level in Models N and L (Fig. 10(c)(d)). A relative displacement of 0.04 m shown in the horizontal axis corresponds to 1 % of the embedment height in series A and 2 % of the embedment height in series B. Zhang et al (1998) suggests that the ultimate earth pressure on the passive side requires a relative displacement of 5-10 % foundation embedment. The relative displacement of Model N in series A is significantly small.

Fig. 11 shows the relations between the earth pressure and the rotational angle of the foundation. Slope angles of the relation between the earth pressure and the rotational angle are almost the same in Models N and L in each series. This suggests that the earth pressure might have been mainly controlled by the rotational angle rather than the relative displacement probably because the relative displacement is small. It is found out that the slope angle is larger in series B than in series A.

To compare the earth pressure between series A and B, earth pressure coefficient is computed from the observed earth pressure, vertical stress and area of foundation surface suffering earth pressures. The earth pressure coefficients on the right and left sides are computed separately. Fig. 12 shows the relations between earth pressure coefficient and the relative displacement of the foundation with the ground in Tests A7 and B7. The earth pressure coefficient becomes large with increasing rotational This confirms that the increase in the earth pressure coefficient is mainly controlled by the angle. increase in rotational angles. The earth pressure coefficient is significantly larger in series B than in series A, depending on an increase in rotational angle. Some of values in earth pressure coefficients are scattered, but the figure indicates that the maximum earth pressure coefficient is about 4 in Test A7 and about 10 in Test B7. The rotational angle of 0.01 rad. in the horizontal axis shown in the figures corresponds to about a displacement of 1 % embedment height in series A and that of 0.02 rad. correspond to a displacement of 2 % embedment height in series B. Adding both the sway and rocking components, the displacement of the foundation top amounts to about 5 % of the embedment height in series B and about 2 % of the embedment height in series A. Based on Mononobe-Okabe's formulas, the ultimate earth pressure coefficient at the passive side is estimated based on an assumption that a frictional angle ϕ is 42 degrees and the ground surface acceleration is 7 m/s². The estimated earth pressure coefficient is about 10, which is in good agreement with the observed value in Test B7. This suggests that the earth pressure coefficient is close to the ultimate value in Test B7.

The reason why the rotational angle is larger in series B than in series A is that the kinematic force from the ground is smaller in series B than in series A, depending on the height of the foundation embedment. This is related to the trends in Fig. 8, in which the amplitude ratio is smaller and the peak period is longer in series B than in series A. In series B, the rotational stiffness is small, inducing a larger rotational angle. In contrast, in series A, the rotational stiffness is relatively large, inducing a small rotational angle. As a result, in series A, the overturning moment reaches the ultimate value before the rotational angle increases significantly. This restrains an increase in earth pressure.

4. SUMMARY

To investigate the effects of foundation embedment on structural response, centrifuge model tests were conducted. The discussion of test results leads to the following conclusions:

- 1) Structures have an ultimate value in overturning base moment. The ultimate values of the overturning moment are almost the same between high-rise buildings and low-rise buildings. As a result, the superstructure acceleration reaches a limit earlier in high-rise buildings, which have a larger rotational radius, than in low-rise buildings.
- 2) The ultimate values of the overturning moment are smaller in the cases with shallow foundation embedment than in the cases with deep foundation embedment. This confirms that the bearing capacity of foundations is related to soil condition.
- 3) Earth pressure coefficients are larger in the cases with shallow foundation embedment than in the cases with deep foundation embedment. This is because the earth pressure coefficients are mainly controlled by rotational angles and the rotational stiffness is smaller in the cases with shallow foundation embedment, inducing a larger rotational angle of a foundation.

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