ON SEISMIC BEHAVIOR OF INCLINED PILES IN VIEW OF NON-LINEAR STRUCTURE-SOIL INTERACTION

Okayama University Graduate student Shimabuku Jorge
Okayama University Professor Takemiya Hirokazu

1. INTRODUCTION

Inclined piles have a poor behavior in past earthquakes. Failures of inclined piles can be attributed more to a lack of understanding of the behavior of inclined piles rather than to the nature of inclined piles themselves. Therefore, this paper is intended to fill these aspects through the study of a typical bridge pier supported by inclined and vertical piles with emphasis on the behavior characteristics of the inclined piles and the superstructure that they support.

2. MODELLING AND RESPONSE ANALYSIS

A 2-D seismic nonlinear soil-structure interaction analysis is conducted based on BEM-FEM hybrid technique[1]. The studied structure corresponds to a typical pile supported bridge of the Hanshin Expressway, where only the angle of inclination of the outer piles (θ) is changed as shown in **Fig. 1**. The considered angles of inclination are 0°, 10°, 15°, 20°, 25° and 30°. The pile's rows are called A, B, C and D for reference. The pier and piles are modeled by beam elements, the neighboring soil is discretized by FEM with the vertical side boundary offset from the area of interest. The inelastic behavior of pier and piles are represented by the modified one component model[2] and the modified Q-hyst model[3]. The axial load variation is considered in the evaluation of the yield bending moment at each computational step from the bending moment-axial force interaction diagram. The nonlinear soil behavior is characterized by the Hardin-Drnevich hyperbolic model and the Mohr stress circle criterion. The motion used in the analysis is the Kobe-JMA-NS record. **Fig. 2** shows the maximum bending moment and horizontal displacement distributions for the piles and pier. The profiles along the pile are chosen from the maximum results of the pile A and pile D. As the angle of inclination increases, the bending moment is reduced at pile top and the peaks of bending moment tend to move downward. Moreover, the large bending moment at layer's interface (G.L. –7 m) does not appear for the 25° and 30° cases, which is due to their considerable angle of inclination. At pier, the smallest drifts of the pier top relative to the pier bottom are obtained for the 10° and 15° cases. In the comparison with the vertical case, there are reductions of 86 per cent and 63 per cent for the 10° and 15° cases, respectively. From the above considerations, its is clear that the inclined piles reduce the footing displacements with a corresponding reduction in pile bending moments especially at pile top. At the same time, inclined piles have better behavior than vertical piles with respect to drift of pier. In addition to peak response values, the ductility values are calculated to evaluate the possible degree of damage associated with the inelastic behavior. The ductility values at pile top and pier bottom are depicted in **Fig. 3**. The inclination of 10° leads to reduction of ductility at pile top for 23 per cent with almost null variation at pier. For the 15° case, the ductility is reduced in 33 per cent at pile top and an increment around 20 per cent is noted at pier bottom. For the 20° case, the ductility is reduced in 69 per cent at pile top; but it is increased in 11 per cent at pier bottom. Consequently, the inclination of piles causes an important reduction in the pile's degree of damage at pile top (also at layer's interface level), while the pier is only slightly affected (i.e. ductility values are almost the same for 10° and 0°). The maximum tensional and compressional forces at inclined piles are shown in **Fig. 4**. In this figure and following, the positive value of axial force corresponds to compressional force. It is clear that any inclination increases the axial response extraordinarily. In example, at the pile top, the tensional force for the inclination of 10° is 2.9 times larger than the 0° case. It is more notorious for tensional forces at deep elevations. These large values reflect that inclined piles pick up some of the kinematic forces from the ground motion through their axial stiffness. This behavior is opposed to the vertical piles, where only the flexural stiffness takes these forces. Since the inclined piles of all cases reach the ultimate tensional force (6548 kN), the axial failure by tension is expected. The relations between the axial force and bending moment at pile top are depicted in **Fig. 5** for all piles. It is noted that as the angle of inclination increases, the tensional forces turn larger and the bending moment turns smaller. Therefore, for inclined piles, the damage at pile top may be due to tensional axial force rather than bending moment. This can be extracted from the curve's parts with large tensional force values which are outside the yield limits (dot lines), especially at pile A and pile C. The type of failure changes from bending to tensional type. **Fig. 6** shows the bending moment-rotation interaction at top of pile D, where it is noted that as the angle of inclination increases, the inelastic behavior disappears. Practically linear behavior is observed for 30°, while the more strong nonlinear behavior corresponds obviously to 0° case. The soil shear strain distributions are shown in **Fig. 7** to investigate its relation with the angles of the inclination of piles. The indicated profiles in this figure correspond to the soil near the outer side of the inclined external pile A and near the outer side of the vertical internal pile B. From

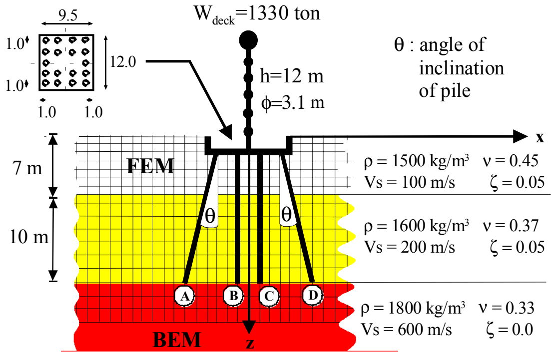

Fig.1 The model of analysis

KEY WORDS: inclined piles, pile nonlinear behavior, bending moment-axial force interaction

〒700-8530 岡山市津島中 3-1-1 岡山大学環境理工学部環境デザイン工学科 Tel(Fax) 086-2518146

this figure, as the angle of inclination increases, the maximum shear strain decreases especially at outer side of the inclined pile A. In this location, the differences among the cases are more notorious around the interface of soil layers. While the 0° and 10° cases have peak soil strains at interface level, the 25° and 30° cases do not vary their strain values at this level. In contrast, this soil behavior is not noted in the outer side of pile B due to vertical arrangement of pile B.

3. CONCLUSIONS

The inclined piles minimize the displacements of footing with a corresponding reduction in pile bending moments and drift of pier. Here, the maximum bending moments tend to move downward. Since the inclined piles pick up some of kinematic forces from ground motion, they should be adequately designed to resist the possible developed tensional forces. The failure at piles changes from bending to tensional type as the angle of inclination increases.

4. REFERENCES

(1) Takemiya, H., and Adam, M., 2D Nonlinear Seismic Ground Analysis by FEM-BEM: The Case of Kobe in Hyogo-ken Nanbu Earthquake, JSCE, No.584/I-42, 19-27. (2) Takemiya, H. and Shimabuku, J.: Nonlinear Seismic Damage Analysis of Bridge Pier Supported by Piles, *The 10th Earthquake Engineering Symposium Proceedings, Volume 2, E1.20.* Yokohama, Japan, 1687-1692, 1998. (3) Shimabuku, J. and Takemiya, H.: Nonlinear Soil-Pile Foundation Interaction Analysis Based on FEM-BEM Hybrid Technique, *Proceedings of the 25th JSCE Earthquake Engineering Symposium*, Tokyo, Japan, 461-464, 1999.

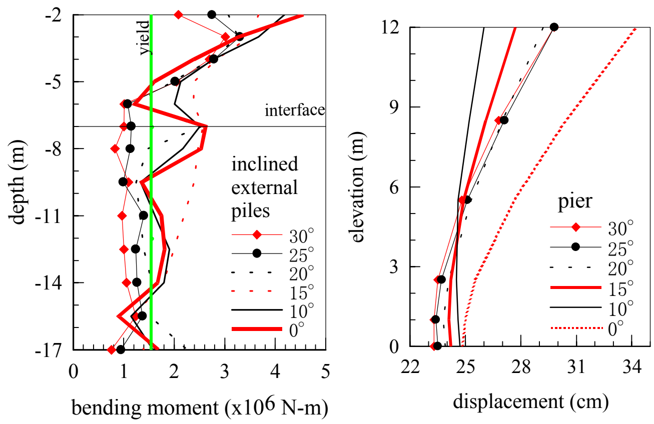

Fig. 2 Maximum bending moment distribution along the pile and horizontal displacement at pier

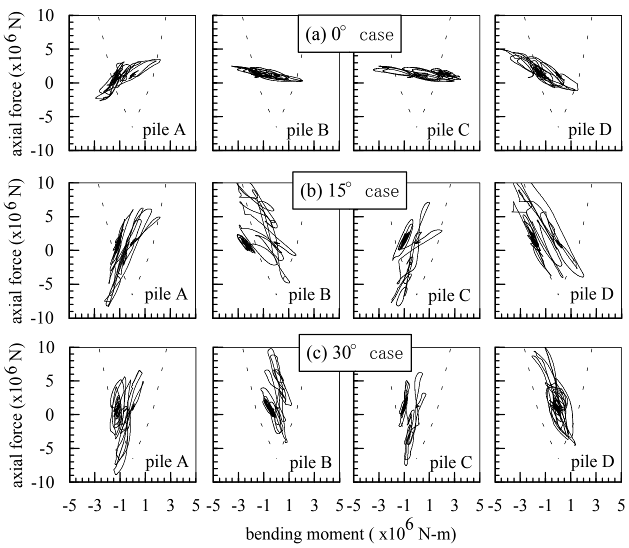

Fig. 5 Bending moment-axial force relationships at pile top

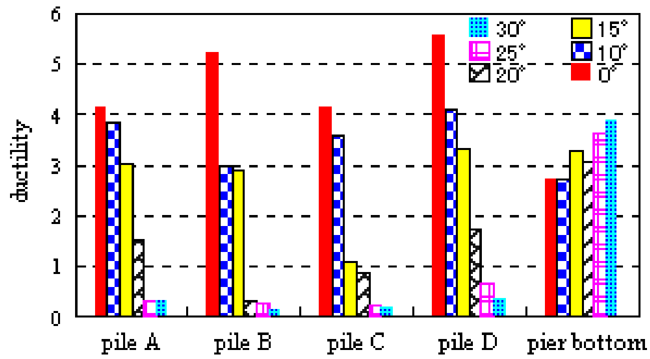

Fig. 3 Ductility values at pile top and pier bottom

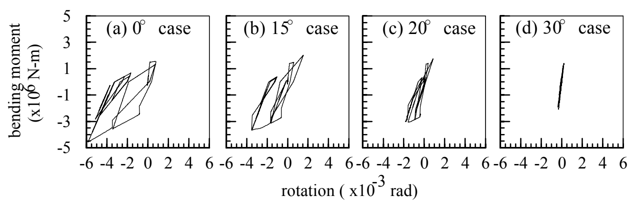

Fig. 6 Bending moment-rotation hysteresis at top of pile D

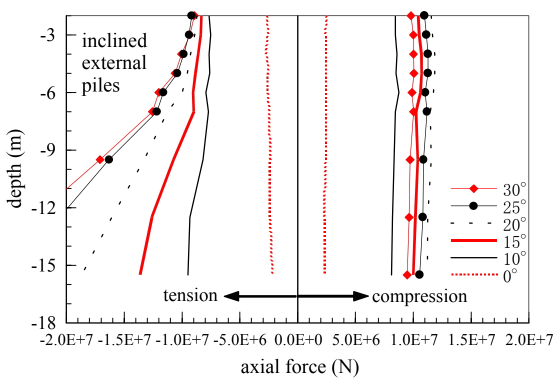

Fig. 4 Maximum axial force profiles along the length of pile

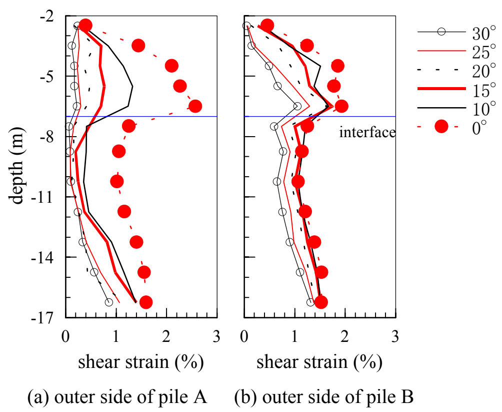

Fig. 7 Maximum shear strain distribution at different locations