

REDESIGN OF SEISMIC DAMAGED PILE FOUNDATIONS BY GROUND IMPROVEMENT

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SUMMARY

Effective aseismic design method for conditions of ground improvement which prevent liquefaction and damages of pile foundation is proposed. This method uses two existing computer programs, in which one is the program NUW2 for 2D effective stress analysis, and the other is the program WAP3 for simulation of sand compaction pile method. By using these programs the 17 ground models which are selected from the damage examples in Kobe area due to 1995 Hyogo-ken nanbu Earthquake, are analyzed. Numerical computations for responses of the ground and the pile foundations including ground improved cases are performed. The conditions of ground improvement are evaluated by using the natural period of the ground layers as the key parameter. These conditions are also related with the responses of super structure on the ground, then the critical conditions for preventing liquefaction and damages of pile foundation are investigated. Main conclusion is that the proposed evaluating method is effective for reducing pile stress under allowable limit in sandy ground layer by using the ground improvement method, but the ground improvement may be difficult to prevent pile failure in soft clayey ground.

INTRODUCTION

Many damages of foundation structures and tilt of structures occurred at reclaimed land during 1995 Hyogo-ken nanbu Earthquake (AIJ [1]). The damages of pile foundations are caused by liquefaction which occurred in surface ground layers due to strong ground motion. There are many countermeasures against liquefaction, which have been developed and conducted in the field, but a few of them have been investigated its efficiency for preventing both liquefaction of the ground and damage of the structure resting on or buried in the ground. Thus it is important to evaluate the non-linear response of the surface ground layers surrounding structure including liquefaction. These non-linear response characteristics should be reflected for the asesmic design process of the structure constructed on or in the surface ground layers.

As the countermeasure against liquefaction, the compacting ground improvement method is considered in this study. We have developed the computer program simulating the compacting ground improvement

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method (Akiyoshi [2]). The computer program for 2D effective stress analysis has been also developed (Akiyoshi [3]). Combining these computer programs, the effective aseismic design method which evaluates the ground improvement condition for preventing liquefaction damage of pile foundation is proposed in this study (Akiyoshi [4]). This proposed method is applied to the damage examples of the pile foundation during Hyogo-ken nanbu earthquake in 1995, and the seismic design condition for preventing liquefaction and damage of pile foundation is investigated.

SEISMIC RESPONSE ANALYSIS METHOD FOR SOIL-PILE SYSTEM

Two analytical methods used in this study are briefly described. Figure 1 shows the analytical model which consists of the surface ground layers, the pile foundations and the single degree of freedom structure (SDOF) on the surface. One of the analytical methods is the 2D effective stress analysis method which analyzes the seismic nonlinear responses of two phase ground and the linear responses of the piles. This method is coded to the existing computer program "NUW2" (Akiyoshi [3]). The program "NUW2" is based on Biot's two phase mixture theory and Iai's constitutive equation (Iai [5]). In the program "NUW2" the pile is modeled as the beam elements. The detail of this analytical procedure can be seen in the reference [3]. Another analytical method is the simulation method of the static and dynamic compaction process of sand compaction pile method. This analytical method is also coded to the existing computer program "WAP3" (Akiyoshi [2]). In the program "WAP3", the simulating method of the dynamic compaction process is based on the accumulation of propagating waves by compaction.

Combining these two programs, seismic responses of the ground and piles are evaluated for the various conditions of ground improvement and natural periods of structures on surface ground. Thus the aseismic design method which consists of above two programs is proposed. This design method is to determine the optimum condition of the compacting ground improvement method which prevents liquefaction and reduces response of pile foundation. The condition which prevents liquefaction and reduces response of pile foundation. The condition which prevents liquefaction and reduces response of pile foundations are evaluated by using two key parameters. One is the natural period of the surface ground layers T_G and the other is that of the structures T_S . The natural period of the surface ground layers T_G is calculated by using the S wave velocity v_{si} and thickness H_i of i-th layer into equation (1).

$$T_G = 4\sum_{i=1}^n (H_i/v_{si}) \tag{1}$$

Figure 2 shows the proposed design flow of ground improvement conditions for preventing liquefaction and damages of pile foundation.



Fig.1 Surface ground layers and SDOF structure

RESULTS OF NUMERICAL COMPUTATIONS AND CONSIDERATION

Model of surface ground layers and pile foundation system

Figure 3 shows the damage examples of pile foundations of buildings due to 1995 Hyogo-ken nanbu Earthquake (AIJ [6], Seo [7]). The examples are represented according to both natural periods of structures and ground layers, and the black triangle symbols show the examples in which both liquefaction and damages of pile foundations occurred. From these damage examples we choose the 17 examples and make the computational models of them. In each model the ground layers are divided to the 2 dimensional finite elements mesh as pile space and 2m for both the horizontal and vertical directions, respectively. Pile foundations are assumed to be arranged in square shape distribution, and the geometrical moment of inertia and the sectional area per unit length equivalent to the sectional area of each building and total number of piles. Piles are modeled by beam elements with linearly elastic characteristics and no relative displacement between pile and soil, and fixed rotation at pile head are assumed. Piles are assumed to be concrete piles (AC pile, PC pile and PHC pile) or steel piles which have the allowable strengths as 7840kPa and 156800kPa, respectively.

The responses of these ground and pile foundation models are calculated to the input seismic wave which is the strong ground motion record of Port Island at depth GL-32 m and NS component in 1995 as maximum acceleration 5.4m/s^2 . In the case of ground improvement by sand compaction pile (SCP) method, the responses of improved ground models by the same conditions of SCP as reference (Akiyoshi [5]) are also analyzed.



Fig.2 Flow of proposed aseismic design

Fig.3 Examples of damaged pile foundations

Effects of ground improvement

Figures 4(a), 5(a) and 6(a) show the vertical distributions of SPT-N value as a parameter of the compacting time from 0sec to 150sec per one stage of lift up of casing pipe in 1m for the cases of the damage example No.1, 10 and 14, respectively. Figures 4(b), 5(b) and 6(b) show the averaged natural period of ground layers versus the above compacting time.

In Figure 4, as the compacting time becomes long, the SPT-N values increase and the natural period of ground layers decreases. In Figure 4(b) the horizontal line of the critical limit of liquefaction means that no liquefaction occurs for the natural period of the ground T_G less than 0.3765sec because the index of liquefaction potential P_L (JRA [8]) is under 5.0 within this range. This suggests that the condition of compacting time 10sec per one stage is enough to prevent liquefaction for this example No.1. For the damage example No.10 in Figure 5 the similar results with the example No.1 in Figure 4 are obtained.



Figure 4 Soil profile and results of ground improvement of the damage example No.1



Figure 5 Soil profile and results of ground improvement of the damage example No.10

In the case of the damage example No.14 in Figure 6, the SPT-N values are not improved effectively because the 10m thickness of clay layer exists under GL-10m. As a result of these N values after improvement, liquefaction still occurs in the sand layer above GL-10m and there is no limit line of liquefaction in Figure 6(b).



Figure 6 Soil profile and results of ground improvement of the damage example No.14

Liquefaction analysis results

Figures 7, 8 and 9 show the vertical distributions of maximum responses of pile displacement for both Figures (a) and excess pore water pressure for both Figures (b), for the damage example No. 1, 10 and 14, respectively. In Figure 7 for the example No.1, the pile displacement decreases because the excess pore water pressure under GL-8m decreases by the ground improvement. In Figure 8 for the example No.10, the pile displacement also decreases upper the depth GL -10m. In the case of the example No.14 in Figure 9, the pile displacements between initial and improved cases are almost same distributions and values, and in each case of improvement the pile displacement becomes large upper the depth GL-12m where is near the boundary between lower deep clay layer and upper shallow sand layer.

Figure 10(a), (b) and (c) show the distributions of bending stress for the example No.1, 10 and 14, respectively. In Figure 10(a) for example No.1, the bending stress in the case of ground improvement is under the allowable one, though the bending stress in initial case is larger than the allowable value at the depth 13m. In the case of example No.10, the bending stress is also smaller than the allowable value. In Figure 10 (c) for example No.14, because the ground improvement fails to prevent liquefaction, the bending stress is still larger than the allowable value in the compacting ground.





(a) Damage example No.1 (b) Damage example No.10 (c) Damage example No.14 Fig.10 Distribution of bending stress of pile

Evaluation of aseismic design

Figure 11(a), (b) and (c) in the cases of damage example No.1, 10 and 14, respectively, show the contour line projections of the acceleration response spectra for the natural periods of the structure and the ground as two axes. In the case of example No.1 in Figure 9(a), the horizontal line of the limit of liquefaction means that no liquefaction occurs in the range of the natural period of ground T_G <0.377sec, and the horizontal line of the limit of pile damage means that there is no damage of pile in the range of the natural period of structure T_G <0.344sec. In this case of example No.1, the optimal point of the design condition for the natural periods exists at the left and lower corner which is the cross of the limit line of pile damage and vertical line of the natural period of the structure. In Figure 11 (b) for the example No.10, the optimal point of the design condition is also represented as the cross point between the limit lines of pile damage and the natural period of the structure. In Figure 11 (c) for the example No.14, it is difficult to find the suitable design condition for preventing liquefaction and pile damages.

In this paper we performed numerical computations for 17 damage examples. Figure 12 shows the possibility of preventing liquefaction and pile damage for both axes of natural period of structure and ground. In Figure 12, the black circle, the white one, the white square and the white triangle represent the initial ground, the case of preventing both liquefaction and pile damage, the case of preventing only liquefaction and the case of preventing only damage of pile, respectively. The cases in which the point of white symbol moves to under the black symbol mean that the natural period becomes short because the ground is improved. Consequently these cases prevent both or one of liquefaction and damage of pile. The cases shown as only black circles mean that the ground improvement is not successful for preventing liquefaction. Table 1 shows the possibility of preventing liquefaction and damage of pile for these 17 examples. The natural period of the ground and structure, the distribution of clay layer are also shown in Table 1. There are each 5 cases of examples which prevent or fail both of liquefaction and damage of pile. Thus it is important to develop the countermeasure for the cases in which fail to prevent both of liquefaction and pile damage.





Fig.12 Improvement for damage examples

No.	Depth	Natural period of ground (sec)		Distribution of alov lover (m)	Natural	Possibility of prevention	
		Initial	Improved	Distribution of clay layer (m)	structure	Liquefaction	Damage of pile
1	20m	0.400	0.321	Not exists	0.190sec	0	0
10	36m	0.800	0.737	20m-30m(10m)	0.160sec	0	0
11	36m	0.800	0.728	18m-28m(10m)	0.120sec	0	0
31	26m	0.420	0.378	14m-16m(2m)	0.250sec	0	0
49	46m	1.070	0.970	24m-32m(8m)	0.240sec	0	0
14	26m	0.360	-	12m-20m(8m), 22m-24m(2m)	0.100sec	×	×
41	38m	0.720	-	16m-26m(10m)	0.220sec	×	×
47	30m	0.630	-	4m-22m(18m)	0.380sec	×	×
63	32m	0.490	-	12m-20m(8m), 24m-26m(2m)	0.260sec	×	×
77	30m	0.630	-	16m-24m(8m)	0.260sec	×	×
13	40m	0.700	0.648	22m-26m(4m), 38m-40m(2m)	0.330sec	0	×
42	20m	0.457	0.350	14m-16m(2m)	0.270sec	0	×
43	22m	0.470	0.420	14m-16m(2m), 20m-22m(2m)	0.220sec	0	×
52	30m	0.760	0.680	12m-14m(2m), 20m-22m(2m)	0.460sec	0	×
62	40m	0.873	0.852	16m-18m(2m), 22m-34m(12m)	0.380sec	0	×
68	30m	0.741	0.600	16m-18m(2m)	0.460sec	0	×
67	40m	1.120	0.964	2m-6m(4m), 16m-20m(4m), 24m-26m(2m), 30m-32m(2m), 38m-40m(2m)	0.180sec	×	0

 Table 1 Evaluation of improvement for damage examples

(\bigcirc : Preventable, \times : Not preventable)

CONCLUSIONS

In this paper the aseismic design method for preventing liquefaction and damage of pile foundation is proposed. This proposed method, which consists of existing computational programs NUW2 and WAP3, evaluates the design condition of ground improvement by the natural period of the ground as key parameter. Applying the proposed design method to 17 damage examples of piles in 1995 Hyogo-ken nanbu Earthquake gives several remarks. First, the effect of ground improvement by sand compaction pile method is possible to be evaluated by averaged natural period of surface layers of ground. Second, because this natural period of ground is related to the compacting time as the condition of ground improvement, proposed method which determines the natural period within preventing liquefaction is reasonable design method. Third, it is also possible to include the method to determine the natural period within preventing damage of pile to the proposed design method. Forth, the proposed method is not applicable in the case of thick clay layer. Finally, there are 5 examples which prevent both liquefaction and pile damage.

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