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Aseismic design by ground improvement for preventing damage of soil-pile foundation-super structure system

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Abstract

The object of this study is to establish the effective aseismic design method for the conditions of ground improvement for preventing liquefaction of the ground damage of pile foundation. The proposed method uses two existing computer programs, NUW2 for 2d effective stress analysis and WAP3 for simulation of the sand compaction pile method. The 17 ground models are selected from the damage examples in which liquefaction and damage of pile foundations occurred in the Kobe area due to the 1995 Hyoga-ken-nambu Earthquake. Numerical computations for responses of the ground and the pile foundations including ground improved cases are performed. By using the natural period of the ground layer as the key parameter, the conditions of ground improvement are evaluated and related to the responses of the super structure on the ground. The critical conclusion is that the proposed evaluation method is effective for reducing pile stress under the allowable limit in the sandy ground layer by using the ground improvement method, but the ground improvement may be difficult when trying to prevent pile failure in soft clayey ground.

1 Introduction

There were many damages of foundation structures and tilt of structures caused by liquefaction which occurred at reclaimed land during 1995 Hyogo-ken-nanbu Earthquake(AIJ[1]). Strong ground motion affects the characteristics of surface ground layers by liquefaction and causes the damages of pile foundation. There

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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 and reflect it for the response of the structure constructed on or in the surface ground layers.

In this study we propose the effective aseismic design method which evaluates the ground improvement condition for preventing liquefaction (Akiyoshi [2]) and damage of pile foundation.

2 Seismic response analysis method for soil–pile system

Figure 1 shows the analytical model which consists of surface ground layers and pile foundations system and the single degree of freedom structure (SDOF) on the surface. Proposed aseismic design method consists of existing computer programs which are the effective stress analysis program "NUW2" (Akiyoshi [3]) and the simulation of the compacting ground improvement "WAP3" (Akiyoshi [4]). The program "NUW2" is based on Biot's two phase mixture theory and Iai's constitutive equation (Iai [5]). The program "WAP3" simulates the static and dynamic compaction process of sand compaction pile method and 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. In this study we pay attention to both of the natural period of the surface ground layers T_G and the structure T_S as key parameters for evaluating above responses for preventing liquefaction and damage of pile foundations. 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).

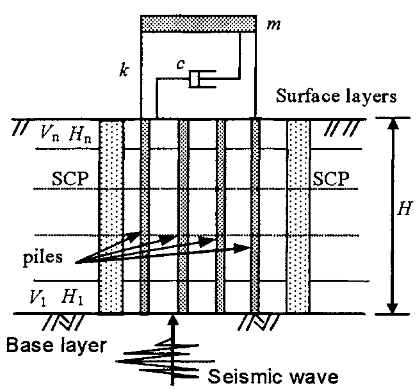

Figure 1: Surface ground layers and SDOF structure.

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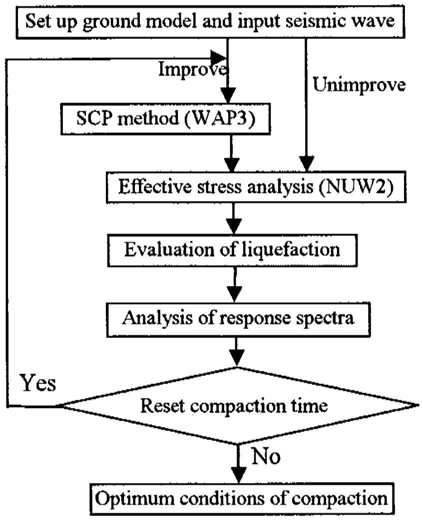

Figure 2: Flow of proposed aseismic design.

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

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

3 Results of numerical computations and consideration

3.1 Model of surface ground layers and pile foundation system

Figure 3 shows the damage examples of pile foundations of buildings during 1995 Hyogo-ken-nanbu Earthquake (AIJ [6], Seo [7]). The examples are represented as symbols 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 prepare the computational models of them. In each model the surface ground layers are divided to the 2-dimensional finite elements mesh at pile space and intervals of 2m for both horizontal and vertical directions, respectively. The strong ground motion record (NS component) at Port Island in depth GL-32m in 1995 is used as the input seismic wave with maximum acceleration 5.4m/s^2. Pile foundations are assumed to be arranged in square shape distribution, and its geometrical moment of inertia and sectional area per unit length are also assumed to be 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.

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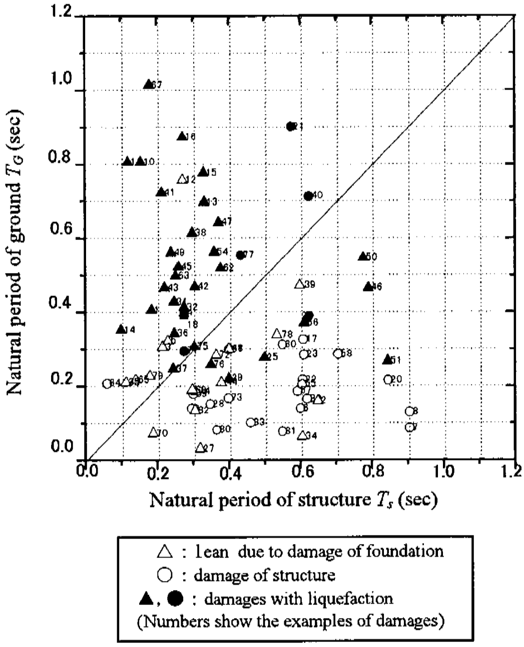

Figure 3. Examples of damaged pile foundations.

In the case of ground improvement by sand compaction pile (SCP) method, the surface ground layer models of above examples are improved by the same conditions of SCP as the reference Akiyoshi [5], and the responses of them are also analyzed.

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.

3.2 Effects of ground improvement

Figures 4(a) and 5(a) show the vertical distributions of SPT-N values 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 and 14, respectively. Figures 4(b) and 5(b) show the averaged natural period of ground layers versus the above compacting time.

In Figure 4 (a) and (b), as the compacting time becomes long, the SPT-N values increase and the natural periods of ground layers decrease. The horizontal line of the critical limit of liquefaction in Figure 4(b) means that no liquefaction occurs for the range of 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

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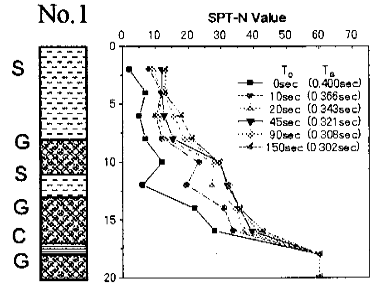
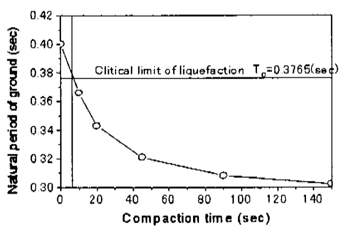
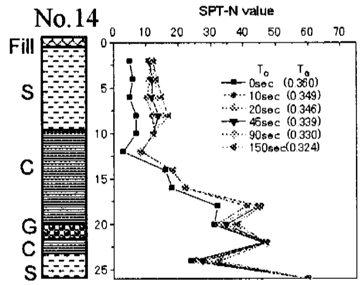


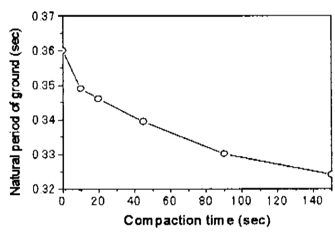
(a)Soil profile and SPT-N value



(b)Relation between natural period of ground and compaction time



(a) Soil profile and SPT-N value



(b) Relation between natural period of ground and compaction time

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

Figure 5: Soil profile and results of ground improvement at the damage example No. 14.

within this range. This suggests that the compacting time 10sec per one stage is enough to prevent liquefaction for this example No.1.

In the case of the damage example No.14 in Figure 5, 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 5(b).

3.3 Results of liquefaction analysis

Figures 6 and 7 show the vertical distributions of maximum responses of the damage example No. 1 and 14, respectively. Both Figures (a) and (b) show the response of the pile displacement and the excess pore water pressure, respectively. In Figure 6 for the example No.1, the pile displacements of the improved cases decrease because of decreasing of the excess pore water pressures under GL-8m by the ground improvement. In the case of the example No.14 in Figure 7, the pile displacements have almost same distributions and values between initial and improved cases, and in each case of improvement the

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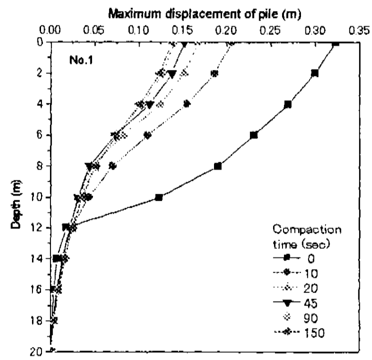
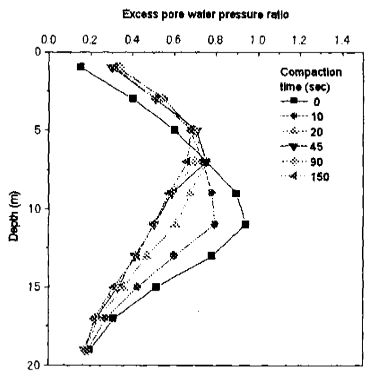
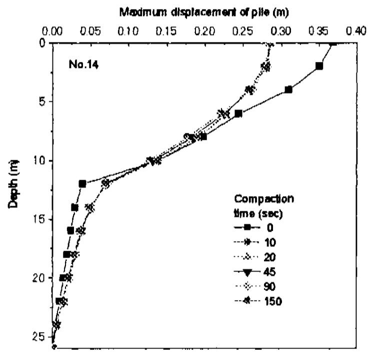


(a) Displacement of pile

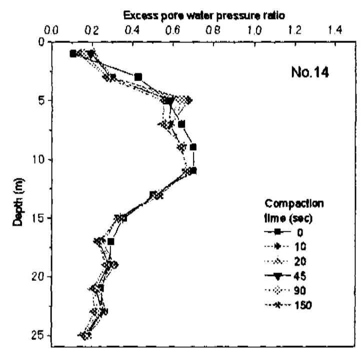


(b) Excess pore water pressure ratio

Figure 6: Distribution of max. responses of damage example No. 1.



(a) Displacement of pile



(b) Excess pore water pressure ratio

Figure 7: Distribution of max. responses of damage example No. 14.

pile displacement becomes large in depth upper GL-12m where is near the boundary between lower deep clay layer and upper shallow sand layer.

Figure 8(a) and (b) show the distributions of bending stress for the example No.1 and 14, respectively. In Figure 8(a) for example No.1, though the bending stress in initial case is larger than the allowable value at the depth 13m, that of the ground improvement case is under the allowable one.

In the case of example No.14 in Figure 8(b), the bending stress is still larger than the allowable value in the compacting ground, because the ground improvement fails to prevent liquefaction.

3.4 Evaluation of aseismic design

Figure 9(a) and (b) show the contour line projections of the acceleration response spectra for both axes of the natural periods of the structure and the ground in the cases of damage example No.1 and 14, respectively. The

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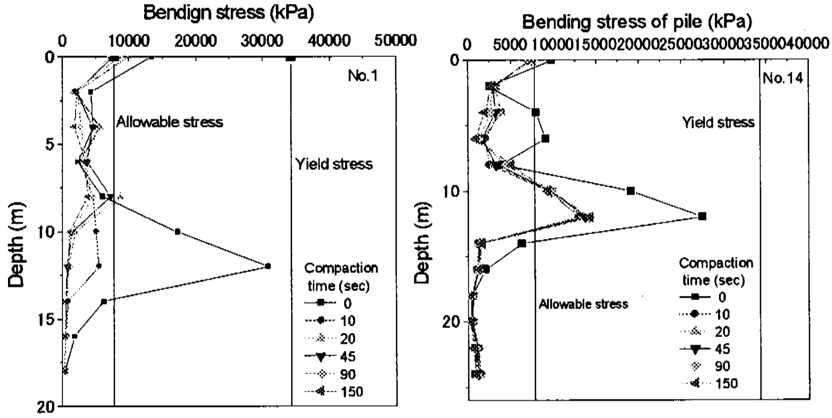
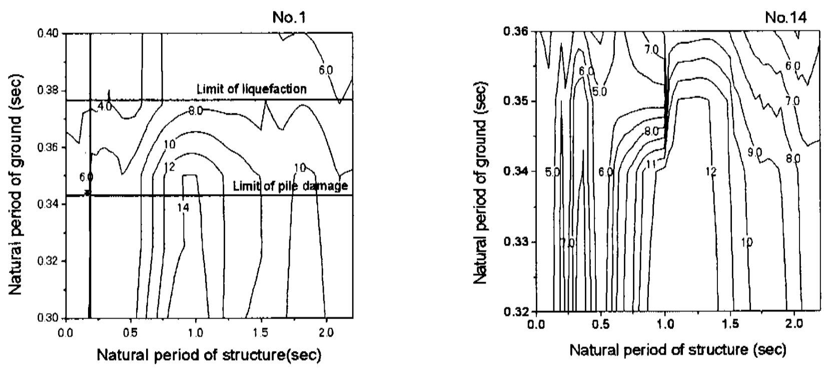


(a) Damage example No.1 (b) Damage example No.14

Figure 8: Distribution of bending stress of pile.



(a) Damage example No.1 (b) Damage example No.14

Figure 9: Distribution of maximum acceleration response.

horizontal line of the limit of liquefaction in Figure 9 (a) 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, there exists the optimal design condition for the natural periods in order to reduce the responses of structure and prevent liquefaction and damage of pile. This optimal condition is shown in Figure 9(a) as the point which is the cross point between the limit line of pile damage

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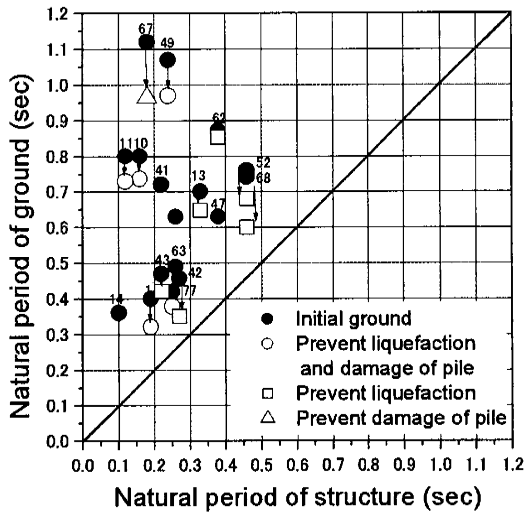

Figure 10: Improvement for damage examples.

(T_G=0.344sec) and the vertical line of the natural period of the structure (T_S=0.19sec).

In Figure 9 (b) 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 10 shows the possibility of preventing liquefaction and pile damage as symbols for both axes of natural period of structure and ground. In Figure 10, the black circle, white one, white square and 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 white symbol is located to under the black symbol mean that the natural period of the ground is improved and becomes short and these cases prevent both of liquefaction and damage of pile or one of them. The cases in which only black circles are shown mean that the ground improvement is not successful in preventing liquefaction.

Table 1 shows the possibility of preventing liquefaction and damage pile with the natural period of the ground and structure and the distribution of clay layer for these 17 examples. There are each 5 cases of examples which prevent or fail to prevent both of liquefaction and damage of pile. There are 6 cases of examples which prevent liquefaction but fail to prevent damage of pile. Thus it is important to develop the countermeasure for the cases in which fail in preventing both of liquefaction and damage of pile.

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Table 1: Evaluation of improvement for damage examples.

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

(○ : Preventable, × : Not preventable)

4 Conclusions

In this paper the aseismic design method for preventing liquefaction and damage of pile foundation is proposed and the design conditions of ground improvement are investigated by the natural period of the ground as key parameter. The main conclusions are summarized as follows;

(1) Effect of ground improvement by sand compaction pile method is possible to be evaluated by natural period of surface ground layers. This natural period of ground is related to the compacting time which is one of the conditions of ground improvement method.
(2) The proposed design method is reasonable design method to determine the natural period within preventing liquefaction.
(3) It is possible to include the method of determining the natural period within preventing damage of pile to the proposed design method. But the proposed

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method is difficult to apply to the surface ground layer which include thick clay layer.

(4) The proposed design method is applied to 17 damage examples of piles in 1995 Hyogo-ken-nanbu Earthquake and there are 5 examples which prevent both liquefaction and damage of piles. But there exist also 5 examples which can not prevent both liquefaction and pile damage.

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