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Evaluation of effect of liquefaction resistance by means of compaction grouting using effective stress analysis

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ABSTRACT

Compaction grouting (CPG) is an in-situ grout injection technique used to improve the liquefaction resistance of loose sandy ground by densification and increasing lateral confining pressure. The present study investigates the effect of lateral confining pressure on liquefaction resistance by numerical simulation such as effective stress finite element method. In the simulation, the increase of lateral confining pressure caused by grout injection was simulated by applying an enforced displacement to the array of double nodes locating at the same coordinate. The increase of the lateral confining pressure produced by the numerical simulation has a good agreement with results of centrifuge model test and field investigation

Keywords: compaction grouting; FEM; effective stress analysis

1 INTRODUCTION

Compaction grouting, which is an in-situ static compaction grout injection technique, has been increasingly used to improve liquefaction resistance of loose sandy ground. An increase in the liquefaction resistance of sand, caused by compaction grouting, is presumed to be a result of three possible mechanisms: (i) an increase in the lateral confining stress, (ii) densification, and (iii) reinforcement by hydrated and hardened grout piles. More specifically, stress changes and densification in the surrounding ground, induced by grout injection, are important causes of the stabilization effects. However, systematic studies of ground condition changes due to compaction grouting are limited in number. In a previous study (Nishimura et al. 2012 and Takano et al. 2013), the influence of ground density and lateral confining stress on liquefaction resistance was investigated, by means of Hollow Cylinder Apparatus (HCA) cyclic simple shear tests and geotechnical centrifuge. The liquefaction resistance curves, obtained by the HCA cyclic simple shear tests, are shown in Fig. 1, for all the initial conditions. Liquefaction resistance was significantly higher for higher earth pressure coefficient K (lateral effective pressure: σ_h' / initial effective overburden pressure σ_{v0}'). An interesting feature of the Soma Silica Sand #5, used in this study, was that its cyclic stability was relatively insensitive to the initial density, at least for the range of D_r = 50–70 %. This paper investigates the effect of lateral confining pressure on liquefaction resistance by numerical simulation, such as the effective stress finite element method. In this simulation, the increase of lateral confining pressure caused by grout injection was simulated by applying an enforced displacement to the array of double nodes locating at the same coordinate. The increase of the lateral confining pressure produced by the numerical simulation has a good agreement with the results of centrifuge model test and field investigation.

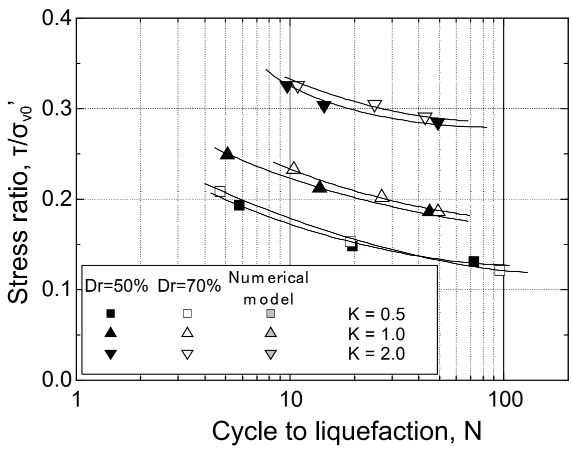

Fig. 1. Liquefaction resistance curves of Soma Silica Sand #5 for different initial K values: occurrence of liquefaction is defined by double shear strain (γ_{vh}) amplitude of 7.5 % (Nishimura et al. 2012).

2 OUTLINE OF NUMERICAL SIMULATION FORMATTING

2.1 Dynamic finite element code

The finite element code for dynamic response analysis, FLIP, developed at Port and Airport Research Institute Japan, was used to simulate the increase of lateral confining pressure, caused by grout injection and its dynamic response. FLIP calculates deformation of ground and structures under dynamic loading, by two-dimensional non-liner dynamic finite element method based on the theory of small-deformation. Note that the undrained condition was presumed, under dynamic analysis; thus, flow of pore water is not considered. Details of this code can be found in Iai 1990.

2.2 Finite element mesh and procedure of simulation

In Fig. 2, the finite element mesh used in this simulation is illustrated. In this paper, assuming uniform loose sandy ground, a fictitious two-dimensional lateral expansion was simulated, to reproduce an increase of K value caused by grout injection. The grout piles are distributed in all three dimensions on a construction site; thus, the deformation by grout injection in full-scale occurs in three dimensions. However, when grout injection is simulated in two dimensions, a comparable level of increase in K value is not able to be simulated using actual pile spacing distance or pile diameter, because of the difference of geometric attenuation between 2D and 3D. The focus of this paper is on liquefaction resistance, induced by increases of K value that are caused by grout injection. At first, an increase in K value, comparable to centrifuge model test, was simulated by static analysis; then dynamic analysis was conducted, based on the results of static simulation. The scenario of seismic wave at Haneda Airport (West-East component: see Fig. 3) was used for dynamic simulation. The boundary condition of initial self-weight analysis and static analysis was set as a vertical roller on lateral side boundary and fixed condition on base boundary. The lateral boundary condition, in dynamic analysis, was set as a periodic boundary, in which both sides of the lateral side boundary is connected, as a ring. Input parameters assuming Soma Silica Sand #5 are shown in Fig. 4. Note that the effect of the difference of relative density was not considered, because it was confirmed by HCA cyclic simple shear tests that cyclic stability was relatively insensitive to the initial density.

The increase of K value observed in experiments or field investigation is stress distribution, therefore it is difficult to set directly an initial condition or input parameters in numerical modelling. To reproduce K

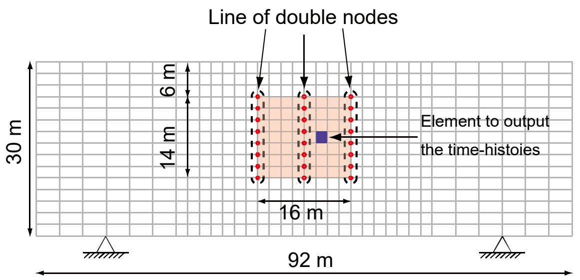

Fig. 2. Finite element mesh illustration.

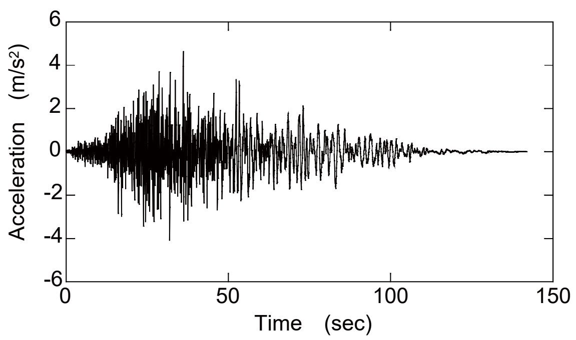

Fig. 3. Predicted Level 2 Haneda Airport seismic wave (East-West component).

Table 1. Input parameters.

Parameter of deformation characteristic		Value	Unit
n	Poisson's ratio at small strain level	0.33	-
G_{max}	Reference initial shear modulus	92000	kPa
p_0'	Reference mean effective confinig pressure	98	kPa
h_{max}	Max. damping coeff.	0.24	kPa
C	Cohesion	0	kPa
f	Angle of internal friction	40	°
r	Unit weight	2000	kPa
f_p	Phase transformation angle	28	°
S_1	Parameters for dilatancy 1	0.003	kg/m^3
W_1	Parameters for dilatancy 2	1.5	°
P_1	Parameters for dilatancy 3	0.8	-
P_2	Parameters for dilatancy 4	0.7	-
C_1	Parameters for dilatancy 5	1.9	-

value, the following procedure was applied: double nodes were set on both sides and the middle part in stabilized zone (1-2, 3-4, 5-6 and 7-8 in Fig. 4 (a)). Double nodes were constrained with each other during initial self-weight analysis, then the double nodes were forced to displace to right and left (Fig. 4 (b)). Double nodes were again constrained, and dynamic loading was applied (Fig. 4 (c)).

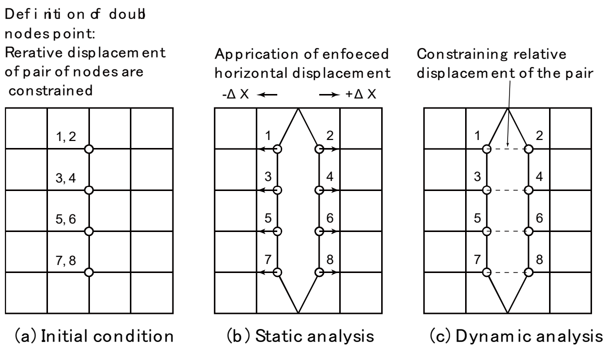

Fig. 4. Illustration of a process to reproduce an increase of K_c value.

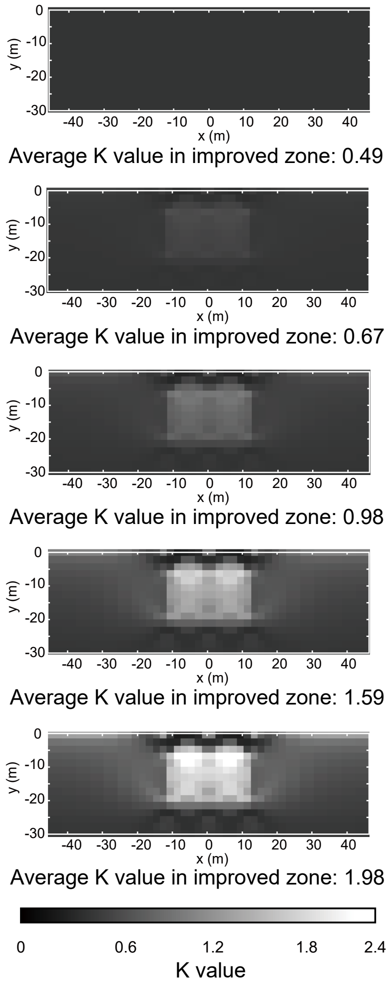

Fig. 5. Distribution of K value after static analysis.

3 RESULTS AND DISCUSSION

3.1 Static analysis

Fig. 5 shows the distribution of K value as a result of static analysis. This distribution is obtained by varying the amount of horizontal displacement (ΔX) of double nodes. Fig. 6 shows the average K value within the improved area, as a function of enforced displacement value. K value measured in practice and centrifuge model test so far in a previous study was distributed from 1 to 3 (Nishimura et al. 2012), thus the corresponding enforced displacement value providing reasonable K value is 0.001 or more. Influence of enforced displacement is evident, with larger displacement values resulting in higher K values. K value has a uniform distribution, with average of 0.6 and 1.0 respectively. On the other hand, K value at a shallower depth, in the case with 1.6 and 2.0 of average K value, is characterized by a larger increase than

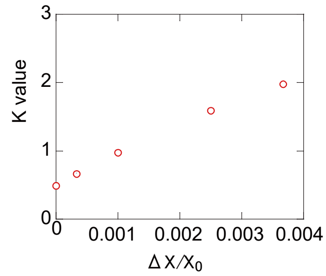

Fig. 6. Average K value within the improved area as a function of enforced displacement value.

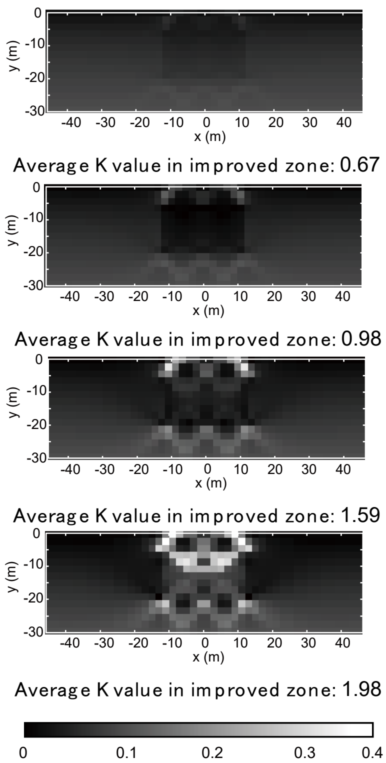

Fig. 7. Distribution of maximum shear strain after static analysis.

deeper one. This feature is traced back to the constitutive model and input parameters of FLIP, in which the shear modulus G is proportional to square of effective confining pressure p'; shear strength, in contrast, G, is proportional to p'. This is a feature common to mechanical characteristics of sand, and it can be observed in literatures. The distribution of maximum shear strain is presented in Fig. 7. As average K value increase, the strain localization appears in improved area, especially in case with 2.0 of average K value. It is therefore probable that the model ground is of more plastic nature, with lager displacement of double nodes.

3.2 Dynamic analysis

The distribution of the ratio of excess pore water pressure, Ru (excess pore water pressure Δu / initial average effective stress p0'), at the end of dynamic loading (140 s), is shown in Fig. 8. It is expected that ground consisted of Soma Silica Sand #5 with a relative density of 50–70% is liquefied without grout injection (K=0.49) when subjected to the scenario seismic wave of Haneda Airport. In contrast, liquefaction is suppressed when average K value is larger than 1.0. The time-histories of Ru, calculated at the central part of improved zone as pointed in Fig. 2, are shown in Fig. 9. As mentioned above, no significant increase of Ru is observed in cases with lager average K value. The other side of this feature is that there is no remarkable difference between the cases with 1.5 and 2.0 of average K value. It is thus implied that certain level of improvement ratio, smaller grout pile spacing or larger pile diameter, does not contribute largely to liquefaction resistance in terms of K value.

4 CONCLUSIONS

Ground responses against anti-liquefaction compaction grouting, focusing on the effect of the increase of lateral confining pressure, were studied by effective stress dynamic finite element analysis. An increase of lateral confining pressure, comparable to centrifuge model test, was simulated by static analysis, then dynamic analysis was conducted based on the results of static simulation. Simulation of a lateral confining pressure increase by the aforementioned method provided reasonable K value distributions compared with centrifuge model test or field data. Liquefaction was suppressed with average K value of 1.0 or more in dynamic analysis. However, there is no remarkable difference between the cases with 1.5 and 2.0 of average K value. It is thus suggested that certain level of improvement ratio, smaller grout pile spacing or larger pile diameter, does not contribute largely to liquefaction resistance in terms of K value.

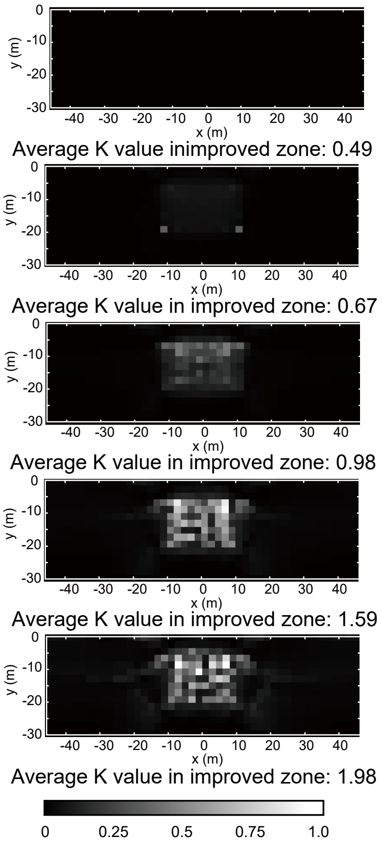

Fig. 8. Distribution of ratio of excess pore water pressure after dynamic analysis.

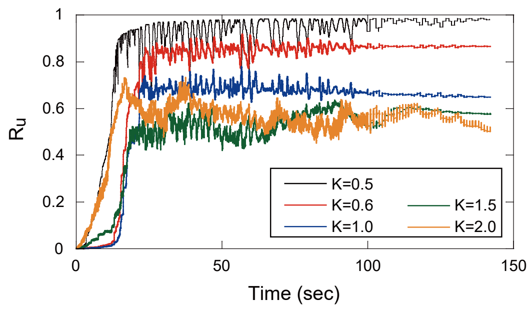

Fig. 9. Time history of ratio of excess pore water pressure during dynamic analysis.

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