Nonlinear analysis of seismic response of a base isolated building on a piled raft foundation with grid-form ground improvement

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ABSTRACT

A seismic observation has been carrying out at a building on a piled raft foundation with grid-form ground improvement. The building is located in Tokyo, and the observation records have been successfully obtained during the 2011 off the Pacific Coast of Tohoku Earthquake. The observed earthquake at this site is ranked in a middle scale. A seismic response analysis using a nonlinear ground model is conducted for this record. An elasto-plastic model based on a subloading Mohr-Coulomb model is used for the ground. In this model, the $G-\gamma$ and $h-\gamma$ relations are directly used to change the status of the subloading surface. A 3D fine finite element mesh model is used with two directional input motions. The simulation results agree well with the observations. The validity of the nonlinear model for the middle scale earthquake is confirmed.

Keywords: piled raft foundation, seismic response analysis, elasto-plastic model, the 2011 off the Pacific Coast of Tohoku Earthquake

1. INTRODUCTION

A seismic observation has been carrying out at the residential building in Tokyo, Japan. The building has a piled raft foundation with grid-form ground improvement. The grid-form ground improvement is to cope with the liquefiable sand as well as to improve the bearing capacity of the raft foundation (Yamashita et al. (2011)).

Many studies on the behavior of a piled raft foundation during earthquakes have been conducted. However only a few case histories exist on the monitoring of the soil-pile-structure interaction behavior during earthquakes such as Mendoza (2000). Therefore our observation is important to investigate the seismic performance of piled raft foundations.

The observation records during the 2011 off the Pacific Coast of Tohoku Earthquake have been successfully obtained at this building (Hamada et al. (2012), Yamashita et al. (2012)). Axial force and bending moment of two piles, earth pressure and pore-water pressure beneath the raft, and accelerations of the ground and structure were measured. The observation records are ranked in the middle scale earthquake at this site.

In the previous study, the seismic response analysis was done using an equivalent linear model for the ground. The analytical results agreed well with these observation records as shown in Onimaru et al. (2012) and Hamada et al. (2014). From this result, validity of the analysis model for a middle scale earthquake was confirmed.

Currently, we are planning to investigate the response for a large scale earthquake based on this model. However the equivalent linear model cannot handle large strain. A nonlinear model is needed for the ground. By applying the appropriate non-linear model for the ground, a seismic response analysis is conducted for the 2011 off the Pacific Coast of Tohoku Earthquake in this study. The analysed seismic response is compared with the observation records and the validity of the nonlinear model is shown.

2. OVERVIEW OF THE BUILDING, GROUND AND EARTHQUAKE OBSERVATION

The building analysed is a residential building in Tokyo. It is a reinforced concrete structure with a base isolation system. The plane section is 30.05 m by 33.25 m, the height is 38.7 m, and the number of stories is 12. It has a piled raft foundation consisting of a raft, piles and grid-form ground improvement. The piles are sixteen precast concrete piles with diameters of 0.8 m to 1.2 m and a length of 45 m.

Fig. 1 shows a schematic view of the building and its foundation with the soil profile. The soil profile down to a depth of 7 m is fill and loose silty sand. And from 7 m to 44 m, the profile is very soft to medium silty clay. The ground water table appears approximately 1.8 m below the ground surface. The
positions of seismic monitors are also shown in the figure.

![Fig. 1 Schematic view of building and foundation with soil profile](image)

**3 ANALYSIS MODEL**

**3.1 Analysis condition**

Fig. 2 shows the finite element (FE) mesh. The number of elements is 213,622 and the number of degrees-of-freedom (DOFs) is 656,543. The building is modeled by elastic bars and shells. The piles are also modeled by elastic bars. Table 1 shows the material of the piles.

Fig. 3 shows the top view of the FE mesh under the raft. To consider the shape and volume of the piles, cavities in the shape of the piles are made in the FE model. The nodes of the piles and the adjacent ground nodes at the same depth are bound by rigid bar elements. The base isolation layer is modeled by tri-linear spring elements.

The lateral boundaries are periodic boundaries. They are positioned at 60 m outside of the building to minimize the boundary effect. The bottom is a viscous boundary.

The input ground motion is based on the observation record of the 2011 off the Pacific Coast of Tohoku Earthquake. Two directional input motions that are the EW wave and the NS wave are applied simultaneously. The time interval is 0.01 s and the analysis time is 300 s. Fig. 4 shows the input accelerations in the EW and NS directions.

The analysis code is an in-house program called MuDIAN developed by Shiomi et al. (1998). This code is parallelized by the hybrid parallel method and is able to calculate a large-DOF model with high speed as described in Shigeno et al. (2014).

![Fig. 2 FE mesh of the ground-structure interaction model](image)

**Table 1 Material characteristics of piles**

| Pile diameter (mm) | 800  | 1000  | 1200  |
|--------------------|------|-------|-------|
| Young's modulus (MN/m²) | 40000| 40000| 40000|
| Damping (%)        | 2    | 2     | 2     |
| Ae of SC pile (m²) | 0.3268| 0.4649| 0.6714|
| Ie of SC pile (m⁴) | 0.02199| 0.04899| 0.10316|
| Ae of PHC pile (m²) | 0.2441| 0.3633| 0.5054|
| Ie of PHC pile (m⁴) | 0.01455| 0.03437| 0.06958|
| Ae : Equivalent cross-sectional area | | | |
| Ie : Equivalent moment of inertia of area | | | |

![Fig. 3 Magnified top view of FE mesh under the raft](image)

![Fig. 4 Input accelerations at GL-75 m. The waves are 2E.](image)
3.2 Constitutive model for ground

A multi-hardening model proposed by Shiomi and Fujiwara (2014) is used as the constitutive model for the ground. This model is based on the multi-dimensional Yoshida model (Ishihara et al. (1985), Yoshida and Tsujino (1993)). The Yoshida model uses a non-linear elastic model for the stress-strain relation. This causes overestimation of the strain under multi directional input-motion. A multi-hardening model uses an elasto-plastic model for the stress-strain relation. Therefore the direction of softening can be considered.

Nonlinearity before the stress reaches yield state is expressed by a hardening coefficient $H'$ defined by equation (1). $G_T$ is the tangential shear modulus that is evaluated from the $\tau-\gamma$ curve. The $\tau-\gamma$ curve under the simple shear condition is obtained from the $G-\gamma$ characteristics. The hardening coefficient $H'$ appears in the denominator of the plastic multiplier in equation (2).

$$H' = \frac{G_T}{1 - \frac{G_T}{G_0}}$$  \hspace{1cm} (1)

$$d\lambda = \frac{\frac{\partial f}{\partial \sigma} D e}{H' + \frac{\partial f}{\partial \sigma}}$$  \hspace{1cm} (2)

where $D_e$ is an elastic modulus tensor, and $f$ is a yield function.

3.3 Modeling of ground and ground improvement

The shear wave velocity distribution in the ground layer is obtained by an optimization method. The error in the transfer function is adapted as a cost function. Observation records of small earthquakes that occurred before the 2011 off the Pacific Coast of Tohoku Earthquake are used in the optimization. The PS logging results are applied as the initial $V_S$ distribution of the optimization. The initial shear modulus distribution for the analysis is created from the optimized $V_S$ distribution. Fig. 5 shows the distribution of the optimized $V_S$.

The nonlinear characteristics of the ground were obtained from the cyclic triaxial tests of the samples. Fig. 6 shows the $G-\gamma$ and $h-\gamma$ relations of each soil layer at this site.

The subloading Mohr-Coulomb model is used for the stress and strain relation of the multi-hardening model. The parameters related to shear strength are needed. From the previous study (Hamada et al. (2014)), the effect of the confined stress is negligible. Therefore, the shear strength is given as cohesion. The cohesion of layers except for being investigated is assumed to follow equation (3).

$$c = G_0' \gamma_0$$  \hspace{1cm} (3)

The grid-form ground improvement is a liquefaction countermeasure. Liquefaction is expected to occur in the silty sand form GL-5.0 m to GL-8.0 m. However, liquefaction was not actually observed during the 2011 off the Pacific Coast of Tohoku Earthquake at this site. From this fact, liquefaction is not considered in the analysis.

Even if the ground is not liquefied, the pore water pressure slightly rises and the shear modulus is reduced. However, the thickness of the silty sand layer is not too large compared with the model. The effect of the shear modulus reduction is assumed to be limited.
assumed to follow the modified HD model expressed by equation (4).

\[
\tau = \frac{G_0}{1 + \left(\frac{\gamma}{\gamma_{\text{as}}}\right)^\gamma} \quad h = h_{\max} \left(1 - \frac{G}{G_0}\right) \quad (4)
\]

where, \( \alpha \) is a parameter. The parameter is set by simulating the uniaxial compression test. The maximum damping \( h_{\max} \) is assumed to be 20% equivalent to the ground. As a result of the simulation, \( \alpha \) is set at 1.06.

Fig. 6 shows the \( G/G_0 - \gamma \) and \( h - \gamma \) relations for the ground improvement.

4 RESULTS

Fig. 7 shows the distribution of the peak acceleration and relative displacement in the EW direction. The results of the equivalent linear analysis are also shown. The analytical acceleration agrees well with the observation except for the ground at GL-1.5 m. However as shown in Fig. 8, the analytical and observed values show no significant difference.

The peak distribution of the relative displacement agrees well with the observations. Especially, the values of the ground agree well. The max displacement of the building is slightly small. The small sift toward the minus direction around the max value causes this distribution.

Fig. 9 shows the distribution of the peak acceleration and relative displacement in the NS direction. The analytical results also agree well with the observations.

In comparison with the equivalent linear analysis, the results of nonlinear analysis are almost the same. The peak shear strain of the ground in the EW direction is 0.16%. The minimum value of \( G/G_0 \) derived from the \( G-\gamma \) curve shown in Fig. 6 is about 0.5. This indicates that the equivalent linear analysis can satisfactorily evaluate the response in this degree of nonlinearity.

Fig. 10 shows the distribution of the peak bending moment of the piles in the EW direction. According to the observation, the bending moment of the pile head of 5B is larger than that of 7B. And the peak value of the pile head of 5B is larger than the value at the lower end of the ground improvement (GL-16 m). The analytical results also show these tendencies.

Fig. 11 shows the time histories of the incremental bending moment of pile 5B from 100 s to 150 s. The observed values indicate the same phase at the lower end of the ground improvement (GL-16 m) and near the pile head (GL-6 m). The analytical results also exhibit the same phase between the two points.
5 CONCLUSIONS

A nonlinear earthquake response analysis with a detailed 3D ground and structure interaction model has been conducted. The input motion is based on the observation records of the 2011 off the Pacific Coast of Tohoku Earthquake. A multi-hardening model is used as the constitutive model of the ground. The model incorporates the elasto-plastic model into the Yoshida model. The analysis results agree well with the observation records of the 2011 off the Pacific Coast of Tohoku Earthquake. The earthquake is ranked in the middle scale at the observation site. Therefore, this result indicates the validity of this analysis model to a middle scale earthquake. This becomes a good preparation for the evaluation of a large scale earthquake.

REFERENCES
1) Hamada, J., Tanikawa, T., Onimaru, S. and Yamashita, K. (2012): Seismic observations on piled raft foundation with ground improvement supporting a base-isolated building, Proceeding of 15thWCEE
2) Hamada, J., Shigeno, Y., Onimaru, S., Tanikawa, T., Nakamura, N., Yamashita, K. (2014): Numerical analysis on seismic response of piled raft foundation with ground improvement based on seismic observation records, Proceeding of 14thIACMAG
3) Ishihara, K., Yoshida, N. and Tsujino, S. (1985): Modeling of stress-strain relations of soils in cyclic loading, Proc. 5th International Conference for Numerical Method in Geomechanics, Nagoya, Vol.1, pp.115-143
4) Mendoza, M. J., Romo, M.P., Orozco, M. and Dominguez, L. (2000): Static and seismic behavior of a friction pile-box foundation in Mexico City clay, Soils & Foundations, Vol.40, No.4, pp.143-154
5) Onimaru, S., Hamada, J., Nakamura, N. and Yamashita, K. (2012): Dynamic soil-structure interaction of a building supported by piled raft and ground improvement during the 2011 Tohoku Earthquake, Proceeding of 15thWCEE.
6) Saito, S. and Konishi, K. (2010): Proceeding of the 9th national symposium on ground improvement, Elastic constant for design of cement-improved soil, pp.287-292 (in Japanese)
7) Shiomi, T., Yoshizawa, M., Onimaru, S. and Tsukuni, S. (1998): Development of structural analysis system considering non-linear behaviors of soil and structure, Takenaka technical research report, No.54, pp.1-8 (in Japanese)
8) Shiomi, T. and Fujiwara, Y. (2014): Liquefaction analysis of Urayasu-site by the multi-hardening model, Proceeding of the special symposium of JGS -Overcoming the Great East Japan Earthquake-, pp.141-145 (in Japanese)
9) Shigeno, Y., Hamada, J., Nakamura, N. (2014): Hybrid parallelization of earthquake response analysis using K computer, Proceeding of 14thIACMAG
10) Yamashita, K., Hamada, J. and Yamada, T. (2011): Field measurements on piled rafts with grid-form deep mixing walls on soft ground, Geotechnical Engineering Journal of the SEAGS & AGSSEA, Vol.42, No.2, 1-10.
11) Yamashita, K., Hamada, J., Onimaru, S. and Higashino, M. (2012): Seismic behavior of piled raft with ground improvement supporting a base-isolated building on soft ground in Tokyo, Soils & Foundations, Special Issue on Geotechnical Aspects of the 2011 off the Pacific Coast of Tohoku Earthquake, Vol.52, No.5, 1000-1015.
12) Yoshida, N. and Tsujino, S. (1993): A simplified practical stress-stain model for the multi-dimensional analysis under repeated loading, The 28th Japan national conference on soil mechanics and foundation engineering, pp.1221-1224 (in Japanese)