# Numerical study on mitigation of liquefaction risk using Tender Net Foundation (TNF)
# (Part 1: Outline of analyses)

Liquefaction
Numerical analysis
TNF system

Int. member Ali Vakilazadsarabi, Takeuchi Construction Inc.
Int. member ○ Kinji Takeuchi, Takeuchi Construction Inc.
Int. member Yasuo Tomono, Takeuchi Construction Inc.
Int. member Han Vo Cong, Takeuchi Construction Inc.
Int. member Tatsunori Matsumoto, Kanazawa University

## 1. INTRODUCTION

Soil improvement is one of the methods to improve the soil mechanical properties, including the liquefaction resistance of the ground. The TNF system is a combination of grid-type soil improvement and single footings. Cong et al. (2022) demonstrated the high performance of the TNF to reduce the settlements of foundations subjected to vertical loads alone, compared to the footing foundation without soil improvement.

In this paper, the performances of a TNF system and a common footing foundation on a liquefiable ground subjected to an earthquake are investigated through numerical analyses.

Fig. 1 shows the schematic view of a TNF system. Through the integration of the soil improvement, the footings, and the slab, the vertical loads are transmitted to the supporting soil (original ground) beneath the TNF system. Also, the shear deformations of the original ground surrounded by the grid walls are suppressed.

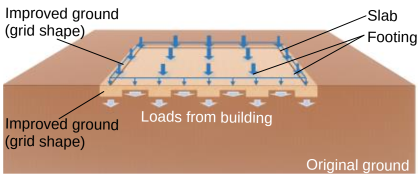


Fig. 1. Section view of a TNF system.

## 2. NUMERICAL ANALYSES OF THE TNF SYSTEM

The target of this analysis is a TNF system for the foundation of a storehouse constructed in Tokyo. The storehouse is a two-storied building having a height of 8.4 m and a floor area of 23 m × 7 m.

### 2.1. Ground conditions

Fig. 2 shows the profiles of the soil layers and SPT *N*-values at the site. The top 17.8 m soil is a reclaimed sand layer underlain by a sandy silt layer (*N* = 2 to 24) and a soft clay layer (*N* = 3 to 5). It is seen that *N*-value in the reclaimed sand varies from 1 to 25. The groundwater level is 0.5 m below the ground surface.

### 2.2. TNF system

Fig. 3 shows the configuration of a TNF system considered in the design process.

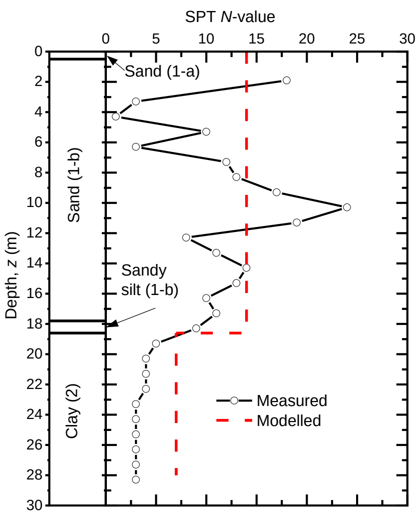


Fig. 2. Profiles of soil layers and SPT *N*-values of a reclaimed ground at Haneda Tokyo International Airport site.

The size of the TNF system is 27 m × 11 m having a primary soil improvement layer with a thickness of 1.5 m, and a secondary soil improvement layer with a thickness of 1.0 m. The thickness of the footings is 0.6 m, and the slab thickness is 0.2 m. A footing foundation without TNF (hereafter called Footing foundation) shown in Fig. 4 was also analyzed in the design process.

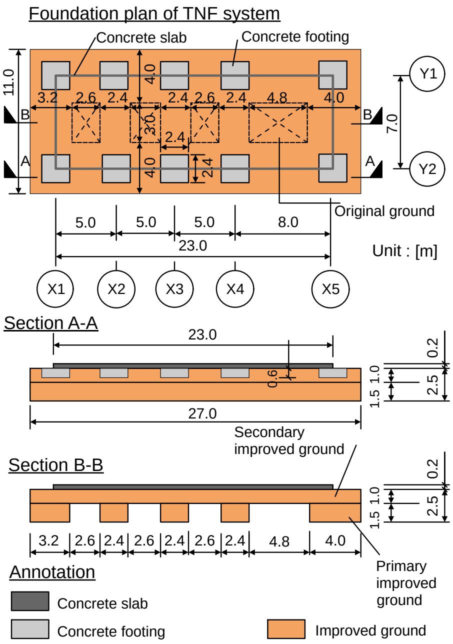


Fig. 3. Configuration of TNF system.

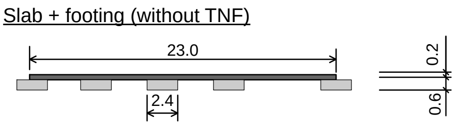


Fig. 4. Footing foundation without TNF.

### 2.3 Analytical model

PLAXIS 3D FEM software was used in the analyses. Fig. 5 shows the analytical model for the TNF system. The ground was simply divided into three layers; sand (1-a), sand (1-b), and clay (2). The storehouse was not explicitly modeled; however, the dead loads of the storehouse were applied on the footings as point loads and the slab as a uniform surface load.

The analytical procedure was as follows.

Step 1: Self-weight analysis of the ground alone.

Step 2: Setting the foundation and self-weight analysis.

Step 3: Seismic analysis.

Step 4: Consolidation analysis.

Boundary conditions were set as follows.

In Steps 1, 2, and 4, displacements normal to the outer vertical surfaces of the ground were fixed. Vertical displacements at the bottom of the ground were fixed.

In Step 3, free-field boundary conditions were set on the outer surfaces of the ground, and the horizontal seismic acceleration in *x*-direction was applied at the bottom of the ground.

As for drainage boundary conditions, fully undrained conditions were set for the ground in Step 3, while drainage was allowed at only the top surface of the ground in Step 4.

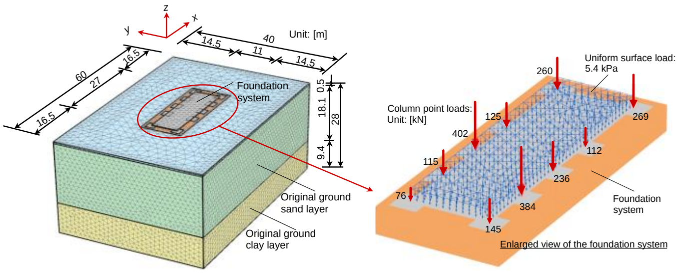


Fig. 5. FEM analysis model.

### 2.4 Soil models used

In the analyses, the UBC3D-PLM model proposed by Beaty et al. (1998) was used for the sand layers, while the Mohr-Coulomb model was adopted for the clay.

The ground was modeled to have three soil layers, as shown in Fig. 2. The physical and mechanical properties of each soil layer were estimated as listed in Table 1, following Vakilazadsarabi et al. (2020). Typical values were used for total density $\rho_t$. The shear wave velocity $V_s$ was estimated using the empirical equation (1) (JRA, 2012).

$$V_s\ (\mathrm{m/s}) = \begin{cases} 100N^{1/3} & \text{for clay} \\ 80N^{1/3} & \text{for sand} \end{cases} \tag{1}$$

Averaged $N$-value in each layer was used for estimating $V_s$. The shear modulus $G$ was calculated using Eq. (2).

$$G = \rho_t V_s^2 \tag{2}$$

Poisson's ratios $\nu$ were assumed as shown in Table 1. The undrained shear strength $c_u$ of the clay was estimated to be 50 kPa using $c_u = 7N$ (kPa).

The UBC3D-PLM is an effective stress plasticity model. The model was developed primarily for sand-like soils having the potential for liquefaction under seismic loading. The model predicts the shear stress-strain behavior of the soil using an assumed hyperbolic relationship and estimates the associated volumetric response of the soil skeleton using a flow rule that is a function of the current stress ratio.

In the analyses, soil parameters listed in Table 2 were used for the sand layers. The relative density $D_r$ was assumed to be 60%. The initial void ratio $e_{init}$ was assumed as 0.54. The other parameters were obtained using $D_r$ and $N$-value, following Galavi et al. (2013), Giridharan et al. (2020), and Puebla (1999).

Coefficients of permeability of the sand and clay were assumed to be $1.0\times10^{-3}$ m/s and $1.0\times10^{-6}$ m/s, respectively.

The slab, footing, primary soil improvement, and secondary soil improvement were treated as linear elastic materials. The mechanical parameters of these materials are listed in Table 3. In Table 3, $F_c$ is the unconfined compression strength of the improved soil. The value of $F_c$ was assumed to be 450 kPa, a typical value of the TNF soil improvement. $E_1$ and $E_2$ were estimated using the empirical equation specified in the Building Center of Japan (2018).

$$E = 180 \times F_c \tag{3}$$

Table 3. Material parameters of the different components of the TNF system and Footing foundation.

| Material | Young's modulus (kPa) | Poisson's ratio, $\nu$ | Remark |
|---|---|---|---|
| Concrete (slab, footing) | $E_c = 23.5\times10^6$ | 0.2 | |
| Primary soil improvement | $E_1 = 81\times10^3$ ($F_c$ = 450 kPa) | 0.2 | $E_c / E_1 = 290$ |
| Secondary soil improvement | $E_2 = 81\times10^3$ ($F_c$ = 450 kPa) | 0.2 | $Ec / E_1 = 290$ |

## 3. CONCLUDING REMARKS

Simulation results of the TNF soil improvement method for the mitigation of liquefaction risk are presented in Part 2 of this series of papers.

## REFERENCES

Beaty, M., and Byrne, P. (1998): An effective stress model for predicting liquefaction behavior of sand, Geotechnical Earthquake Engineering and Soil Dynamics III ASCE Geotechnical Special Publication, No.75, 1:766–777,1998.

Cong, H.V., Takeuchi, K., Vakilazadsarabi, A., and Matsumoto, T. (2022): Parametric numerical study on deformation of the Tender Net Foundation subjected to vertical loading, 11th International Conference on Stress Wave Theory and Design and Testing Methods for Deep Foundations, Rotterdam, the Netherlands.

Galavi, V., Petalas, A., and Brinkgreve, RBJ. (2013): Finite element modeling of seismic liquefaction in soils, Geotechnical engineering journal of the SEGAS and AGSSEA, 44 (3), 55-64.

Giridharan, S., Gowda, S., Stolle, D.F.E, and Moormann, C. (2020): Comparison of UBCSAND and Hypoplastic soil model predictions using the material point method, Soils, and Foundations, Elsevier, 60, 989-1000.

Japan Road Association (JRA) (2012): Specifications for highway bridges V: Seismic design (in Japanese).

Puebla, H. (1999): A constitutive model for sand and the analysis of the CanLex embankments: Ph.D. dissertation, University of British Columbia.

The Building Center of Japan (2018): Guidelines for design and quality control of soil improvement.

Vakilazadsarabi, A., Han Vo Cong, and Takeuchi, K. (2020): Dynamic analysis of soil liquefaction due to ground motions by using TNF soil improvement method, 17th World Conference on Earthquake Engineering, Paper No.: 2a-0026, 12pp., Sendai, Japan.

Table 1. Physical and mechanical properties of each soil layers.

| Layer name | Soil type | Top level (m) | Bottom level (m) | Layer thickness (m) | Total density, $\rho_t$ (ton/m³) | Unit weight, $\gamma_t$ (kN/m³) | Ave. $N$-value | Shear wave velocity, $V_s$ (m/s) | Shear modulus, $G$ (kPa) | Young's modulus, $E$ (kPa) | Poisson's ratio, $\nu$ | Cohesion, $c$ (kPa) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 - a | sandy | 0.00 | 0.5 | 0.5 | 1.78 | 17.15 | 14 | 192.8 | - | - | 0.2 | - |
| 1 - b | sandy | 0.5 | 18.6 | 18.1 | 1.78 | 19.10 | 14 | 192.8 | - | - | 0.2 | - |
| 2 | clay | 18.60 | 28.0 | 9.40 | 1.50 | 14.70 | 7 | 243.6 | $8.71\times10^4$ | $2.27\times10^5$ | 0.3 | 50 |

Table 2. Parameters of UBC3D-PLM model used for sand layer.

| $D_r$ (%) | $e_{init}$ | $k_B^e$ | $k_G^e$ | $k_G^p$ | $m_e$ | $n_e$ | $n_p$ | $\varphi_{cv}$ (deg.) | $\varphi_p$ (deg.) | $c$ (kPa) | $f_{dense}$ | $f_{Epost}$ | $R_f$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 60.0 | 0.54 | 765 | 1094 | 940 | 0.50 | 0.50 | 0.40 | 25.9 | 27.5 | 1.00 | 1.00 | 1.00 | 0.73 |

$D_r$ = Relative density, $e_{init}$ = Initial void ratio, $k_B^e$ = Elastic bulk modulus factor, $k_G^e$ = Elastic shear modulus factor, $k_G^p$ = Plastic shear modulus factor, $m_e$ = Rate of stress dependency of elastic bulk modulus, $n_e$ = Rate of stress dependency of elastic shear modulus, $n_p$ = Rate of stress dependency of plastic shear modulus, $\varphi_{cv}$ = Constant volume friction angle, $\varphi_p$ = Peak friction angle, $c$ = Cohesion, $f_{dense}$ = Densification factor, $f_{Epost}$ = Post-liquefaction factor, $R_f$ = Failure ratio