Parametric numerical study on deformation of the Tender Net Foundation subjected to vertical loading

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ABSTRACT

Raft (footing) foundation on soft ground does not have enough bearing capacity, and often has excessive average and differential settlements. In that case, deep foundations (pile foundations) have been usually employed to minimize settlements of the foundation. Another solution is ground improvement. TNF (Tender Net Foundation) method is one of ground improvement methods for building foundations. The TNF has been developed by Takeuchi Construction Company Inc. in Japan since 1993, and it has been widely applied in more than 1600 projects as of Dec. 2021, including factories, workshops, schools, warehouses, and shopping malls in Japan. The TNF is a combination of grid-shaped soil improvement and shallow ground improvement, on which concrete slab and footings are constructed. In this paper, performances of various types of TNF are numerically investigated using the PLAXIS 3D FEM software. Influences of depth of grid-shaped improvement and thickness of shallow improvement on foundation settlements are estimated through the analyses. Furthermore, behaviors of TNFs on original grounds with various stiffness are analyzed for an appropriate design of TNF.

Keywords: TNF method, soil improvement, vertical loading, differential settlement, FEM, parametric study

1 INTRODUCTION

Piles have been used for foundations in soft ground. Piles are driven to a hard-bearing stratum through the upper soft ground. Hence pile foundations are often time and cost-consuming.

The TNF method is one of ground (soil) improvement methods that reinforces soft ground in grid shape by blending soil with cement as solidification material (see Fig. 1).

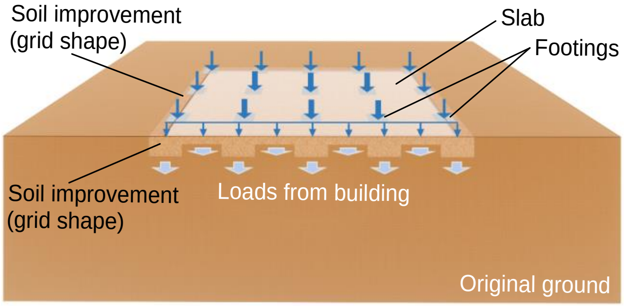


Fig. 1. Section view of a TNF system.

Cement powder with lower elution of hexad chrome is mixed with the original soil at the site for environmental friendliness. The mass of cement per unit soil volume is varied so that the improved soil has an unconfined compression strength q_u of 300 to 450 kPa in common.

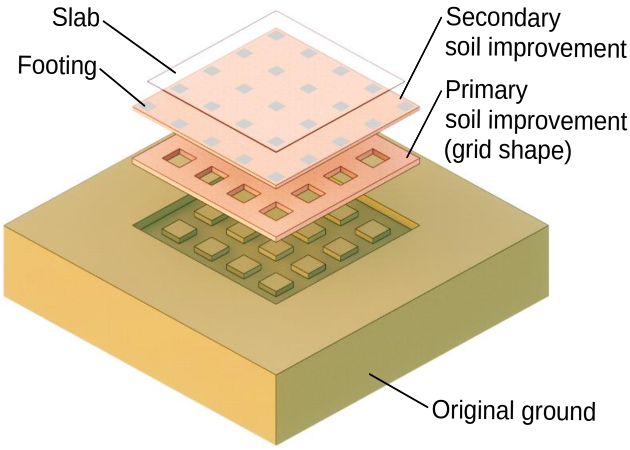


Fig. 2. Composition of TNF system.

Through the integration of the soil improvement, the footings, and the slab, the vertical loads are transferred uniformly to the supporting soil (original ground) under the TNF system. The shear deformations of the original ground surrounded by the grid walls are suppressed.

The TNF system does not need underground beams connecting footings in most cases. Concreting work for the footings is done in the holes excavated from the top surface of the soil improvement. Thereafter, concreting work for the slab is followed (see Fig. 2).

Fig. 3 shows an example of the TNF system just after the completion of footings. An advantage of the TNF system is that the construction site is kept clean during the whole construction period as shown in Fig. 3.

Fig. 3. Example of a construction site of TNF system (at the stage of completion of footings).

In the TNF system, the soft ground is improved to depths of 2 to 4 meters as usual. Hence, the construction time of the TNF system is shorter than that of the pile foundations, which can help shorten the progress of building construction and reduce the costs of machinery and human resources for construction. Also, TNF soil improvement blended with solidification material would be easier to be removed than the pile system.

The TNF system could be a promising alternative to the conventional pile foundation (Takeuchi Construction Inc., 2021).

In this paper, the performances of various types of TNF are numerically investigated using PLAXIS 3D FEM software (Bentley, 2021). Influences of the depth of primary soil improvement and thickness of secondary soil improvement on foundation settlements are estimated through the analyses. Furthermore, behaviors of TNFs on the original ground with various stiffness are analyzed for an appropriate design of TNF.

2 NUMERICAL STUDY ON SETTLEMENTS OF TNF SYSTEMS

In this section, the effect of the foundation system type on settlements of the slab is investigated through 3D FEM analyses.

2.1 Parametric study of the type of foundation system

Fig. 4 shows the detailed configuration of a typical TNF system with a thickness of secondary soil improvement of 1.0 m, and a primary soil improvement of 1.5 m thick having the grid shape. The specific dimensions of other parts also are given in Fig. 4.

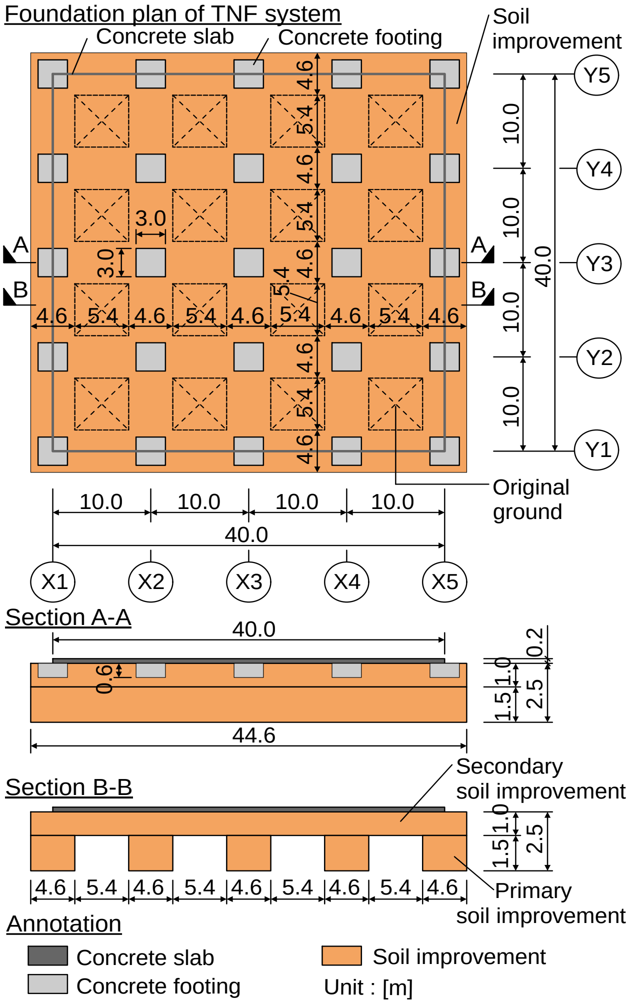


Fig. 4. Configuration of TNF system.

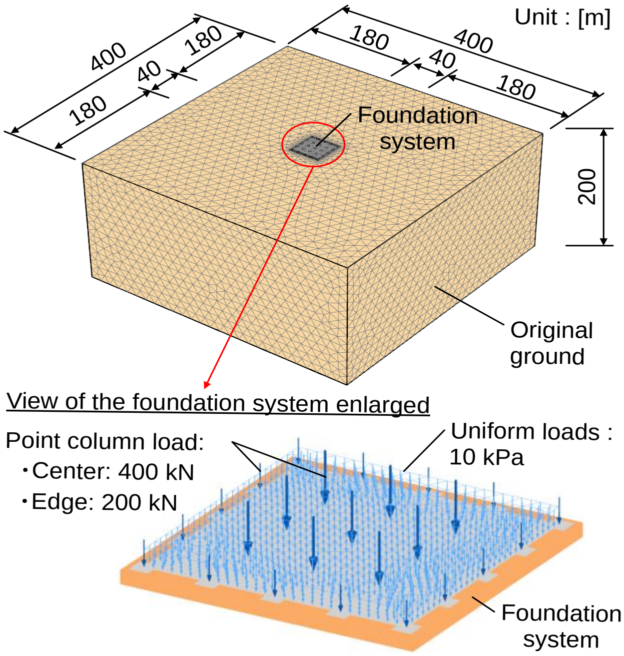


Fig. 5. FEM analysis model.

Fig. 5 shows the FEM analysis model of the ground and foundation system. The ground size of 400 × 400 × 200 m is large enough to simulate settlements of the ground and foundation system with negligible influences of the boundary conditions. The foundation system located at the center of the ground with the vertical load is also shown in detail in the figure. This load condition is used throughout all cases in this parametric study.

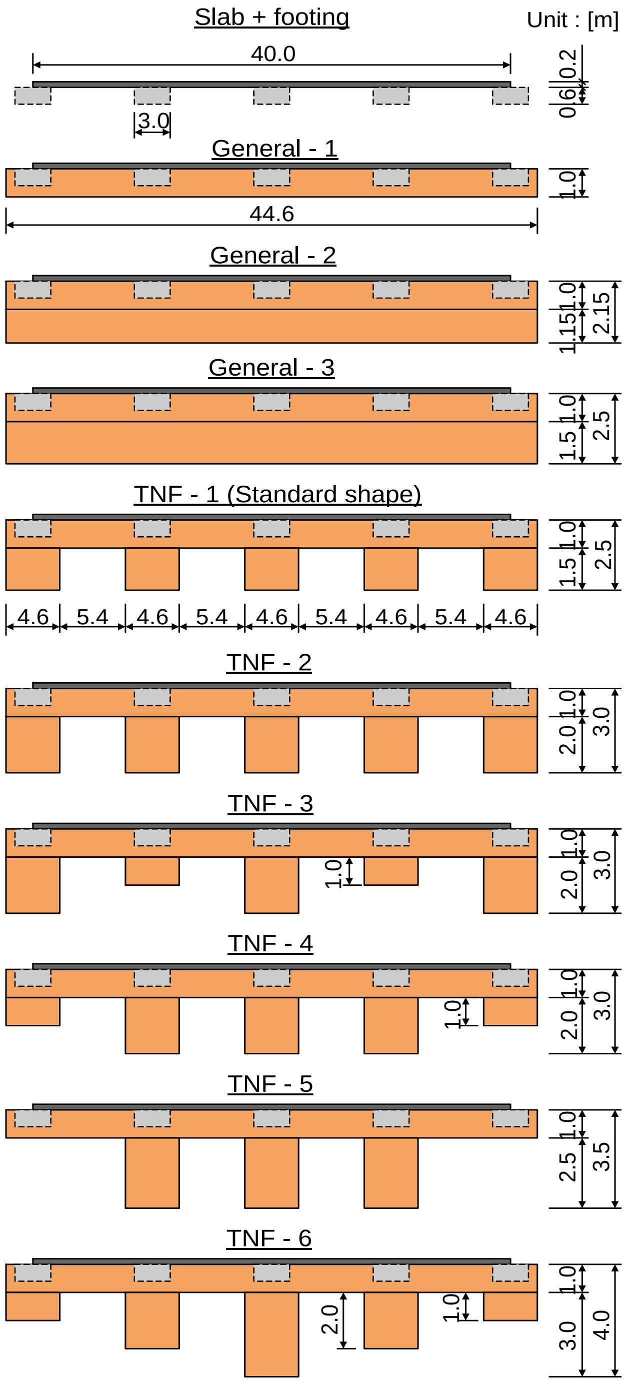


Fig. 6. Foundation system shapes.

Fig. 6 shows four types of foundations and six shapes of TNF systems to be analyzed. "Slab + footing" is the foundation system without soil improvement, and General - 1, 2, 3 are the foundations with conventional shallow soil improvement methods. TNF - 1, 2, 3, 4, 5, 6 are TNF systems. The slabs and footings have the same forms in all the TNF cases, while the thickness and the shape of soil improvement are varied as shown in Fig. 6.

In this parametric study, the deformations of the foundation systems subjected to vertical loading are analyzed with the linear elastic theory. The material parameters of parts of the foundation system are listed in Table 1.

Table 1. The material parameters applied for the TNF system analysis model.

Material	Young's modulus, E (kPa)	Poisson's ratio, ν	Remark
Concrete (Slab, Footing)	E_c = 23,500,000	0.2	
Original ground	E_s = 2,350	0.2	E_c/ E_s= 10,000
Primary soil improvement	E_1 = 81,000 (F_c = 450 kPa)	0.2	E_1/ E_s = 35, E_c/ E_1= 290
Secondary soil improvement	E_2 = 81,000 (F_c = 450 kPa)	0.2	E_2/ E_s = 35, E_c/ E_2= 290

E_1 and E_2 in Table 1 are defined as the secant modulus E_{50} by equation (1) specified in the Building Center of Japan (2018).

$$E_{50} = 180 \times F_c \tag{1}$$

where F_c is the unconfined compression strength of the soil improvement.

The Building Center of Japan (2019) specifies the empirical equation (2) to estimate Young's modulus E_s of the original ground from SPT N-value.

$$E_s = 2.8\ N\ (\text{MPa}) \tag{2}$$

In this series of analyses, N was assumed to be 0.8, considering a very soft ground, because the TNF has been applied to very soft soils having N ranging from 0 to 3.

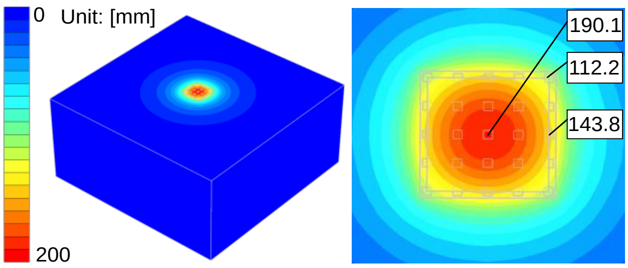


Fig. 7. Contour of settlement of TNF - 1.

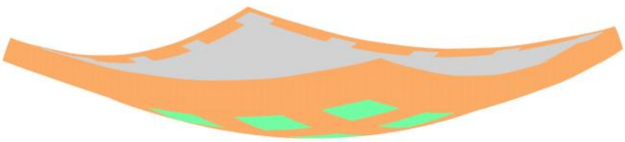


Fig. 8. Deformation of TNF - 1 (scaled up 100 times).

Fig. 7 shows the calculated contour of settlements of the slab and the ground surface in the case of TNF - 1 subjected to the vertical loads in Fig. 5. Zoom-up of deformation of the TNF system is shown in Fig. 8. It is seen that the foundation has a dish shape. The maximum settlement occurs at the center of the foundation system and the settlement gradually decreases towards the corners and edges of the foundation system.

Similar analyses were conducted on all types of foundations (“Slab + footing”, General - 1, 2, 3).

Fig. 10 and Fig. 11 compare the distributions of settlements of the slab along Section A-A and Section C-C shown in Fig. 9, respectively. Remember here that the thickness of the secondary soil improvement is 1.0 m in all the cases except “Slab + footing”. The thickness of the primary soil improvement is 0.0 m in “Slab + footing” and in General - 1, 1.15 m in General - 2, and 1.5 m in General - 3 and in TNF - 1.

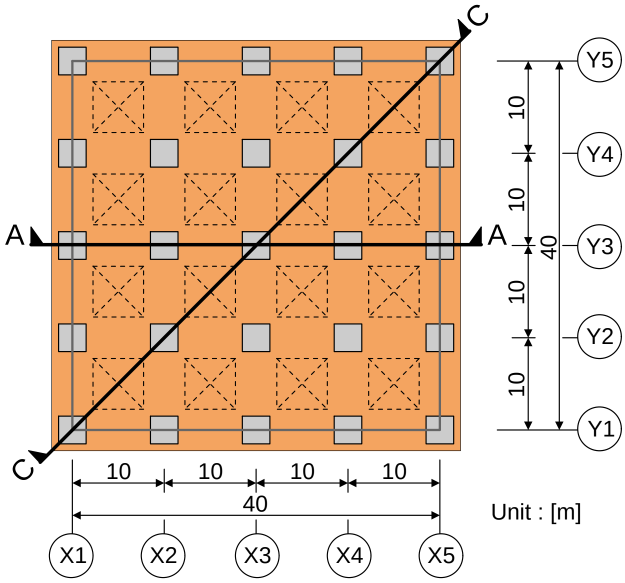
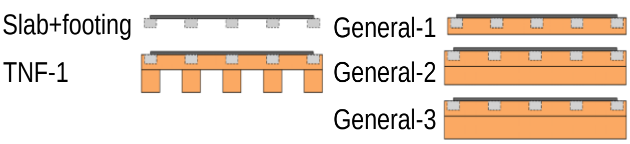


Fig. 9. Sections A-A and C-C for considering the settlement results.

In all the cases, the maximum settlement occurs at the center of the foundation system, and the settlement gradually decreases towards the edges (Fig. 10) and corners (Fig. 11) of the foundation system.

It is seen from the comparison of the results of General 1, 2, and 3 (the conventional systems) that the settlements do not seem to be reduced furthermore for the total thickness of the primary and secondary soil improvements greater than 2.5 m.



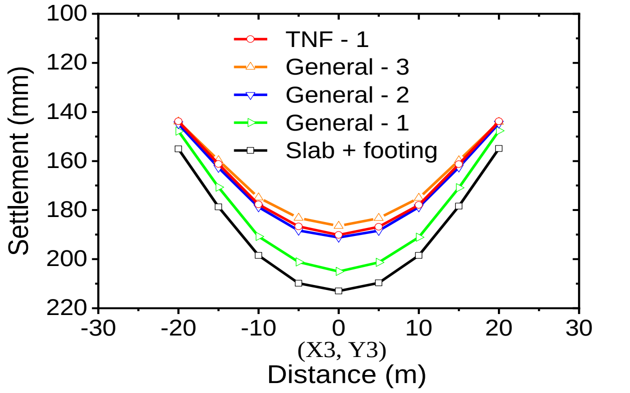


Fig. 10. Distributions of settlements of the foundations along Section A-A.

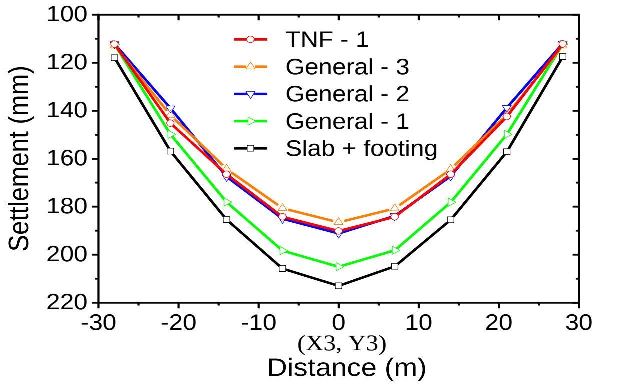


Fig. 11. Distributions of settlements of the foundations along Section C-C.

In this paper, maximum relative settlement is defined as the difference between settlements at the center and corners.

Fig. 12 shows the maximum settlement ratio, the maximum relative settlement ratio, and the soil improvement volume ratio of each foundation to TNF - 1.

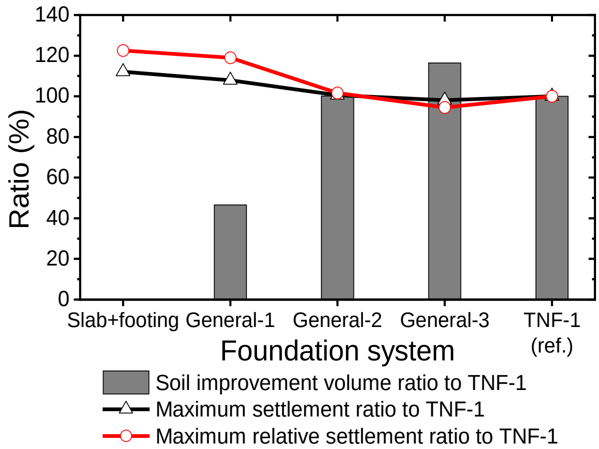


Fig. 12. Effect of the foundation system on the settlements.

Although the soil improvement volumes of “Slab + footing” and General - 1 are zero or less, the maximum settlement and maximum relative settlement of these foundations are larger than those of the other foundations.

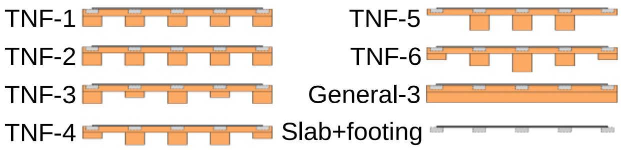
It is seen that General-2, General-3, and TNF-1 are more effective in suppressing maximum relative settlement than their effect on maximum settlement. This aspect is preferable for building foundations.

Although General - 3 has the smallest value of maximum relative settlement ratio, the soil improvement volume ratio is about 20% as large as those in General - 2 or TNF - 1. Among the foundations considered in the analyses, TNF - 1 would be the best choice, considering the reduction of settlement and volume of soil improvement. Hence, in the next section, the effects of various shapes of TNFs on the reduction of foundation settlements are analyzed.

2.2 Parametric study of TNFs having various shapes

In this section, the effect of the shape of TNFs on settlement is investigated. Six cases of the TNFs (see Fig. 6) are analyzed.

Calculated distributions of settlements and relative settlements of the slab along Section C-C are shown in Fig. 13 and Fig. 14, respectively. Here, relative settlement is the difference between settlements at different points and the settlement at the corners.



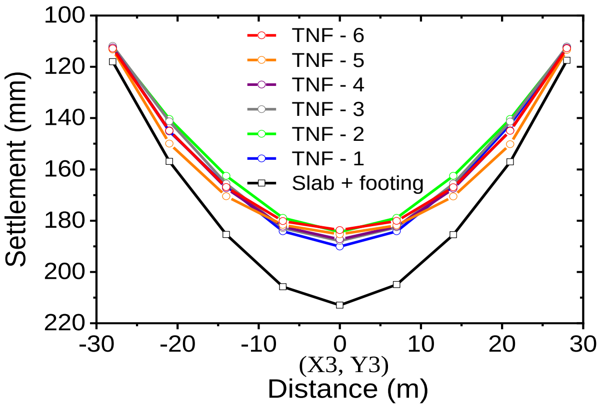


Fig. 13. Distributions of settlements of the TNFs along Section C-C.

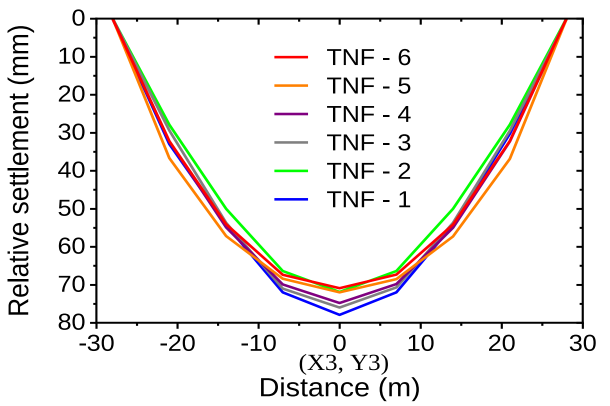


Fig. 14. Distributions of relative settlements of the TNFs along Section C-C.

It is seen from Fig. 13 that all the cases of the TNF system have a smaller value of settlement than "Slab + footing".

Fig. 14 shows that the relative settlement at the center (at the intersection of axes X3 and Y3) decreases in the order of TNF - 1, TNF - 3, TNF - 4, TNF - 5, TNF - 2, TNF - 6. Meanwhile, at 15 m away from the center, the relative settlement of TNF - 5 is the largest.

Fig. 15 shows the maximum relative settlement ratio and the soil improvement volume ratio of each TNF to TNF - 1. As General - 3 was superior to the other foundation types to reduce the foundation settlements (see Fig. 11), the results of General - 3 are added to the figure for comparison purposes.

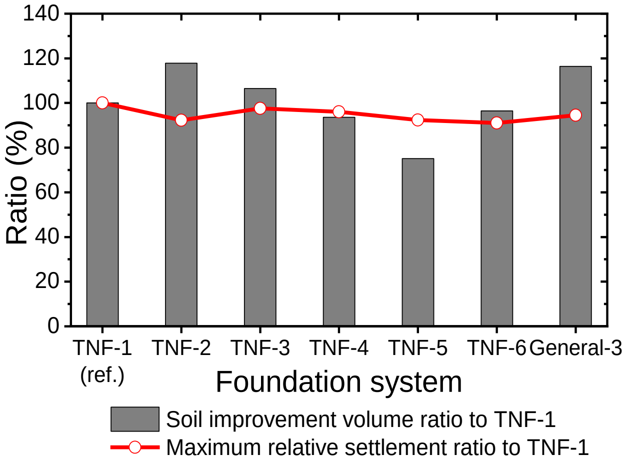


Fig. 15. Effect of TNF system shape on the relative settlement.

It is seen from the comparison between TNF - 2 and General - 3 that the maximum relative settlement of TNF - 2 is less than that of General - 3, although the volumes of soil improvement in TNF - 2 and General - 3 are equal.

TNF - 2 and TNF - 6 are effective to reduce the maximum relative settlement. However, the required volume of soil improvement in TNF - 2 is 118% of that in TNF - 1, while the required volume of soil improvement in TNF - 6 is 96% of that in TNF - 1.

TNF - 5 is a very efficient foundation because the maximum relative settlement is reduced reasonably with less volume of soil improvement. However, in practice, it is difficult to employ TNF - 5 because column loads from the superstructure are applied along the edges of the foundation system.

2.3 Parametric study of Young's modulus of the original ground

In this section, the influence of Young's modulus of the original ground E_s on foundation settlements is numerically investigated. TNF - 6 is selected as the target foundation because TNF - 6 was demonstrated to be an efficient foundation in Section 2.2. Only E_s was varied in the analyses with the other calculation conditions described in Section 2.1.

Calculated distributions of settlements and relative settlements of the slab along Section C-C (see Fig. 9) are shown in Fig. 16 and Fig. 17, respectively.

As mentioned earlier, the Building Center of Japan (2019) specifies the empirical equation $(2)_{bis}$ to estimate E_s from SPT N-value.

$$E_s = 2.8\,N \text{ (MPa)} \qquad (2)_{bis}$$

In the analyses, N was varied from 0.8 to 10.

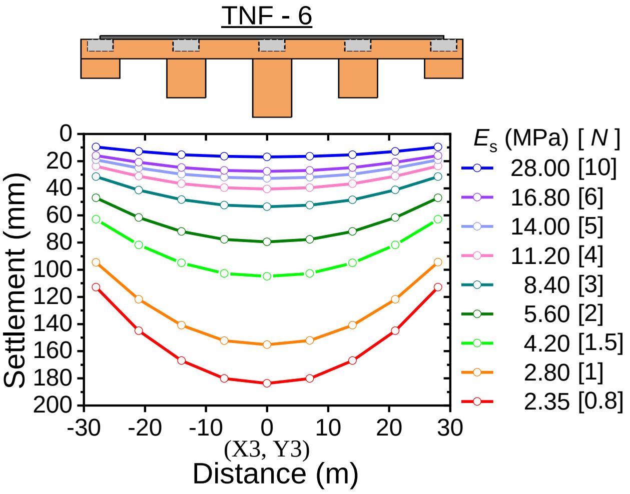


Fig. 16. Distributions of settlements of the TNF - 6 along Section C-C with various Young's modulus of the original ground.

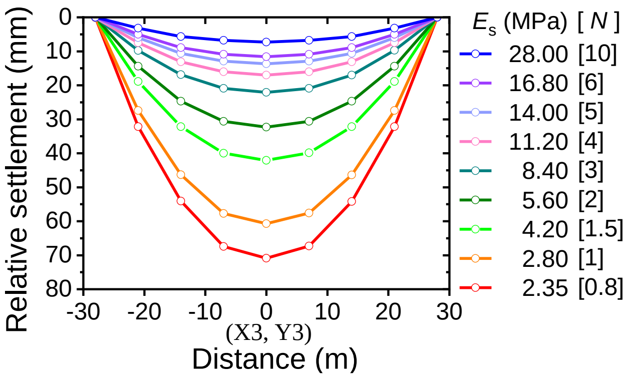


Fig. 17. Distributions of relative settlements of the TNF - 6 along Section C-C with various Young's modulus of the original ground.

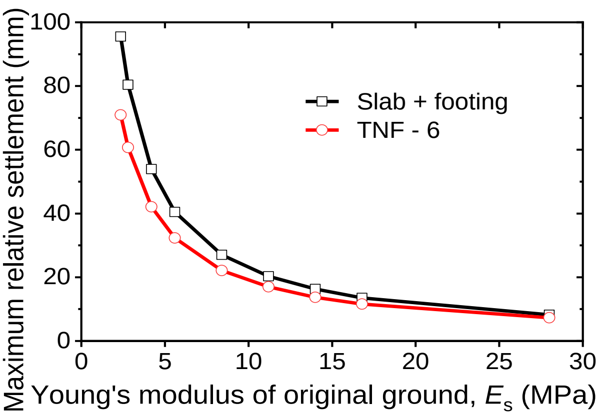


Fig. 18. Effect of Young's modulus of the original ground on the relative settlement.

It is seen from Fig. 16 and Fig. 17 that settlements and relative settlements increase with decreasing value of E_s.

Fig. 18 shows the influence of E_s on the maximum relative settlements of the slab in two cases of "Slab + footing" and TNF - 6.

It is seen from Fig. 18 that in the case of original ground having E_s greater than about 15 MPa (corresponding to $N > 5$), the difference of maximum relative settlement between "Slab + footing" and TNF - 6 is not significant. Meanwhile, in the case of original ground having E_s less than about 15 MPa (corresponding to $N \leq 5$), the maximum relative settlement of the TNF - 6 is much lower than "Slab + footing" and the difference increases with decreasing E_s. The results of Fig. 18 indicate that the TNF system is efficient for the soft ground having N-value less than or equal to 5.

3 CONCLUDING REMARK

In this paper, a series of numerical analyses (linear elastic FEA) was carried out to compare the effect of different foundation system shapes, such as foundation without soil improvement, foundations with conventional shallow soil improvement and TNFs, on the foundation settlements. And, efficient application of a TNF was analyzed considering different values of Young's modulus E_s of the original ground.

The main conclusions from the analyses with foundation conditions considered in this particular research are as follows:

1) The TNF system can reduce the volume of soil improvement than conventional shallow soil improvement methods for the same settlements.
2) The TNF is efficient for soft ground having E_s less than about 15 MPa, compared to a foundation without soil improvement.

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