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Design of pretensioned soil nailing systems in excavations

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ABSTRACT: In the present study, analytical design procedures are proposed to evaluate the maximum pretension forces and to estimate stability of the pretension soil nailing system. In addition, modified bearing plate system is proposed and reliability analysis focusing on probability of a failure against the punching shear is carried out. The predicted results are compared with data obtained from the actual excavation site in which construction is made using the pretension soil nailing system. Based on the proposed procedures, effects of both a radius of the influence circle and the dilatancy angle on the thickness of shotcret facing and the bonded length are also analyzed. Further, efficiencies of the pretension soil nailing system in terms of a reduction both in deformations and nail lengths are examined in detail throughout illustrative examples and the FLAC^{2D} program analysis.

1 INTRODUCTION

The ground anchor system occasionally may not be used because of space limitations in urban excavation sites nearby the existing structures. In these cases, soil nailing system with relatively short lengths of nails can be efficiently adopted as an alternative method. The general soil nailing system, however, may result in excessive deformations particularly in an upper excavation zone of the weak subsoils. The pretension soil nailing system then, could play important roles to reduce deformations as well as to improve stability. However, there is currently no specific rational design procedure with respect to the pretension soil nailing system. In the present study, analytical design procedures are proposed to evaluate the maximum pretension forces and to estimate local or overall stability of the pretension soil nailing system. Also dealt with a determination of the required thickness of the shotcrete facing. In addition, modified bearing plate system is proposed and reliability analysis focusing on probability of a failure against the punching shear is carried out.

2 FUNDAMENTAL APPROACH

2.1 *Mobilized shear stress and maximum pretension force*

Systematic measured data describing interaction behavior characteristics between the pretension soil nails and the in-situ soils are extremely limited. Therefore, in the case when the pretension force is applied to the nail, shear stress expected to mobilize at the interface between the nail and surrounding soils, τ_{mob} (see Fig. 1), is approximately estimated based on the research results proposed by the Lieng & Feng(1997) for the case of ground anchors. That is,

$$\tau_{mob} = \tau_0\{1 + 2(1+\nu)\tan^2\psi\} + 2\sigma_m \tan\psi \frac{(R_I / R_0) - 1}{\ln(R_I / R_0)} \quad (1)$$

where, $\tan\psi = \delta R / \delta z$ (See Fig. 2)
ψ = dilatancy angle
R_0 = radius of drilled hole
R_I = radius of influence circle
ν = Poisson's ratio
σ_m = mean normal stress
τ_0 = shear stress mobilized at the nail-soil interface in the case when the pretension force is not applied

Based on the limit equilibrium method of stability analysis(Kim et al., 1995) with a bilinear failure surface, the minimum safety factor against a sliding and the effective nail length are determined at every excavation stage. This procedure leads to a determination of τ_0 expected to mobilize in the case when the pretension force is not applied. Seepage pressures acting on the failure surface are also taken into account by solving the Laplace's equation throughout a conformal mapping process.

Based on the procedure of safety evaluation previously described and the Eq. (1), shear force expected to mobilize at the nail-soil interface, T_{mob}, is determined. Final evaluation of the maximum pretension force, T_0, that can be applied to the nail is made by comparing with a tensile yield strength, T_{yield}, of the re-bar as follows.

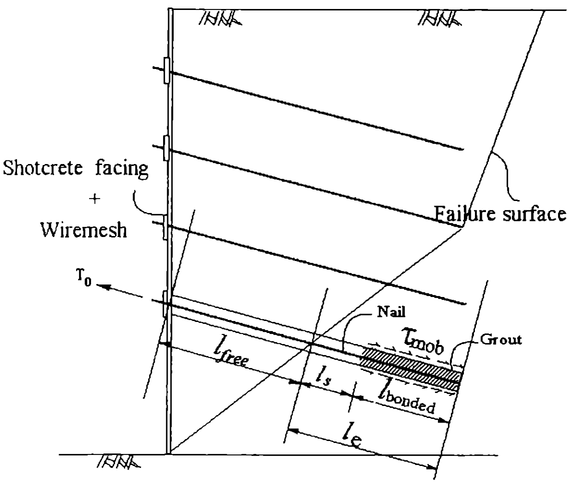


Figure 1. Description of the bonded length.

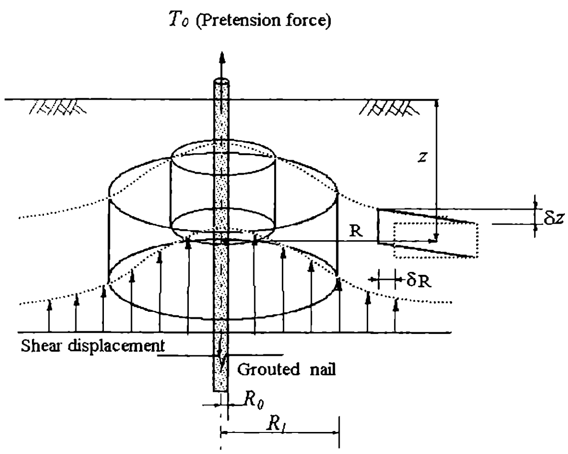


Figure 2. Description of the influence circle.

$$T_{mob} = \pi\, d_{hole} l_e\, \tau_{mob} / s_h \tag{2}$$

$$T_{yield} = A_{re-bar} \sigma_y / s_h \tag{3}$$

$$T_0 = Min.(T_{mob}\ ,\ T_{yield}\ ) \tag{4}$$

where, s_h = horizontal nail spacing, A_{re-bar} = cross-sectional area of the re-bar.

2.2 *Bonded length*

In the process of applying the pretension force, sufficient bonded length is required to prevent pullout between the nail and the in-situ soils. As indicated in Fig. 1, such bonded length required, l_{bonded}, is determined as follows.

$$l_{bonded} = \frac{T_0}{\pi\ d_{hole}\ \tau_{mob}} \tag{5}$$

However, in the case when the pretension force is applied, the mobilized shear stress at the interface between the nail and the in-situ soils cannot exceed the ultimate bonded strength, τ_u, at the rebar-cement grout interface. Therefore, the following criterion is necessary for further check.

$$l_{bonded} = Max.\left(\frac{T_0}{\pi\, d_{rebar}\, \tau_u}\ ,\ \frac{T_0}{\pi\, d_{hole}\, \tau_{mob}}\right) \tag{6}$$

2.3 *Total skin frictional force*

The total skin frictional force along the effective length of a nail, l_e(see Fig. 1), is composed of two components. The first shear stress component is due to all factors except for the pretension force, while the second component is developed by an addition of the pretension force.

$$(T_{max})_{mob} = \frac{\pi\, d_{hole}}{s_h}\{l_{bonded}\tau_{mob} + (l_e - l_{bonded})\tau_0\} \tag{7}$$

2.4 *Nail-soil interaction*

During the pretension process, behavior characteristics between the nail and the in-situ soils as well as interactions between closely spaced group of nails may significantly result in a densification of surrounding soils.

Examining various cases of the superposition of the influence circles as schematically shown in Fig. 3, Hanna & Ghaly(1994) proposed an empirical expression to reflect changes in soil properties during the anchoring process. Shear strength in surrounding soils adjacent to the nail to which the pretension force is applied, is then assumed to change as in Eq. (8).

$$\phi_{den} = \phi + \Delta\phi\ ,\quad \Delta\phi = \frac{c_d}{s_h / d_{hole}} \cdot \frac{\phi^4}{10^6} \tag{8}$$

3 DESIGN OF THE SHOTCRETE FACING

3.1 *Introduction*

The present analytical design procedures also deal with determinations of the required thickness of a shotcrete facing and the necessary quantity of a wire mesh when the pretension force is applied. Similar to a plate supported by columns, an element of the shotcrete facing wall attached at its four corners to the nails is considered. The bending moment and shear force induced by the soil pressures and nail forces are calculated on the basis of a

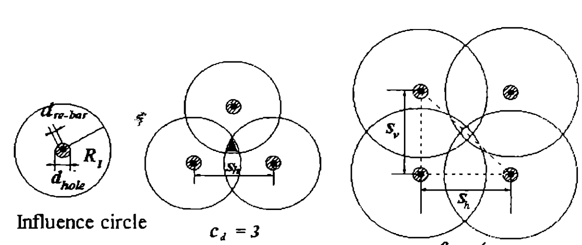


Figure 3. Superposition of the influence circles.

plate theory. The maximum horizontal displacement expected to occur at a middle point of each element is also calculated based on a plate theory. The stability calculations for the facing are then performed following the LRFD approach on the strength limit state (FHWA, 1996). Detailed derivations of the relevant equations are omitted in this paper due to a space limitation.

3.2 *Modified bearing plate system*

Punching shear failure is of particular concern due to an additional pretension force applied to the facing wall. This may result in an increase in the required thickness of a shotcrete facing, which can cause some difficulties in construction. As an efficient countermeasure to solve this problem appropriately, modified bearing plate system connected by 4 bridges as shown in Fig. 4-b is proposed in the present study. This system focuses on a dispersion of the pretension force, ensuring that local stability against the punching shear failure is satisfied.

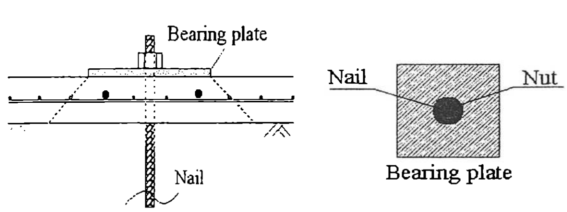
3.3 *Probability of the punching shear failure*

The pretension soil nailing system has not yet been sufficiently used in the Korea so that meaningful experimental data are extremely limited. In order to compensate for a lack of measured data and to enhance the validity of the proposed design procedure, reliability analysis on the probability of the punching shear failure of the shotcrete facing wall is additionally carried out. The procedures are briefly described below.

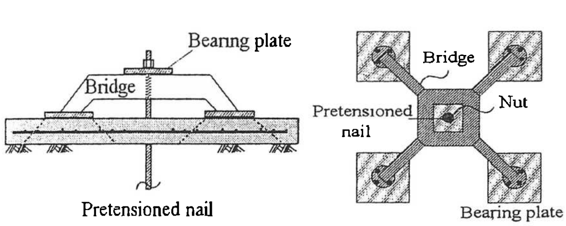
Safety margin, Z, of the pretension soil nailing system can be expressed as follows.

$$Z = R - S = g(\sigma_{ck}, \phi, \gamma, T_0) \tag{9}$$

Geometrically, $g(X)=0$ defined as the limit state equation, is an n-dimensional surface that may be called the "failure surface". One side of the failure surface is the



a) General bearing plate system.



b) Modified bearing plate system.

Figure 4. Schematics of the bearing plate system.

safe state, $g(X)>0$, whereas the other side of the failure surface is the failure state, $g(X)<0$. Probability of the punching shear failure, P_f, is then defined as in Eq.(10). The corresponding reliability, R_0, is subsequently defined as in Eq. (11).

$$P_f = \Phi(-\beta) \tag{10}$$

$$R_0 = 1 - P_f \tag{11}$$

4 PARAMETRIC STUDIES

For purposes of analyzing the effects of a radius of the influence circle(R_I) and the dilatancy angle(ψ) on the required thickness of a shotcrete facing wall and the required bonded length, parametric studies for the case of the pretension soil nailing system are carried out. Detailed values of the selected soil properties are summarized in Table 1 and a cross section with relevant geometric conditions is shown in Fig. 5, respectively.

Table 1. Soil properties adopted in parametric studies.

Soil layers	Unit weight (kN/m^3)	Internal frictional angle	Cohesion (kN/m^2)	Poisson's ratio
Soil 1	17.66	25 °	0.98	0.33
Soil 2	18.64	28 °	9.80	0.30
Soil 3	19.62	33 °	29.43	0.27

In the present parametric studies, the radius of an influence circle is assumed to vary from 0.5 to 2.0m based on the research results of the Liang & Feng(1997). The dilatancy angle is also assumed to vary from 5° to 15° on the basis of the guidelines proposed by the Vermeer & Borst(1997). Application of the pretension force is made up to the 5th nail. Seepage pressures due to a groundwater table located at a depth of 5.0m below the top surface as indicated in Fig. 5 are taken into account and analyses are performed using the proposed design procedures described in the previous chapters. Results of the parametric studies are illustrated in Figs. 6 and 7.

As can be observed in Figs. 6 and 7, increasing values of R_I and ψ leads to a decrease of both the required thickness of a shotcrete facing and the required bonded length. It is also observed in Figs. 6 and 7 that decreasing rates of the required thickness and bonded length as ψ increases from 5° to 10° are much greater than those as ψ increases from 10° to 15°.

The results previously analyzed may be attributed to the facts that increasing a value of R_I leads to an increase of the number of the influence circles superposed, resulting in a partial increase of the internal frictional angle in surrounding soils. Also, an increase of ψ represents a buildup of the soil shear strength(Vermeer & Borst, 1984).

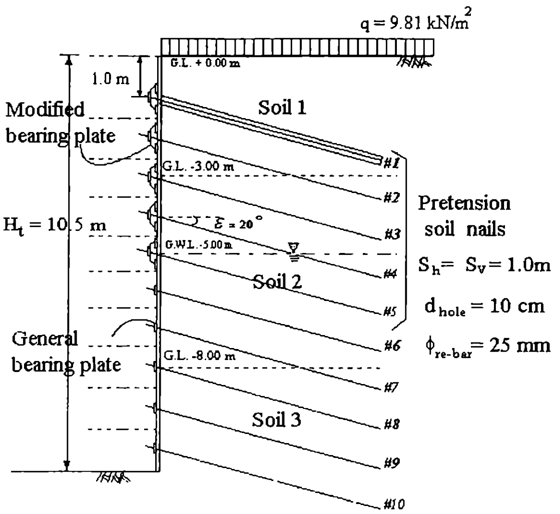


Figure 5. A cross section of the pretension soil nailing system (nail length = 9.0m).

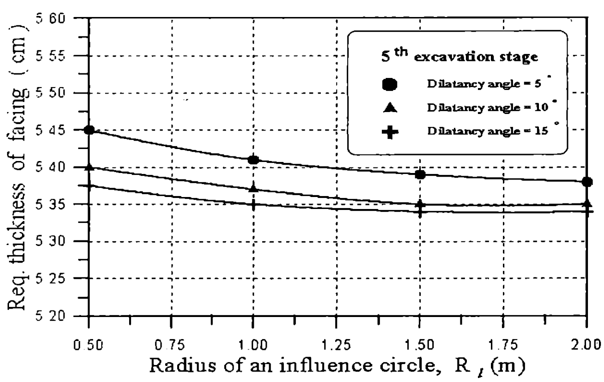


Figure 6. Relationship between radius of influence circle and required thickness of shotcrete facing.

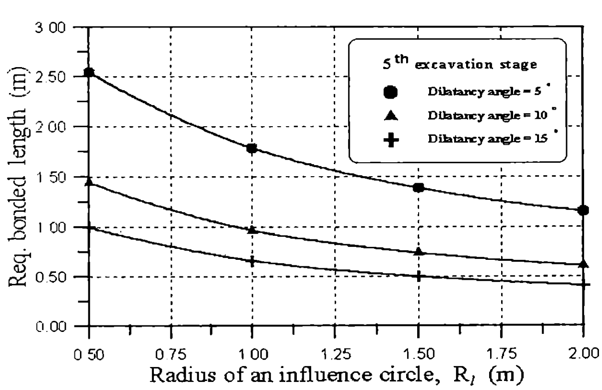


Figure 7. Relationship between radius of influence circle and required bonded length.

5 COMPARISONS WITH DATA FROM THE ACTUAL CONSTRUCTION SITE

As previously mentioned, the pretension soil nailing system has not yet been broadly used in the Korea. Since both full-scale experimental data and results of laboratory model tests are not presently available, restricted comparisons with data obtained from the actual construction site are performed in the present study. Subsoil properties pertinent to the actual excavation site are summarized in Table 2 and a cross section with relevant geometric conditions is shown in Fig. 8. No groundwater existed in the actual excavation site and the maximum pretension force applied to the nail was limited to 98.1kN. The attachment of grouted nails to the shotcrete facing was made using general type of a square steel plate 1.5 to 2.0 cm thick and 30 to 40 cm wide.

Further based on the proposed procedures in chapters 2 and 3, predictions are made assuming that a radius of the influence circle and the dilatancy angle are 0.5m and 5°, respectively. These values are assumed referring to the results of parametric studies in chapter 4 and are regarded as conservative.

As summarized in Table 3, values of the pretension forces applied to the nails in the actual construction site are much smaller than predicted values of the maximum pretension forces that can be possibly allowable. It is also realized in Table 3 that actually constructed thickness of the shotcrete facing exceed the required thickness estimated using the proposed procedures up to the 4^{th} nail level. It is further realized that although the facing thickness actually constructed in the 5^{th}, 6^{th}, 7^{th}, and 8^{th} nail level do not exactly fulfill the requirements, there was no significant problem of structural stability, since the actual pretension forces were much smaller than predicted values of the maximum pretension forces.

6 EFFICIENCY OF THE PRETENSION SOIL NAILING SYSTEM

Using the same soil properties and geometric conditions described in Table 1 and Fig. 5 respectively, efficiency

Table 2. Subsoil properties in the actual excavation site.

Soil layers	Unit weight (kN/m^3)	Internal frictional angle	Cohesion (kN/m^2)	Poisson's Ratio
Soil 1	16.68	25°	0.0	0.33
Soil 2	17.66	30°	9.8	0.30

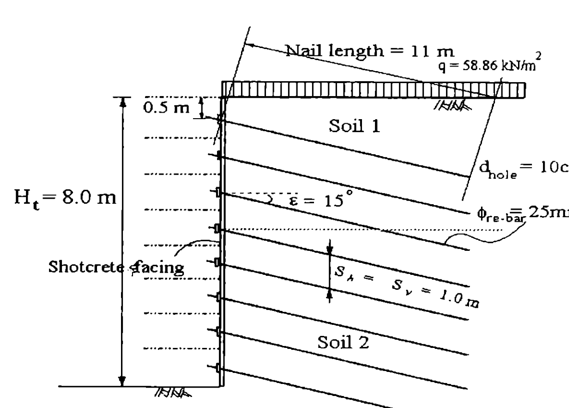


Figure 8. A cross section of the actual excavation site.

Table 3. Results of comparisons.

Nail number	Prediction		Data from the actual excavation site	
	Max. pre-tension force(kN)	Required thickness of the facing(cm)	Applied preten-sion force (kN)	Applied thickness of the fac-ing(cm)
#1 nail	56.70	11.98	49.05	15.00
#2 nail	76.13	12.92	49.05	15.00
#3 nail	91.43	13.78	49.05	15.00
#4 nail	105.46	14.60	49.05	15.00
#5 nail	119.19	15.39	98.10	15.00
#6 nail	132.63	16.16	98.10	15.00
#7 nail	147.35	16.90	98.10	15.00
#8 nail	160.79	17.85	98.10	15.00

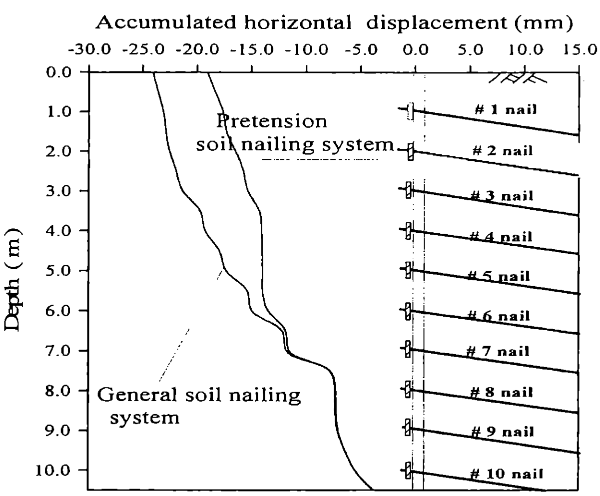


Figure 9. Comparison of accumulated horizontal displacement between pretension soil nailing system and general soil nailing system.

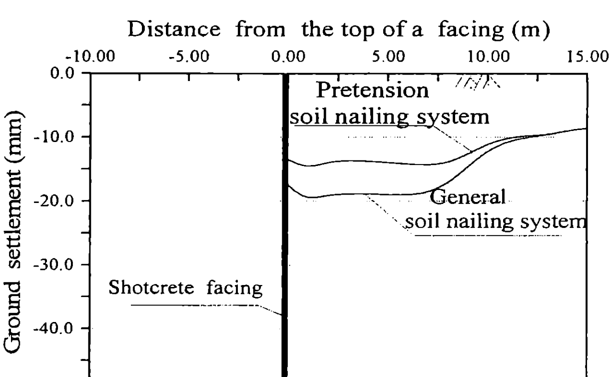


Figure 10. Comparison of ground settlement between pretension soil nailing system and general soil nailing system.

of the pretension soil nailing system is examined. Applying the maximum pretension forces and the required thickness of the shotcrete facing evaluated on the basis of the proposed procedures, the $FLAC^{2D}$ program analyses

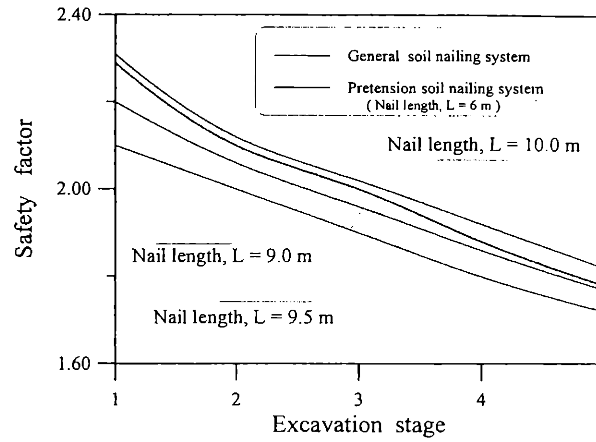


Figure 11. Comparison of nail length between pretension soil nailing system and general soil nailing system.

are performed at every excavation stages to estimate accumulated deformations. In the $FLAC^{2D}$ program analyses, seepage pressures due to an existence of the ground water are dealt with and nails are modeled as cable elements. Modified bearing plate system(See Fig. 4) is adopted in the present analyses.

As clearly observed in Fig. 9, accumulated displacement of the facing with depths at the final excavation stage are remarkably reduced in the upper part of the nailed soil wall. In comparison to the general soil nailing system constructed without prestressing, a reduction of the maximum displacement in magnitude is 5.02mm(21%) in the case of applying the pretension forces up to the 5^{th} nail. Similarly, settlements at the ground surface adjacent to the facing wall are reduced in the case of applying the pretension forces up to the 5^{th} nail as illustrated in Fig. 10. Dominant reductions in settlements are taken place within a horizontal distance of 7.5m from the top of the facing wall. A reduction of the maximum settlement in magnitude is 4.87mm(25%). It is inferred from the distinct features analyzed in Figs. 9 and 10 that the pretension soil nailing system can possibly be used to control deformations within allowable limits in cases when excessive deformations are expected to occur.

Fig. 11 shows the results of a comparison associated with nail lengths required to achieve the same safety factors for both cases of the pretension soil nailing system and the general soil nailing system. The present analysis is done based on the procedures proposed in chapters 2 and 3. The applied pretension forces up to the 5^{th} grouted nail are denoted in Fig. 12. A single layer of the subsoil is considered and pertinent properties assumed are $\gamma = 19.62\ kN/m^3$, $\phi = 30°$, and $c = 9.81\ kN/m^2$. Analyzing the results of Fig. 11, it can be concluded that the pretension soil nailing system with comparatively short nails of 6m in length is much more efficient, producing almost the same safety factors as in the case of the general soil nailing system with nails of 10m in length.

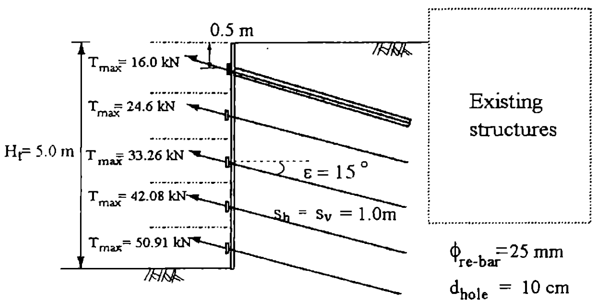


Figure 12. A cross section used in the comparison.

7 RELIABILITY ANALYSIS

Using the procedures briefly described in section 3.3, reliability analyses with respect to a probability of the punching shear failure for the shotcrete facing wall are carried out. Analyzed cross section is the same as that previously shown in Fig. 5, in which the pretension force is applied from the 1st top nail to the 5th nail.

Average values and standard deviations of the maximum pretension forces up to the 5th nail are evaluated based on the results of analyses corresponding to the collated 21 cases(R_l = 0.5~2.0m and ψ = 5~15°, see Figs. 6 and 7). Average values and standard deviations of soil unit weight, soil internal friction angle, and ultimate compressive strength at 28 days of the shotcrete are also determined referring to the details proposed by the Smith(1986). Results of reliability analyses with respect to the punching shear failure of shotcrete facing wall are summarized in Table 4. The modified bearing plate system previously described in Fig. 4 is also adopted in the present analysis.

Analyzing the results in Table 4, it is realized that the modified bearing plate system may provide advantages in terms of a reduction of the shotcrete facing thickness. It is also realized that a general standard of the maximum reliability in practice (95% or the above) is satisfied in the case of the modified bearing plate system as compared to 93.7% in the case of the general bearing plate.

8 CONCLUSIONS

In the present study, analytical design procedures are proposed to evaluate the maximum pretension forces that can be applied to the corresponding nails, and to estimate local or overall stability of the pretension soil nailing system, including a determination of the required thickness of the shotcrete facing.

Validity of the proposed procedures is examined comparing with data obtained from the actual construction site. Reliability analysis of the shotcrete facing focusing on the punching shear failure is further performed mainly both to compensate for an insufficiency in the systematic measured data and to increase a confidence of the proposed procedure. As an efficient resolution of the excessive facing thickness due to the additionally applied pretension force, modified bearing plate system is also proposed.

From the analyses conducted in the present study, it is partly proven that the pretension soil nailing system has advantages in reducing both the facing displacements and the adjacent ground settlements. It is also partly proven that the pretension soil nailing system with relatively short lengths of nails can possibly be applied to urban excavation sites in which space limitations occasionally exist due to the adjoining structures. Throughout the analyses, it is also realized that the modified bearing plate system may be advantageous both to reduce the facing thickness and to increase the reliability.

Table 4. Results of reliability analyses.

No.	Req. thickness of facing (cm)	Probability of failure(%)
#1 nail	3.78* (7.93**)	0.02* (6.3**)
#2 nail	3.67 (8.43)	0.59 (4.9)
#3 nail	4.19 (9.89)	0.99 (4.5)
#4 nail	4.70 (11.08)	1.92 (4.8)
#5 nail	5.37 (12.53)	1.74 (3.8)

*: modified bearing plate system, **: general bearing plate system.

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