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Stability Analysis and Design of the Pretension Soil Nailing System

프리텐션 쏘일네일링 시스템의 안정해석 및 설계

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요 지

쏘일네일링 공법을 도심지 지하굴착 공사에 있어, 지중매설물이 인접하여 존재하거나 대지경계선 등의 준수 등 시공조건에 따라서 설치네일의 길이가 제한되는 경우 및 연약한 지반을 보강할 경우 등과 같은 벽체변위 및 지표침하 억제와 안정성 증대 등을 위하여, 지반앵커공법과 유사한 프리텐션 방식의 도입이 필요한 실정이다. 지반앵커공법과 유사한 프리텐션 방식의 쏘일네일링 공법을 도입하게 될 경우, 단계별 굴착시 발생하는 변위를 최소화할 수 있을 것으로 예상되며 국부적인 안정성도 증대할 것으로 사료된다. 따라서, 본 연구에서는 단계별 굴착시 유발되는 벽체변위 및 침하량 등을 억제하기 위한 노력의 일환으로, 프리텐션 쏘일네일링 시스템을 개발하였다. 또한 최대 프리텐션하중 및 프리텐션 시스템의 안정성을 평가하기 위해, 영향원 반경, 다이레이턴시 각, 정착길이 등을 반영한 설계기법을 제안하였으며, 펀칭전단파괴에 저항할 수 있는 숏크리트의 요구두께를 결정하는 신뢰도 평가기법을 제안하였다. 아울러 설계예제와 $FLAC^{2D}$ 프로그램 수치해석을 통해 프리텐션에 의한 변위 감소효과를 살펴봤으며, 전단강도감소기법을 도입한 안정해석이 $FLAC^{2D}$ 프로그램을 토대로 수행되었다.

Abstract

The ground anchor support system may not be occasionally used because of space limitations in urban excavation sites nearby the existing structures. In this case, soil nailing system with relatively short length of nails could be efficiently adopted as an alternative method. The general soil nailing support system, however, may result in excessive deformations particularly in an excavation zone of the existing weak subsoils. Pretensioning the soil nails then could play important roles to reduce deformations mainly in the upper part of the nailed-soil excavation system as well as to improve local stability. In this study, a newly modified soil nailing technology named as the PSN (Pretension Soil Nailing), is developed to reduce both facing displacements and ground surface settlements in top-down excavation process as well as to increase the global stability. Up to now, the analytical procedure and design technique are proposed to evaluate maximum pretension force and stability of the PSN system. Also, proposed are techniques to determine the required thickness of a shotcrete facing and to estimate probability of a failure against the punching shear. Based on the proposed procedure and technique, effects of the radius of a influence circle and dilatancy angle on the thickness of a shotcrete facing, bonded length and safety factors are analyzed. In addition, effects of the reduction of deformations expected by pretension of the soil nails are examined in detail throughout an illustrative example and the $FLAC^{2D}$ program analysis. And a numerical approach is proposed PSN system using the shear strength reduction technique with the $FLAC^{2D}$ program.

Keywords : Bonded length, Influence circle, Pretension force, Pretension soil nailing system, Punching shear

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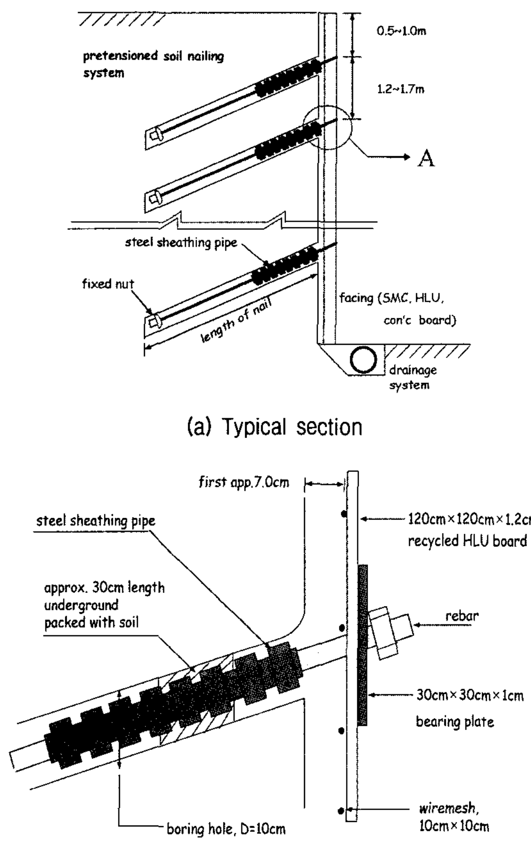
1. Introduction

The general soil nailing (GSN) system has usually been applied for temporary pit excavation, the support of the cut slopes for road construction, and the support of natural slopes next to houses since its first use in 1993 for temporary retaining walls in Korea. Also, this system can be utilized diversely in the underpinning of an existing building, the support of an existing retaining wall, and the support of tunnel openings and fractured zones in shallow tunnels (FHWA-SA-96-069). However, ground anchor support system occasionally may not be used because of space limitations in urban excavation sites nearby the existing structures. In this case, the GSN system with relatively short length of nails could be efficiently adopted as an alternative method. The GSN support system, however, may result in excessive deformations particularly in an excavation zone of the existing weak subsoils. Pretensioning the soil nails then could play important roles to reduce deformations mainly in the upper part of the nailed-soil excavation system as well as to improve local stability. A typical section of the PSN system is shown in Fig. 1 (Park, 2003).

In the present study, analytical design procedures are proposed to evaluate the maximum pretension forces and to estimate local or overall stability of the PSN system. Also this study dealt with a determination of the required thickness of the shotcrete facing. In addition, modified facing wall system (Hand Lay Up (HLU) board + shotcrete / Sheet Mold Compound (SMC) board + shotcrete) is proposed focusing on a failure against the punching shear.



(a) Typical section

(b) Detail "A"

Fig. 1. Construction details of the PSN system

2. Basic Concept

2.1 Components of the Pretension Soil Nail

The pretension soil nail consists of fixed nut, hole centralizer, steel sheathing pipe and re-bar as shown in Fig. 2. The fixed nut acts as a friction resistance transmitter on the cement grout to the re-bar of the nails. The sheathing pipes function as separating cement grout and re-bar of nails.

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 facing wall system connected by HLU (FRP as type of Hand Lay Up) and SMC (FRP as type Sheet Mold Compound) board, as shown in Fig. 3, 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.

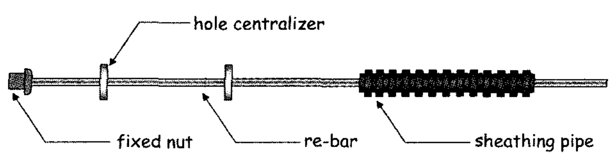
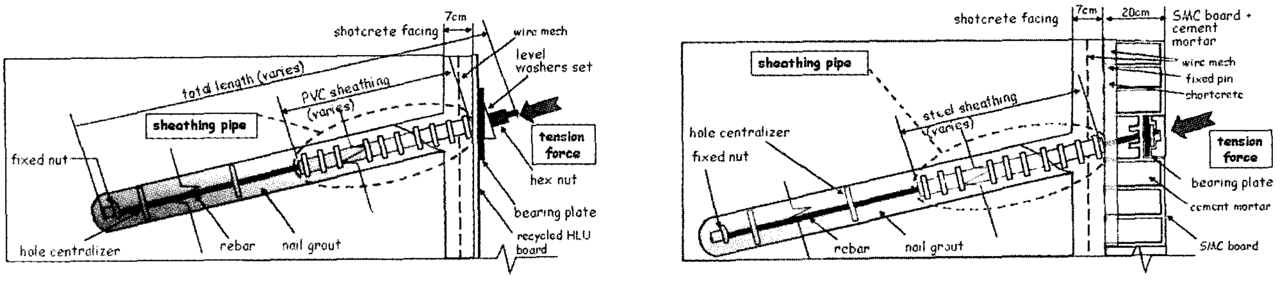


Fig. 2. Components of the pretension soil nail



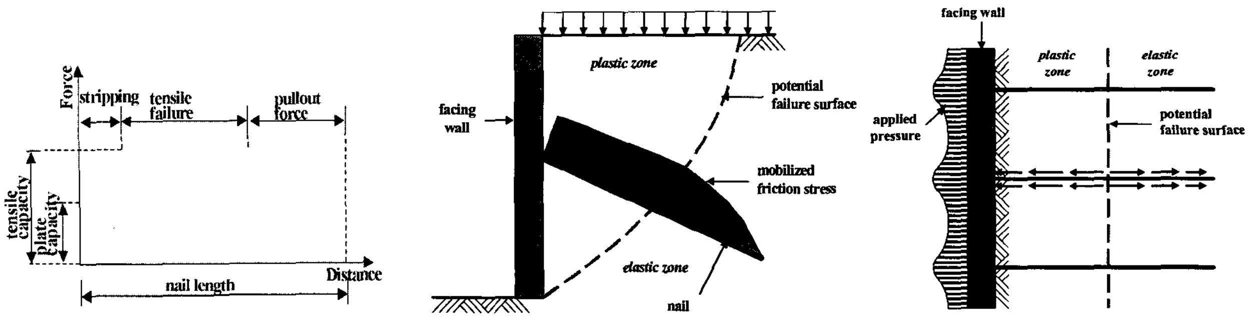
(a) Temporary facing wall system

(b) Permanent facing wall system

Fig. 3. Facing wall of the PSN systems

2.2 Effect of the Pretension Force

At any point along the length of a soil nail, the force which is applied to the slip surface by the soil nail is given by minimum of three forces. A typical soil nail force diagram, which exhibits all three failure modes, is shown in Figs. 4 & 5. In this case (see Fig. 4), the plate capacity is less than the tensile capacity, and therefore "stripping" is a possible failure mode. If the plate capacity is greater than or equal to the tensile capacity, then stripping cannot occur, and the soil nail force diagram will be determined only by the tensile and pull-out failure modes. If the soil nail pull-out strength is specified as material dependent, then the pull-out force and stripping force are contributed by each segment of the soil nail which passes through different materials. In the PSN system (see Fig. 5), for large scale stripping to occur, the plate capacity must be exceeded and cement grout must fill in the sheathing pipe. Systematically 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, friction stress expected to mobilize at the interface between the nail and surrounding soils is approximately estimated based on the research results proposed by the Lieng & Feng (1997)

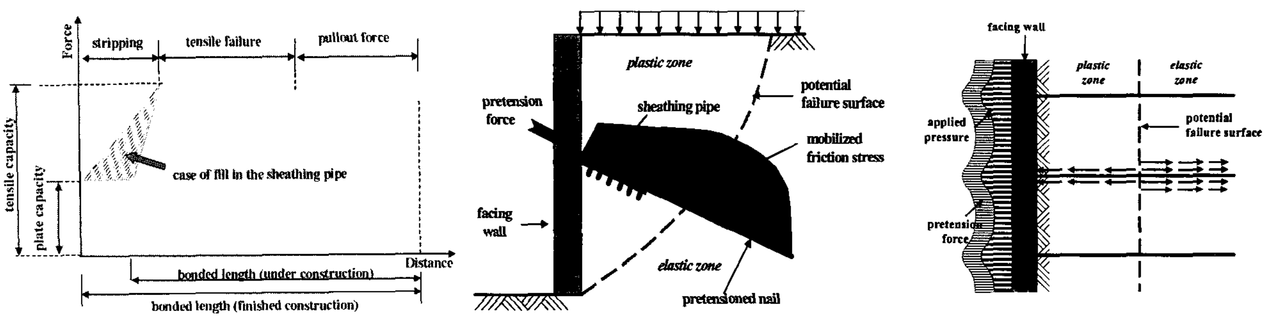


(a) Force diagram

(b) Friction diagram

(c) Resistance force diagram

Fig. 4. The GSN system



(a) Force diagram

(b) Friction diagram

(c) Resistance force diagram

Fig. 5. The PSN system

for the case of ground anchor.

2.3 Determination of the Pretension Force

The pretension force can be evaluated with interaction of skin friction developed between soil nail and soil through in-situ pull-out test. Skin friction can be generated between soil nail and soil which have the relation of pull-out force and displacement as elastic and plastic limit, respectively. It is based on skin friction mobilization law that Frank and Zhao (Schlosser, 1991; Schlosser & Unterreiner, 1991) proposed. The skin friction mobilization law by Frank and Zhao explains elastic behavior within 1/2 point of the maximum skin friction (q_{smax}) according to the relation of pull-out force and displacement. Therefore, skin frictions (q_s) are calculated based on the results of pull-out force of the laboratory pull-out test. These results are obtained from skin friction- displacement curve as expressed below.

$$q_s = \frac{T}{\rho L_s} \qquad (1)$$

where, T : pull-out force, ρ : nail perimeter ($\pi \cdot d$), and L_s : length in contact with the soil.

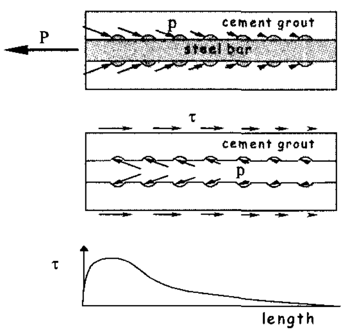
Therefore, in this study the skin friction, developed within elastic limit extent, was converted into pull-out force and the applicable pretension force was decided. Also, the skin friction, developed within plastic limit extent, was converted into maximum displacement and the applicable pretension force was decided.

2.4 Distribution of Nail Force at the Pull-out Tests

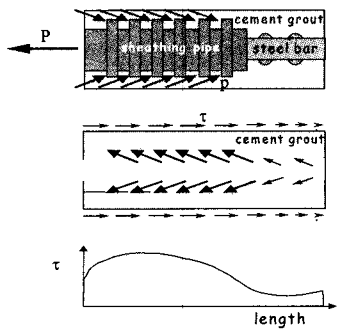
In the pull-out test, typical distributions of nail forces of the conventional soil nails and the pretension soil nails are shown in Fig. 6. In the conventional soil nails, the maximum nail force usually occurs at the nail head. Also, the maximum nail force in the pretension soil nails occurs at the sheathing pipe.

2.5 Construction Sequence

The PSN system construction typically involves the



(a) Conventional soil nails



(b) Pretension soil nails

Fig. 6. Distribution of the nail forces from the pull-out tests

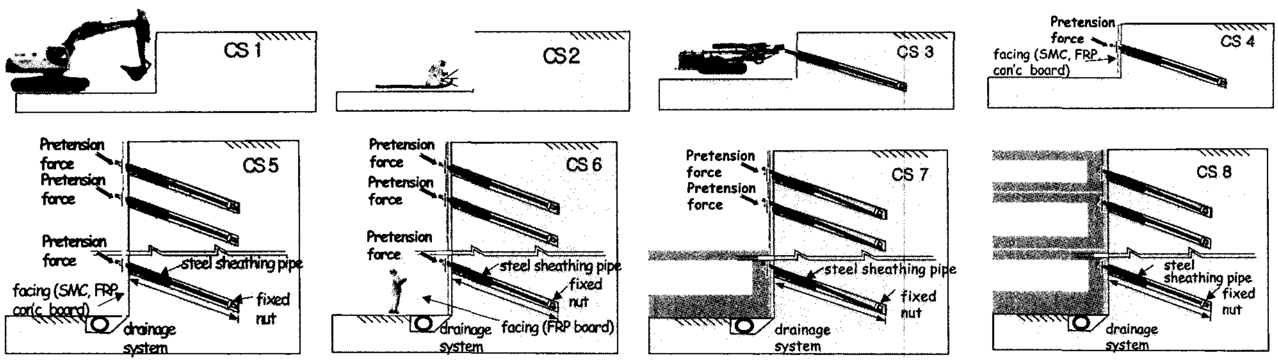


Fig. 7. Construction sequence of the PSN system

following 8 CS (Construction Step), as shown in Fig. 7 ; CS 1 : Excavate cut, CS 2 : Spray shotcrete upon excavated face, CS 3 : Install nails, CS 4 : Apply pretension force, CS 5 : Repeat process to final grade, CS 6 : Remove SMC boards (3~4m from final grade), CS 7 : Place walls, CS 8 : Place final walls.

3. Analytical Technique for the PSN System

3.1 Mobilized Shear Stress, Maximum Pretension Force, and Bonded Length

Systematically 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, which is expected to mobilize at the interface between the nail and surrounding soils, τ_{mob} (see Fig. 8), is approximately estimated based on the research results proposed by the Lieng & Feng (1997) for the case of ground anchors. That is,

$$\tau_{mob} = (\sigma_m - \sigma_{wr}) \cdot \tan\phi' + c' \cdot 1 + 2(1+\nu) \cdot \tan^2\psi + 2(\sigma_m - \sigma_{wr}) \cdot \tan\psi \frac{(R_I/R_o) - 1}{\ln(R_I/R_o)} \quad (2)$$

where, $\tan\psi = \delta_R / \delta_z$ (See Fig. 9), ψ = dilatancy angle, R_0 = radius of drilled hole, R_I = radius of influence circle, ν = Poisson's ratio, σ_m = mean normal stress, and 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 (Juran & Elias, 1990; Kim et al., 1995; Kim & Park, 2004) 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 which is 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. (2), shear force expected to mobilize at the nail-soil interface, T_{yield}, 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 the Eq. (3).

$$T_0 = Min.\left(T_{mob} = \frac{\pi \cdot d_{hole} \cdot l_e \cdot \tau_{mob}}{S_h},\ T_{yield} = \frac{A_{re-bar} \cdot \sigma_y}{S_h} \right) \quad (3)$$

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

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. 10, such bonded length required, l_{bonded}, is determined as follows.

$$l_{bonded} = \frac{T_0}{\pi \cdot d_{hole} \cdot \tau_{mob}} \quad (4)$$

However, in the case when the pretension force is

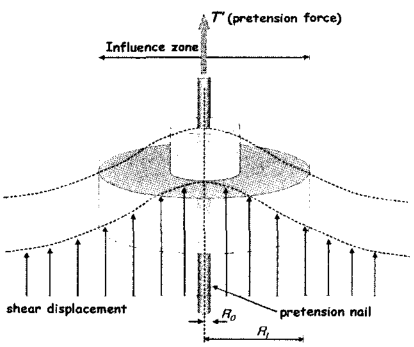


Fig. 8. Description of the bonded length

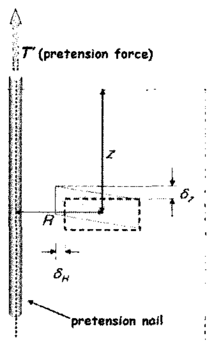


Fig. 9. Description of the dilatancy angle

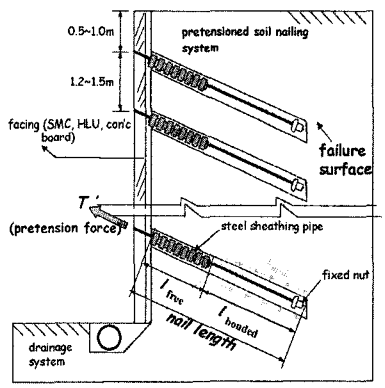


Fig. 10. Description of the influence circle

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.

$$l_{bonded} = Max.\left(\frac{T_0}{\pi \cdot d_{rebar} \cdot \tau_u}, \frac{T_0}{\pi \cdot d_{hole} \cdot \tau_{mob}}\right) \quad (5)$$

3.2 Total Skin Frictional Force and Nail-Soil Interaction

The total skin frictional force along the effective length of a nail, l_e (see Fig. 11), 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.

$$\text{If } l_{bonded} \leq l_e, \quad (T_{\max})_{mob} = \frac{\pi\, d_{hole}}{S_h}\{l_{bonded}\,\tau_{mob}\}$$

$$\text{If } l_{bonded} > l_e, \quad (T_{\max})_{mob} = \frac{\pi\, d_{hole}}{S_h}\{l_{bonded}\,\tau_{mob} + (l_e - l_{bonded})\tau_0\} \quad (6)$$

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 result in a significantly densification of surrounding soils. Examining various cases of the superposition of the influence circles as schematically shown in Fig. 12, 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. (7).

$$\phi_{den} = \phi + \triangle\phi, \quad \triangle\phi = \frac{c_d}{s_h / d_{hole}} \cdot \frac{\phi^4}{10^6} \quad (7)$$

4. Parametric Study

4.1 Effects of Influence Circle and Dilatancy Angle

For purposes of analyzing the effects of a radius of the influence circle (R_l) 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 PSN 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. 13, respectively.

In the present parametric studies, the radius of an influence circle is assumed to vary from 0.5 to 2.0 m

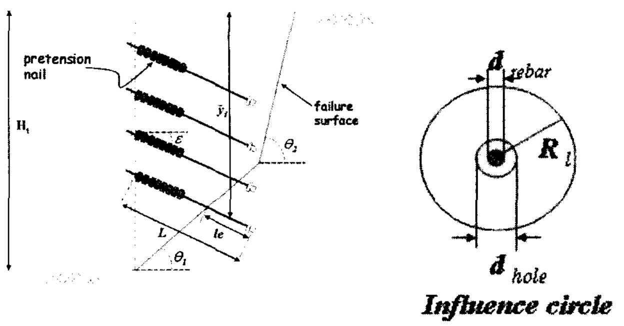


Fig. 11. Description of the effective length

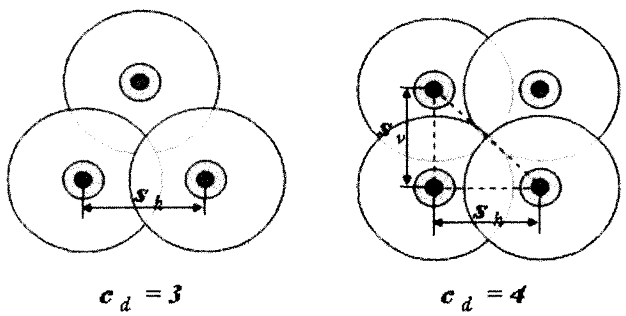


Fig. 12. Superposition of the influence circles

Table 1. Soil properties adopted in parametric studies

Soil layers	Unit weight (kN/m^3)	Internal friction angle	Cohesion (kN/m^2)	Poisson's ratio
Deposit	17.66	25°	0.00	0.33
Weathered Soil	18.64	28°	0.98	0.30
Weathered Rock	19.62	33°	29.43	0.27
Remarks	▶Shotcrete : $\sigma_{ck} = 17.65 MN/m^2$, $E = 1.97\times10^4 MN/m^2$, $v = 0.18$			

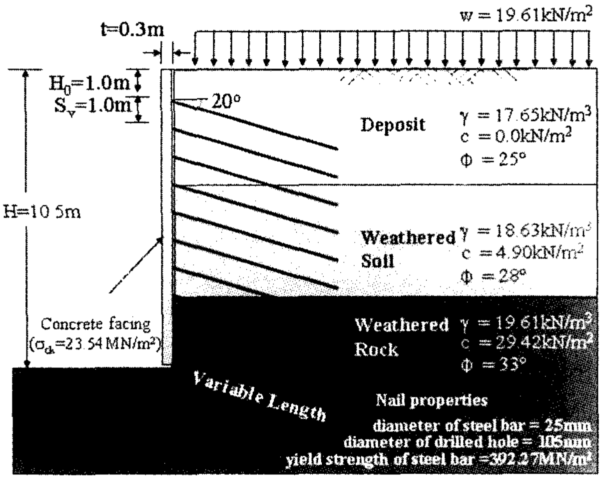


Fig. 13. A cross section of the PSN system

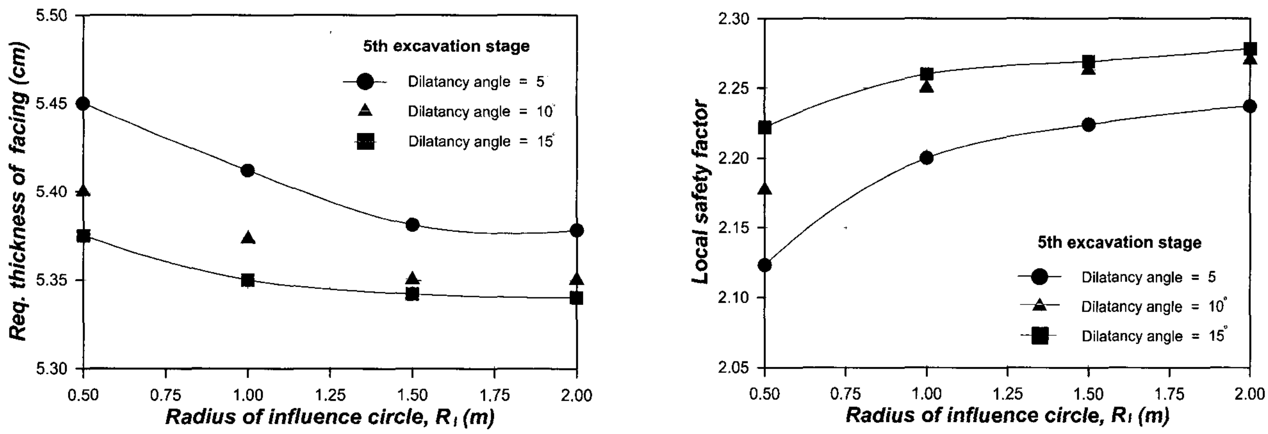
based on the research results of the Liang & Feng (1997). The dilatancy angle is also assumed to vary from 5° to 15° on the basis of the guidelines proposed by the Vermeer & Borst (1998). Application of the pretension force is made up to the 5th nail. Seepage pressures due to a groundwater table located at a depth of 5.0 m below the top surface as indicated in Fig. 13 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 Fig. 14.

As can be observed in Fig. 14, increasing values of R_I and ψ lead to a decrease of both the required thickness of a shotcrete facing and the required bonded length. It is also observed in Fig. 14 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, 1998).

4.2 Analyses of Safety Factor and Required Thickness of Facing

As previously mentioned, the PSN system has not yet been broadly used in Korea. Since full-scale experimental data are not presently available, restricted analysis data obtained from the numerical analysis are performed in the present study. Based on the proposed procedure and technique, effects of the thickness of a shotcrete facing, bonded length and safety factors on pretension force are analyzed. In addition, effects of the reduction of deformations expected by pretension of the soil nails are examined in detail throughout an illustrative example and $FLAC^{2D}$ program analysis. And a numerical approach is further made to determine a postulated failure surface as well as a minimum safety factor of the proposed PSN system using the shear strength reduction technique and the $FLAC^{2D}$ program. Global minimum safety factors and



(a) Required thickness of shotcrete facing

(b) Local safety factor

Fig. 14. Effect of radius of influence circle and required thickness of shotcrete facing

local safety factors at various excavation stages computed in case of the PSN system are analyzed through comparisons with the results expected in the case of the general soil nailing system. Based on the soil properties and geometric conditions described in Table 1 and Fig. 13, respectively, efficiency of the PSN system is examined. 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 facing wall system (See Fig. 3) is adopted in the present analyses.

As summarized in Table 2, values of the local minimum safety factors at the PSN system are much larger than predicted values of the local minimum safety factors at the GNS system. It is estimated as 1.47, the minimum safety factor of the final excavation step that application of the pretension force is made up to the 5th nails. This means, it tends to increase so small that the increase rate of safety factor remains under 5.0%, compared with the safety factor of 1.40 which is not applied pretension force. But, in each step of the excavation, the effective range of local increment of safety factor was estimated by fair value of 28.6% to 49.2%. Also, it agrees with the results analyzed by shear strength reduction technique which is proposed in this study. While, in the case of prestressed nail which is installed 1st to 5th step, it is estimated that the shotcreted facing of the PSN system may require more thickness about 1.2 to 2.6 times compared with the thickness of generally shotcreted facing. Further, based on the proposed facing wall system (HLU board + shotcrete, Fig. 3 (a)) in chapter 2, it is estimated that the thickness of shotcreted front facing of the PSN system is almost the same as that of the GSN system or can be reduced to lower level than that of the GSN system.

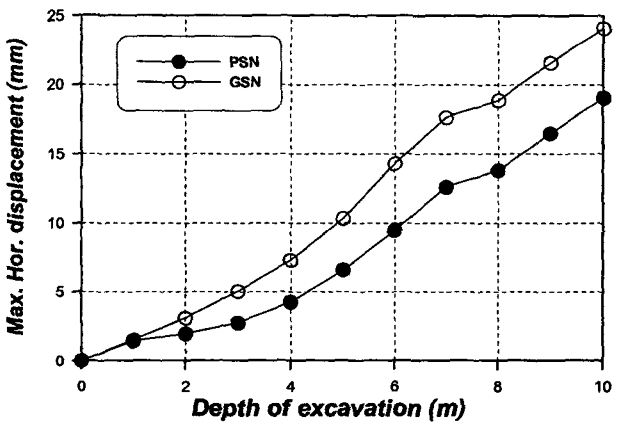
4.3 Reduction of Max. Displacement and Settlement

As previously mentioned, the PSN system has not yet been broadly used in the Korea. Since full-scale experimental data are not presently available, restricted analysis data obtained from the numerical analysis are performed in the present study. 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 are performed at every excavation stages to estimate accumulated deformations. As clearly observed in Fig. 15 (a), accumulated displacement of the facing wall with depths at the final excavation stage is 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

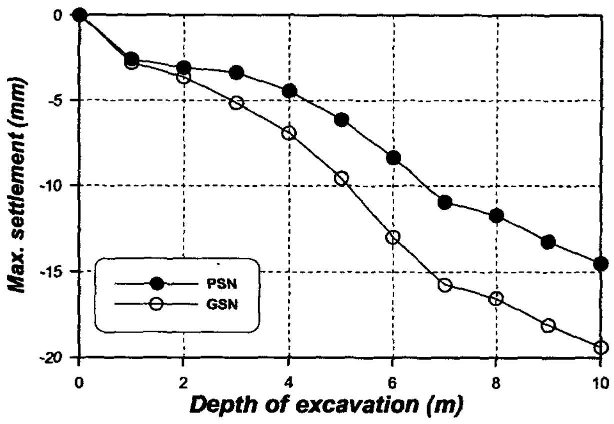
Table 2. Results of comparison

Excavation stage	PSN system			GSN system	
	Local minimum safety factor LEM / SSR	Req. thickness of facing(cm)	Req. bonded length(m) / Max. pretension force(ton)	Local minimum safety factor LEM / SSR	Req. thickness of facing (cm)
1 step	2.73 / 2.70	1.53*(7.93)	1.09 / 4.15	1.83 / 1.82	6.71
2 step	2.75 / 2.71	1.48*(8.43)	1.02 / 5.24	2.07 / 2.05	4.91
3 step	2.64 / 2.63	1.72*(9.80)	0.99 / 6.40	1.96 / 1.94	4.88
4 step	2.58 / 2.54	1.96*(11.08)	0.97 / 7.65	1.87 / 1.85	4.85
5 step	2.28 / 2.25	2.29*(12.53)	1.01 / 8.93	1.78 / 1.76	4.83
6 step	2.15 / 2.13	2.09*	-	1.70 / 1.69	4.81
7 step	2.04 / 2.02	2.08*	-	1.62 / 1.62	4.79
8 step	1.94 / 1.92	2.07*	-	1.55 / 1.52	4.77
9 step	1.68 / 1.67	2.06*	-	1.47 / 1.46	4.75
Final step	1.47 / 1.45	2.05*	-	1.40 / 1.39	4.73

▶ Remarks : ① * : HLU board + Shotcrete, ② ( ) : only shotcrete, ③ SSR : Shear Strength Reduction technique (by $FLAC^{2D}$ pro.), ④ LEM : Limit Equilibrium Method (by proposed procedure and technique)



(a) Max. Hor. displacement



(b) Max. settlement

Fig. 15. Comparison of accumulated horizontal displacement between PSN system and GSN system

the maximum displacement in magnitude is 5.02 mm (21%) in the case of applying the pretension forces up to the 5th 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 5th nail as illustrated in Fig. 15 (b). Dominant reductions in settlements are taken place within a horizontal distance of 7.5 m from the top of the facing wall. The magnitude of a reduction of the maximum settlement is 4.87 mm (25%). It is inferred from the distinct features analyzed in Fig. 13 that the PSN system can possibly be used to control deformations within allowable limits in cases when excessive deformations are expected to occur.

5. 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 global stability of the PSN 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 shear strength reduction technique with the $FLAC^{2D}$ program. As an efficient resolution of the excessive facing thickness due to the additionally applied pretension force, modified facing wall system is also proposed.

From the analyses conducted in the present study, it is partly proven that the PSN system has advantages in reducing both the facing displacements and the adjacent ground settlements. It is also partly proven that the PSN 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 facing wall system may be advantageous both to reduce the facing thickness and to increase the reliability.

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