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An Experimental Study on Behavior Characteristics of the Pretension Soil Nailing Systems

프리텐션 쏘일네일링 시스템의 거동특성에 관한 실험적 고찰

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요 지

쏘일네일링 공법은 도심지 지하굴착 공사에 있어, 지중매설물이 인접하여 존재하거나 대지경계선 등의 준수 등 시공조건에 따라서 설치네일의 길이가 제한되는 경우 및 연약한 지반조건으로 구성된 사면을 보강할 경우 등과 같은 벽체변위 및 지표침하 억제와 안정성 증대 등을 위하여, 지반앵커공법(ground anchor system)과 유사한 프리텐션 방식의 도입이 필요한 실정이다. 지반앵커공법과 유사한 프리텐션(pretension) 방식의 쏘일네일링 공법을 도입하게 될 경우, 프리텐션 하중에 의해 네일 두부에 부착된 지압판 등은 전면벽체에 수동토압을 유발시키게 되므로, 일반 쏘일네일링 벽체에서 발생하는 주동토압을 어느 정도 경감시킬 수 있을 것으로 기대되며, 아울러 단계별 굴착시 발생하는 변위를 최소화할 수 있을 것으로 예상된다. 따라서, 본 연구에서는 단계별 굴착시 유발되는 벽체변위 및 침하량 등을 억제하기 위한 노력의 일환으로, 프리텐션 쏘일네일링 시스템을 개발하였다. 또한 본 연구에서는 실내모형실험을 토대로 프리텐션 쏘일네일링 벽체의 거동특성 및 발휘되는 토압 등을 정량적으로 분석하여 프리텐션 효과에 따른 쏘일네일링 벽체의 파괴유형을 규명하였다. 아울러, 프리텐션 효과가 쏘일네일링 벽체 안정성에 미치는 영향을 검토하여, 향후 예상되는 프리텐션 효과에 따른 수평토압 감소 및 주면마찰력 증가 등의 지반-네일 상호작용을 고려한 해석기법개발에 필요한 기초적인 자료를 제시하고자 한다.

Abstract

Application of the soil nailing method is continuously extending in maintaining stable excavations and slopes. 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, 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 an 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 PSN system has been investigated mainly focusing on an establishment of the design procedure. In the present study, laboratory model tests are carried out to investigate the failure mechanism and behavior characteristics of the PSN system. Various results of model tests are also analyzed to provide a fundamental basis for the efficient design.

Keywords : Behavior characteristics, Global stability, Laboratory model tests, Pretension soil nailing system

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1. Introduction

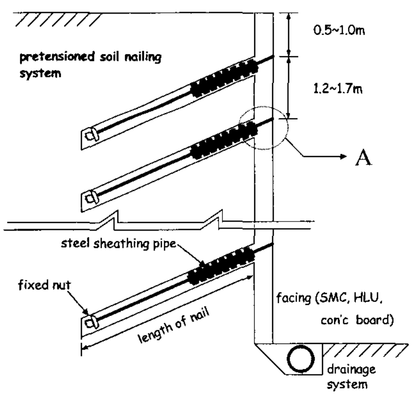
The general soil nailing (GSN) system has usually been applied for temporary pit excavation, the support of the cut slopes for road construction, and the support of natural slopes next to houses since its first use in 1993 for temporary retaining walls in Korea. Also, this system can be utilized diversely 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. 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 an 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 this study with a laboratory model test, the following factors will be analyzed by the different pretension force: 1) The behavior of the pretension soil nailed reinforced body; 2) The pull-out force acting on the head of the nail; 3) The failure mode of the pretension soil nailed wall; 4) The displacement of the pretension soil nailed wall at the allowable state and the limit state; and 5) The tensile force distribution at the nail head. Finally, basic data to develop the pretension soil nailed interaction model will be suggested.

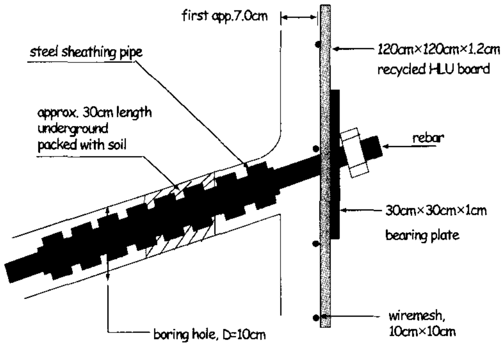
2. Basic Concept

2.1 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. 2 & 3. In this case (see Fig. 2), 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. 3), in order for large scale stripping to occur, the plate capacity must be exceeded and cement grout must fill in the sheathing pipe. 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, friction stress expected to mobilize at the interface between the

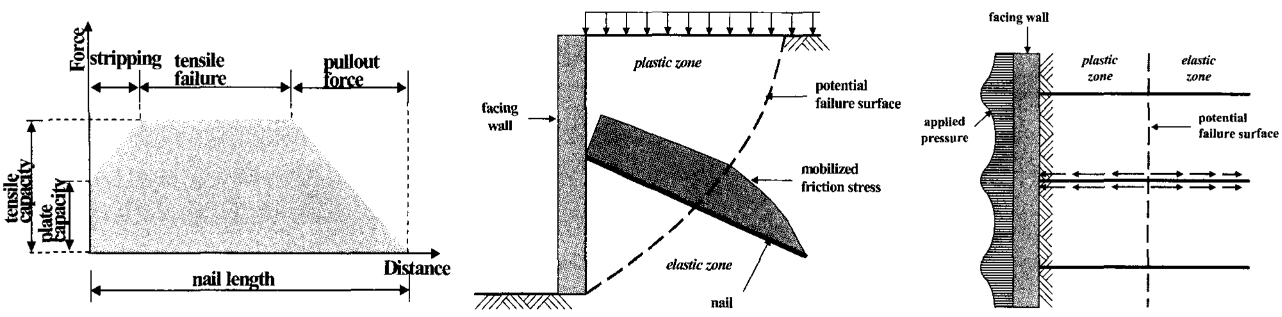


(a) Typical section



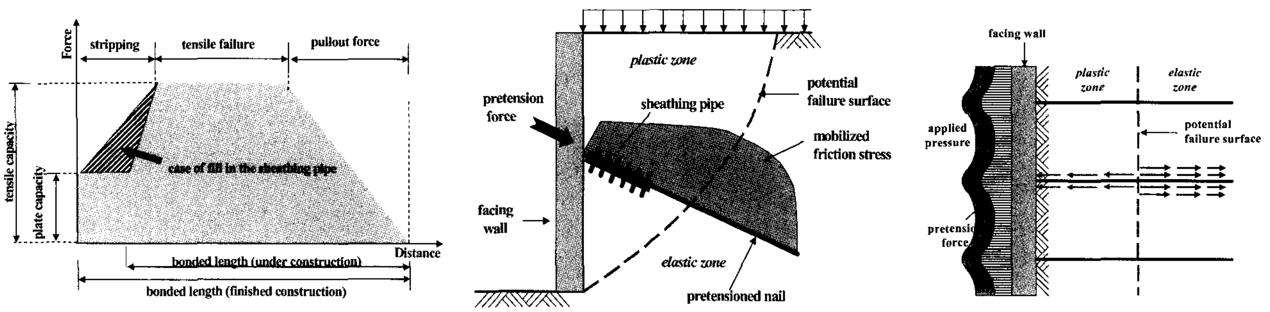
(b) Detail "A"

Fig. 1. Construction details of the PSN system



(a) Force diagram (b) Friction diagram (c) Resistance force diagram

Fig. 2. The GSN system



(a) Force diagram (b) Friction diagram (c) Resistance force diagram

Fig. 3. The PSN system

nail and surrounding soils is approximately estimated based on the research results proposed by the Lieng & Feng (1997) for the case of ground anchor.

2.2 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 examined 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 et al., 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 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.

$$q_s = \frac{T}{\rho L_s} \tag{1}$$

where, T : pull-out force,

ρ : nail perimeter ($\pi \cdot d$), and

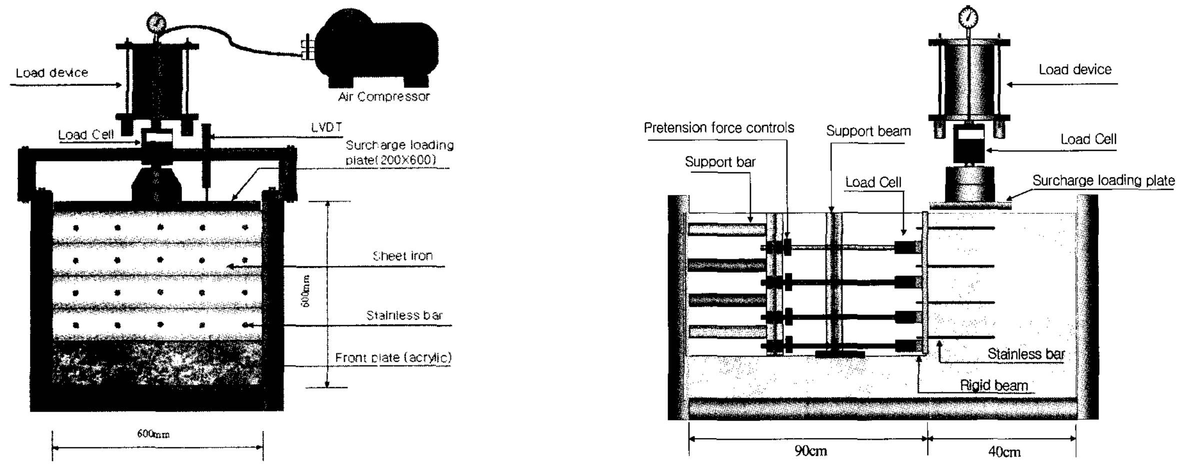
L_s : length in contact with the soil

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.

3. Laboratory Model Test

3.1 Introduction

The laboratory model test is conducted to examine the effect of the pretension force on the soil nailed body with the consideration of the length of a soil nail and the surcharge load location. The apparatus includes a 1300mm long × 600mm wide × 600mm deep soil tube as shown in



(a) A front view (b) A side view

Fig. 4. The apparatus of laboratory model test

Fig. 4 (Kim et al., 2001; Yoo et al., 2001; Kim et al., 2002; Kim et al., 2003; Park, 2003).

The soil used in this model is composed of Jumunjin standard sand and weathered granitic soil (with a ratio of 1:1.5) and the soil body is self-supported after excavation. Excavation will be performed in steps in consideration of the construction process of a soil nailed wall system in the field. The grain size distribution curve of the soil is shown in Fig. 5 and its index properties are shown in Table 1.

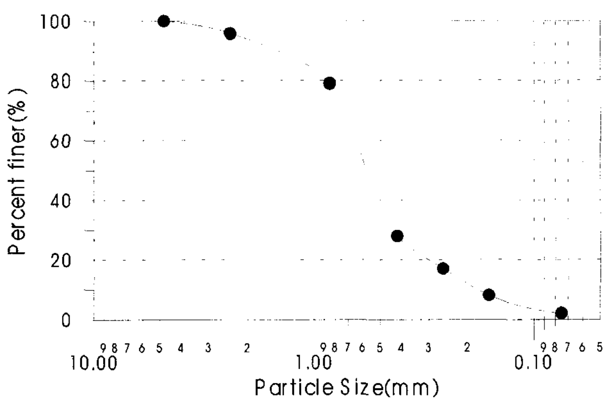


Fig. 5. The size distribution curve

Table 1. The properties of the soil

Items	Values
Unit weight	1.49tf/m^3
Friction angle	34°
Cohesion	0.8tf/m^2
Limit of liquidity	28.8%
Limit of plasticity	17.6%

Two types of stainless bars will be used for the nails, the first type will be 200mm long and 3mm in diameter, and the second type will be 300mm long and 3mm in diameter. The 10mm long protrusion spiral line is used at the nail head to tie the front plate and the sheet iron together. The sheet iron, acting as a shotcrete in the field construction, has dimension of 600mm long ×100mm wide with 0.2mm thickness. The acrylic plates (600mm long×400mm wide with 2mm thickness) are used for the front plate and act as a rigid wall in the field construction. The surcharge loading plate is 600mm long×200mm wide. Five LVDTs, one 5-ton capacity load cell (to measure load), four 3kg capacity load cells (to measure nail tension) are installed at the surcharge loading plate and the front plate. The vertical and horizontal displacements of the wall and tensile force on the nails, varying with excavation step and surcharge loading, are calculated through the data logger.

3.2 Test Procedure

The laboratory model tests are conducted by applying static loading. Loading is applied at each excavation interval by an air compressor until failure of the wall occurs. To distribute the load on soil nailed body equally, the point load produced by the loading device is converted to a uniformly distributed load by a 600mm long × 200mm wide by 12mm thick plate. Also, the nail protruding through the front plate is connected to the front plate by fixed rings to measure the load acting on the nail and the front plate separately. The pull-out force acting on the nail head (located in the center of each stage) is measured by placing a load cell between the fixed ring. The load acting on the soil nailed body is measured by placing the load cell placed between the loading device and the loading plate. LVDTs located at the top of the stiffened loading plate and the center of each stage are used to measure vertical and horizontal displacement and settlement. Also, four different pull-out tests (pull-out speed of 1mm/min) with the strain control method are conducted for different nail diameters and nail installation depths. The twelve laboratory model tests (Table 2) and two pull-out tests (Table 3) were conducted to verify the effects of the pretension force.

Table 2. Case of laboratory model tests

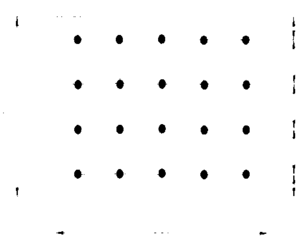
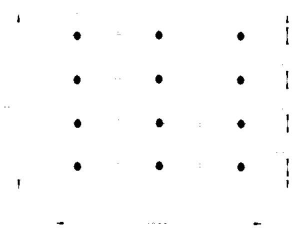
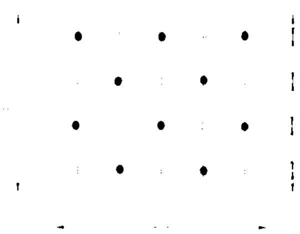
Case	Thickness of the front plate (mm)	Pretension force (kg)	Nail length (mm)	Number of installation nail	The loading device	Type of installation nail
A-1	2	0	200	20 (Type I)	20cm×60cm	
A-2		19				
A-3		28				
A-4		37				
A-5		0	300		30cm×60cm	
A-6		25				
A-7		37				
A-8		50				
B-1	2	0	200	12 (Type II)	20cm×60cm	
B-2		11				
B-3		17				
B-4		22				
B-5		0	300		30cm×60cm	
B-6		15				
B-7		22				
B-8		30				
C-1	2	0	200	10 (Type III)	20cm×60cm	
C-2		10				
C-3		14				
C-4		18				
C-5		0	300		30cm×60cm	
C-6		12				
C-7		18				
C-8		25				

Table 3. Specifications and result of pull-out tests

No.	Insertion depth (mm)	Nail diameter (mm)	Nail length (mm)	pretension force (kg)	
				elastic limit state	plastic limit state
1	150	3	200	0.95	1.86
2	150	3	300	1.27	2.54

4. Test Results & Analysis

4.1 Failure Pressure and Settlement with Increased Pretension Force

In the laboratory model tests are performed in order to investigate interaction among surcharge pressure, vertical and horizontal displacement, influence caused by nail length and installation form, etc., and orientation of failure surcharge pressure caused by pretension force being varied in soil nailing system. In this study, failure pressure means pressure of moment when large vertical displacement is occurred abruptly with small increase in surcharge pressure. In other words, failure pressure is pressure of moment occurring failure, and related to the whole stability of soil nailing system directly. Results of the laboratory model tests are shown in Table 4.

4.2 The Pressure at Failure with Increased Pretension Force

The relationships between failure pressure versus pretension force of the PSN systems, which can examine increasing pretension force and failure pressure patterns until failure, are shown in Fig. 6.

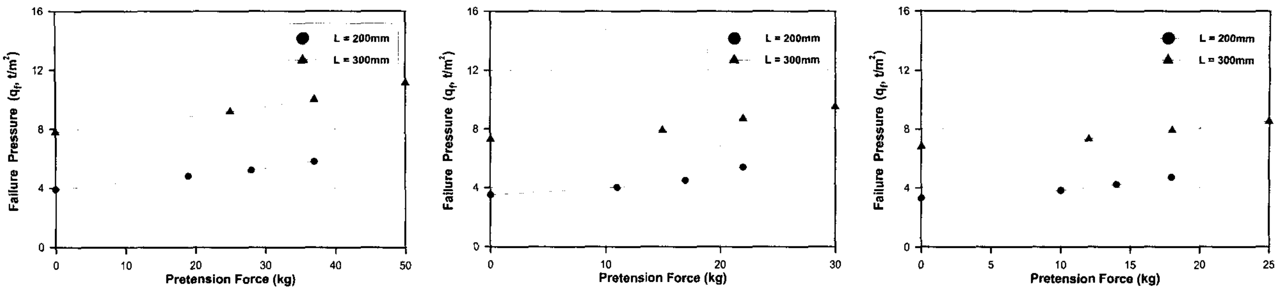
In spite of the different pretension force conditions and nail lengths in cases A, B and C, the pressures at failure are linearly increased by 1.38～1.54 times of the elastic pretension force.

4.3 Horizontal Displacement with Increased Pretension Force

The test case A series, the horizontal displacement at different depths along the front plate with the failure pressures (q_f) are shown in Fig. 7.

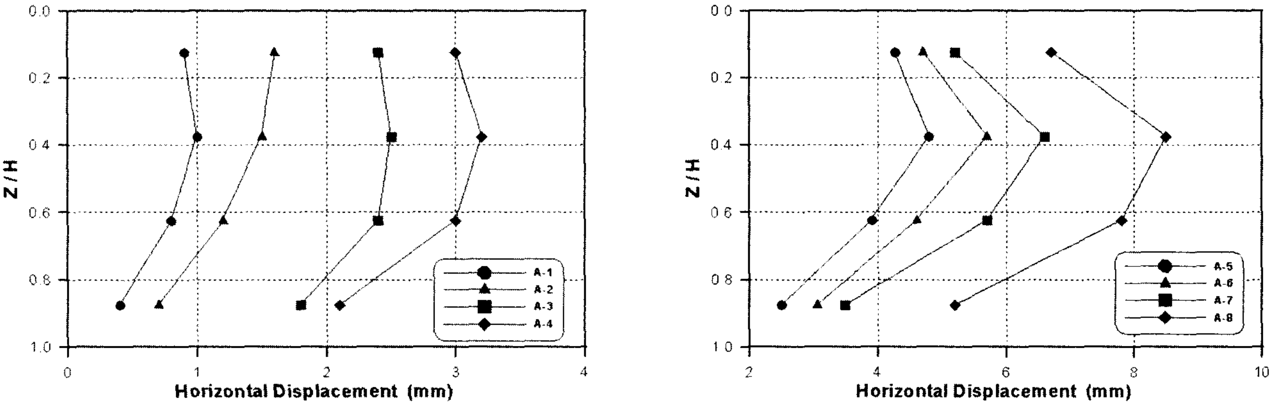
Table 4. Failure pressure and settlement with increasing pretension force

Case	Type of installation nail	Nail length (mm)	Pretension force (kg)	Failure pressure (q_f, t/m^2)	Settlement at failure pressure (mm)	Settlement of the PSN system at failure pressure of the GSN system (mm)
A-1	TYPE I	200	0	3.9	3.7	
A-2			19	4.8	5.3	3.1
A-3			28	5.2	5.7	2.4
A-4			37	5.8	6.6	2.2
A-5		300	0	7.7	7.8	
A-6			25	9.2	11.1	6.9
A-7			37	10.2	13.0	6.1
A-8			50	11.1	14.0	5.1
B-1	TYPE II	200	0	3.5	3.6	
B-2			11	4.0	5.3	3.6
B-3			17	4.5	6.4	2.2
B-4			22	5.4	9.5	2
B-5		300	0	7.3	7.0	
B-6			15	7.9	10.1	6.4
B-7			22	8.7	11.1	6.0
B-8			30	9.5	12.6	5.0
C-1	TYPE III	200	0	3.3	3.4	
C-2			10	3.8	4.5	3.0
C-3			14	4.2	5.3	2.5
C-4			18	4.7	6.4	2.1
C-5		300	0	6.8	6.5	
C-6			12	7.3	7.5	6.2
C-7			18	7.9	9.2	5.7
C-8			25	8.5	9.7	4.8



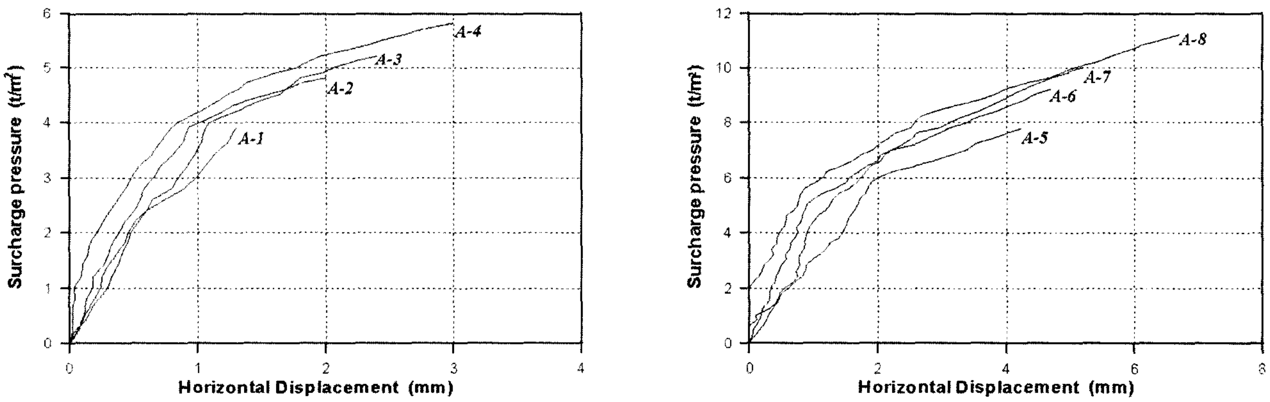
(a) Case A series (b) Case B series (c) Case C series

Fig. 6. Relationship of the failure pressure versus pretension force of the PSN systems



(a) Nail length = 200mm (b) Nail length = 300mm

Fig. 7. The horizontal displacement with the failure pressures (qf)



(a) Nail length = 200mm (b) Nail length = 300mm

Fig. 8. The relationships between surcharge pressure and the hor. displacement at the point of z/H ratio 0.375

From the Fig. 7, it is found out that the z/H ratios of 0.375 and 0.625 were evident where the horizontal displacement has increased and the impacted surface deformed with arch shape. In addition, the relationship between the surcharge pressure and the maximum horizontal displacement at the point of z/H ratio, 0.375 can be summarized in Fig. 8. In case of the nail length of 200mm, Fig. 8 (a), regarding the GSN system's failure surcharge pressure point of 3.9t/m^2, horizontal displacement has decreased by around 40% with a pretension force of 37kg by 3.7mm for case A-1 and 2.2mm for case A-4, respectively.

Furthermore, the analysis of horizontal displacement using 300mm nail, Fig. 8 (b), using 7.7t/m^2 of surcharge pressure resulted in 7.7mm for case A-5 and 5.1mm for case A-8. As such, if the pretension force is increased, it is evident that the horizontal displacement is decreasing which is caused by the increased surcharge pressure. Also, the relationship between increased pretension force and decreased horizontal displacement shows that the shorter nails are more appropriate for the given force than the longer specimen.

4.4 Earth Pressure Acting on the Soil Nailed Wall with Increased Pretension Force

4.4.1 Nondimensional Constant, *TN*

Modified equation (2) is proposed to verify the earth pressure acting on the soil nailed wall with a rigid front plate. In this equation, $\cos\theta$ is eliminated because the nail is inserted horizontally, the overburden pressure term ($\gamma \cdot z$) is modified to include a surcharge pressure ($\gamma \cdot z + q$) and $T_{\max}$ is changed to T_i, which is the tension at the nail head (T_o) at each depth by assuming the maximum nail tension forces ($T_{\max}$) is equal to the tension forces at the nail head(Park, 2003).

$$TN = \frac{T_i}{\sigma_v \cdot S_H \cdot S_V} = \frac{T_i}{(\gamma \cdot z + q) \cdot S_H \cdot S_V} \quad (2)$$

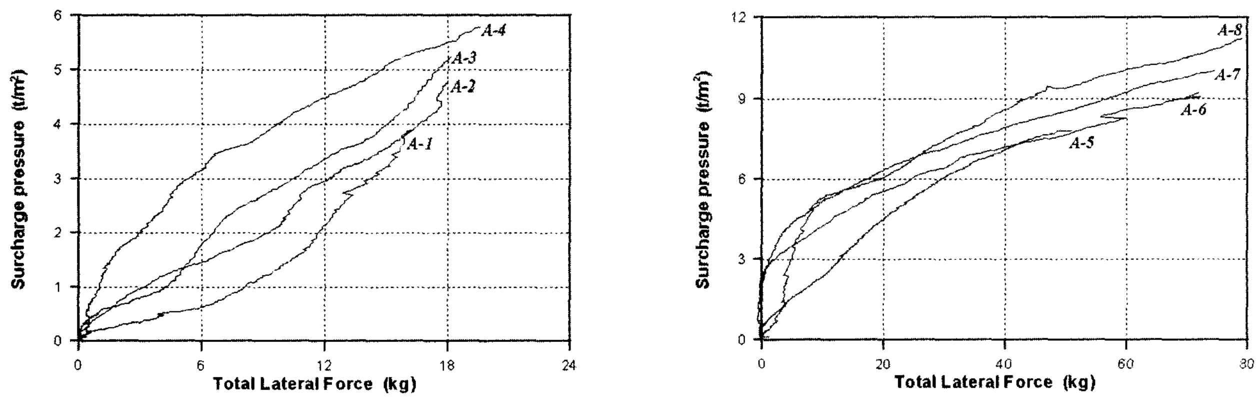
Where, T_i : the nail tensile force at each depth (T_o),
γ : the total unit weight of the soil,
z : the nail depth,
q : the surcharge pressure,
S_H : the horizontal nail distance, and
S_V : the vertical nail distances.

Several reports on soil nailed wall technology including the Clouterre project in France have indicated that the ratio $T_o / T_{\max}$ is always less than 1 and the ratio is amplified by increasing the front plate rigidity. In this test, the maximum nail tensile force ($T_{\max}$) is assumed to be equal to the tensile force at the nail head (T_o), because a highly rigid wall is used instead of a ductile wall (usually the case for soil nailed walls) and because the nail length is relatively short.

4.4.2 Earth Pressure Acting on the Soil Nailed Wall with Increased Pretension Force

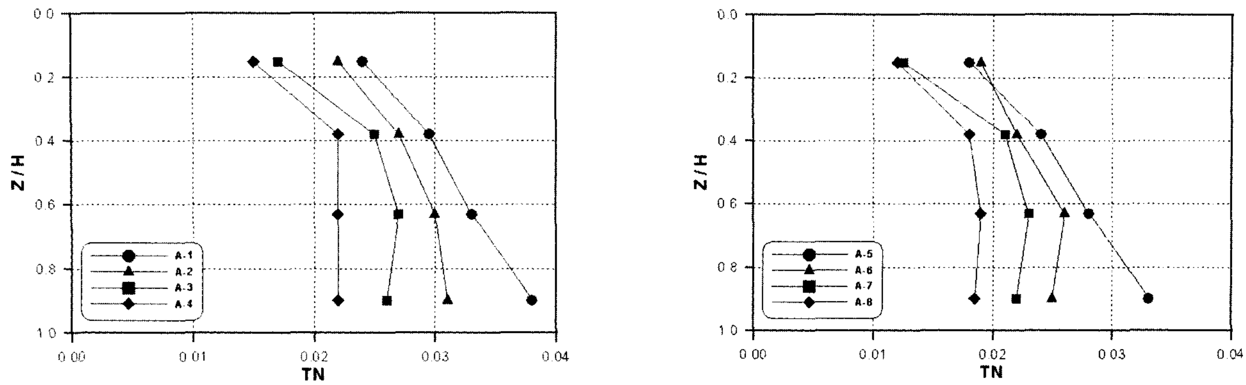
The relationship between total lateral force and surcharge pressure that measured by load cell, which is located 10, 20, 30 and 40cm below from the upside of front plate, is shown in Fig. 9.

From the test results shown in Fig. 9 (a), total lateral force was analyzed with criteria of failure surcharge pressure (3.9t/m^2) of GSN system and it was estimated that 16.4kg in case A-1 and 9.4kg in case A-4, as a result, total lateral force was decreased by 42% at pressed pretension force of 37kg. From the results of the tests shown in Fig. 9 (b), total lateral force was analyzed with criteria of failure surcharge pressure (7.7t/m^2) of GSN system and it was estimated at 50.9kg in case A-5 and 34.7kg in case A-8. As a result, total lateral force was decreased by 31% when pressed pretension force is 50kg. Therefore, the pretension forces were increased up from elastic zone to plastic zone that total lateral force with



(a) Nail length = 200mm (b) Nail length = 300mm

Fig. 9. Relationship of total lateral force and surcharge pressure with increased the pretension force



(a) Nail length = 200mm (b) Nail length = 300mm

Fig. 10. The tensile force at the nail head with increased the pretension force

the same surcharge pressure condition decreased by 16～42% and 23～31% in case of nail length is 200mm and 300mm.

Based on the assumptions in section 4.4.1, the tensile force at the nail head (T_o) as a function of depth in case A series is shown in Fig. 10 to analyze earth pressure distributions acting on the pretension force along the soil nailed wall.

The *TN* distributions at the failure surcharge pressure state (q_f) in Fig. 10 show a similar trend to trapezoidal shaped earth pressure profiles. But, by increasing the load stages, cases A-1 and A-5 show an increasing *TN* at the bottom and yield a similar trend to triangular shaped earth pressure profiles at failure. This indicates that the trapezoidal shaped earth pressure profiles acting on the PSN systems are observed at failure load state and that triangular shaped earth pressure profiles acting on the GSN systems are observed at failure. Also, the load at the allowable limit ($\delta_{h(\max)}/H$ = 0.4%; Juran, 1990; Manual for Design and Construction Monitoring of Soil Nail Walls, FHWA-SA-96-069) in all cases is around 52% of the maximum skin friction (q_{smax}), which is 25～50% of the failure surcharge pressure (q_f). This predicts that the *TN* versus *z/H* profile in this section is trapezoid in shape. These results are concluded that if the allowable limit is ignored, then a triangular shaped earth pressure profile is acting on the GSN system, and if the allowable limit is considered, then a trapezoidal shaped earth pressure profile is acting on the PSN system.

5. Conclusions

This study examined failure load by various pretension forces, displacement at the wall and tensile forces acting at the nail head. Also, the earth pressure distributions acting on the soil nailed body were observed by analyzing the effect of various pretension forces. The results are summarized as follows.

(1) According to the results from the failure pressure versus pretension force of the PSN systems relationships, in spite of the different pretension force conditions and nail lengths in cases A, B and C, the pressures at failure are linearly increased by 1.38～1.54 times of the elastic pretension force (see Fig. 6).

(2) In the case of the horizontal displacement at different depths along the front plate acting on the soil nailed wall with increased pretension force, it is found out that the z/H ratios of 0.375 and 0.625 were evident where the horizontal displacement has increased and the impacted surface deformed with arch shape (see Fig. 7).

(3) The result from the relationship between the surcharge pressure and the maximum horizontal displacement at the point of *z/H* ratio, 0.375, is: in case of the nail length of 200mm, regarding the GSN system's failure surcharge pressure point of 3.9t/m^2, horizontal displacement has decreased by around 40% with a pretension force of 37kg by 3.7mm for case A-1 and 2.2mm for case A-4. Furthermore, the

analysis of horizontal displacement using 300mm nail, using 7.7t/m^2 of surcharge pressure resulted in 7.7mm for case A-5 and 5.1mm for case A-8. As such, the pretension force is increased, and it is evident that the horizontal displacement is decreasing which is caused by the increased surcharge pressure. Also, the relationship between increased pretension force and decreased horizontal displacement was found out that the shorter nails are superior to the longer specimen (see Fig. 8).

(4) The pretension forces were increased up from elastic zone to plastic zone that total lateral force with same surcharge pressure condition decreased by 16~42% and 23~31% in case nail length is 200mm and 300mm (see Fig. 9).

(5) Based on the assumptions in section 4.4.1, the TN distributions at the failure surcharge pressure state (qf) show a similar trend to trapezoidal shaped earth pressure profiles. But, by increasing the load stages, cases A-1 and A-5 show an increasing TN at the bottom and yield a similar trend to triangular shaped earth pressure profiles at failure. This indicates that the trapezoidal shaped earth pressure profiles acting on the PSN systems are observed at failure load state and that triangular shaped earth pressure profiles acting on the GSN systems are observed at failure (see Fig. 10). Also, the load at the allowable limit ($\delta_{h(\max)}/H$= 0.4%) in all cases is around 52% of the maximum skin friction (q_{smax}), which is 25~50% of the failure surcharge pressure (q_f). This predicts that the *TN* versus *z/H* profile in this section is trapezoid in shape. These results are concluded that if the allowable limit is ignored, then a triangular shaped earth pressure profile is acting on the GSN system, and if the allowable limit is considered, then a trapezoidal shaped earth pressure profile is acting on the PSN system.

(6) In order to properly analyze the behavior of the soil nailed body and nail front plate interactions for the different pretension forces in the future, laboratory and field tests are desired with various loads and various nail conditions.

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