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Performance of IPS Earth Retention System in Soft Clay

연약지반에 적용된 IPS 흙막이 시스템의 거동 특성

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요 지

본 연구에서는 도심지 연약 지반에 적용된 IPS(Innovative Prestressed Support) 흙막이 시스템의 거동을 파악하고 안정성을 확인하였다. 새로운 IPS 흙막이 시스템은 강선의 인장 저항을 이용하여 띠장의 강성을 획기적으로 증가시켜 버팀보의 설치 간격을 대폭 증가시키는 공법이다. IPS 흙막이 시스템이 적용된 현장은 부산 북부 지역내에 위치한 폭 28.8m, 길이 52.0m 그리고 굴착 깊이 16.1m 규모의 굴착 현장으로서 느슨한 매립토와 연약 점토로 이루어져 있으며 두께 650mm의 지중 연속벽, 5 단의 IPS 시스템과 중앙 스트럿으로 지지되어 있다. 시공이 진행되는 동안에 경사계 6 곳, 지하 수위계 4 곳, IPS 띠장에 설치된 변위계 30 곳, 스트럿에 설치된 변형율계 20 곳에서 현장 데이터를 계측 수집하였다. 연약 지반에 적용된 IPS 흙막이 공법은 성공적으로 수행되었다. IPS 흙막이 공법의 시공을 통하여 공법의 적용성을 확인하였으며 현장 계측 결과를 분석하고 예비 설계 내용과 비교하여 연약 지반에서의 IPS 흙막이 공법의 거동을 확인하고 안정성을 평가하였다.

Abstract

The performance of innovative prestressed support (IPS) earth retention system applied in soft clay was investigated and presented. The IPS wale system provides a high flexural stiffness to resist the bending by lateral earth pressure, and transfers lateral earth pressure to strut supports. The IPS wale system provides a larger spacing of support than conventional braced and anchored systems. The IPS earth retention system was selected for temporary earth support in a building construction in North Busan area. The excavation was made 28.8 m wide, 52.0 m long, and 16.1 m deep through loose fill to soft clay. The IPS system consists of 650 mm thick slurry walls, and five levels of IPS wales and struts. Field monitoring data were collected including wall deflections at six locations, ground water levels at four locations, IPS wale deflections at thirty locations, and axial loads on struts at twenty locations, during construction. The IPS earth retention system applied in soft clay performed successfully within a designed criterion. Field measurements were compared with design assumptions of the IPS earth retention system. The applicability and stability of the IPS earth retention system in soft clay were investigated and evaluated.

Keywords : Clayey soil, IPS earth retention system, Stability, Urban excavation

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1. Introduction

Innovative prestressed support (IPS) earth retention systems, which were developed as an alternative method to strut supports and anchored supports, have been applied in various excavations, for examples water lines, buildings in urban area, subway stations, and bridge piers. The basic mechanism and design method of the IPS earth retention system were proposed by Han et al. (2003), Kim et al. (2004), and Kim et al. (2005). In order to investigate a stability of IPS earth retention system, a pilot test of the IPS system was performed in a trench excavation for water lines (Kim et al. 2004) and a field monitoring of the IPS earth retention system was performed in an urban excavation site with multi-layered ground conditions (Kim et al. 2005).

The IPS earth retention system was applied in soft clay in North Busan. The excavation was 28.8 m in width, 52.0 m in length, and 16.1 m in depth. The IPS system consisted of slurry wall, thirty IPS wales, forty corner struts, and six center struts. As can be seen in Photo 1, the IPS earth retention system in soft clay performed successfully, providing larger workspace than conventional support systems.

This paper summarizes the field performance of the IPS earth retention system applied in soft clay. A field monitoring was conducted during excavation. The field performance data were collected and analyzed in order to evaluate the stability of the IPS earth retention system, and were compared with the design predictions.

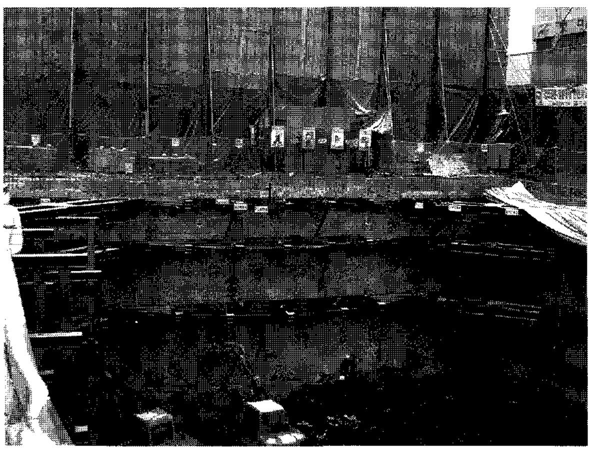


Photo 1. IPS earth retention system applied in soft clay

2. IPS Earth Retention System in Soft Clay

2.1 Site Location

This project is the construction of an official building, which consists of 10 stories of super-structure and four levels of basement on pile groups. A plan view of site locations is shown in Fig. 1. The site was surrounded by the roads, 15 m wide to the north, 15 m wide to the east, and 30 m wide to the south. The eight storied building is located in the vicinity of the west side of the excavation. The Nak-Dong River is located 650 m west away from the site and flows to the south.

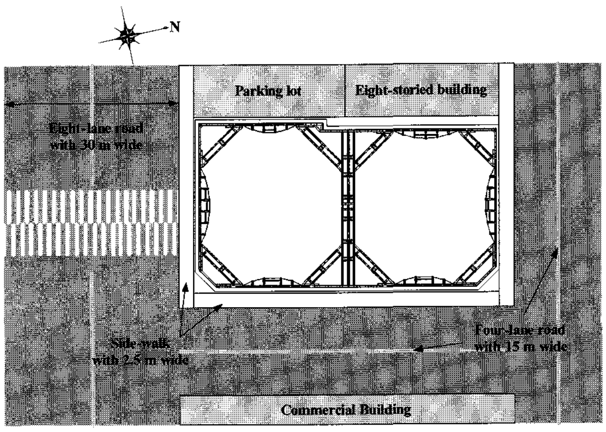


Fig. 1. Plan view of site locations

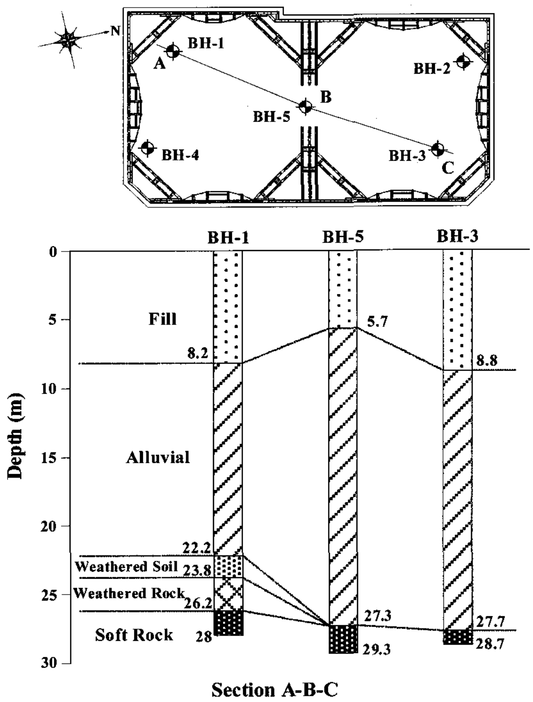


Fig. 2. Boring locations and soil profile distribution

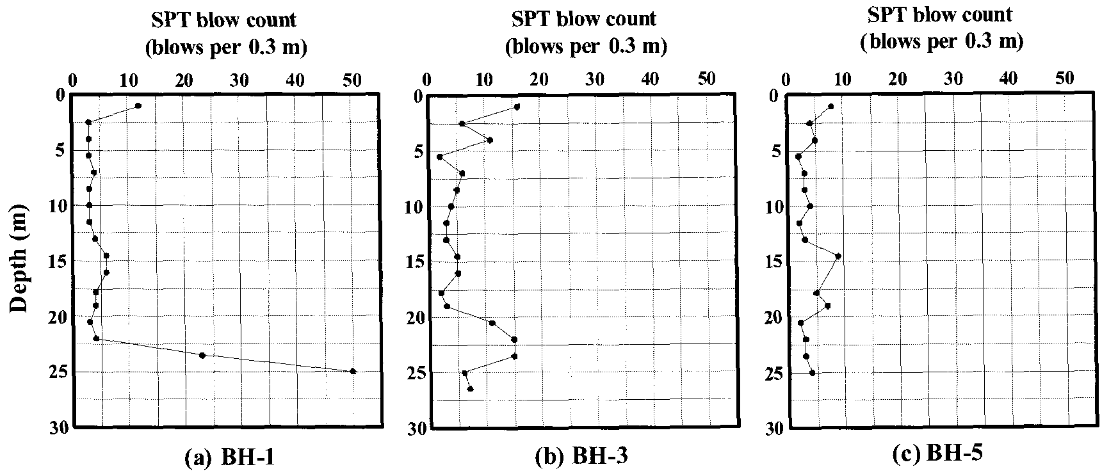


Fig. 3. Standard penetration test profile

2.2 Subsurface Conditions

The plan of borings, the soil profiles, and the standard penetration test profiles in the site were shown in Fig. 2 and Fig. 3. Five borings were drilled to identify the subsurface soil profile of the site. The subsurface soil consists of fill, silty clay, and soft rock. Fill is a composite of gravel, silty clay, and clayey sand. Dark gray silty clay with a shell underlies fill. Soft rock has gray brown color and is moderately weathered. Fill has SPT values ranging from 3 to 10. The silty clay has N values ranging from 2 to 7. Soft rock record N values less than 50 blows/50 mm. Soft rock is located at a depth of about 27.0 m below the street surface. The total unit weight of the clay is 18 kN/m^3. The undrained shear strength of the clay is very variable, and generally ranges from 7 to 67 kPa. The sensitivity of the clay is within the range of between 1.9 and 4.3. The ground water existed at 8.25 m from the ground surface.

2.3 IPS Earth Retention System

A plan view and typical section of the excavation are shown in Figs. 4 and 5, respectively. The excavation was 28.8 m wide, 52.0 m long and 16.1 m deep. A 650 mm-thick slurry wall was used to support the retained ground and the depth of the wall was 29.0 m. The wall was internally braced with five levels of IPS wales, corner struts, and center struts.

The IPS wale consists of wale, legs to support, steel wires, and hydraulic jacks as shown in Fig. 6. Details of the IPS wale are tabulated in Table 1. Corner struts consist of two H-beams and one steel plate. Beams with H300×300×10×15 (mm) were used at the first level. Beams with H350×350×12×19 (mm) were used to each

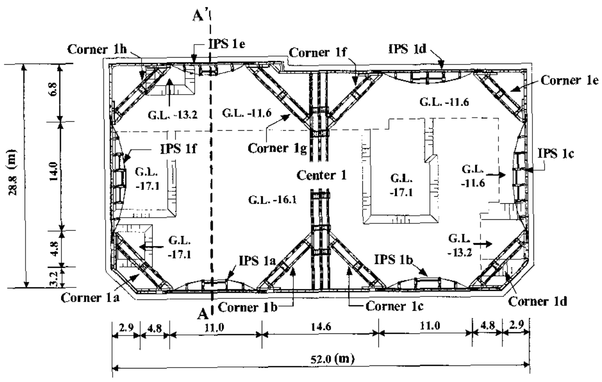


Fig. 4. Plan view of excavation

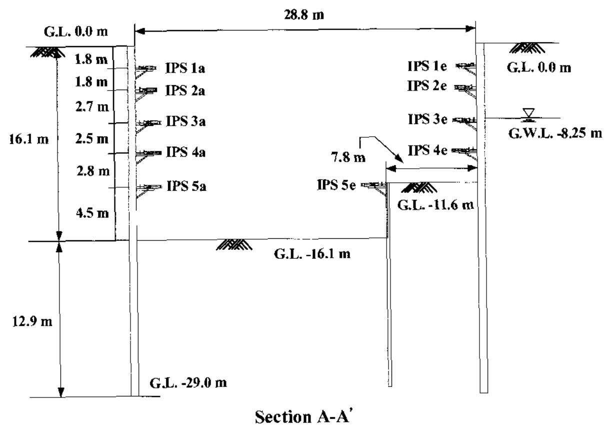


Fig. 5. Typical section of IPS wall

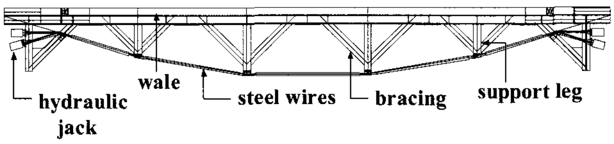


Fig. 6. Components of the IPS wale system

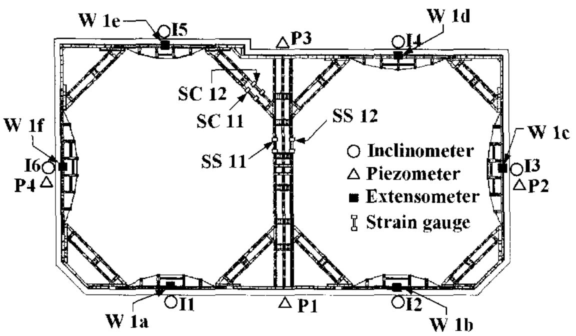
corner at the second to the fifth level. The length of H-beam was 5.5 m. The steel plate with 720 mm wide, 1,350 mm long, and 12 mm thick was bolted to two corner beams in order to prevent a buckling of corner beam from lateral earth pressures due to ground excavation. The center strut support consists of six H-beams and four steel plates. H-beams with H300×300×10×15 (mm) were used at the first level. Beams with H350×350×12×19 (mm) were used at the second to the sixth level. In order to prevent a buckling of the center strut support from lateral earth pressures by ground excavation, each H-beam used was bolted with steel plate with 720 mm wide, 2,700 mm long, and 12 mm thick.

2.4 Instrumentation

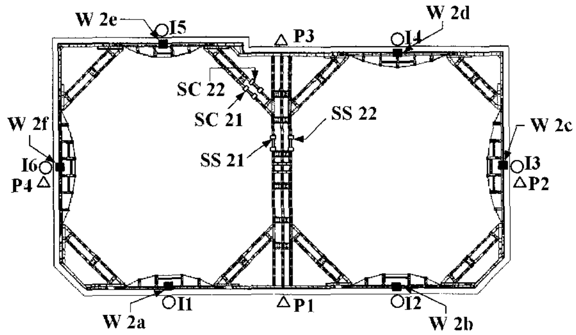
The instruments for field monitoring included six inclinometers, four piezometers, twenty vibrating wire strain gauges, and thirty extensometers. The wall deflections were observed using wall inclinometers during excavation. The inclinometer casings were installed just behind the wall located at the mid-span of the IPS wales and embedded to the depth of 20.0 m to 24.0 m below the ground surface. The ground water level was monitored using piezometers. Vibrating wire strain gauges were used to measure the changes in strut loads, and were attached on the corner struts and center strut installed at each floor. The extensometers were installed at the mid-span of the

Table 1. IPS wale data

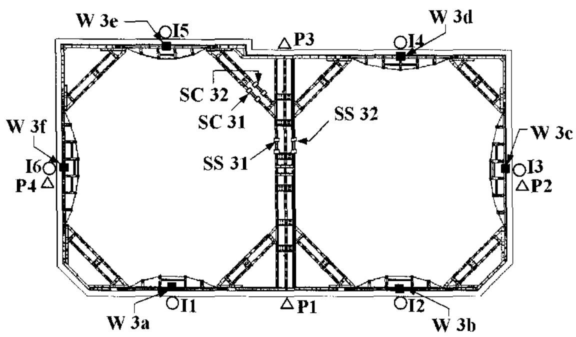
IPS wales		H-beam	Steel wires	Length of wales	Length of legs
1st level	IPS 1a, b	H300×300×10×15	ϕ15.2 mm, 7EA	11.0 m	1.29 m
	IPS 1c	H300×300×10×15	ϕ15.2 mm, 8EA	14.0 m	1.54 m
	IPS 1d	H300×300×10×15	ϕ15.2 mm, 7EA	13.0 m	1.44 m
	IPS 1e	H300×300×10×15	ϕ15.2 mm, 6EA	11.0 m	1.24 m
	IPS 1f	H300×300×10×15	ϕ15.2 mm, 8EA	14.0 m	1.54 m
2nd level	IPS 2a, b	H350×350×12×19	ϕ15.2 mm, 13EA	11.0 m	1.29 m
	IPS 2c	H350×350×12×19	ϕ15.2 mm, 17EA	14.0 m	1.54 m
	IPS 2d	H350×350×12×19	ϕ15.2 mm, 16EA	13.0 m	1.44 m
	IPS 2e	H350×350×12×19	ϕ15.2 mm, 11EA	11.0 m	1.24 m
	IPS 2f	H350×350×12×19	ϕ15.2 mm, 17EA	14.0 m	1.54 m
3rd level	IPS 3a, b	H350×350×12×19	ϕ15.2 mm, 15EA	11.0 m	1.29 m
	IPS 3c	H350×350×12×19	ϕ15.2 mm, 18EA	14.0 m	1.54 m
	IPS 3d	H350×350×12×19	ϕ15.2 mm, 18EA	13.0 m	1.49 m
	IPS 3e	H350×350×12×19	ϕ15.2 mm, 15EA	11.0 m	1.29 m
	IPS 3f	H350×350×12×19	ϕ15.2 mm, 18EA	14.0 m	1.54 m
4th level	IPS 4a, b	H350×350×12×19	ϕ15.2 mm, 27EA	11.0 m	1.29 m
	IPS 4c	H350×350×12×19	ϕ15.2 mm, 34EA	14.0 m	1.54 m
	IPS 4d	H350×350×12×19	ϕ15.2 mm, 33EA	13.0 m	1.49 m
	IPS 4e	H350×350×12×19	ϕ15.2 mm, 27EA	11.0 m	1.29 m
	IPS 4f	H350×350×12×19	ϕ15.2 mm, 34EA	14.0 m	1.54 m
5th level	IPS 5a	H350×350×12×19	ϕ15.2 mm, 27EA	13.0 m	1.49 m
	IPS 5b	H350×350×12×19	ϕ15.2 mm, 15EA	8.0 m	1.04 m
	IPS 5c	H350×350×12×19	ϕ15.2 mm, 25EA	12.0 m	1.44 m
	IPS 5d	H350×350×12×19	ϕ15.2 mm, 19EA	10.0 m	1.24 m
	IPS 5e	H350×350×12×19	ϕ15.2 mm, 30EA	16.0 m	1.54 m
	IPS 5f	H350×350×12×19	ϕ15.2 mm, 19EA	9.0 m	1.14 m



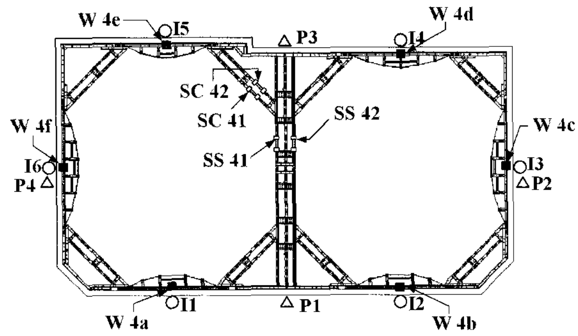
(a) Instruments on 1st level



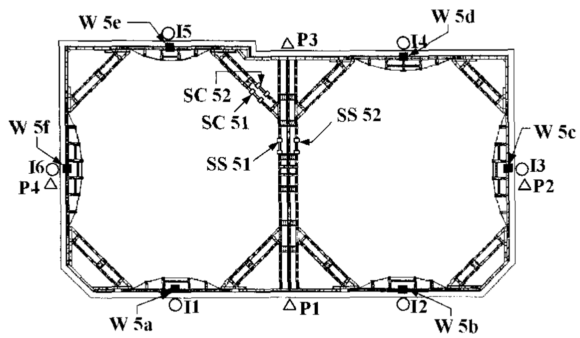
(b) Instruments on 2st level



(c) Instruments on 3st level



(d) Instruments on 4st level



(e) Instruments on 5st level

Fig. 7. Instrumentation layout

IPS wales in order to measure the horizontal deflections of the IPS wales during excavation. The location of the instruments is schematically described in Fig. 7.

2.5 Construction Sequence

Fourteen major construction stages are tabulated in Table 2. Prestresses on steel wires of the IPS wales and preloads on the corner struts and center struts are tabulated in Table 3.

3. Measured Performance

Field observation of the IPS earth retention system is summarized. The field monitoring began with the start of the slurry wall installation and was conducted in sequence up to the completion of the final ground excavation. The trends of the IPS wall deflection profiles obtained from the inclinometers were analyzed. The lateral deflections of the IPS wales from the extensometers were measured and compared with the designed assumptions. The loads on corner struts and center struts were observed and compared with the design predictions.

Table 2. Construction sequences

Step 1	Install the slurry wall.	Day 30
Step 2	Excavate to the depth of 2.8 m.	Day 38
Step 3	Install the IPS wales, corner struts, and center support at 1.8 m from the top of the wall. Prestress the IPS wales and preloading the center support.	Day 44
Step 4	Excavate to the depth of 4.8 m.	Day 50
Step 5	Install the IPS wales, corner struts, and center support at 3.6 m from the top of the wall. Prestress the IPS wales and preloading the center support.	Day 52
Step 6	Excavate to the depth of 7.3 m.	Day 59
Step 7	Install the IPS wales, corner struts, and center support at 6.3 m from the top of the wall. Prestress the IPS wales and preloading the center support.	Day 64
Step 8	Excavate to the depth of 9.8 m.	Day 81
Step 9	Install the IPS wales, corner struts, and center support at 8.8 m from the top of the wall. Prestress the IPS wales and preloading the center support.	Day 85
Step 10	Excavate to the depth of 12.6 m.	Day 91
Step 11	Install the IPS wales, corner struts, and center support at 11.6 m from the top of the wall. Prestress the IPS wales and preloading the center support.	Day 93
Step 12	Excavate to the depth of 16.1 m.	Day 102
Step 13	Install the center support at 13.8 m from the top of the wall and preloading the center support.	Day 112
Step 14	Excavate partially to the depth of 17.1 m.	Day 119

Table 3. Prestresses conditions of IPS earth retention system Unit (kN)

		IPS a	IPS b	IPS c	IPS d	IPS e	IPS f	Corners	Center
1st level	Design	1,205	1,205	1,533	1,424	1,205	1,533	1,402	2,803
	Actual	929	834	1,164	980	784	1,156	1,764	2,646
2nd level	Design	2,790	2,790	3,550	3,297	2,790	3,550	2,320	6,492
	Actual	1,980	1,980	2,440	2,254	1,611	2,440	1,764	3,528
3rd level	Design	3,482	3,482	4,431	4,115	3,482	4,431	2,896	8,102
	Actual	2,150	2,150	2,663	2,570	2,136	2,667	2,646	4,410
4th level	Design	3,482	3,482	4,431	4,115	3,482	4,431	2,896	8,102
	Actual	3,914	3,884	4,766	4,678	3,904	4,719	2,646	4,410
5th level	Design	3,956	2,434	3,652	3,043	4,809	2,739	2,784	7,790
	Actual	3,796	2,222	3,623	2,789	4,113	2,751	2,646	4,410
6th level	Design	–	–	–	–	–	–	–	6,855
	Actual	–	–	–	–	–	–	–	4,410

3.1 Lateral Deflections

The lateral wall deflection profile developed during main construction activities was shown in Fig. 8. The lateral wall deflections were measured by inclinometers 1 and 2, which were installed just behind the wall located at the mid-span of the IPS wales. When the excavation reached final grade, the maximum lateral wall deflections were 28.1 mm at the location of I1 and 31.2 mm at the location of I2, respectively. These results indicated that the maximum lateral wall deflections were less than 0.2% of excavation depth. The maximum lateral deflection of the IPS wall was 0.18% of the excavation depth. It was less than the deflection predicted using the Clough and O'Rourke (1990) chart for excavation cases in soft to medium clay. The maximum lateral deflection was less than the 0.2%H - 0.5%H reported by Ou et al. (1993) for excavations with a high factor of safety against basal heave, and was less than the results of numerical experiments reported by Hashash and Whittle (1996) for a braced diaphragm wall in a deep clay deposit. It was less than 0.2%H suggested by Wong et al. (1997) for

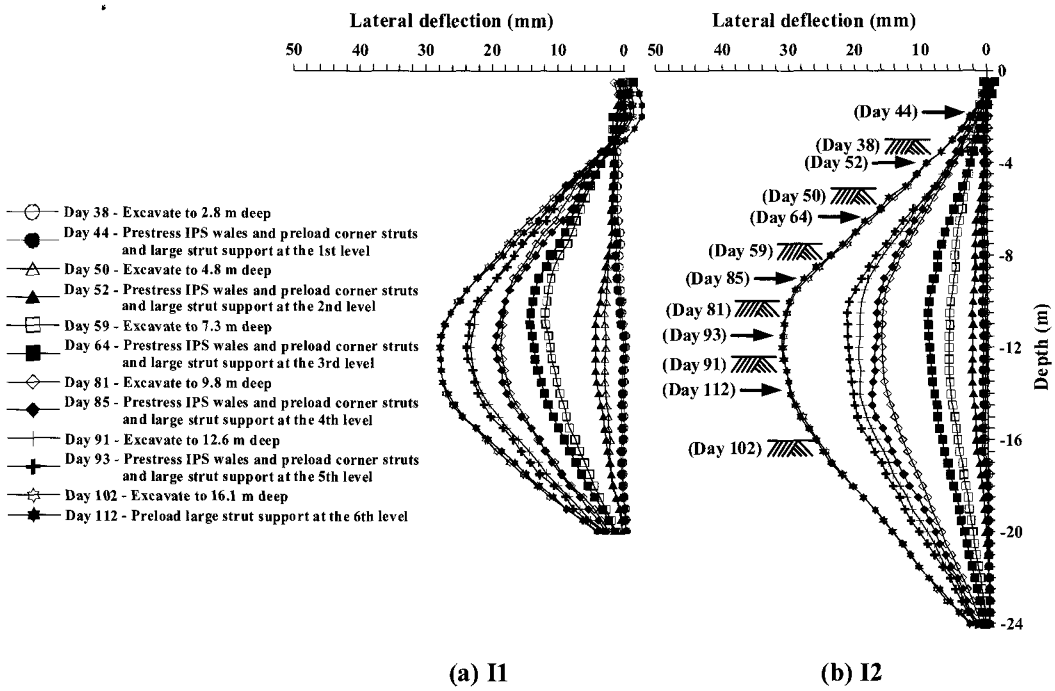


Fig. 8. Lateral deflection profiles of IPS wall during construction (a) inclinometer 1, and (b) inclinometer 2

excavations supported by rigid walls, with a combined thickness of soft-soil layers of less than 90% of the depth of excavation overlying stiff soils. The measured lateral wall deflection profiles represented a bulged fashion at 4.0 m above the soft clay stratum. This pattern for the IPS wall is comparable with wall deflection performances in soft clay reported in the literature (Lee et al. 1998; Finno et al. 2002).

The lateral deflection measured at the center location of the IPS wale during construction was shown in Fig. 9. The measured lateral deflections gradually increased throughout construction, excepting that the measurement at the location of W2a on the center of the IPS 2a remained constant with few variations. The maximum lateral deflection measured at the center of the IPS wale by the extensometer was 6.7 mm at the location of W2b, 12.6 mm at the location of W 3b, and 12.2 mm at the location of W 4b. The measured deflection was within about 30% of the design assumption by Han et al. (2003).

3.2 Apparent Pressure Envelope by Loads on Struts

The axial loads measured on corner strut 1g to 5 g during construction are shown in Fig. 10. The loads at the location of corner 1g were measured from 620 kN

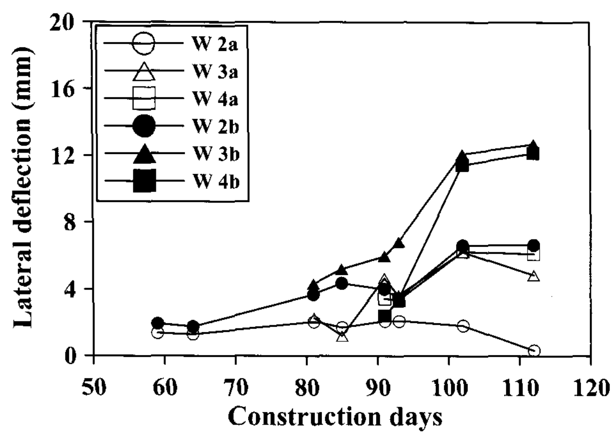


Fig. 9. Lateral deflections of the IPS wales during construction

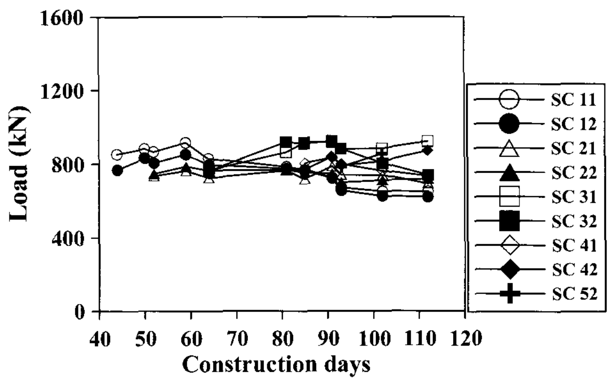


Fig. 10. Loads on corner struts during construction

to 916 kN. The loads measured at the location of corner 2 g ranged from 693 kN to 786 kN. At the location of corner 3 g, the measured loads varied from 761 kN to 924 kN. The loads at the location of corner 4 g were measured from 762 kN to 872 kN. The loads measured at the location of corner 5g ranged from 784 kN to 856 kN.

The axial load measured on center strut 1 to 5 is shown in Fig. 11. The loads measured at the location of center 1 ranged from 668 kN to 858 kN. The loads at the location of center 2 were measured from 771 kN to 940 kN. At the location of center 3, the measured loads ranged from 857 kN to 1021 kN. The loads measured at the location of center 4 varied from 898 kN to 1005 kN. The loads at the location of center 5 were measured from 855 kN to 917 kN.

The maximum strut loads after final excavation were converted into apparent pressures and compared with the Terzaghi and Peck's apparent earth pressure envelope for a soft to medium clay, as illustrated in Fig. 12. The pressures on struts at the first level ranged from 89% to 126% of the Terzaghi and Peck's apparent earth pressure envelope. The pressures at the first level exceeded the Terzaghi and Peck's apparent earth pressure envelope. This trend may have been caused by application of preload as much as approximately 126% of the design prediction. The pressures on struts at the second level varied from 58% to 68% of the apparent earth pressure by Terzaghi and Peck (1967). At the third level, the pressures on struts ranged from 62% to 95% of the Terzaghi and Peck's apparent earth pressure envelope. The pressures on struts at the fourth level varied from 62% to 90% of the Terzaghi and Peck's apparent earth pressure envelope. The pressures on struts at the fifth level ranged from 60% to 93% of the Terzaghi and Peck's apparent earth pressure envelope.

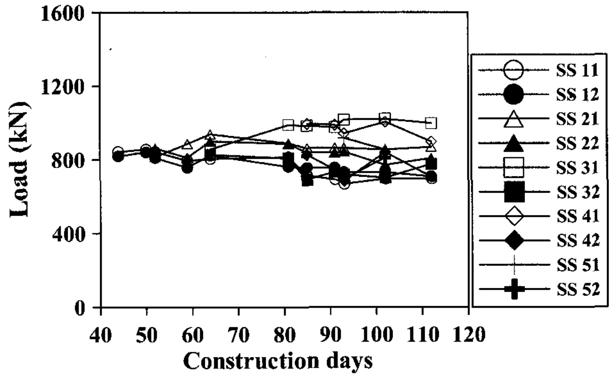


Fig. 11. Loads on center struts during construction

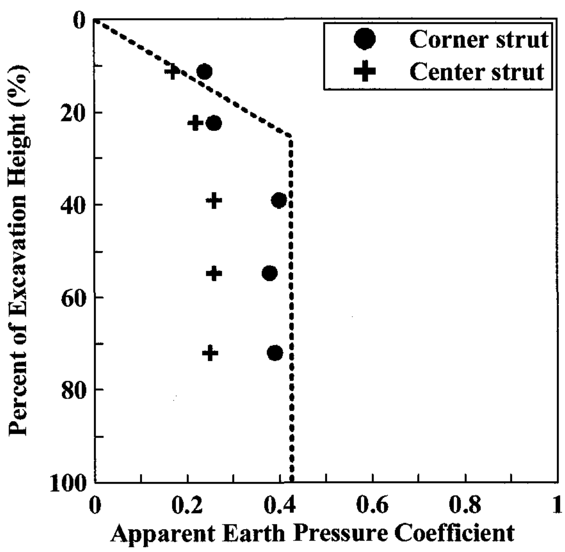


Fig. 12. Comparison of measured and the Terzaghi and Peck's design earth pressure envelope (1967)

4. Discussion of Results

The behavior of members of the IPS earth retention system was investigated from analyzing the results of field measurements. The deflection behavior of the IPS wall showed a bulged shape which is quite common in soft clay. The IPS wale system proved to restrict wall deflection by the application of the prestress load.

For maximum lateral deflection of the IPS wall, the measured data was within the recommendations by other researchers for braced and anchored walls. It was notified that the deflection behavior of the IPS wall was similar to those of the braced and anchored walls.

The apparent earth pressures converted from loads on struts in the IPS wall matched with the Terzaghi and Peck's apparent earth pressure diagram. It was recognized that the earth pressure behavior on the IPS wall was similar to those of the braced and anchored walls.

5. Conclusions

The stability and applicability of the IPS earth retention system applied in soft clay were evaluated. Field monitoring data such as the lateral wall deflection, the ground water level, the IPS wale deflection, and the strut support load were collected during excavation. Based on the measurements, the following conclusions can be drawn:

(1) The IPS earth retention system in soft clay performed successfully. The IPS earth retention system proved to provide a large workspace. The amount of steel beams reduced 30% compared to strutted excavation in quantity.

(2) The maximum lateral wall deflection of the IPS wall represented to be 0.18% of the excavation depth. The results were less than the deflection predicted by other researchers (Clough and O'Rourke 1990; Ou et al. 1993; Hashash and Whittle 1996; Wong et al. 1997). The lateral wall deflection profile showed a bulged fashion above the soft clay stratum. This trend is comparable with the results reported by Lee et al. (1998) and Finno et al. (2002) for wall deflection performance in deep excavation.

(3) The maximum strut loads after final excavation were converted into apparent pressures and compared with the Terzaghi and Peck's apparent earth pressure envelope for a soft to medium clay. The pressures on struts ranged from 89% to 126% at the first level, and ranged from 58% to 68% at the second level, and ranged from 62% to 95% at the third level, and ranged from 62% to 90% at the fourth level, and ranged from 60% to 93% at the fifth level, when compared with the Terzaghi and Peck's apparent earth pressure envelope.

(4) The excessive stresses or buckling of strut members were not observed. The axial compressive stresses on struts were within the allowable stresses.

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