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Study on Load Transfer Characteristics of Sand Compaction Piles in Soft Soil Deposits

연약지반의 모래다짐말뚝에 대한 하중전이 연구

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요 지

모래다짐말뚝은 압밀침하촉진과 지지력향상을 도모할 수 있는 연약지반 개량공법으로 그 사용성이 증가하고 있다. 본 연구에서는 실내시험과 3-D 유한요소해석을 수행하여 30-40%의 저치환율 모래다짐말뚝의 하중전이특성을 고찰해본다. 또한, 이러한 연구결과는 실험치와의 검증을 통하여 모래다짐말뚝 하중전이특성평가를 위한 간편법을 제시하는데 사용되었다.

Abstract

Sand Compaction Pile (SCP) is a soft-ground improvement technique used for not only accelerating consolidation but also increasing bearing capacity of soils. In this study, laboratory tests and 3-D finite element analysis were performed to investigate the characteristics of load transfer in SCP with an emphasis on free-strain behavior of piles with low replacement ratios in the range of 30 to 50%. Through these focused tests and numerical analyses, we proposed a simplified method to analyze the load transfer characteristics of SCP in soft ground. Moreover, it was shown that estimated normal stresses in SCP using the proposed method were in a reasonable agreement with actual values.

Keywords : Finite element analysis, Free strain, Load transfer characteristics, Replacement ratio, Sand compaction pile (SCP), Stress concentration ratio

1. Introduction

The ground improvement techniques utilizing driven materials include sand drain, paper drain, pack drain, stone column pile, SCP, etc. These methods have been widely used to improve soft soil deposits by accelerating consolidation period, reducing settlement, and reinforcing the soils. Particularly, SCP is known not only to improve the soil strength but also keep soils from liquefaction. With this reason, SCP is becoming a common ground improvement method for port-related reclamation works such as the Inchon container terminal construction (1999) and Busan New Port development (1999).

There has been numerous research performed over the world to investigate physical characteristics of SCP. As experimental studies, Greenwood (1970) suggested an effective chart that could calculate settlement and

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strength of soil with various SCP spacing.

Hughes and Withers (1974), Hughes et al. (1975), Wong (1975), Datye (1983), and Soyez et al. (1985) recommended equations to compute shear failure and punching failure as well as bulging failure. Takemura et al. (1991) examined the behavior of SCP-treated ground through centrifuge model tests and Rahman et al. (2001) also performed centrifuge tests to observe lateral movements of SCP-treated ground due to backfill of marine structures.

As analytical studies, Aboshi et al. (1979) and Balaam and Booker (1981) provided an equilibrium method to analyze the behavior of single SCP in the semi-infinite soft soil deposits. Goughnor and Bayuk (1979) and Priebe (1976) introduced a concept of "unit cell", which combines SCP with influence zones, and suggested a stress concentration ratio due to difference of stiffness between SCP and surrounding soils. The findings from this study have been adopted in practice. Alamgir et al. (1994) recommended a computational method for stresses in SCP and soils based on a theory of equal strain.

These experimental and analytical studies are generally based on the assumption of "equal strain", which represents the condition that SCP and surrounding soils behave under the same strain. However, in reality where preloading is applied, SCP and soils follow the free-strain condition, which shows different movements relative to each other and the aforementioned studies do not necessarily reflect the field condition. Recently, Poorooshasb et al. (1996) and Alamgir et al. (1996) studied the SCP behavior under the free-strain condition. However, since their studies were based on the assumption of a linear stress-strain relation of SCP and soils, they have limitations to predict plastic behaviors of composite soils with SCP and consequently raise the necessity of developing methodologies that can better estimate the plastic behavior of the composite material. Furthermore, high replacement ratios of 70% or greater become prevailing in Korean standard regardless of field and load conditions. The use of these high replacement ratios renders SCP method very difficult to employ as a result of several shortages (i.e., costly borrow sands and low construction efficiency).

With this background, this study focuses on low replacement ratios (i.e., 30 to 50%) to provide a logical design guideline for optimal case-by-case replacement ratios. The study utilizes laboratory model tests under the free-strain condition and 3-D finite element analyses and consequently provides recommendations for the existing SCP design method on load transfer characteristics with a consideration of plastic behaviors of SCP in soft ground.

2. SCP Model Test

2.1 Physical Properties of Soil and SCP

The Jumoonjin standard sand [0.3mm(sieve#50)<

Table 1. Physical properties of the Jumoonjin standard sand

Property		Test result
Max. diameter (mm)	D_{max}	0.850 (No. 20)
Min. diameter (mm)	D_{min}	0.075 (No. 200)
Diameter for 10% finer by weight (mm)	D_{10}	0.41
Diameter for 60% finer by weight (mm)	D_{60}	0.48
Coeff. of uniformity	C_u	1.17
Coeff. of curvature	C_c	1.23
Max. void ratio	e_{max}	0.897
Min. void ratio	e_{min}	0.628
Max. dry unit weight (kN/m^3)	γ_{dmax}	16.09
Min. dry unit weight (kN/m^3)	γ_{dmin}	13.82
Specific gravity	G_s	2.63
Moisture content (%)	w	0.3
Modulus of elasticity (MPa)	E	40
Internal friction angle (°)	ϕ	35
Unified Soil Classification System	US ASTM D2487	SP

Table 2. Physical properties of clay

Property			Test result
Specific gravity (Gs)			2.72
Modulus of elasticity (MPa)			5.0
Atterberg Limits		Liquid Limit, LL (%)	72.3
		Plastic Limit, PL (%)	27.4
		Plastic Index, PI (%)	44.9
Direct shear test		c (kPa)	2.0
		ϕ (°)	0.0
Triaxial test	UU test	c (kPa)	2.0
		ϕ (°)	0.0
	CU test	c (kPa)	0.0
		ϕ (°)	30.8
Consolidation test		P_c (kPa)	10.0
		C_c	0.505

Diameter(D)<0.6mm(sieve#30)] was used for SCP and its physical properties obtained from laboratory tests are shown in Table 1. For the original ground, clays were taken from the Kimhae site (a nearby soil improvement site) and its physical properties obtained from laboratory tests are shown in Table 2.

2.2 Test and Measuring Devices

As shown in Fig. 1, the test device used in this study is a cylinder with a height of 550 mm and a diameter of 500mm and consists of base plate, main frame, base, and cover. Each part was assembled by bolt and easy to dismantle. Stress/strain gauges are installed in the specimen under double drainage condition and a rubber membrane is also attached in order to apply flexible loading. Table 3 shows a list of measuring devices used in this study.

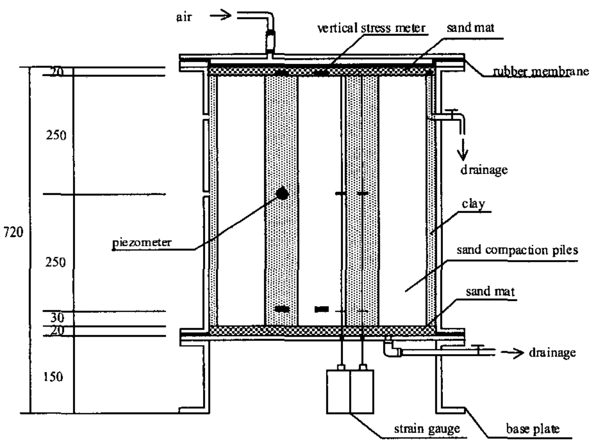


Fig. 1. Specifications of model test device

Table 3. Specifications of measuring devices for SCP model test

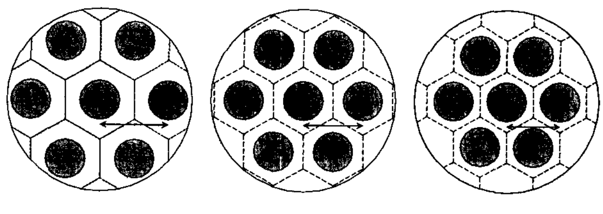
Measuring item	Device	Total No.	Measuring range	Accuracy
Normal stress	pressure cell	5	0~5000 kPa	0.1 kPa
Settlement	displacement transducer	6	0~1000 mm	0.2 mm
Pore pressure	pore pressure transducer	1	0~200 kPa	0.1 kPa

2.3 Test Procedures

Test load is applied by air pressure using an air compressor from 50 to 200 kPa with an increment of 50 kPa. A regulator is used to keep the loads constant during each loading period. During each loading, stress and displacement are measured at 0, 8, 15, 30 seconds, 1, 2, 4, 8, 15, 30 minutes, 1, and 2 hours. After 2 hours, the specimen is measured every 2 hours until settlement at the loading period is considered complete. SCP spacing with replacement ratio (a_s) is presented in Table 4 and its layout is shown in Fig. 2.

2.4 Test Results

Fig. 3 shows stress vs. load curves with varying a_s.



(a) a_s=30% (b) a_s=40% (c) a_s=50%

Fig. 2. Cross-sections of composite ground with various replacement ratios

Table 4. SCP spacing for various replacement ratios

Replacement ratio, a_s (%)	30	40	50
Spacing, x (cm)	18.6	16.1	14.4

The load is applied at the cover (z=0 mm) and base (z=500 mm). At z=0 mm, no significant difference for normal stress of soils and SCP is observed while SCP carries more stress than soils at z=500 mm and the difference increases with load and a_s. In other words, normal stress in SCP at the base increases as applied load and replacement ratio increase.

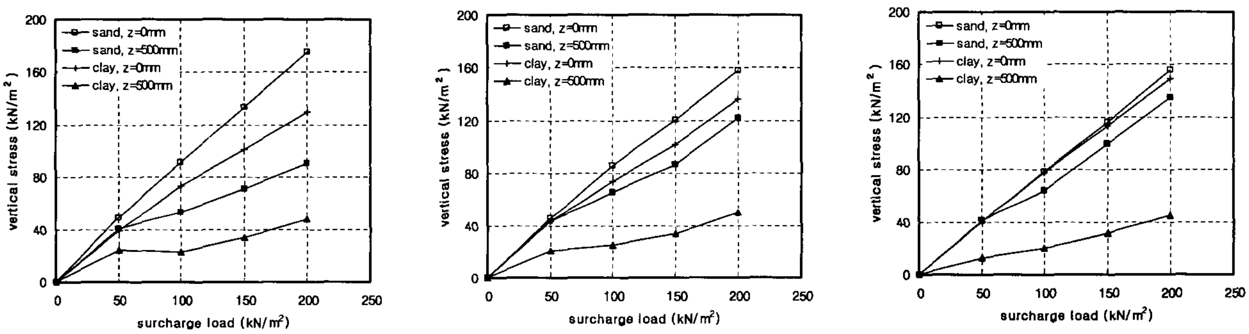
Stress concentration ratios (n) at z=0 and 500 mm are shown in Fig. 4. The stress concentration ratio, n ($=\sigma_s/\sigma_c$), represents a ratio of normal stress taken by SCP (σ_s) to that of original ground (σ_c). Theoretically, n at z=0 mm should be 1 regardless of a_s due to the assumed condition of free-strain. However, test results show that actual n ranges from 1 to 1.5. An explanation for this error would be that when settlement occurs with an applied load, the load is not completely transferred to one side with larger displacement due to the flexibility of rubber membrane. Nevertheless, n is close enough to 1 at z=0 mm, which indicates no load transfer between soils and SCP takes place at the surface. At z=500 mm, n increases up to 3 with a_s=50%, which indicates that when depth and a_s increase, shear stress in clay soils decreases due to less settlement and consequently shear stress transferred to the interface of SCP and clay soils increases relatively.

In conclusion based on the laboratory model tests, load transfer in the SCP composite ground increases with depth and replacement ratio. Also, relative displacement of SCP to the original ground decreases as depth or replacement ratio increases.

3. 3-D Finite Element Analysis for SCP

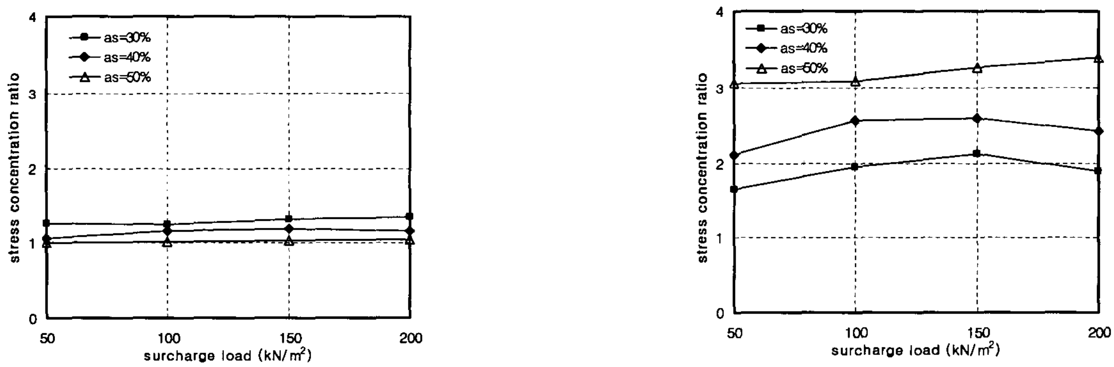
3.1 Finite Element Modeling

3-D finite element analyses were performed to numerically verify the laboratory model tests. Fig. 5 shows a schematic diagram of this analysis. As shown in Fig. 5, the model is under free-strain condition at the top, supported on a rigid base, and has a triangular



(a) a_s=30% (b) a_s=40% (c) a_s=50%

Fig. 3. Load-stress curves at z=0 and 500 mm with various replacement ratios



(a) surface (z=0 mm) (b) base (z=500 mm)

Fig. 4. Stress concentration ratios with various replacement ratios

Table 5. Center-to-center distance for various replacement ratios (Model test)

Replacement ratio, a_s (%)	C.T.C. distance, x (cm)	Remark
30	9.8	Equivalent to spacing in an unit cell
40	8.5	
50	7.6	

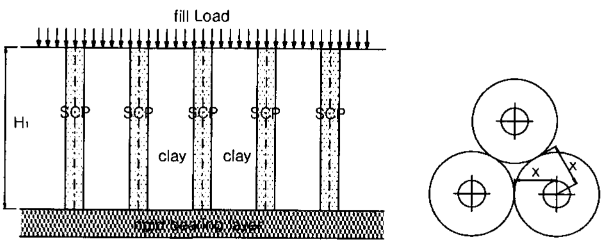


Fig. 5. Schematic diagram of model test

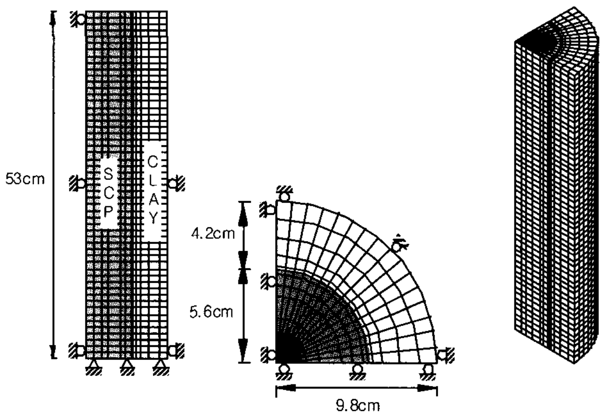


Fig. 6. Mesh drawings for finite element analysis

pattern for SCP. In Table 5, center-to-center distances of SCP used for the 3-D finite element analysis are presented.

Fig. 6 illustrates 3-D mesh for a_s=30%. The dimension of model is assigned the same as the laboratory test and only quarter of the model is used for mesh due to axi-symmetry of the model. The model consists of 8-node brick elements and the height of element is set to 1.0 cm in order to better examine the analysis results (i.e., settlement, stress distribution, etc.) For boundary conditions, the bottom layer of the mesh is fixed against movement and nodes on side planes are set to free against settlement, but fixed against movement in any other directions.

3.2 Constitutive Model and Material Properties

In this study, a finite element analysis software, ABAQUS, was used with the extended Drucker-Prager stress-strain model. Properties of sand and clay were obtained from laboratory tests (i.e., triaxial test, etc.) and the values for both elastic and plastic ranges are summarized in Table 6. It should be noted that triaxial test was repeated three times and the average was chosen for the representative values in the table. In addition, typical values were selected for Poisson's ratios and unit weight of sand was chosen as <70% of the maximum compaction density while unit weight of clay was chosen the same as that from laboratory model test.

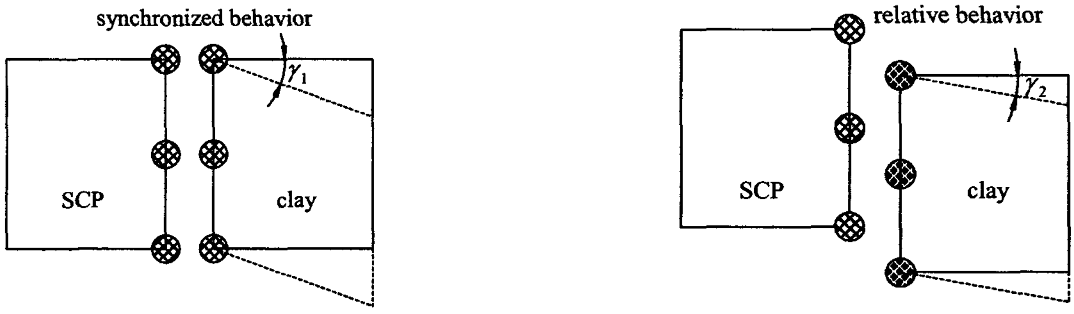
3.3 Analytical Procedures and Interface Modeling

In order to consider relative displacements occurring on the interface between SCP and clay soils, we used a

Table 6. Material properties for finite element analysis

Material	Analytical model	Properties (Elastic)			Properties (Plastic)			
		E(MPa)	ν	γ (kN/m^3)	c(kPa)	ϕ(°)	β*(°)	ψ**(°)
SCP	Drucker-Prager	40	0.3	20.0	3	35.0	54.8	0.0
Clay	Plastic	5	0.4	17.5	2	0.0	–	0.0
Interface	Coulomb's slip	Friction angle (δ°)			6.6			
		Coeff. of friction (μ=tan δ)			0.12			
		Allowable displacement (mm)			5			

β* : material angle of friction, in the p-t plane(°)
ψ** : dilation angle(=0°), in the t-P plane



(a) with slip element (b) without slip element

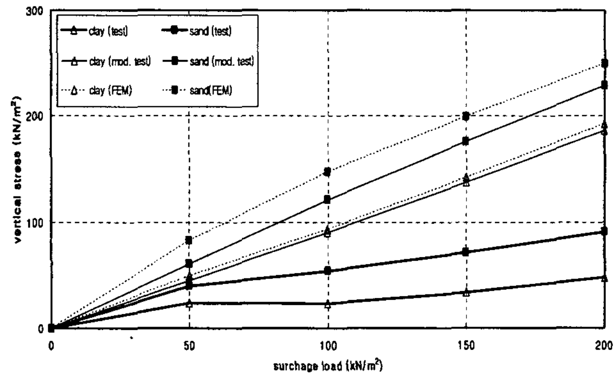
Fig. 7. Behaviors of model with/without slip element

tangential slip surface element in our model. Fig. 7 illustrates that such an element is capable of considering relative movement of elements with different rigidity and consequently analyzing actual behavior of the elements on the interface. The tangential slip surface element in this analysis is based on the Coulomb's stress-strain relation and its maximum allowable displacement is assumed to be 5mm. This maximum allowable displacement is in a reasonable agreement with the typical in-situ displacement (1.0-8.0 mm) proposed by Broms (1979).

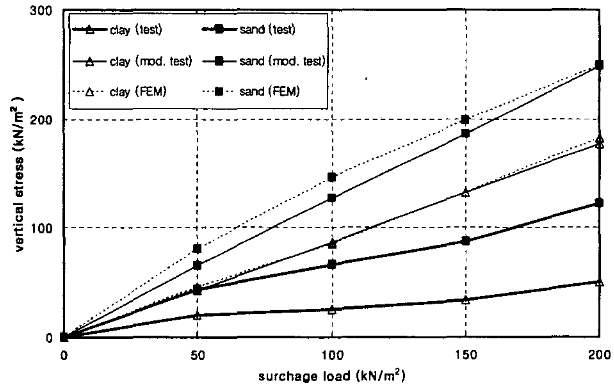
Also, a friction angle between SCP and clay soils was obtained from direct shear tests, whose bottom shear box was filled with the Jumoonjin standard sand and compacted to 70% of the maximum compaction density while the top shear box was filled with saturated clays. Load is applied from 50 to 200 kPa with an increment of 50 kPa. The effective stress analysis was performed assuming the whole layer to be saturated.

3.4 Analysis Results

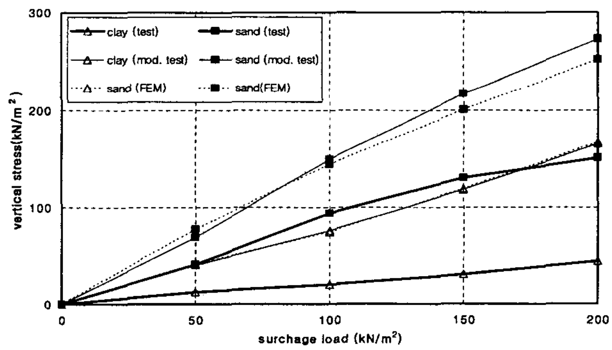
In Fig. 8, normal stresses at z=500 mm are plotted against loads with various replacement ratios. Also, they are compared with curves from the laboratory model tests. As shown in the Fig., SCP carries more stress than soils at z=500 mm and stress taken by SCP increases as replacement ratio increases, whose trend was seen from the laboratory model test as well. However, some discrepancies between analytical values and laboratory values can be detected in Fig. 8. This might be explained by the difference existed in boundary conditions of both



(a) a_s=30%

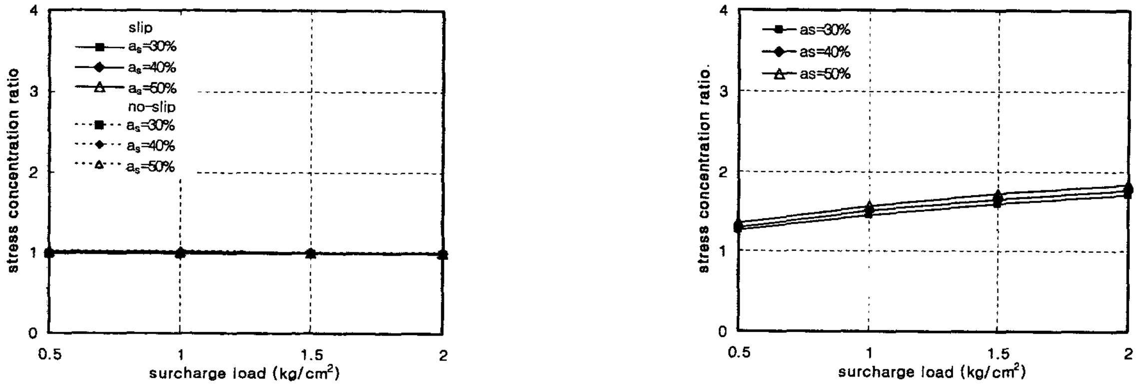


(b) a_s=40%



(c) a_s=50%

Fig. 8. Load-stress at the base with various replacement ratios



(a) surface (z=0 mm)　　(b) base (z=500 mm)

Fig. 9. Stress concentration ratios with various replacement ratios

methods. The laboratory model test unlike the numerical analysis, which sets the lateral displacement of clay on the boundary to fix as seen in Fig. 6, is confined on the sides allowing no lateral displacement. Additionally, it should be noted that skin friction generated on the sidewall of test specimen reduces load transferred to the bottom. Hence, it is essential to account for the loss of load on the sidewall of specimen. The modification was applied appropriately (i.e., distributing the load loss based on an area ratio of SCP/clay to the total ground) and presented in Fig. 8. As seen in the Fig., the modified test results and finite element analysis results show an exceptionally good agreement.

Fig. 9 shows stress concentration ratios vs. loads at depths of z=0 and z=500 mm with varying replacement ratios. The Fig. presents a similar trend (i.e., no load transfer at z=0 and some load transfer at z=500 mm) to Fig. 4 from the laboratory tests although n from the numerical analysis is smaller than n from laboratory test at z=500 mm. We believe this minor difference generated from the change of undrained shear strength in the test specimen due to drainage occurred during the test.

4. Parametric Study

No in-situ test on the behavior of this composite ground (i.e., SCP and clay) has been performed to date in Korea. Moreover, the laboratory model test has some inherent limitations such as scale factor, test condition set-up, measuring accuracy, etc. Therefore, in this study, a complementary parameter-sensitivity study was performed to overcome those drawbacks in laboratory model test and estimate actual behaviors of the composite ground. Table 7 presents the list of parameter for this purpose.

Table 7. Inputs of SCP for numerical analysis

Item		Input
SCP	Diameter (D)	2 m
	Length (H_l)	15 m
	Layout pattern	rectangular
Base		hard clay or bedrock
Replacement ratio (%)		30, 40, 50
Original ground (clay)		soft, medium stiff, stiff
Interface friction	δ (°)	6, 10,15, 20
	μ =tan δ	0.1, 0.17, 0.27, 0.36
Surcharge (t/m²)		5, 10, 15, 20, 25

4.1 General Model Section and Finite Element Modeling

General model section and plan were selected from examples of the existing port construction projects as shown in Fig. 10. SCPs with a diameter of 2 meter, a length of 15 m, and a 2-meter base layer (i.e., hard clay and bedrock) were analyzed for the condition immediately after SCP construction and before surcharging. SCPs were also modeled with a square pattern as shown in the Fig. Table 8 presents replacement ratio and pile spacing with the selected layout pattern. Finite element modeling was performed similarly to the Section 3.2.

Table 8. Center-to-center distance for various replacement ratios (Numerical analysis)

Replacement ratio, a_s (%)	C.T.C. distance, x (cm)	Remark
30	162	Equivalent to spacing in an unit cell
40	140	
50	125	

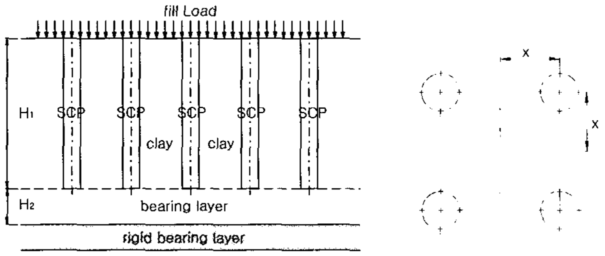


Fig. 10. Schematic diagram of composite ground (Parametric study)

4.2 Constitutive Model and Material Properties

For the material properties in this FEM study, values applied to the site were used for SCP and the original clay soils were analyzed for three consistencies (i.e., soft, medium stiff, and stiff). These properties are summarized in Table 9. The extended Drucker-Prager constitutive model was chosen for the analysis. Also, the interface between SCP and clay was modeled as tangential slip surface with friction angles ranging from 6 to 20° and a condition of normal-behavior contact was applied to the tip of SCP. For a loading condition, a surcharge of 5-25 ton/m^2 is applied at the surface.

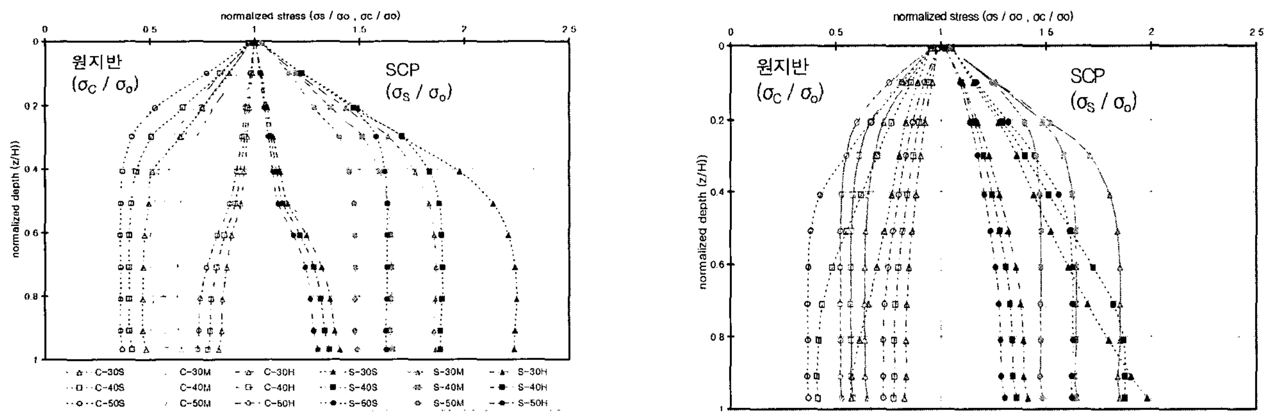
4.3 Analysis Results

4.3.1 Normal Stresses in SCP and Clay

Fig. 11 shows normalized stress (i.e., stress in SCP or clay / surcharge load) against normalized depth (i.e.,

Table 9. Material properties for finite element analysis (Parametric study)

Material		Analytical model	Elastic properties			Plastic properties			
			E (MPa)	ν	γ (kN/m^3)	cu (kPa)	ϕ (°)	β(°)	ψ(°)
SCP (D=2.0 m)		Drucker–Prager	40	0.3	20.0	3	35.0	54.8	0.0
Clay	Soft	Plastic	5	0.4	17.5	10	–	–	–
	Medium stiff		10	0.4	17.5	20	–	–	–
	Stiff		20	0.4	18.0	50	–	–	–
Base	Hard clay	Plastic	20	0.4	18.0	50	–	–	–
	Bedrock	Drucker–Prager	500	0.3	20.0	50	35.0	54.8	0.0
Interface		Coulomb's slip	Friction angle (δ°)			6, 10, 15, 20			
			Fric.coeff. (m=tan δ)			0.10, 0.17, 0.27, 0.36			
			Allowable displacement (mm)			5			



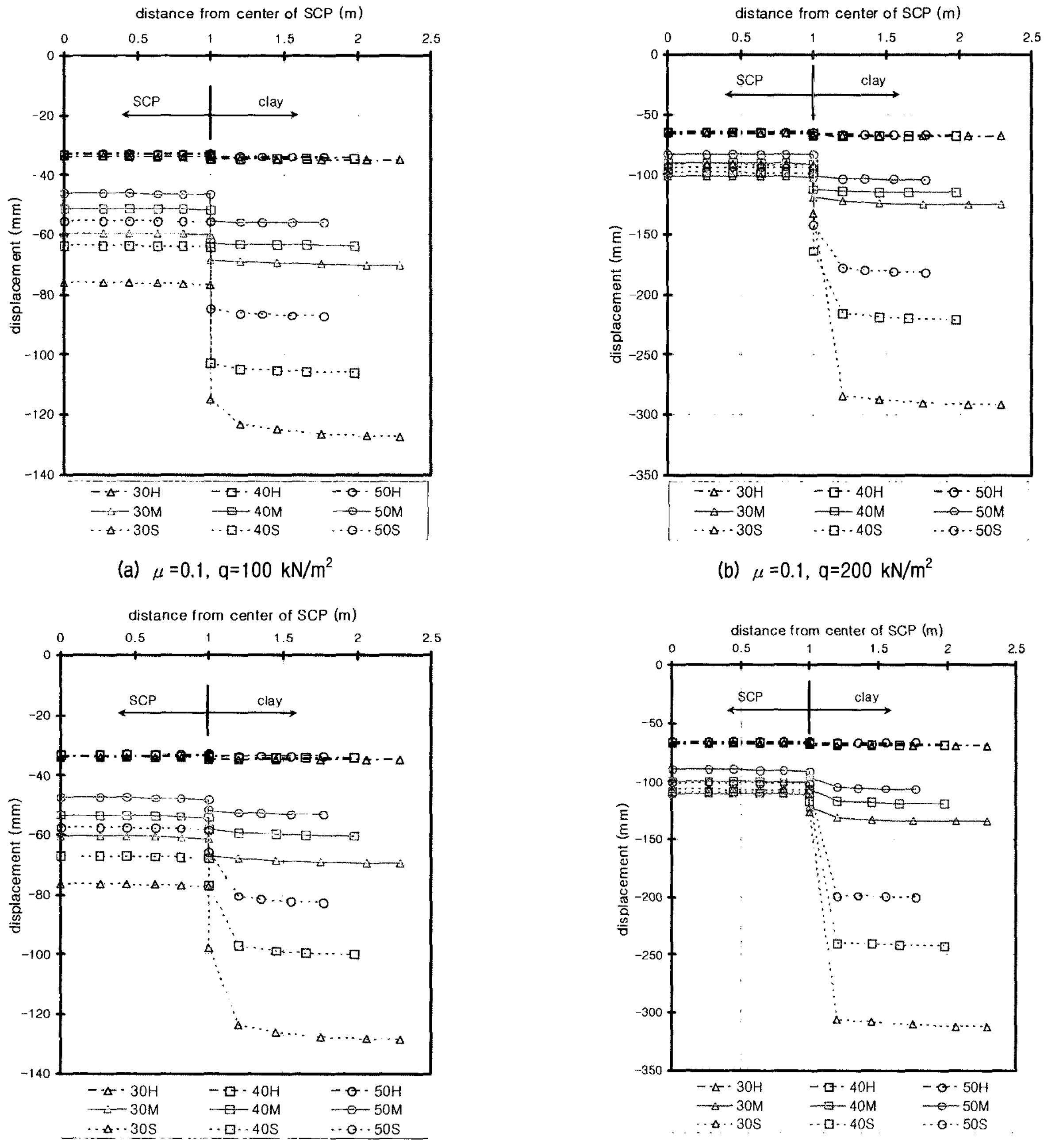
(a) with a surcharge of 50 kN/m^2 (b) with a surcharge of 250 kN/m^2

Fig. 11. Depth-stress curves of SCP and clay

depth / SCP length) at the interface of SCP and clay. As shown in the Fig., normal stress in SCP increases as depth increases but vice versa for clay although they show the same stress at the surface. This trend corresponds with what we found from the previous sections. Also, it can be observed that a stress increase ratio in SCP and a stress reduction ratio in clay increase significantly near the surface, but remain constant below some depths, which get shallower with high replacement ratios, as they approach to the tip of SCP. At the tip, stress increases with high replacement ratios and more competent soil properties.

4.3.2 Vertical Displacement of SCP and Clay

Fig. 12 presents SCP-clay settlements from the center of SCP radiately. Settlements in SCP/clay and relative displacements on the SCP-clay interface increase with weaker clays, lower replacement ratios, and a high



(a) μ =0.1, q=100 kN/m^2

(b) μ =0.1, q=200 kN/m^2

(c) μ =0.4, q=100 kN/m^2

(d) μ =0.4, q=200 kN/m^2

Fig. 12. Displacement of SCP and clay with radial distances

surcharge load. In other words, SCP settles less and takes more stress concentration resulting in occupying more resistances to external loads than clay. Also, settlements occur less when the friction coefficient (μ) is larger. Through these findings, one may say that the relative displacement of SCP and clay in the composite ground is significantly influenced by friction on the interface between two objects with different rigidity.

4.3.3 Stress Concentration Ratio

Fig. 13 plots stress concentration ratio (n) in SCP against depth for two different surcharges. As seen in the Fig., n increases near the ground surface and remains almost constant below certain depths. n is more sensitive to the consistency of clay than replacement ratio and weaker clays show higher n values. Also, although n increases with higher replacement ratios near the ground surface, the opposite trend (i.e., n decreases with higher replacement ratios) is shown below certain depths.

5. Analytical Model for SCP

5.1 Analytical Approach on Load Transfer Characteristics

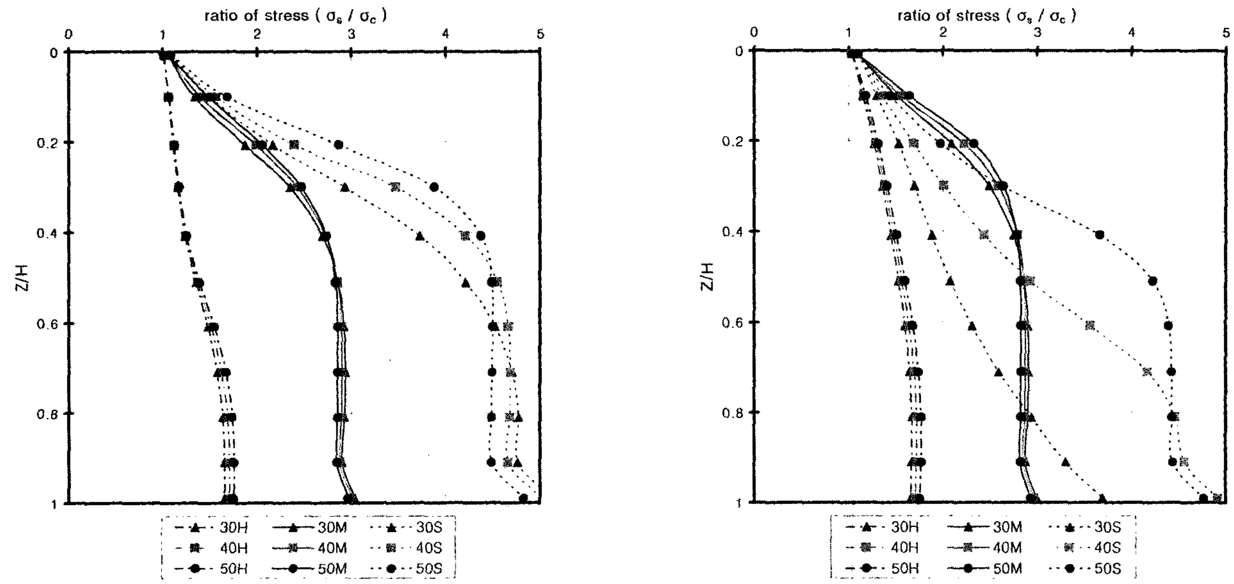
As discussed previously, when an external load is applied to a composite ground, a stress transfer occurs on the interface of SCP and clay due to their stiffness difference. This was examined by Kim et al. (2002) and, according to this study, load-settlement relation of the composite ground is similar to the pile skin-friction when settlements occur in soft ground. Besides, Kim et al. (2002) suggested an analytical solution for estimating shear stresses of SCP and the original ground introducing a load transfer function. In this paper, the load transfer mechanism is reviewed through those previous studies.

Fig. 14 illustrates a deformed shape of the composite ground and Fig. 15 shows a free-body-diagram for an element of SCP under the stress equilibrium state. Following is an equilibrium equation for the vertical direction for the SCP element shown in Fig. 16;

$$(\sigma_{cz}+\Delta\sigma_{cz})\frac{\pi d_0^{\,2}}{4}-\sigma_{cz}\frac{\pi d_0^{\,2}}{4}-\tau_{az}\pi d_0\Delta z=0 \qquad (1)$$

Where, σ_{cz} = normal stress at the top of SCP
$\Delta\sigma_{cz}$ = incremental normal stress
Δ_z = length of SCP element
d_0 = SCP diameter

Below is an equilibrium equation for nearby soil elements corresponding to SCP



(a) with a surcharge of 100 kN/m^2 (b) with a surcharge of 250 kN/m^2

Fig. 13. Stress ratio with depth (μ=0.1)

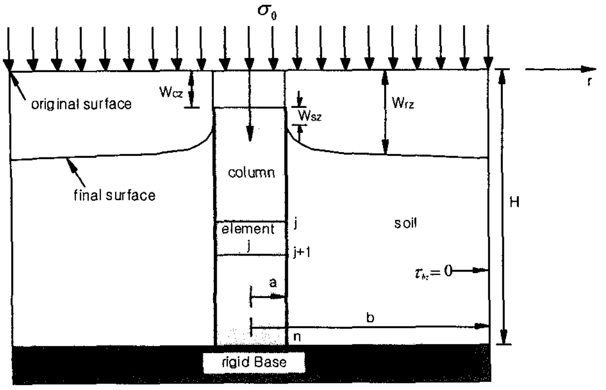


Fig. 14. Deformed shape of composite ground

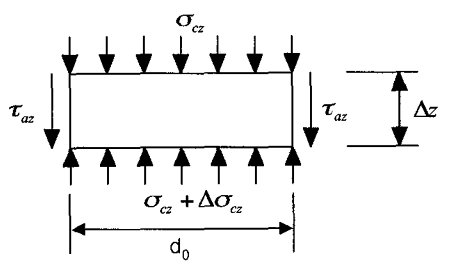


Fig. 15. Free body diagram of a SCP element

$$\frac{\partial}{\partial r}(r\tau_{rz})+\frac{\partial \sigma_{rz}}{\partial z}+0 \qquad (2)$$

Where, r = radiative distance of ground

τ_{rz} = shear stress at depth z and radiative distance r

σ_{rz} = normal stress at depth z and radiative distance r

Suppose the same boundary conditions with Eq.3 are applied to Eqs 1 and 2, normal stress and transferred shear stress in an SCP element (j element) can be estimated when SCP is divided equally into n-pieces.

$$w_{rz} = w_{cz} + w_{sz} \quad (r = a) \qquad (3a)$$

$$w_{rz} = w_{bz} \quad (r = b) \qquad (3b)$$

$$\sigma_{c(j+1)} = \sigma_{c(j)} + \frac{2\Delta H}{a}\tau_{(j)(trans)} \qquad (4a)$$

$$\tau_{(j)(trans)} = \frac{G}{a}\frac{1}{\ln(b/a)}(w_{b(j)} - w_{c(j)} - w_{s(j)}) \qquad (4b)$$

Where, b = radius of unit cell

w_{cz} = settlement of SCP

w_{sz} = relative displacement on the interface of SCP and clay

w_{bz} = settlement on the boundary of unit cell (r=b)

(j) = j[th] element when SCP is divided equally into n-pieces

ΔH = length of an element of SCP

The applicability of this analytical method derived from the transfer function, Eq. (4), was reviewed by comparison with numerical analyses using elastic and plastic models. Fig. 16 compares analysis result from the numerical analysis with that from the proposed analytical method based on elastic model while Fig. 17 performs the same comparison with elasto-plastic model. The comparisons indicate that analytical method produces an excellent match in outputs with numerical analysis when elastic model is used and analytical method shows 2 to 5 times larger estimated stresses than numerical analysis when elasto-plastic model is used. We find this difference resulted from the dominant plastic behavior of soft clay when surcharge is applied. The analytical method is based on the theory of elasticity and SCP

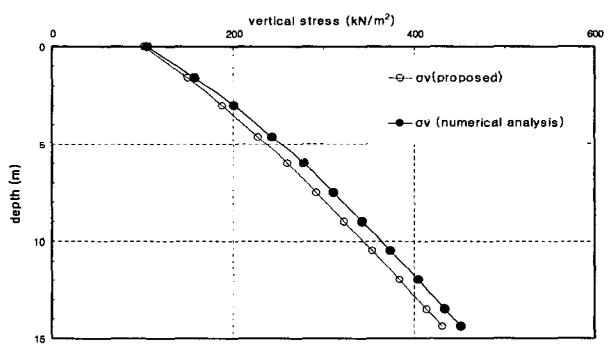


Fig. 16. Comparison of proposed solution and numerical analysis in an elastic ground (a_s=30, q=100 kN/m²)

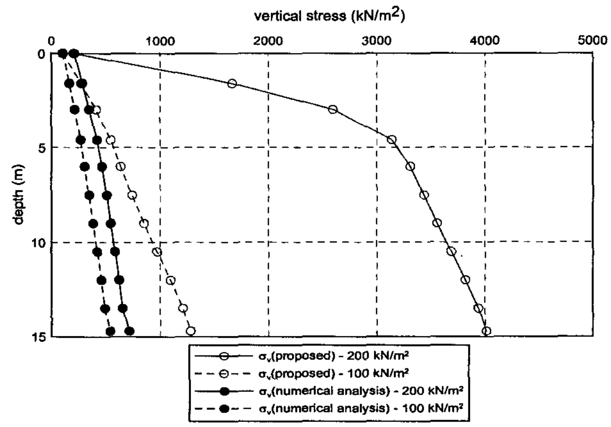


Fig. 17. Comparison of proposed solution and numerical analysis in an elasto-plastic ground (a_s=50%, q=100 kN/m²)

Table 10. Invariables in reduction factor function

Surcharge (t/m^2)	Replacement ratio, a_s (%)	a	b
10	30	0.70	−0.45
	40	0.56	−0.30
	50	0.50	−0.20
20	30	0.42	−0.37
	40	0.32	−0.24
	50	0.28	−0.23
Remark	f(x)=ax+b		

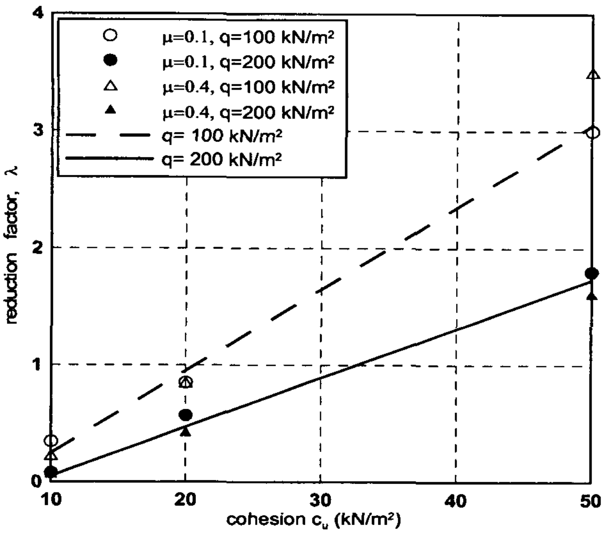


Fig. 18. Reduction factor with a replacement ratio of 30%

installed in soft clay has a tendency of overestimating normal stress.

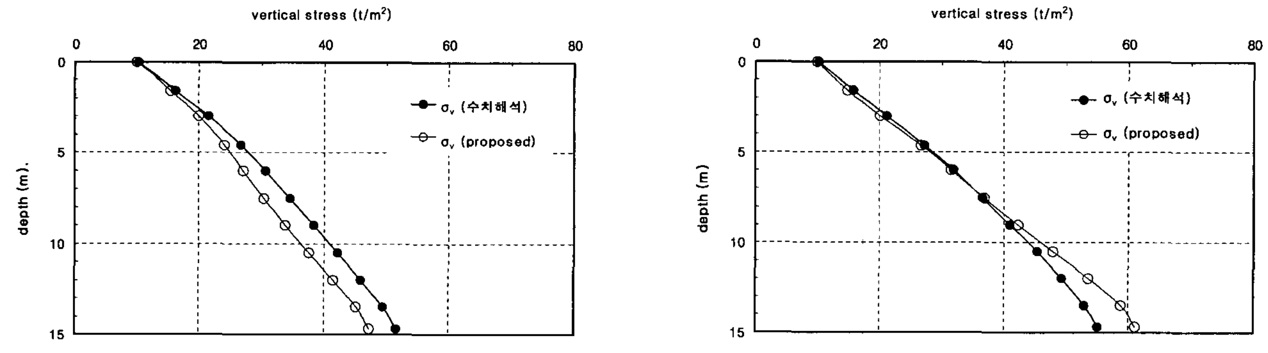
Because SCP is generally constructed in soft clay deposits, it is unavoidable that the proposed analytical method solely based on the theory of elasticity needs to be modified to assess the normal stress in SCP appropriately. Therefore, in this study, we recommend a new modification factor (i.e., reduction factor) considering conditions of soil, replacement ratio, and surcharge load to enable the previous analytical method to adequately estimate the plastic behavior of soft clay.

According to Kim (2003), although estimation from the transfer function based on the elasticity theory shows erratic stress values, the shape of stress distribution is normally acceptable. Therefore, various parametric studies were performed to find a reduction factor that adequately reflects the plastic behavior of the composite ground and it was found that the reduction factor shows an approximate linear relation with undrained shear strength of surrounding clay soils, which could consequently provide a reduction factor by a linear regression. Table 10 presents invariables a and b for the regression with various replacement ratios. In addition, an example of estimating reduction factor for a replacement ratio of 30% is shown in Fig. 18. As a result, a modified transfer function (i.e., modified from Eq.4b) utilizing a reduction factor (λ) can be expressed as following;

$$\tau_{(j)(trans)} = \frac{\lambda G}{a}\frac{1}{\ln(b/a)}(w_{b(j)} - w_{c(j)} - w_{s(j)}) \quad (5)$$

5.2 Verification of Analytical Method

For the purpose of verifying the feasibility of the modified analytical method (Eqs. 4a and 5), analysis results were compared with results from 3-D finite element analysis for soft clay and medium stiff clay as shown in Fig. 19, in which a replacement ratio of 50%



(a) soft clay

(b) medium stiff clay

Fig. 19. Comparison of proposed solution and numerical analysis after an application of reduction factor (a_s=50%, surcharge 10 t/m^2)

and a surcharge of $10 t/m^2$ are used.

It is found that for soft clay ground as shown in Fig. 19 (a), the modified analytical method shows slightly less stress values than the numerical analysis, but still in an acceptable range. For medium stiff clay in Fig. 19 (b), the modified analytical method produces almost identical stress values with numerical analysis although it shows some deviations as depth increases.

6. Conclusions

The objective of this paper is to recommend a stress-strain relation of the composite ground (i.e., SCP + soft clay) under the free-strain condition. Laboratory model tests and finite element analyses were performed for various replacement ratios and the results were reviewed to suggest a new simplified solution considering load transfer mechanism due to the interaction between SCP and surrounding soils. Our findings can be summarized as followings;

(1) In the composite ground under the free-strain condition, shear stress occurs on the interface of SCP and clay and consequently stress in clay is transferred to SCP. It is found that a stress concentration ratio ($n=\sigma_s/\sigma_c$) increases with depth and a high replacement ratio (a_s) gives a rise to the transferred stress and n, but reduces the settlement of the composite ground.

(2) The transferred shear stress in the composite ground under the free-strain condition is similar to negative skin friction. For this reason, skin friction analysis utilizing a load transfer function was performed and resulted in a reasonably good agreement with laboratory model test and 3-D finite element analysis.

(3) The analytical method in this study produces results that match the results from numerical analysis in the elastic ground. However, it was observed that the method overestimates the normal stress in the elasto-plastic ground, which corresponds to our case. Therefore, we recommended a modified solution using a reduction factor (λ) and the modified method appears to predict the normal stress in such a composite soft ground reasonably well.

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