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Smear Effect on Consolidation Behaviors of SCP-improved Ground

SCP 개량지반의 압밀거동에 대한 스미어 효과

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요 지

SCP 개량지반은 연약지반에 타설된 모래말뚝과 주변 연약지반으로 구성된 복합지반을 형성한다. 복합지반에 상재하중이 작용할 경우, SCP쪽으로 반경방향의 흐름에 의하여 시간의존적인 압밀거동이 유발될 뿐만 아니라, SCP와 주변 연약지반 사이에서 강성도 차이로 인하여 응력전이가 유발된다. 본 논문은 SCP 개량지반의 압밀거동에 대한 교란효과의 영향을 고려하기 위하여 원통형 실린더 지반에 대한 수치해석을 수행하였다. 수치해석결과 연약지반의 교란영역은 유효응력-간극수압의 거동, 응력전이기구, 응력분담비에 영향을 줌을 알 수 있었다. 또한 SCP와 점토 사이의 응력전이량은 상부 z/H=0.25에서 가장 크며, 깊이가 증가함에 따라 감소한다. 응력분담비는 상수값이 아니라 압밀과정에 의존하며, 교란영역을 가진 연약지반의 응력분담비는 교란영역이 없는 연약지반의 응력분담비보다 큼을 알 수 있다.

Abstract

Sand compaction pile (SCP)-improved ground is composite soil which consists of the SCP and the surrounding soft soil. When a surcharge load is applied to composite ground, time-dependent behaviors occur in the composite soil due to consolidation according to radial flow toward the SCP. In addition, stress transfer also takes place between the SCP and the soft soil. This paper presents the numerical results of cylindrical composite ground that was conducted to investigate smear effect on consolidation behaviors of SCP-improved ground. The results showed that the smeared zone of soft clay had a significant effect on effective stress-pore water pressure response, stress transfer mechanism and stress concentration ratio of composite ground. Amount of stress transfer between the clay and the SCP was maximum in depth of z/H=0.25, and decreased with depth. Stress concentration ratio of composite ground was not constant, but depended on consolidation process. It was also found that the value of stress concentration ratio in soft clay with smeared zone was larger than that in soft clay without smeared zone.

Keywords : Composite ground, Consolidation, SCP, Smear, Stress transfer

1. Introduction

In order to accelerate the rate of consolidation settlement, to reduce the settlement, and to increase the bearing capacity for soft ground, the sand compaction pile (SCP) method has usually been applied. SCP is composed of compacted sand pile intruded into the soft clay foundation by displacement method. SCP-improved ground is composite soil which consists of the sand pile and the surrounding soft soil, as shown in Fig. 1. The behaviors of composite ground depend on several parameters, including area replacement ratio, stress concentration ratio, consolidation characteristics of the soft soil due to radial drainage through the sand pile,

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and stress transfer mechanism between the sand pile and the soft soil.

The area replacement ratio (a_s) is defined as the ratio of the sand pile area to the whole area of the equivalent cylindrical unit cell (Eq. 1). When a surcharge load (q) is applied to composite ground, concentration of stress takes place in SCP, which is stiffer and stronger than the ambient soil as shown in Fig. 1. The distribution of vertical stress within the unit cell can be expressed by stress concentration ratio (m) defined in Eq. 2.

$$a_s = \frac{A_s}{A_s + A_c} \tag{1}$$

$$m = \sigma_s / \sigma_c \tag{2}$$

where A_s = the area of the SCP; A_c = the area of the surrounding soft soil; σ_s = the stress in the SCP; σ_c = the stress in the surrounding soft soil.

Several laboratory model tests were performed to analyze behaviors of composite ground associated with area replacement ratio (Juran and Guermazi, 1988; Jung et al., 1999). A simple and analytical solution was also suggested based on the assumptions of equal strain and theory of elasticity (Balaam and Booker, 1981). Alamgir et al. (1996) suggested a simple theoretical approach to predict the deformation behaviors of soft ground improved by columnar inclusions such as stone columns/granular piles, sand compaction pile, and etc. They considered the interaction of shear stresses to take into account the stress transfer between the column and the surrounding soil. However, the elastic solution is only considered in the proposed approach for simplicity. Han and Ye (1999) proposed a simplified method for computing the rate of consolidation based on Terzaghi's one-dimensional and Barron's solutions by assuming that composite soil has elastic behavior defined by a constant modulus of deformation, E_s, and a constant Poisson's ratio, ν_s.

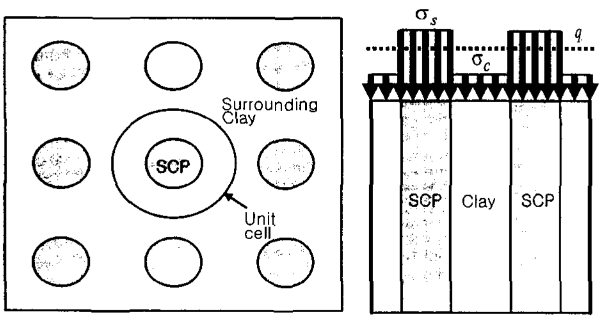


Fig. 1. Composite soil consisted of SCP and surrounding soft soil

Various methods for installation of SCP such as vibro-compaction method, vibro-compozer method, cased-borehole method, and etc, have been used worldwide depending on applicability and availability of equipment in the locality. The vibro-compozer method is frequently used in Korea and Japan. Fig. 2 illustrates the installation procedure of SCP. SCP is constructed by driving the casing pipe to the required depth, and filling the casing with specified volume of sand. The casing is then extracted and partially redriven using the vibratory hammer starting from the bottom. This process is repeated until a fully penetrating compacted sand pile is constructed.

The SCP installation results in disturbance to the soil

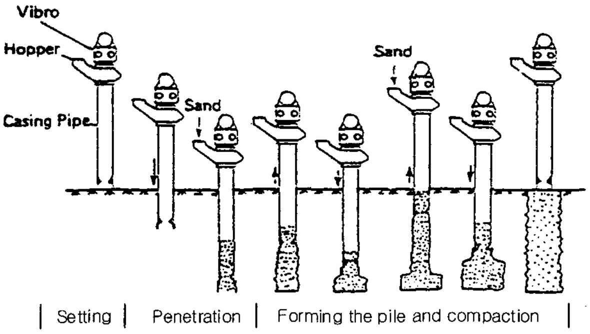


Fig. 2. The vibro-composer method (After Aboshi and Suematsu, 1985)

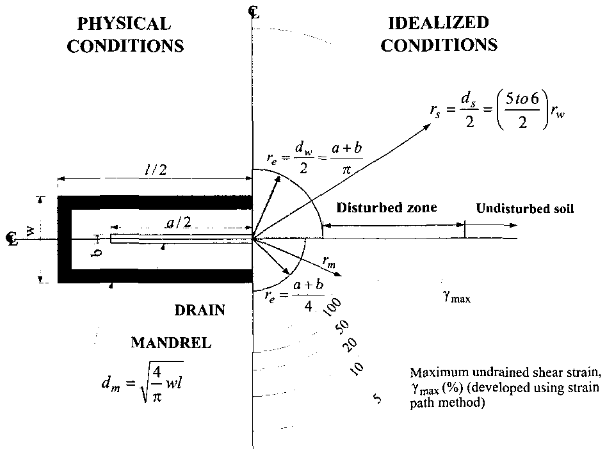


Fig. 3. Approximation of the smeared zone around the mandrel (after Rixner et al., 1986)

surrounding the SCP. It is well known that for the case of vertical drains as shown in Fig. 3, the disturbance is dependent on the mandrel size and shape, soil macrofabric, and installation procedure. For design purposes, it has been evaluated by Jamiolkowksi et al. (1981) that the radius ratio (S) of the smeared zone to the drain well could be related to the cross-sectional dimension of the mandrel as follows:

$$S = \frac{r_s}{r_w} = \frac{5\ to\ 6}{2} \tag{3}$$

where r_s is the radius of the smeared zone; r_w is the radius of a circle with an area equal to the cross-sectional area of the mandrel.

Bergado et al. (1991) showed that the smeared zone could be assumed to be twice the equivalent mandrel diameter (Eq. 4) and the horizontal hydraulic conductivity in the smeared zone (k_h') was approximately equal to the vertical hydraulic conductivity in the undisturbed zone (k_v) (Eq. 5) from both laboratory and full-scale investigations. They also obtained faster settlement rate in the small mandrel area than in the large mandrel area indicating lesser smeared zone in the former than the latter.

$$r_s = 2 r_w \tag{4}$$

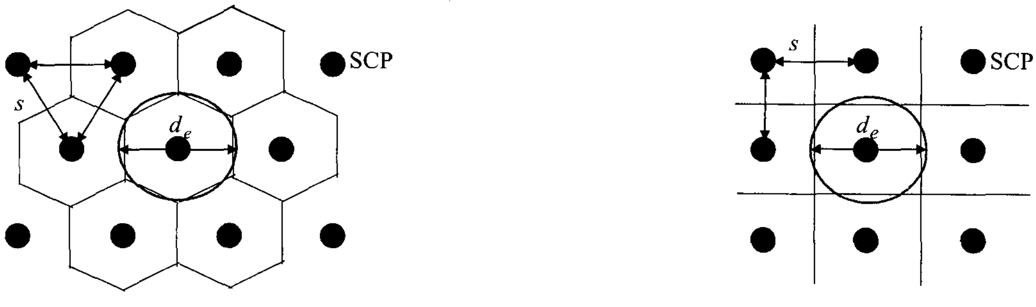
$$k_h' = k_v \tag{5}$$

The important consideration in design and analysis for SCP-improved soil is time-dependent nonlinear consolidation characteristics of the soft soil due to radial drainage through sand pile. Because smear effect is an important factor in evaluating consolidation rate of soft clay, it is necessary to consider smear effect on stress transfer mechanism and stress concentration ratio of SCP-improved ground. This paper presents the numerical results of cylindrical composite ground that was conducted to investigate smear effect on consolidation characteristics of SCP-improved ground. Especially, characteristics of effective stress-pore water pressure response, stress transfer mechanism between sand pile and soft soil, and stress concentration ratio were focused.

2. Numerical Model for SCP-improved Ground

Fig. 4 illustrates typical patterns for SCP installation and the diameter of equivalent soil cylinder (d_e). SCP is generally installed in either triangular or square patterns. The 3-D spatial flows and the corresponding behaviors of consolidation occur in SCP-improved ground. It is necessary to incorporate the 3-D characteristics of consolidation into the analysis technique. But it requires a lot of time to make finite element mesh and computational efforts for the 3-D analysis. Therefore, equivalent cylindrical unit cell was considered in this study for simplicity as shown in Fig. 5. It is recognized that the consolidation behaviors of unit cell adequately represents the behaviors of the composite ground (Barksdale and Bachus, 1983; Balaam and Booker, 1985).

Numerical program CRISP (Britto and Gunn, 1987) is used to simulate time-dependent consolidation behaviors



$d_e = 1.05s$

(a) Triangular Pattern

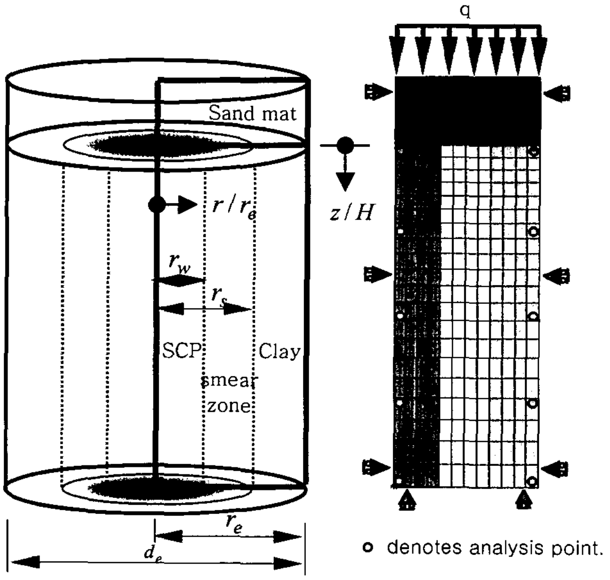
$d_e = 1.13s$

(b) Square Pattern

Fig. 4. Typical patterns for SCP and the diameter of equivalent soil cylinder

Table 1. Material properties for numerical analysis

Soil type	Used model	Parameter	No smear (S=1)	Smear (S>1)	Remark
SCP and Sand mat	Mohr-Coulomb elastic and plastic	Eo (kPa)	14000	14000	r_w=0.35m r_e=1.13m Spacing of SCP = 2.0m C_h= 4E-3m^2/day
		ν	0.3	0.3	
		c	0	0	
		ϕ (deg)	30	30	
		γ_{bulk} (kN/m^3)	19	19	
		k_h (m/day)	0.864	0.864	
		k_v (m/day)	0.864	0.864	
Clay	Modified Cam-clay	κ	0.04	0.04	
		λ	0.265	0.265	
		e_{cs}	1.6	1.6	
		M	1.02	1.02	
		ν	0.4	0.4	
		γ_{bulk} (kN/m^3)	17	17	
		k_h (m/day)	6.26E-5	2.72E-5	$k_h' = k_v$
		k_v (m/day)	2.72E-5	2.72E-5	$k_v' = k_v$



o denotes analysis point.

(a) Unit cell (b) Finite element mesh (S=2)

Fig. 5. Axisymmetric finite element mesh for cylindrical composite ground

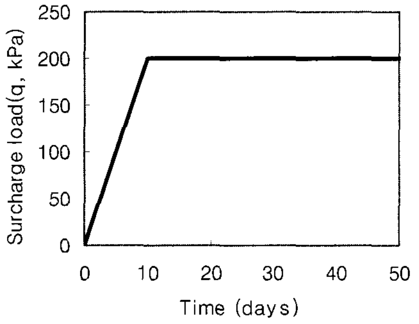


Fig. 6. Loading schedule

of composite ground accounting for smear effect. In order to predict accurately nonlinear consolidation behaviors of composite soil, Modified-Cam clay model was used for clay deposit and Mohr-Coulomb plastic model for SCP and sand mat. Material parameters used in analysis are shown in Table 1, which are taken from design parameters used in Busan New Port Development (Busan New Port Corp., 1999).

To consider smear effect on consolidation behavior, the horizontal hydraulic conductivity in the smeared zone was assumed to be equal to the vertical hydraulic conductivity in the undisturbed zone, i.e., $k_h' = k_v$, according to Bergardo's observations (1991). Well resistance effect was ignored in this analysis because of very large discharge capacity of SCP. The value of the hydraulic conductivity of SCP is above 10,000 times larger than that of the surrounding clay. The surcharge load (q) of 200 kPa was applied to SCP-improved ground as shown in Fig. 6.

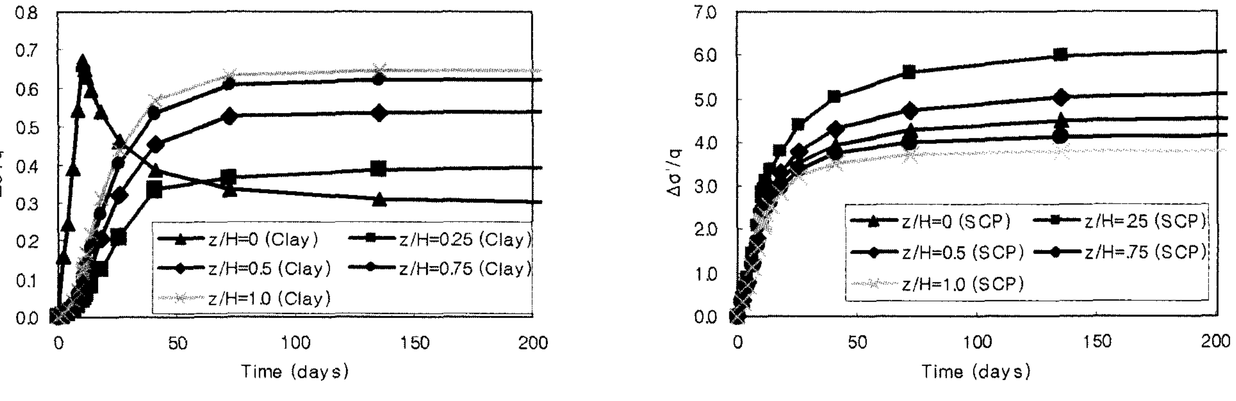
3. Smear Effects on Consolidation Behaviors

3.1 Effective Stress-Pore Water Pressure Response

Total stress is increased in SCP-improved ground when the surcharge load (*q*) is applied. Increases in effective stress and excess pore water pressure take place due to increase in total stress. In case of SCP, effective stress was rapidly increased due to large hydraulic conductivity. Therefore, no excess pore water occurred. In case of soft clay deposit, however, excess pore water pressure was rapidly induced by surcharge load during construction stage and then effective stress was gradually increased due to dissipation of excess pore water pressure.

Fig. 7 demonstrates the variation of normalized effective stress increases ($\Delta\sigma'/q$) with time in clay and SCP deposit. Effective stresses of clay deposit in Fig. 7(a), except the case of z/H≈0, were increased after construction due to consolidation. However, the values of increases in normalized effective stress were less than 1. It indicates that some portion of surcharge load was transferred to SCP. The corresponding increase in effective stress of SCP took place due to stress transfer between the clay and the SCP as shown in Fig. 7(b). The value of $\Delta\sigma'/q$ of SCP approached to 3~6. From Fig. 8, it can be seen that amount of stress transfer between the clay and the SCP was maximum in depth of z/H=0.25 and decreased with the increase in depth. For the case of z/H≈0 (clay) as shown in Fig. 7(a), effective stress was rapidly increased during construction due to short length of drainage and then decreased after construction due to stress transfer between the clay and the SCP (Kim et al., 2004).

Variations of excess pore water pressures of soft clay with and without smeared zone are shown in Fig. 9. Excess pore water pressure was increased during construction period and then decreased due to consolidation process. For the case of S=1 (without smeared zone), its value approached to 0.8*q*, whereas the value of excess pore water pressure in cases of S=2, 3 (with smeared zone) approached to about 0.9*q*. Dissipation rate of excess pore pressure with time was decreased due to the



(a) Clay

(b) SCP

Fig. 7. Variations of normalized effective stresses in soft clay and SCP deposits

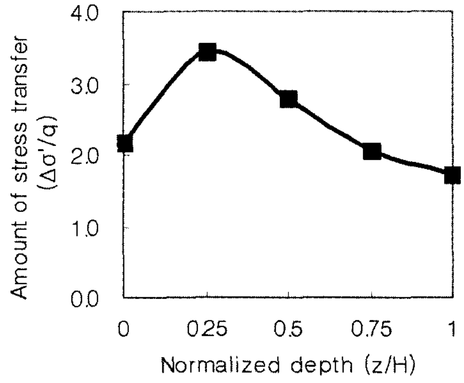


Fig. 8. Amount of normalized stress transfer with depth

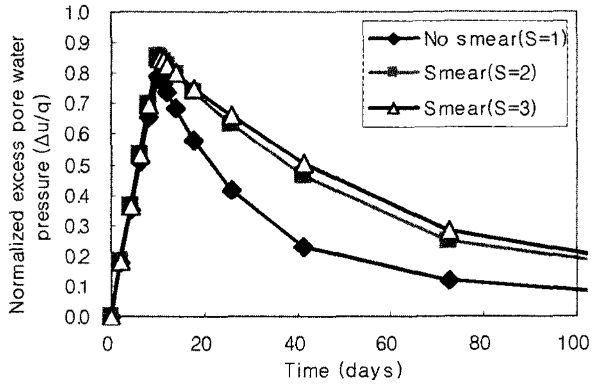
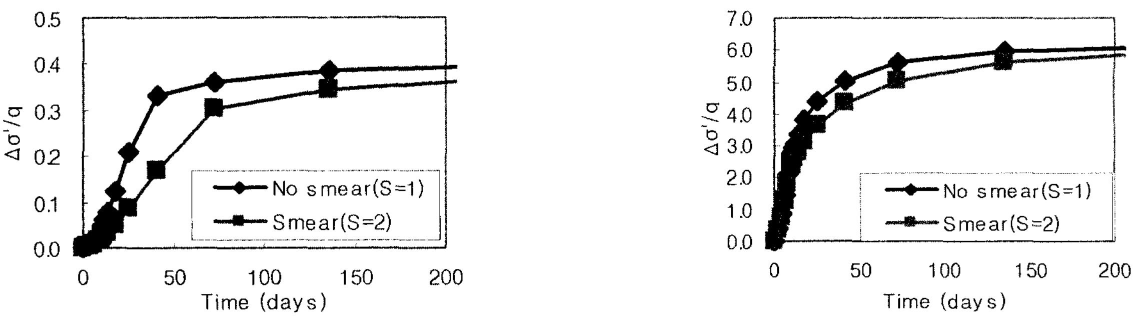


Fig. 9. Dissipation of normalized excess pore water pressure ($\Delta u/q$) with time in clay(z/H=0.25)



(a) Clay

(b) SCP

Fig. 10. Variations of normalized effective stresses at clay and SCP deposits at depth z/H=0.25

smear effect. It indicates that the smearing of soft clay reduces the hydraulic conductivity due to changing of soil fabric and destroying horizontal drainage fine layers.

Fig. 10 demonstrates comparison of increases in normalized effective stress of SCP-improved ground with and without the smear zone. Increase in effective stress of clay in Fig. 10(a) took place due to consolidation of soft clay. On the other hand, increase in effective stress of SCP in Fig. 10(b) was induced from stress transfer mechanism between SCP and clay deposit. The amount of increase in effective stress was reduced with smear effect. It indicates that slower rate of consolidation occurred in the smeared zone.

3.2 Settlement

Distribution of normalized settlement (S/S_{max}) with radius is shown in Fig. 11. An amount of the normalized settlement varied from 0.9 to 1.0. The result from Fig. 11 indicates that free strain takes place in composite ground. Angular distortion of settlement is very large at the interface between SCP and clay. According to the numerical analysis of Kim et al. (2004), abrupt changes in effective stress as well as shear stress take place at the interface. Fig. 12 presents comparison of the time-settlement relations of SCP-improved ground with and without the smear zone. It was found that the smearing of the soft clay reduced the rate of consolidation settlement due to reduction of the horizontal hydraulic conductivity.

Fig. 13 illustrates comparison of degrees of consolidation with the Hansbo's solution (1981). As shown in Fig. 13, the calculated degrees of consolidation ($U = S_t / S_{final}$) from the numerical analysis are higher than that of Hansbo. This result is similar to the observation of Han et al. (2002). This is because the calculated degree of consolidation considers the modular ratio of SCP to the surrounding soil or stress concentration ratio, which accelerates the rate of consolidation. Stress concentration is not considered in the Hansbo's solution. In addition, the Hansbo's theory assumes that the consolidation behavior takes place in radial drainage system which has linear compressibility characteristics without any vertical drainage. It can be also seen that from Fig. 13, the soil

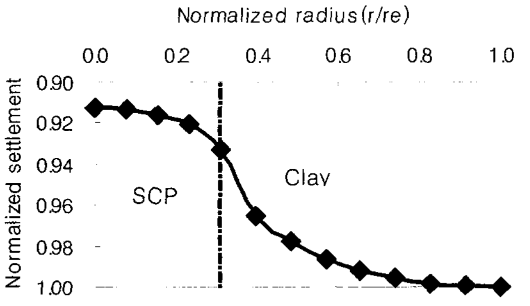


Fig. 11. Normalized settlement(S/S_{max}) distributions with radius

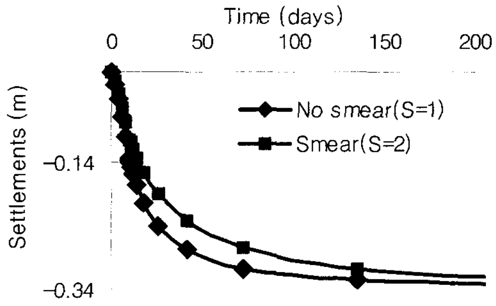


Fig. 12. Variation of settlement with time

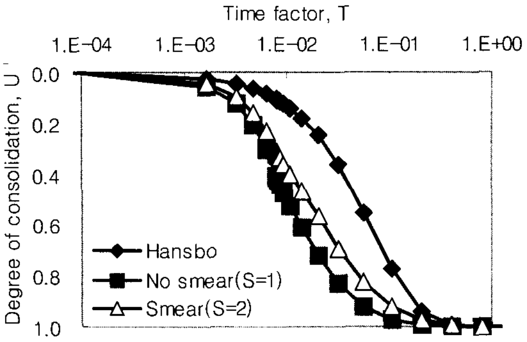


Fig. 13. Comparison of degrees of consolidation

disturbance caused by SCP installation reduces the rate of consolidation of SCP-improved ground.

3.3 Stress Concentration Ratio

Fig. 14 shows variations of stress concentration ratio with time for SCP-improved ground. The stress concentration ratio with an initial value of 1 at initial stage was generally increased during construction (before 10th day). It indicates that SCP mainly resisted to applied load during construction. After construction (after 10th day), however, the stress concentration ratio was rapidly decreased at initial stage of consolidation associated with rapid decrease in excess pore water pressure and then decreased gradually with time. It was found that stress concentration ratio of composite ground was not constant and depended on consolidation process. It is also worth noting that as shown in Fig. 14 the value of stress concentration ratio in soft clay with smeared zone was larger than that in soft clay without smeared zone. However, it converged to the steady stress concentration ratio with the value of 5.5 irrespective of the smeared zone after the end of consolidation.

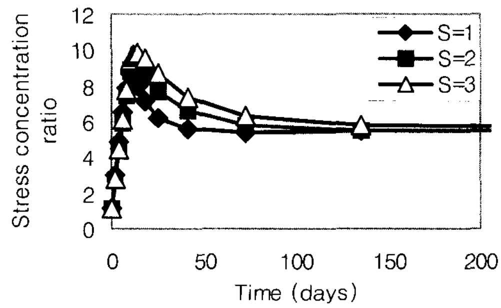


Fig. 14. Variation of stress concentration ratio with time

4. Conclusions

The numerical analysis was conducted to investigate smear effects on consolidation behaviors of SCP-improved composite ground. The results showed that the smeared zone had a significant effect on consolidation characteristics of soft clay including the stress transfer mechanism and stress concentration ratio of composite ground. From the results of analysis, the following conclusions could be drawn:

(1) Amount of stress transfer between the clay and the SCP was maximum in depth of z/H=0.25 and decreased with depth.
(2) The smearing of the soft clay during SCP installation reduced the dissipation rate of excess pore pressure as well as the rate of consolidation settlement due to reduction of the hydraulic conductivity.
(3) The calculated degree of consolidation from the numerical analysis was higher than that of Hansbo because stress concentration accelerated the rate of consolidation.
(4) Stress concentration ratio of SCP-improved ground was not constant and depended on consolidation process. It was also found that during consolidation the value of stress concentration ratio in soft clay with smeared zone was larger than that in soft clay without smeared zone. However, it converged to the steady stress concentration ratio irrespective of the smeared zone after the end of consolidation.

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