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Evaluation of Ultimate Bearing Capacity on Granular Compaction Pile Considering Various Stresses in a Ground

지중응력의 변화를 고려한 조립토 다짐말뚝의 극한지지력 평가

Kang, Yun[1] 강 윤 Yun, Ji-Yeon[2] 윤 지 연
Chang, Weon-Ho[3] 장 원 호 Kim, Hong-Taek[4] 김 홍 택

요 지

조립토 다짐말뚝(granular compaction pile)공법은 비교적 강성이 크고 압축성이 작은 자갈, 쇄석 및 모래 등의 조립질 재료를 사용하여 연약한 지반에 말뚝을 조성하는 공법으로, 기초지반의 지지력 증가, 침하량 감소 및 압밀배수 촉진 등에 의한 지반개량 효과 뿐만 아니라, 사질토 지반에 적용시 지진에 의한 액상화 방지효과도 큰 공법으로 알려져 있으나 국내에서는 아직까지 널리 사용되지 않고 있다. 일반적으로 조립토 다짐말뚝은 Piled-raft system으로 시공되므로, 이 때 조립토 다짐말뚝의 극한지지력에 대한 평가는 팽창파괴 중심부의 깊이에 따라 달라지게 된다. 또한 조립토 다짐말뚝과 주변지반과의 하중분담에 대한 영향 및 지반내에서 조립토 다짐말뚝에 작용하는 구속응력의 변화를 적절하게 고려하여 조립토 다짐말뚝의 극한지지력이 결정되어야 한다. 본 연구에서는, 김 등(1998)에 의하여 연구되었던 조립토 다짐말뚝의 극한지지력 평가에 대한 해석기법을 토대로, 단일 말뚝에 대하여 상재하중의 크기, 재하면적의 크기 및 파괴깊이에 따른 수평구속응력의 변화를 고려하여 극한지지력을 산정하기 위한 기법을 부시네스크 식을 이용하여 제안하였다. 또한 제안된 조립토 다짐말뚝의 극한지지력 평가 기법의 타당성을 실내모형 실험 및 수치해석 프로그램인 PFC-2D 프로그램을 이용한 수치해석 결과와의 비교, 분석을 통해 검증하였다.

Abstract

Granular compaction pile has the load bearing capacity of the soft ground increase and has the settlement of foundation built on the reinforced soil reduce. The granular compaction group piles also have the consolidation of the soft ground accelerate and prevent the liquefaction caused by earthquake using the granular materials such as sand, gravel, stone etc. However, this method is not widely used in Korea. The granular compaction piles are constructed by grouping them with a raft system. The confining pressure at the center of bulging failure depth is a major variable in estimating the ultimate bearing capacity of the granular compaction piles. Therefore, a share of loading is determined considering the effect of load concentration ratio between the granular compaction piles and surrounding soils, and the variation of the magnitude of the confining pressure. In this study, a method for the determination of the ultimate bearing capacity is proposed to apply a change of the horizontal pressure considering bulging failure depth, surcharge, and loaded area. Also, the ultimate bearing capacity of the granular compaction pile is evaluated on the basis of previous study(Kim et al., 1998) on the estimation of the ultimate bearing capacity and compared with the results obtained from laboratory scale model tests and DEM numerical analysis using the PFC-2D program.

Keywords : Boussinesq equation, Confining pressure, Granular compaction pile, Load concentration ratio, Ultimate bearing capacity

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[1] Member, Graduate Student, Dept. of Civil Engrg., Hongik Univ. (antps43@hotmail.com)
[2] Member, Graduate Student, Dept. of Civil Engrg., Hongik Univ.
[3] Executive Director, Dept. of Highway, Seoyeong Eng. Co., Ltd.
[4] Member, Prof., Dept. of Civil Engrg., Hongik Univ.

1. Introduction

Granular compaction pile(G.C.P.) has the load bearing capacity of the soft ground increase and has the settlement of foundation built on reinforced soil reduce. The granular compaction piles also have the consolidation of soft ground accelerate and prevent the liquefaction caused by earthquakes using granular materials such as sand, gravel, stone etc.(Hu et al., 1997).

The confining pressure at the center of bulging failure depth is a major variable in estimating the ultimate bearing capacity of the granular compaction piles. Therefore, a share of loading is determined considering the effect of load concentration ratio between the granular compaction piles and surrounding soils, and the variation of the magnitude proposed by Kim et al.(1998) for the determination of the ultimate bearing capacity applying the theory for Expansion of Cavities by Vesic, A. S.(1972) to the granular compaction pile. However, this method has the problem of how to accurately calculate a change of the confining pressure.

In this study, a method for the determination of the ultimate bearing capacity is proposed to apply the change of the horizontal confining pressure considering bulging failure depth, surcharge and loaded area. Also, the ultimate bearing capacity of the granular compaction pile is evaluated on the basis of previous study(Kim et al., 1998) on the estimation of the ultimate bearing capacity and compared with the results obtained from laboratory scale model tests and DEM numerical analysis using the PFC-2D program.

2. Ultimate Bearing Capacity of Granular Compaction Pile

2.1 Theory for Expansion of Cavities by Vesic

When the load is applied on granular compaction pile, expansion of cavity pressure causes plasticity failure in ground around granular compaction pile where bulging failure depth. is expected. As shown in Eq. (1), Vesic (1972) defined expansion of cavities pressure using radial stress equilibrium condition and Mohr-Coulomb failure criterion.

$$p_u = F_q \cdot q + F_c \cdot c \tag{1}$$

where, q = Horizontal stress in ground at depth center of bulging failure

c = Cohesion of soil

$$F_q = (I_{rr} \sec\phi)^{\frac{\sin\phi}{1+\sin\phi}}(1 + \sin\phi)$$

$$F_c = c \cdot \cot\phi \cdot (F_q - 1)$$

$$I_{rr} = \frac{i_r}{1 + i_r \cdot \varDelta \cdot \sec\phi}$$

$$i_r = \frac{E_s}{2(1+\nu)(c + q\tan\phi)}$$

ϕ = Friction angle of soil

$\varDelta$ = Average volumetric strain of soil

E_s = Elastic modulus of soil

ν = Poission's ratio of soil

Ultimate bearing capacity of granular compaction pile is represented by the vector of cross for expansion of cavity pressure that causes radial plasticity failure in ground, and can be written as following Eq. (2).

$$Q_{ult} = (F_q \cdot q + F_c \cdot c)\left(\frac{1 + \sin\phi_p}{1 - \sin\phi_p}\right)A_p \tag{2}$$

where, ϕ_p = Friction angle of granular compaction pile

A_p = Section Area of granular compaction pile

2.2 Determination for the Confining Stress

2.2.1 Determination for Horizontal Stress Using Elastic Method

Ultimate bearing capacity of granular compaction pile about bulging failure mode is determined considering the effect of horizontal confining stress at the center of bulging failure depth. In this study, considering the effect of variation of horizontal stress in ground for variable bulging failure depth, magnitude of load and loaded area, the increment of horizontal stress at the center of bulging failure can be obtained as the Boussinesq equation using elasticity theory(namely "elastic method"), which is equal to following Eq. (3).

$$\Delta q=\left[1-\frac{l_c}{\sqrt{d_e^2+l_c^2}}\times\left(1+\frac{1}{2}\left(\frac{d_e}{\sqrt{d_e^2+l_c^2}}\right)^2\right)\right]\times q_s \quad (3)$$

where, d_e = Radius for loaded area

l_c = Center of bulging failure

q_s = Shared load in ground

Using the increment of horizontal stress as shown in Eq. (3), the confining stress for granular compaction pile at the center of bulging failure can be obtained in Eq. (4).

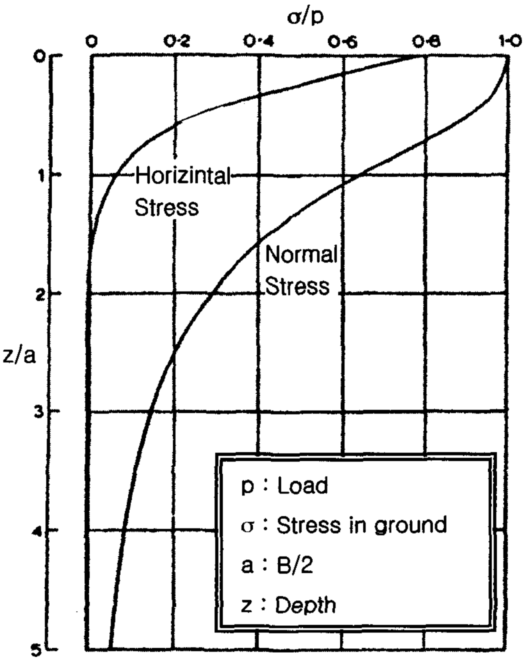
$$q=K_0\gamma_t l_c+\Delta q \qquad (4)$$

where, K_0 = Coefficient of earth pressure at rest

γ_t = Total unit weight of soil

2.2.2 Determination for Horizontal Stress Using Mixing Method

Fig. 1 illustrates vertical and horizontal stress produced by using Boussinesq equation as loading in the ground. But, in evaluating horizontal stress in soft ground which is main subject of this study, it is possible that elastic method is not sufficient for application because soft ground shows elasto-plastic behavior rather than elastic behavior. Therefore, to modify these problems, this study proposes a method that is "mixing method" which active coefficient of earth pressure multiplies normal stress (σ_z) obtained from the Boussinesq equation based on elasticity theory in order to obtain horizontal confining stress in the ground. This method is used to calculate earth pressure acting on retaining wall, and it is found to apply well to the ground that shows elasto-plastic behavior. The increment of normal stress at the center of bulging failure using Boussinesq equation based on elastic theory is shown in Eq. (5) and normal stress distribution in the ground as loading is shown in Fig. 1



(a)

Fig. 1. Stress in ground

$$\Delta\sigma_v=\left\{1-\left(\frac{l_c}{\sqrt{d_e{}^2+l_c{}^2}}\right)^3\right\}\times q_s \qquad (5)$$

where, $\Delta\sigma_v$ = Increment of normal stress

Active earth pressure occurs, because transformation of granular compaction pile is led to radial direction in bulging failure of granular compaction piles according to the increase of loading. The increment of horizontal stress, the increment of normal stress ($\Delta\sigma_v$) obtained from Eq. (5) multiplied by the coefficient of active earth pressure, is obtained in Eq. (6)

$$\Delta q=\Delta\sigma_v\times K_a \qquad (6)$$

where, K_a = Coefficient of active earth pressure

Using the increment of horizontal stress shown in Eq. (6), the confining stress for granular compaction pile at the center of bulging failure can be obtained in Eq. (4)

2.3 Load Concentration Ratio

As shown in Fig. 2, the load mobilized to raft is individually transferred to ground and piles, and causes settlement of the ground. Based on the above concept, Rao et al. (1985) defined load concentration ratio(m) in Eq. (7). According to Juran et al.(1991), value of m increases as consolidation progresses in ground due to loading on raft, and value of m decreases when bulging

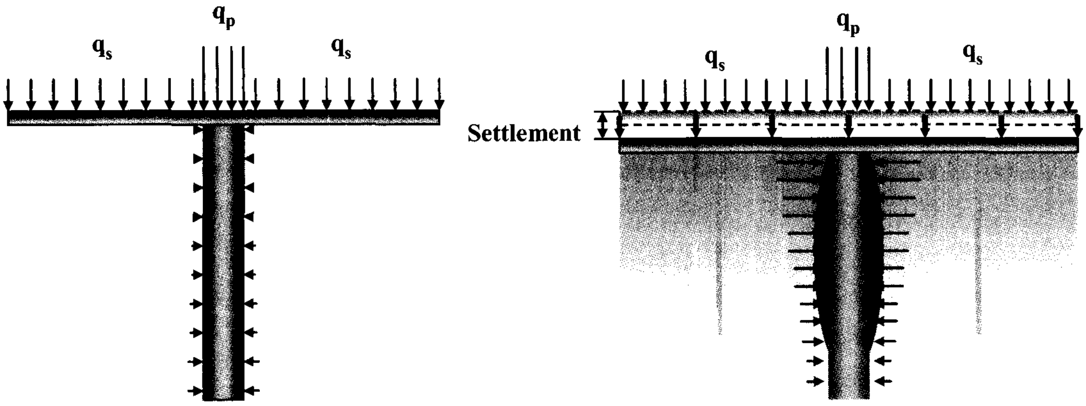
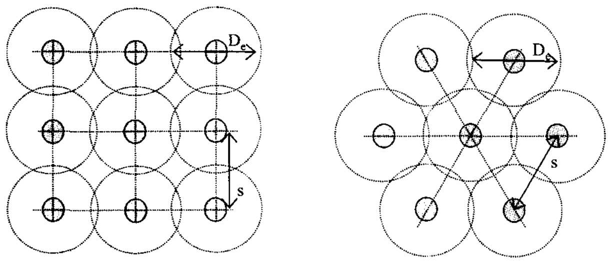


Fig. 2. Behaviour for G.C.P. and ground under the raft



(a) Squared installation $D_e = 1.128s$ (b) Triangled installation $D_e = 1.050s$

where, s = Distance of installation

Fig. 3. G.C.P. of effective diameter

failure of granular compaction pile appeares.

$$m = \frac{q_p}{q_s} = \frac{E_p}{E_s} \qquad (7)$$

where, q_p= Shared load in pile

E_p= Elastic modulus of pile

Loaded area for the granular compaction pile system can assume the shape of circle on the center of each piles, and the diameter of circle is defined as effective diameter(De). Effective diameter of the granular compaction pile as form of installation for piles is illustrated in Fig. 3.

3. Laboratory Model Tests

3.1 Summary for Laboratory Model Tests

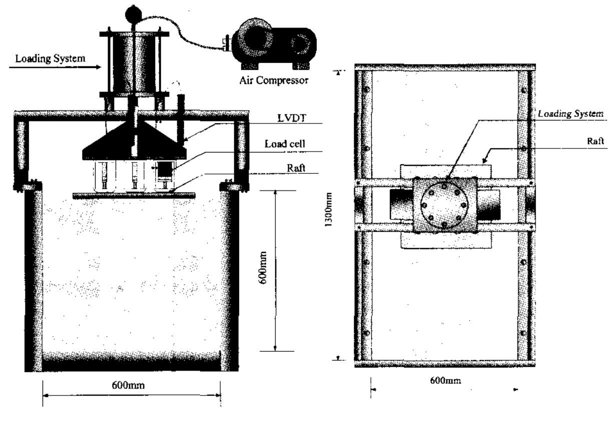


Fig. 4. Laboratory model test system

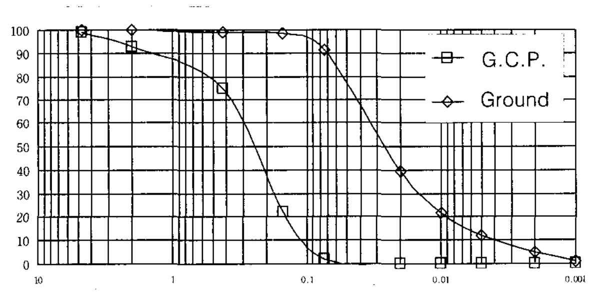


Fig. 5 Grain size distribution

Laboratory model test system(see Fig. 4) used in this study was composed of loading system, test box (600mm ×600mm×1300mm), the granular compaction pile and model ground reduced scale ground.

Also, to obtain load concentration ratio, pressure cells were installed under the raft, and load-controlled method was used. Sample of soil for laboratory model tests was selected out of typical soft ground in Korea. Sample of ground was collected in Sihwa-region of Masanpo, Hwaseongsi, Gyeonggido, and sample of sand was collected in Daeeunri, Yonggungmyeon, Yecheongun, Gyeongsangbukdo. These samples were

Table 1. Physical properties

	Gs	LL (%)	PI (%)	USCS
G.C.P.	2.63	-	N.P	SP
Soil	2.71	24.2	18.9	ML

Table 2. Properties for laboratory model tests

Granular compaction pile				
Diameter (cm)	Unit weight (t/m^3)	Elastic modulus (t/m^2)	Poission's Ratio	Friction angle (°)
5.0	2.0	4500	0.3	40
Ground				
Cohesion (t/m^2)	Unit weight (t/m^3)	Elastic modulus (t/m^2)	Poission's Ratio	Friction angle (°)
2.5~2.8	1.6	300	0.3	0

tested for physical properties on the basis of Korea Industrial Standard. The results from test for physical properties are presented in Table 1, and grain size distribution is shown in Fig. 5.

Properties for laboratory model tests are presented in Table 2.

3.2 Process of Laboratory Model Tests

To verify application of estimation methods to ultimate bearing capacity of granular compaction pile proposed in this study, two estimation methods, namely elastic method and mixing method, were performed as laboratory model tests. Load concentration ratio is measured by installing pressure cells under the raft, and process for laboratory model tests is presented in Fig. 6.

Laboratory model tests are performed as shown in Table 3, and undrained shear stress of ground was measured by using Tor-Vane, which is used for in-situ investigation. Consequently, the results of undrained shear stress of ground are measured as 2.5 kg/cm^2 at a case of $B = 3D$, and 2.8 kg/cm^2 at cases of $B = 5D$ and $B = 7D$.

Table 3. Case for laboratory model tests

Diameter	Size of raft	Length
5cm	15cm × 15cm	30cm
	25cm × 25cm	
	35cm × 35cm	

4. Numerical Analysis

PFC-2D in this study is numerical analysis program which uses Distinct Element Method (DEM). PFC-2D. This program is effective to express interaction of granular particle, and appropriate one in this study. Properties for numerical analysis are presented in Table 4, and Fig. 7 illustrates simplified condition for numerical analysis. Properties for PFC-2D were changed as shown in table 4 to perform effective numerical analysis.

Table 4. Properties for numerical analysis

Granular compaction pile				
Diameter (cm)	Unit weight (t/m^3)	Elastic modulus (t/m^2)	Poission's Ratio	Friction angle (°)
1.0	2.0	4500	0.3	40
Ground				
Cohesion (t/m^2)	Unit weight (t/m^3)	Elastic modulus (t/m^2)	Poission's Ratio	Friction angle (°)
2.0	1.6	300	0.3	0

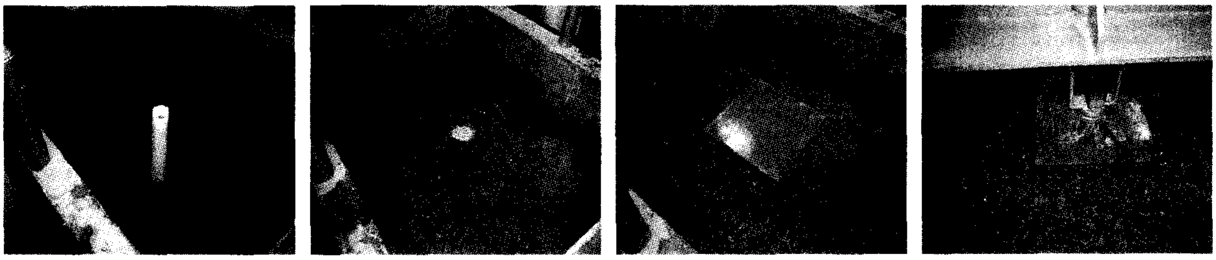

(1) Install the caisson (2) Prepare the model ground (3) Install the raft (4) Load on the raft

Fig. 6. Proceeding for laboratory model test

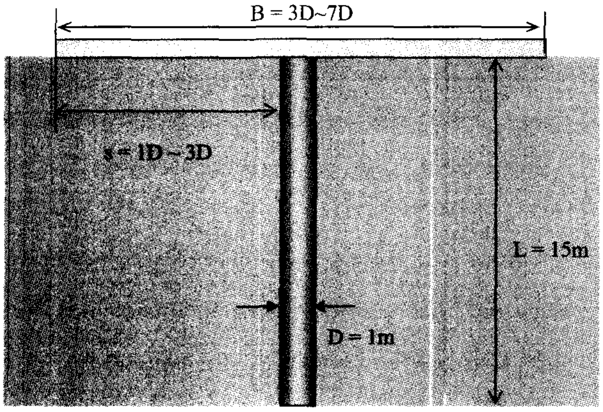
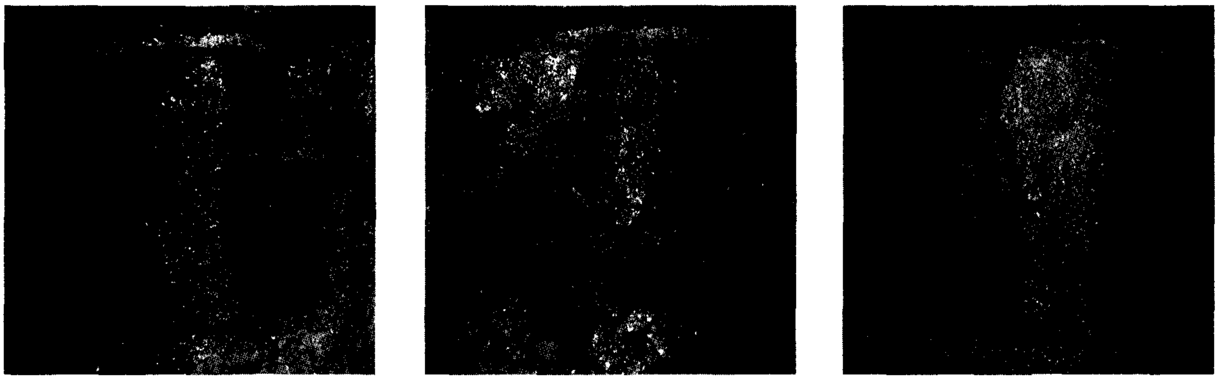


Fig. 7. Condition for numerical analysis

5. Results and Analysis

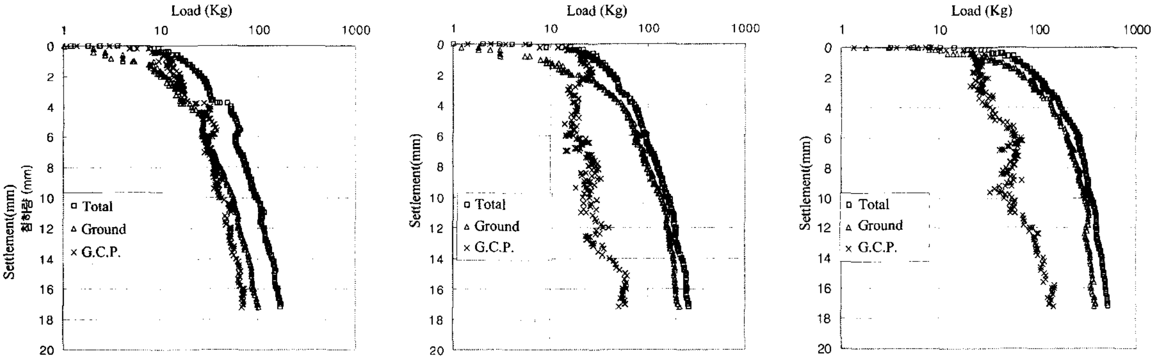
5.1 Results from Laboratory Model Tests

In this study, to search relationship between effective diameter and ultimate bearing capacity of granular compaction pile, load-settlement relation that acts on granular compaction pile during changing raft width into 15cm (3D), 25cm(5D) and 35cm(7D) is obtained by laboratory model tests. Fig. 8 shows the section of failure shape of granular compaction pile in each case. As shown in Fig. 8, the result represents that granular compaction pile acting on load shows the shape of bulging failure. Fig. 9 shows the load-settlement curve of granular compaction pile. As shown in Fig. 9, because Fig. 9 shows the shape of typical failure curve line on piles, the result can be concluded by evaluating ultimate bearing capacity of granular compaction pile and the load concentration ratio by load-settlement relation obtained from Fig. 9. Therefore, Fig. 10 represents the change of load concentration ratio by settlement of raft on the basis of load-settlement relation. As shown in Fig. 10, load concentration ratio decreases as settlement appears in all cases. According to the result from laboratory test by Juran et al.(1991), load concentration ratio increased as



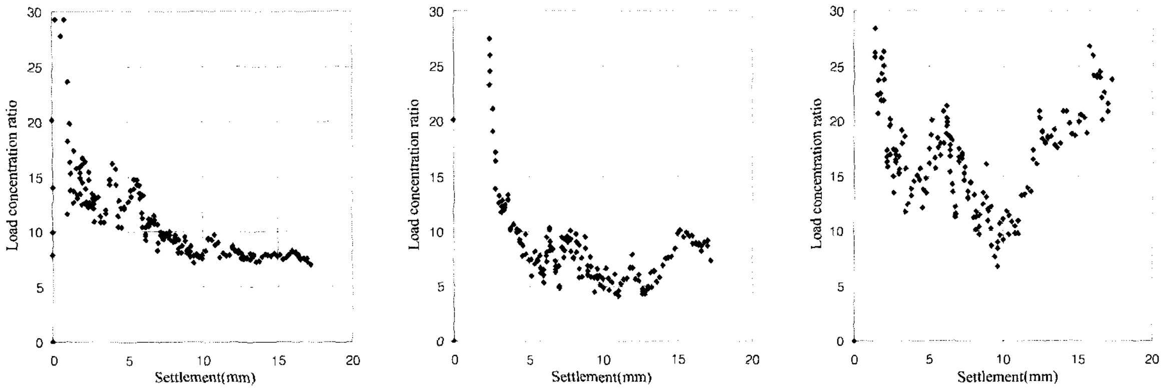
(a) B = 3D(15cm) (b) B = 5D(25cm) (c) B = 7D(35cm)

Fig. 8. Failure shape of G.C.P. by results from laboratory model tests



(a) B = 3D(15cm) (b) B = 5D(25cm) (c) B = 7D(35cm)

Fig. 9. Load-settlement curve of G.C.P.



(a) B = 3D(15cm) (b) B = 5D(25cm) (c) B = 7D(35cm)

Fig. 10. Change of load concentration ratio with settlement

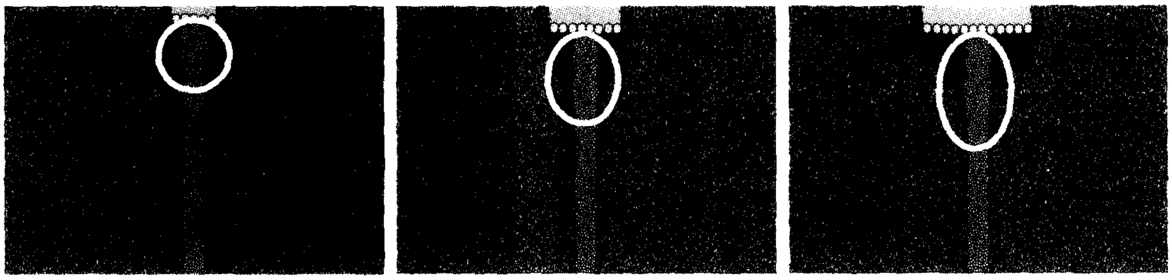
loading progressed. This result was achieved from the test by using triaxial pressure cell. In this test by using triaxial pressure cell, consolidation of ground was considered on condition that clay of model ground was fixed and drain was progressed. The results from laboratory model test are shown in Fig. 13. The laboratory model tests were performed using actual constructed basis and not considering consolidation of ground because the loading step because the loading step in the laboratory model tests was relatively faster than that in the tests by Juran et al.(1991). was relatively faster in the laboratory model tests than that in the tests by Juran et al.(1991).

5.2 Results from Numerical Analysis

To examine the relationship how width of raft and failure shape of granular compaction pile and failure depth, this study performed numerical analysis using PFC-2D program in DEM analysis program. Fig. 11. represents the results from numerical analysis performed by changing width of raft from 3D to 7D and bulging failure shape of granular compaction pile by width of raft. As shown in Fig. 11, when width of raft is 3D, shape of bulging failure appears clearly in shallow depth, but bulging failure is getting deeper as the width of raft increases and diameter of granular compaction pile in the center of that bulging failure decreases. The effect that controls bulging failure increases as the width of raft increases, therefore bulging failure depth is deeper. This results conform to the purpose of this study.

5.3 Estimations of Ultimate Bearing Capacity

To verify application of estimation methods for ultimate bearing capacity of granular compaction pile proposed in this study, these two estimation methods, namely elastic method and mixing method, were compared with laboratory model tests such as numerical analysis and estimation method of ultimate bearing capacity proposed by Kim et al.(1998). These results from above



(a) B = 3D (b) B = 5D (c) B = 7D

Fig. 11. Failure shape of G.C.P. by obtained from the results of numerical analysis

Table 5. Results from estimation methods for ultimate bearing capacity of G.C.P. (Units : kgf)

Width of raft			3D	5D	7D
Proposed Method by this study	Elastic Method (Boussinesq Equation)	c = 2.0t/m^2	12.06	13.51	14.57
		c = 3.0t/m^2	15.83	17.74	19.12
	Mixed Method ($\Delta\sigma_v \times K_a$)	c = 2.0t/m^2	16.71	18.47	18.91
		c = 3.0t/m^2	21.22	24.25	24.83
Proposed Method by Kim et al.		c = 2.0t/m^2	23.21	23.21	23.21
		c = 3.0t/m^2	29.22	29.22	29.22
Results from laboratory model test (c = 2.5~2.8t/m^2)			18.57	19.91	21.84
Results from numerical analysis (c = 2.0t/m^2)			19.12	20.42	22.45

comparison are presented in Table 5. As shown in Table 5, results from elastic method and mixing method present that ultimate bearing capacity of granular compaction pile is smaller than that of the other results.

As shown in the result from numerical analysis, ultimate bearing capacity of granular compaction pile is greater, because granular compaction pile is analyzed in 2D numerical analysis.

According to the method proposed by Kim et al.(1998), the tests show equal results because effect for increment of ultimate bearing capacity as the width of raft cannot be considered. However, the other methods consider the effect of width of raft. Especially, the results from mixing method are similar to results from laboratory model tests. In elastic method, horizontal stress is underestimated as depth of ground is getting deeper. Therefore, mixing method is concluded as the effective method to measure horizontal stress.

5.4 Parametric Study

This study analyzed the relationship between ultimate bearing capacity of granular compaction pile and major design parameters by changing major design parameters such as cohesion, unit weight of soil and friction angle of granular compaction pile in the estimation method proposed by Kim et al.(1998) and two estimation methods proposed by this study, namely, elastic method and mixing method. Data used in the above analysis and case of analysis are presented in Table 6 and Table 7, and result of analysis are shown in Fig. 12.

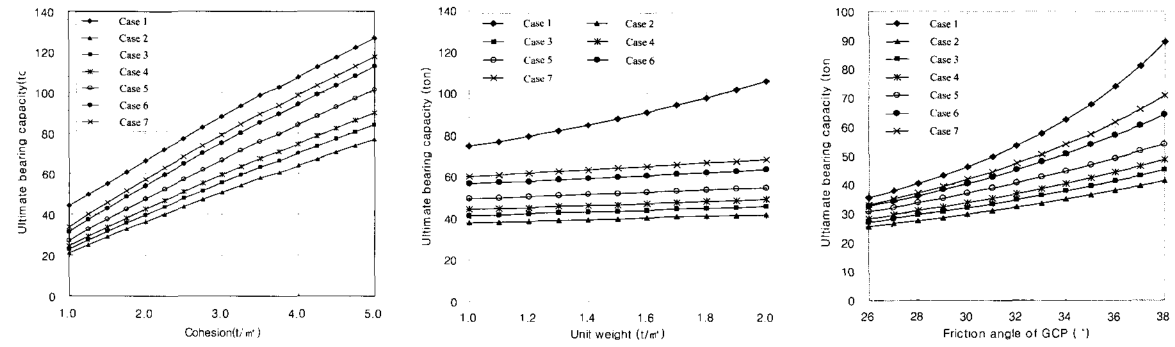
As shown in Fig. 12(a), when cohesion of soil increases from c = 1 t/m^2 to c = 5 t/m^2, ultimate bearing capacity of granular compaction pile increases linearly from 186.5% to 268.9% in all estimation methods. As shown in Fig. 12(b), when unit weight of soil increases from 1.0 t/m^3 to 2.0 t/m^3, ultimate bearing capacity of granular compaction pile increases by about 40.6% in the method proposed by Kim et al.(1998), but it increases from 13.5% to 13.9% in the other methods proposed in this study. Consequently, it shows that ultimate bearing capacity is much more affected by unit weight of soil in method proposed by Kim et al.(1998) than that in the other methods proposed in this study. As shown in Fig.

Table 6. Properties for parameters analysis

Granular compaction pile				
Length (m)	Unit weight (t/m^3)	Elastic modulus (t/m^2)	Poission's Ratio	Friction angle (°)
10.0	2.0	5000	0.3	26~38
Ground				
Cohesion (t/m^2)	Unit weight (t/m^3)	Elastic modulus (t/m^2)	Poission's Ratio	Friction angle (°)
1.0~5.0	1.0~2.0	600	0.3	0

Table 7. Case of analysis

Estimation Method		Case No.
Proposed method by Kim et al.		Case 1
Elastic Method	B = 3D	Case 2
	B = 5D	Case 3
	B = 7D	Case 4
Mixed Method	B = 3D	Case 5
	B = 5D	Case 6
	B = 7D	Case 7



(a) Cohesion (b) Unit weight (c) Friction angle for G.C.P.

Fig. 12. Results from parameteric study

12(c), when friction angle of granular compaction pile increases from 26° to 38°, ultimate bearing capacity increases by 139.7% in the method proposed by Kim et al.(1998) and also it increases by 73.3% ~ 79.5%, 74.1% ~ 108.3% in elastic method and mixing method, respectively. It shows that ultimate bearing capacity is greatly affected by friction angle of granular compaction pile in all cases.

These results indicate that increment of ultimate bearing capacity is less affected by major design parameters in two methods proposed in this study than that in the method proposed by Kim et al.(1998), and ultimate bearing capacity is less affected by unit weight of soil and much affected by cohesion of soil.

6. Conclusion

In this study, a change of the horizontal pressure considering various stresses in the ground is applied to the confining pressure, and the ultimate bearing capacity of the granular compaction pile is evaluated on the basis of previous study on the estimation of the ultimate bearing capacity and compared with the results obtained from laboratory scale model tests and DEM numerical analysis using the PFC-2D program. Based on this study, several conclusions and summaries are as belows :

(1) Considering the effect of variation of horizontal stress in the ground for loaded area, the magnitude of load, variable bulging failure depth and the increment of horizontal stress at the center of bulging failure, this study proposes the two methods, namely elastic method and mixing method.

(2) Results from elastic method and mixing method present that the ultimate bearing capacity of granular compaction pile is smaller than those from laboratory model tests, numerical analysis and estimation method of ultimate bearing capacity proposed by Kim et al.(1998), but the mixing method proposed in this study is concluded as the effective method to measure horizontal confining stress and to calculate ultimate bearing capacity of granular compaction pile.

(3) Results from parametric studies indicate that increment of bearing capacity is less affected by major design parameters in two methods proposed in this study than that in the method proposed by Kim et al.(1998) and ultimate bearing capacity is less affected by unit weight of soil and much affected by cohesion of soil.

Acknowledgments

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