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Centrifuge Modeling of Circular Sallow Foundation Reinforced with a Thin Sleeve

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ABSTRACT

A reinforcing method for a surface circular foundation with a thin flexible underground structure, called "sleeve", is proposed in this paper. The sleeve wraps soil cylinder underneath a surface circular foundation to confine lateral movements of the soil cylinder. This constraint increases lateral confining pressure, which improves shear strength and stiffness of the soil cylinder underneath the circular foundation. Consequently, the bearing capacity of the surface circular foundation increases and reaches that of massive conventional embedded foundations. In this paper, a series of loading tests of model footings on model sand was conducted to investigate the effects of reinforcement with a sleeve structure. The circular model foundation was made of aluminium with a diameter of 30 mm. A sleeve structure with dimensions of 40 mm in diameter and 30 mm in height was made from a thin polyethylene terephthalate film with a thickness of 0.1 mm. Comparisons of performances of foundations between embedded foundations and surface foundation with sleeve were made and the advantages of surface foundation with sleeve are discussed. The results showed that the surface foundation of 1.5 m in diameter with sleeve provided similar values of bearing capacity obtained from a conventional massive foundation embedded at 1.5 m in prototype scale.

Key words: *Shallow foundation, Sleeve foundation, Bearing capacity, Reinforcement, Centrifuge model test*

1. Introduction

For many years, many researches have been conducted how to reinforce the foundations or for soil reinforcement, using different technics and materials. For example, Chen *et al.* (2016) carried out an experimental study on reinforced foundation using transparent soil techniques. Sawwaf and Nazer (2005) investigated an improvement of footing by using Unplasticized Polyvinyl Chloride Cylinders (UPVC) to confine soil around the footing. Eid *et al.* (2009) studied the behavior of the square foundations resting on confined sand, using the walls to confine sand laterally. Abu-Farsakh *et al.* (2013) used the geosynthetic to reinforce sand and evaluated the settlement. However, the effectiveness for practical scales of foundations have not been sufficiently investigated.

2. Background and objective of the project

Concrete has been used in the constructions as the essential element, mainly in foundation work, hence the main source of raw material could be scarce, which can imply an increment cost of acquisition, and consequently the construction work cost becomes high. It is therefore important to investigate a method of reducing costs for the foundation construction.

The aim of this research is to develop a low cost reinforcement for foundations. To achieve this objective, the authors concentrated into the method to reduce the volume of concrete of foundations by confining soil underneath the foundation with a thin circular structure. In this research sleeve was chosen to wrap and confine soil and reinforce the foundation. Tensile strength of the material used for sleeve was examined in this study. A series of vertical loading tests of model circular foundations on sand was conducted under both gravitational and centrifugal force fields to verify the effects of sleeve on reinforcement of bearing capacity in prototype scales.

3. Model description

3.1. Model footings and test cases

Three cases of foundations were employed, as shown in **Fig. 1** and **Table 1**. In all cases, the diameter of models of circular footing was 30 mm.

A series of preliminary tests was conducted by Takatsuji *et al.* (2017), under 1 G to determine the diameter and height of sleeve. According to the results, D_s=40mm and h_s=30mm were employed for centrifuge tests.

Twelve cases of centrifuge loading test were carried out to evaluate the performance of reinforcement using sleeve for practical sizes of footings. Diameters of footing employed were 0.39 m to 1.50 m in prototype scale**,** considering the ability of the centrifuge apparatus used.

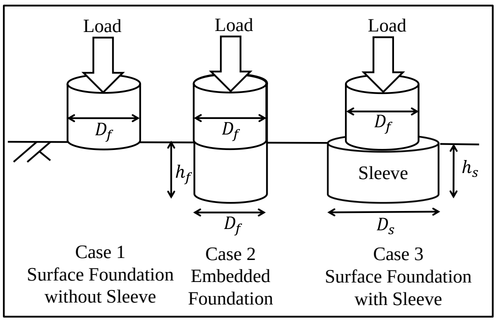


Fig. 1 Cases in tested in the centrifuge apparatus

Table 1. Model footings and test cases

	Case 1	Case 2	Case 3
Footing	Surface	Embedded	Surface
Sleeve	none	none	t=0.1mm PET film

Pattern	Accel.	All	Case 2	Case 3	
	(G)	D_f (m)	h_f(m)	D_s (m)	h_s(m)
Prelim-inary	1	0.03	NA	0.03-0.06	0.01-0.06
1	50	1.50	1.50	2.00	1.50
2	38	1.14	1.14	1.52	1.14
3	25	0.75	0.75	1.00	0.75
4	13	0.39	0.39	0.52	0.39

D_f: diameter of footing, h_f: embedment length of footing,
D_s: diameter of sleeve, h_s: height of sleeve

Note: dimensions in prototype scale except t

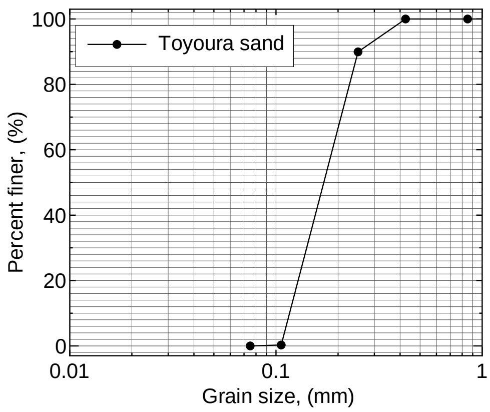


Fig. 2 Grain size distribution of the sand

3.2. Properties of the sand used

The sand used in this study was Toyoura sand, which is fine sand. The density of soil particles, ρ_s=2.628 g/cm^3, was determined according to the Japanese Industrial Standards (JIS) A 1202. The maximum and minimum densities were also measured by JIS A 1224 as ρ_{dmax} = 1.638g/cm^3 and ρ_{dmin} = 1.351g/cm^3, respectively. The corresponding maximum and minimum void ratios measured were e_{max} = 0.946 and e_{min} = 0.605, respectively. The particle size distribution was obtained by the sieving analyses method according to JIS A 1204, and the result is shown in **Fig. 2**, with the effective particle sizes $D_{10} = 0.121$ mm, D_{30}=0.141 mm and D_{60}=0.187 mm. Coefficient of uniformity U_c and coefficient of curvature $U_c{}'$ are 1.545 and 0.879, respectively.

3.3. Material to simulate sleeve

The material for the sleeve model employed in this study was KOKUYO OA VF-1 transparent polyethylene terephthalate (PET) film with a 0.1 mm thickness corresponding to 144 g/m^2. To measure the mechanical properties of PET film, a series of tensile test was carried out with five samples. A universal testing machine (Instron model 5985) was employed to obtain the relationships between tensile strain and tensile stress, as shown in **Fig. 3**. All samples yielded at a tensile stress of 120 MPa.

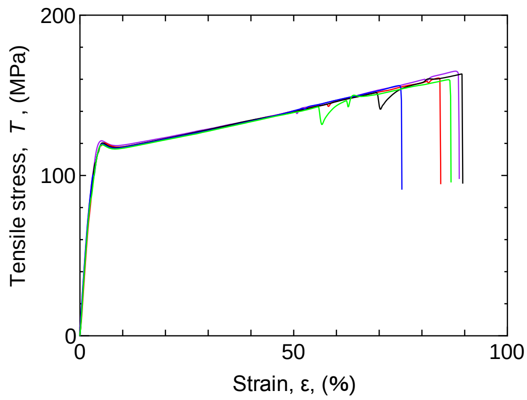
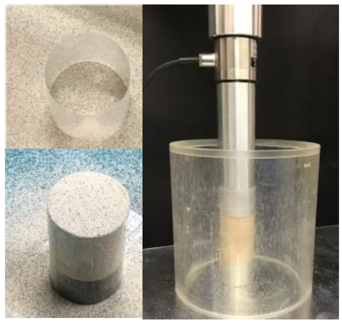


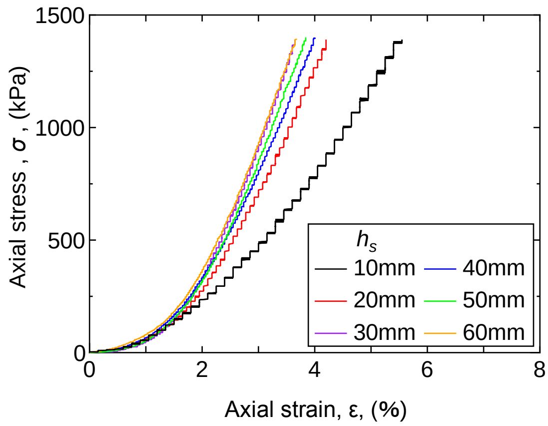
Fig. 3 Result of the tensile stress

Figs. 4(a-c) illustrate a series of uniaxial compression test on sand cylinders, with a diameter D_s of 30 mm and various heights, confined laterally with a thin PET sleeve. Firstly the PET film was cut and connected both ends each other to make a circular sleeve with 30 mm diameter and various prescribed heights for h_s=10 mm to 60 mm. Secondly, the sleeve was attached around a cylindrical pedestal made of aluminum, then Toyoura sand was poured into the sleeve by air pluviation method, as **Fig. 4(a)** shows. A cylindrical cap made of aluminum was placed on the top of the sand cylinder after sand heap on the top was scraped to be flat. Axial load was applied through the cap and the relationships between axial stress and axial strain were obtained. Tangential moduli were gradually increasing with increasing axial strains that developed lateral hoop reaction in the sleeve (see **Fig. 4(c)**). The ultimate value of axial stress σ_u can be estimated from the tensile strength of the PET sleeve σ_t and the internal friction angle of sand φ as **Eq. 1**, however, σ_u could not be determined due to the limit of the loading apparatus used. In **Eq. 1**, t and D_s are the thickness and the diameter of the sleeve, respectively.

$$\sigma_u = 2\frac{t}{D_s}\frac{1+\sin\varphi}{1-\sin\varphi}\sigma_t \qquad (1)$$



(a) sleeve (b)compression test



(c)results

Figs. 4(a-c) Compression test on sand cylinder

4. Centrifuge tests

4.1. Test setup

Fig. 5 shows the test setup for centrifuge tests and an example of footing with sleeve. The embedded model

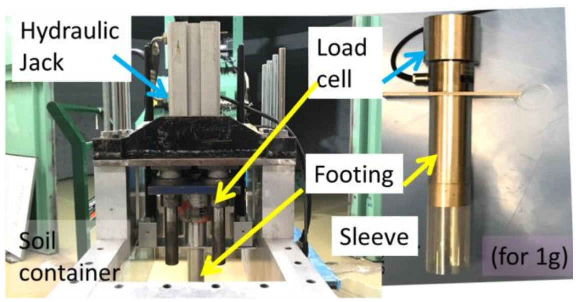


Fig. 5 Test setup

footing used was made of aluminum with 30 mm diameter and height with 30 mm, to set up the experiment for Case 2. The soil container used was a rigid rectangular box of which dimensions were 450 mm in length, 200 mm in width and 350 mm in height.

4.2. Preparation of model sand

The model sand was prepared by means of a method of air pluviation. A spot hopper was used for 1 G preliminary tests, while a line hopper was used for centrifuge tests. A typical method of air pluviation was introduced by Ueno (2000).

The apparatus used for centrifuges tests consists of a line hopper with trapezoidal section with dimensions of 0.4 x 0.4 x 0.04 m and an automatic alternative sweeper with constant velocities. The line hopper is placed on and guided by two longitudinal beams supported by two transversal beams. The transversal beams are suspended from rectangular steel frame by chains through 4 pulleys to move upward or downward.

For the Case 1, the container was fixed below the line hopper, and filled with sand into two layers of a 100 mm height each. The sand was dropped from a 700 mm height through the air with a constant sweep rate of the line hopper having an opening of 4 mm. The relative density measured was D_r=50 % corresponding to dry density of ρ_d=1.50 g/cm^3.

For Case 2 and Case 3, the box was filled with sand into 3 layers. The first layer was 100 mm thick sand, the second layer was 70 mm thick sand. Then the sleeve or model foundation was installed on the center of the container just touching the ground, and the last layer of 30 mm was filled. Care was taken during the installation of the foundation model into the sand to keep the ground condition uniform in each case.

Similar pouring procedure was employed for preliminary 1 G tests by using a spot hopper.

5. Results and discussions

Fig. 6 shows relationships between load intensity and settlement for Case 1 and Case 3 with various sleeve diameters D_s, obtained from a part of the results of preliminary tests examined by Takatsuji *et al.* (2017). The case with D_s=40 mm brought the best performance for the cases with D_f =30 mm. Curves with larger D_s showed

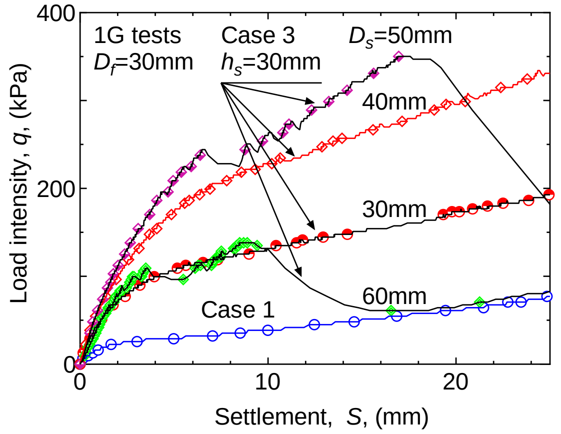


Fig. 6 A part of results of preliminary tests under 1G.

sudden drops even the sleeves were not broken.

Fig. 7 shows the result of the centrifuge test for Pattern 1. The results show that Case 2 and Case 3, just after the applying load, have the same increment of q-S relationship until the load reaches q=2,500 kPa at S=200 mm. In Case 2, the curve yields at this point. While in Case 3, q increased to the peak at 5,500 kPa for settlement S=620 mm.

The clear breaking of the sleeve in Case 3 was detected from the changes in circumferential strain induced in the sleeve, as shown in **Fig. 8**. The clear breaking in the joint parts of the sleeve was observed after the tests. While the q for Case 1 and Case 2 at the same settlement, S=620 mm, were q=1,900 kPa and q=4,600 kPa, respectively.

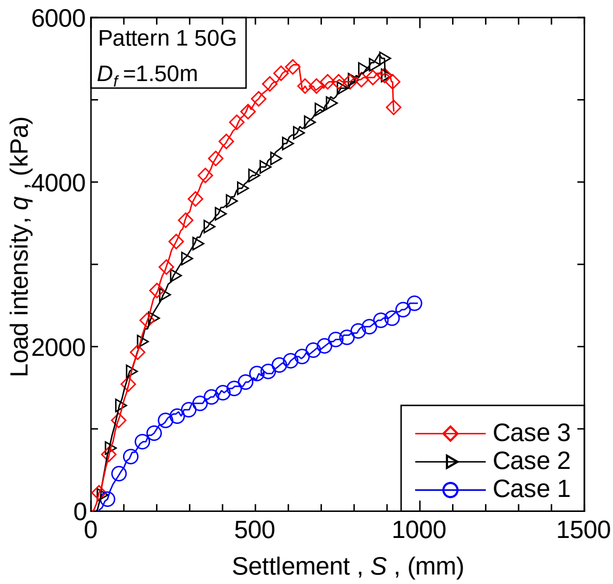


Fig. 7 Load-settlement relationships for Pattern 1

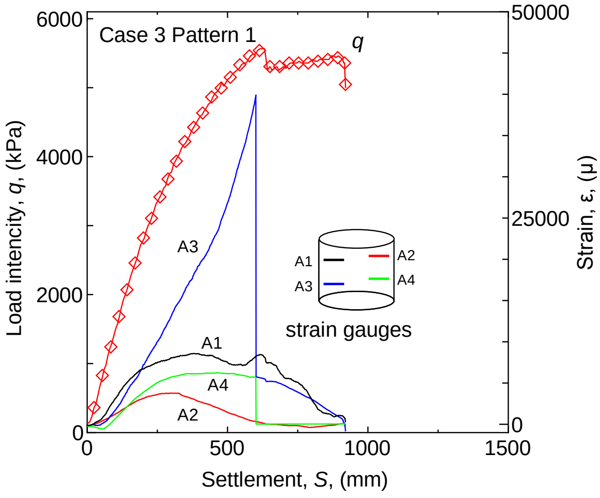


Fig. 8 Changes in circumferential strain in a sleeve

Fig. 9 shows the results for Pattern 2. The values obtained from Case 2 and Case 3 just after the applying load have the same increment of *q-S* relationship until *q*=1,450 kPa and *S*=80 mm, while Case 1 has the lowest 600 kPa. After *q* for Case 3 increased from 1,450 kPa to 4,500 kPa at the same settlement of *S*=370 mm, the sleeve was broken (this broken was in the joint part). At same settlement, Case 2 has the load of *q*=3,500 kPa while Case 1 again shows the lowest value of *q*=1,200 kPa.

Fig. 10 shows the result for Pattern 3. Case 3 shows the highest value comparison with Case 2. The load was increased until *q*=3,750 kPa with *S*=300 mm. Case 2 and Case 3 for the same settlement have *q*=2,250 kPa and *q*=700 kPa, respectively.

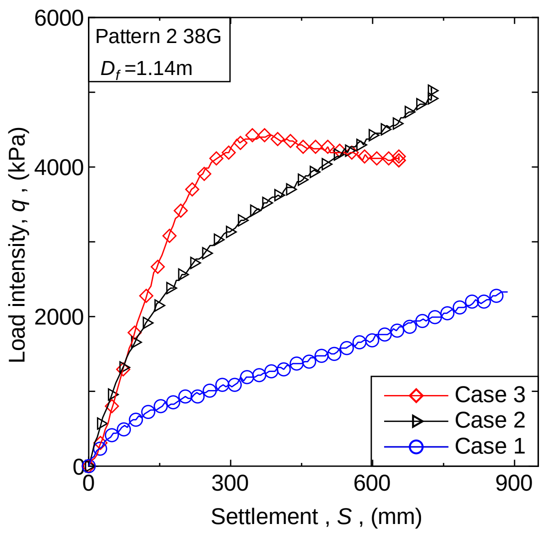


Fig. 9 Load-settlement relationships for Pattern 2

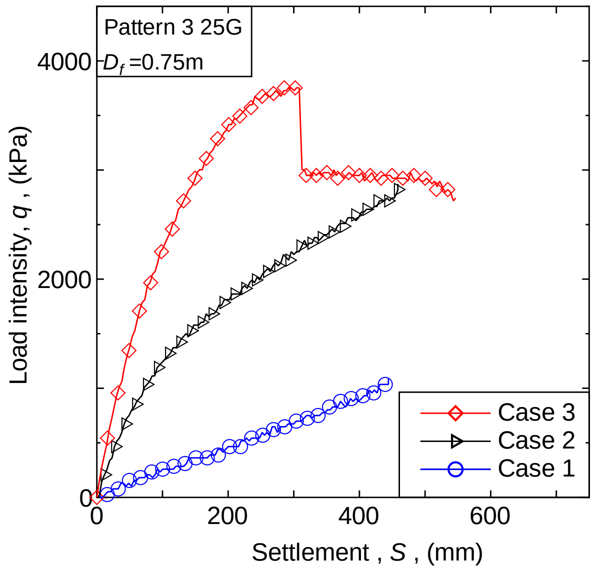


Fig. 10 Load-settlement relationships for Pattern 3

Fig. 11 shows the result for Pattern 4. The curve of Case 3 shows ascending curve with a peak of *q-S* relationship at *q*=3,000 kPa and *S*=170 mm, while the *q* for the Case 1 and Case 2 for the same *S*=170 mm were *q* =600 kPa and *q*=1,400 kPa, respectively.

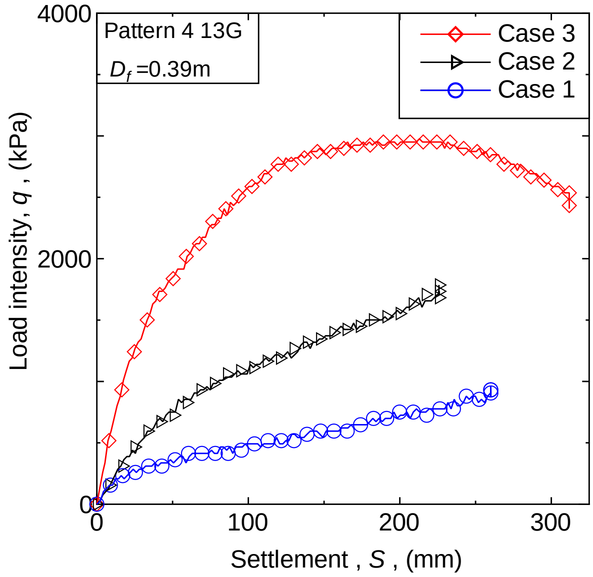


Fig. 11 Load-settlement relationships for Pattern 4

The improvement of bearing capacity was also investigated by Sawwaf and Nazar (2005), using stiff small cell with diameters up to 200 mm. They concluded that, when footing is loaded, such confinement resists the lateral displacements of the soil particles underneath the footing and confines the soil. Then the strength and stiffness of confined sand are increased enough to replace massive concrete foundations. This sequence results in a significant decrease in the vertical settlement and hence improving the bearing capacity (Eid *et al*. 2009). Similar results were obtained from the present study for actual size of foundations, even reinforcement made of a flexible thin film.

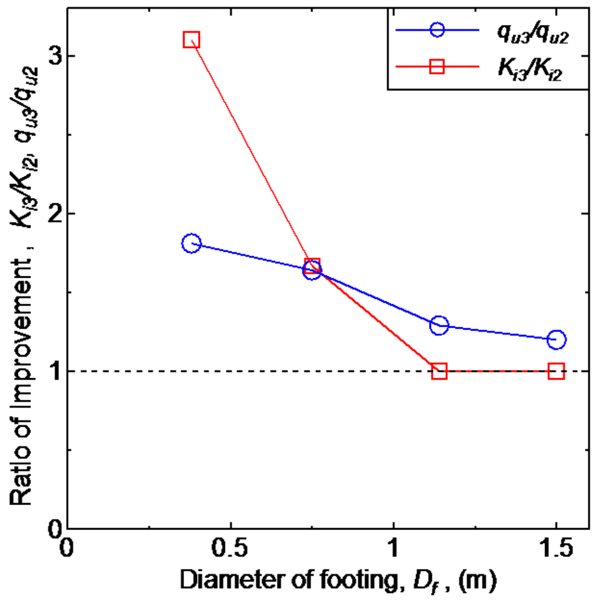


Fig. 12 Ratio of Improvement

Based on the data in **Figs. 8 to 12**, the relationship between the ratios of improvements (K_{i3}/K_{i2}, q_{u3}/q_{u2}) and diameter of footing (D_f) was obtained, as shown in **Fig. 12**. Where, K_{i3} and K_{i2} are tangential initial coefficients of subgrade reaction at the origin, for Case 3 and Case 2 respectively. While q_{u3} is the ultimate bearing capacity obtained from Case 3 and q_{u2} is the load intensity for Case 2 at the same settlement. The figure shows a clear reducing tendency of ratios K_{i3}/K_{i2} and q_{u3}/q_{u2} with increasing diameter of footing. However, the results show that massive embedded footings can be replaced by a thin flexible sleeve and the reinforcing effects of sleeve are still effective, even the size of footings exceeds 1 m.

6. Conclusion

The objective of this study is to evaluate the effects of sleeve as the reinforcement for the shallow foundations, and also making comparison among the sleeve reinforced, the embedded and the simple surface circular foundations. A series of vertical loading tests under the centrifugal force fields was conducted to verify the reinforcing effects of the sleeve at the scale of the real structures. The relationships between loading intensity (q) and settlement (S) were compared and the ratios of improvement were discussed.

Based on the test results, it can be concluded as follows.

(1) In the case where the sleeve is broken it was seen that the load was close to the embedded foundation.
(2) It was verified that the sleeve reinforcement was sufficiently effective against load for the size of actual structures.
(3) Massive embedded footings, used for conventional circular shallow foundations, can be replaced by thin circular sleeves.

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