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The bearing capacity of circular footings on sand with thin layer: An experimental study

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Abstract. Thin layers have substantial effects on the ultimate bearing capacity, despite their seeming insignificant. In this research, the effects of a thin layer on the ultimate bearing capacity of a circular footing on the sand bed are investigated by small-scale physical models. The investigations were carried out by varying the material type, thickness, and depth of the thin layer. The results indicate that the weak thin layer decreases both the ultimate bearing capacity and stiffness of the soil-footing system and the strong thin layer increases both the ultimate bearing capacity and the soil-footing system stiffness. The amount of this effect depends on the thickness, depth of deposition, and the material type of the thin layer. According to the results, the weak layer for the critical depth of 1B led to the most reduction in ultimate bearing capacity by 26% (from 183 kPa to 135 kPa), while no effects were observed at the depth of 2B. The strong layer is also for the state where this layer is just below the footing, had the highest increase in ultimate bearing capacity by 329% (from 183 kPa to 603 kPa), but at a depth of about 1.25B, it was ineffective.

Keywords: physical model; stiffness; strong thin layer; ultimate bearing capacity; weak thin layer

1. Introduction

The footing is the one of the important parts of a structure that transfers the weight of the structure into the natural ground. A foundation itself is a structure, often constructed from concrete. Circular foundations as one of the common types of shallow foundations are extensively used in transferring loads from the structure to the underlying soils and the rock bed. In many cases, the ground materials are not uniform and may have thin layers, which are not usually detected in the geotechnical site investigations.

In general, despite their seeming insignificance, there are some details in the ground that have significant effects on soil-foundation system behavior such as slip surfaces, shear bands, and thin layers (Valor et al. 2017). Terzaghi (1929) termed "these features minor geologic details and pointed out their enormous potential effects on the safety of dams." Terzaghi (1936) mentioned: "… the earth in its natural state is never uniform … Its properties are too complicated for the rigorous theoretical treatment … Even an approximate mathematical solution for some of the most common problems is extremely difficult."

In the literature review, the study of the two-layer soils ultimate bearing capacity (e.g. strong layer overlying weak layer or vice versa) has been relatively carried out by Erdal (2015), Arghadeep and Murali (2017), Kamal (2014), Maryam (2016). In addition, the study on three-layer soils have been conducted by Priti and Manohar (2013) and Arushi *et al*. (2017), but very little study has been performed on the effects of a thin layer.

Valor *et al.* (2017) investigated the failure mechanism and the ultimate bearing capacity of strip foundations resting on the sandy bed with a weak layer. Based on this study at depths less than about $4B$ (B is the foundation wide), the horizontal weak thin layer significantly affects the ultimate bearing capacity and the failure mechanism. The results showed that the weak thin layer of wet bentonite decreases ultimate bearing capacity by 80%.

Ziccarelli *et al.* (2017) studied the failure mechanism and the ultimate bearing capacity of strip foundations resting on the sandy soil with a weak layer using centrifuge experiments on the small-scale experimental models. Based on their study, at a critical depth less than about $4B$ (B is the foundation wide) the horizontal weak thin layer significantly affects the ultimate bearing capacity and the failure mechanism, for the tested materials (talc powder and sand making up the weak thin layer). Generally, this critical depth is a function of the angles of shearing resistance of the sandy soil and the material making up of the weak thin layer. The results demonstrated a decrease up to 50% in the ultimate bearing capacity for weak thin layers made from talc powder with an angle of shearing resistance equals to 27°.

Oda and Win (1990) focused their attention on the ultimate bearing capacity of the foundation resting on the sandy bed with a saturated clay layer. In their study, a glass tank with internal dimensions of 40 cm length, 6 cm width, and 30 cm height was used. According to their study, a weak layer can affect the ultimate bearing capacity with a depth of up to $5B$ (B being the footing width).

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Poulos (2005) investigated the clay seem effect on the pile tip load capacity and stiffness. According to his study, the presence of clay seem reduces the load capacity and stiffness of the pile tip.

It is quite clear from the literature review that very few studies have been carried out on the thin layer effects. In particular, the effects of the strong thin layer have not been studied. Besides, it is worthy to know that the circular footing has not been used either. Therefore, in this study, the influences of the horizontal thin layer on the ultimate bearing capacity of the circular foundation resting on the sandy bed were studied by implicating a small-scale physical model for the soil-foundation system.

2. Experimental program

2.1 Experimental set-up and testing procedure

The problem of the soil-circular footing system is schematically illustrated in Fig. 1. The problem is investigated under the axisymmetric condition, and the circular foundation is rigid. This foundation rests on the soil surface, on the other hand, the initial depth of embedment is nil. Fig. 1 shows a typical schematic of the foundation model on the sandy bed.

The studies were performed by the material type, thickness, and depth of the thin layer variations. For the bed sand, crushed uniform silica sand (SP) with medium density was used. For the thin layer, materials with different strength properties (strong and weak) in comparison with the sandy bed were used. To perform the tests, a small-scale experimental model was designed and built (Fig. 2).

2.2 Test box, model foundation and loading mechanism

Model tests were performed by a cylindrical steel tank with a diameter of 70 cm and a height of 70 cm. The problem is investigated under axisymmetric conditions. To achieve the desired density of sand, the sand raining screen is designed and located at the top of the testing frame, and the sand is discharged at a constant height of 60 cm.

The rigid foundation model was constructed by using mild steel. The diameter of the foundation (B) was 8 cm and the thickness was 1 cm.

According to Boussinesq theory and pressure isobars, in the case of a circular foundation, at a depth of about $4R$ (R being the footing radius) and $2R$ the distance from the center of the foundation about twice the radius of the foundation on each side of the foundation, the vertical pressure decreases by 10%. If this criterion is considered as 5% of vertical pressure, the mentioned distances will be approximately $5.5R$ and $2.5R$ (Murthy, 2002). Therefore, considering the depth and radius of the cylindrical tank selected in this study, $17.5R$ and $8.75R$ (on each side), respectively, the tank boundaries will not have any negative effect on the response.

The pressure is transferred to the foundation by implicating a hydraulic jack at a constant rate of displacement of 1 mm/min. The load applied by using a hydraulic jack recorded by a load cell fitted to the shaft of the hydraulic jack. The settlements of the foundation are measured by a high-precision dial gauge with a measurement accuracy of at least 0.01 mm.

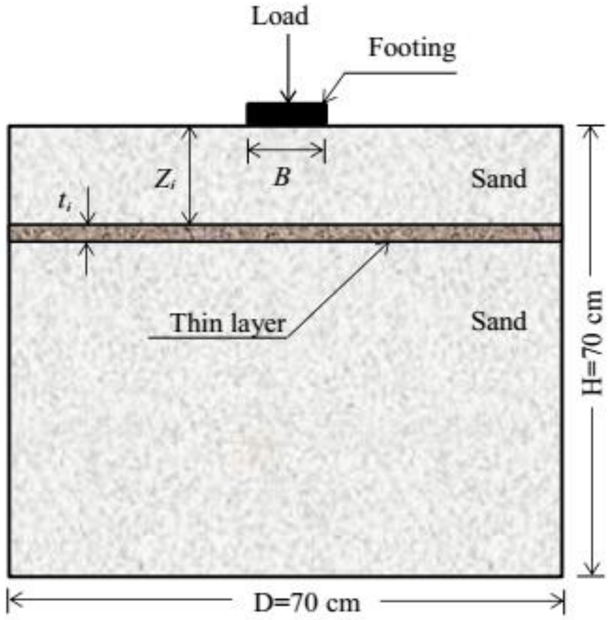

Fig. 1 Scheme of the problem

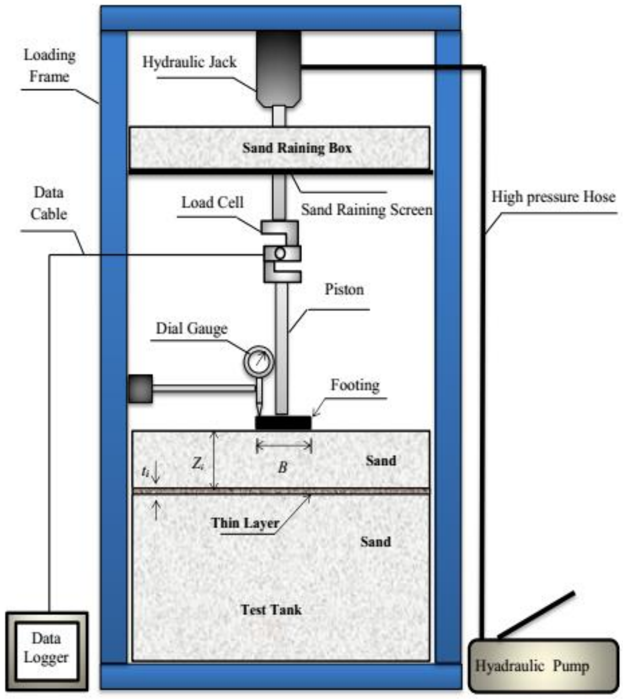

Fig. 2 Section view of the physical model

2.3 The Sand properties

The sand used in the model was provided from silica sand factory located on the Hamedan-Malayer road. The sand was used in air-dried conditions. In accordance with the Unified Soil Classification System (USCS), the sand is

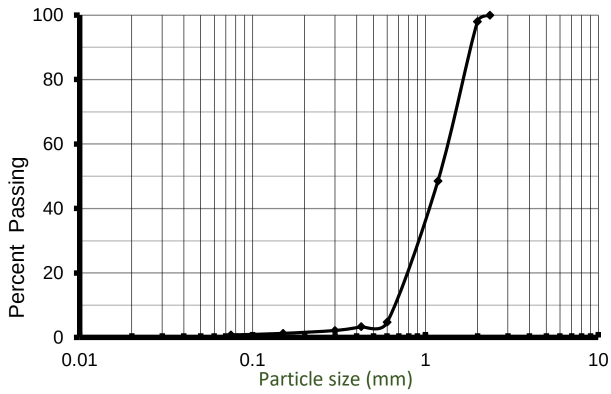

Fig. 3 Particle-size distribution curve for sand

Table 1 Properties of sand used in the model tests

Property	Value	Standard No.
Maximum grain size, D_{max} (mm)	2.38	
Diameter corresponding to 60% finer, D_{60} (mm)	1.45	
Average grain size, D_{50} (mm)	1.25	
Diameter corresponding to 30%, D_{30} (mm)	0.9	ASTM D C136
Effective grain size, D_{10} (mm)	0.67	
Uniformity coefficient, C_u	2.16	
Coefficient of curvature, C_c	0.83	
Specific gravity, G_s	2.66	ASTM D 854
Maximum dry unit weight, γ_{dmax} (kN/m^3)	19.85	ASTM D 4254
Minimum dry unit weight, γ_{dmin} (kN/m^3)	13.73	ASTM D 4253
Dry unit weight, γ_d (kN/m^3)	15.71	
Relative density, D_r (%)	41	
Classification (USCS)	*SP*	ASTM D 2487

described as poorly graded sand (*SP*). Fig. 3 shows the grading curve for silica sand. To achieve uniform relative density in the experiments, the sand is poured from the same fall height using the dry raining method. To get the desired relative density, a fall height of 60 cm is considered. For each experiment, the box was emptied and re-filled. Some of the physical properties of sand are shown in Table 1.

Determination of the relative density, D_r, was in accordance with the ASTM standards D 4253 and D 4253. According to the recommendations of many authors, since the ratio B/d_{50} is greater than 50, the particle size effects are negligible (Bolton and Lau (1989), Taylor (1995); Toyosawa *et al*. (2013)).

Masayuki *et al*. (2017) studied the effect of fines on the compression behavior of poorly graded silica sand. Based on this study the degree of particle crushing tended to decrease as the fines content increased, but since the stress level existing in the tested physical models is low and due to the mineralogy and grading of the sand, particles crushing of sand during the experiments are negligible.

The shear strength parameters of the sand were determined by seven direct shear tests in accordance with ASTM D 3080. The parameters of the shear strength of

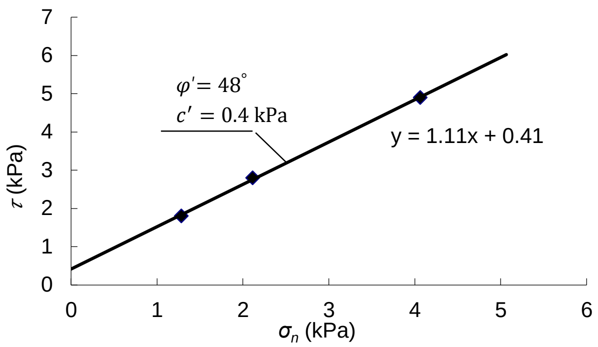

Fig. 4 Results of direct shear test on sand bed at low effective stresses (1 kPa $< \sigma_v <$ 4 kPa)

Table 2 Physical properties of weak layer used in the model tests

Property	Valu	Standard No.
Specific gravity, G_s	2.68	ASTM D854
Unit weight, γ (kN/m^3)	12.1	ASTM D6683
Liquid limit (%)	26	
Plastic limit (%)	18	ASTM D4318
Plasticity index (%)	8.0	
Classification (USCS)	*CL*	ASTM D2487
Water content (%)	5.5	ASTM D2216

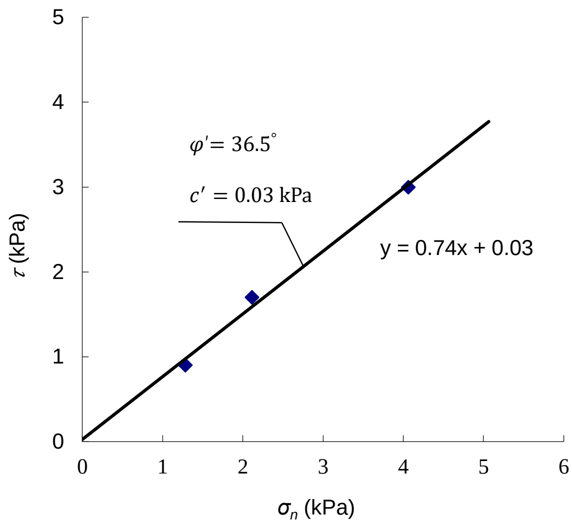

Fig. 5 Results of direct shear test on weak layer at low effective stresses (1 kPa $< \sigma_v <$ 4 kPa)

sand are the function of the effective stress level. It is remarkable that for the effective depth in the small-scale soil model, the stress level is less than about 4 kPa. The result of the direct shear test corresponding to the model stresses level (1 kPa $< \sigma_v <$ 4 kPa) is presented in Fig. 4.

2.4 Weak layer properties

The weak layer is made of materials that have lower shear strength properties than the sandy bed. For the weak layer, the compressible clay powder with *CL* classification

Table 3 Engineering properties of strong layer used in the model tests

Property	Value	Standard No.
Unit weight, γ (kN/m^3)	19.12	ASTM D6683
Cohesion (kPa)	350	ASTM D2664
Angle of internal friction (degree)	38	

was used. Clay powder with a natural moisture content of 5.5% was used consistently in all of the experiments. Some of the engineering properties of the weak thin layer are shown in Table 2. Due to the low moisture content of the clay, there will be no pore pressure and consequently no excess pore pressure in the experiments. The parameters of the shear strength of the clay were determined by seven direct shear tests. The results show that the parameters of the shear strength of the weak thin layer materials are not as the function of the level of the effective stress. The result of the direct shear test corresponding to the model stresses level (1 kPa $< \sigma_v <$ 4 kPa) is presented in Fig. 5.

2.5 Strong layer properties

The strong layer is made of materials that have higher shear strength properties than the sandy bed. For the strong layer, a sand asphalt mixture was used. Some of the engineering properties of the strong thin layer are shown in Table 3. It should be noted that all the experimental models with a strong asphalt layer were carried out at an ambient temperature of 28 °C.

2.6 Experimental method

At the test beginning, the sand raining screen device was located directly above the test box. Then the following the sand was deposited in the 4 cm thick layers by using the raining method. During sand raining, the sand density was controlled by placing the cans of specified volume in different locations of the box. The weak and strong thin layers were made using simple templates at the specified depths and thicknesses and the subsequent sand layers were poured to the required level and were followed by placing of the foundation model at a specific location on the surface of the sandy bed. At the end, the vertical pressure is transferred to the foundation model by a manual hydraulic jack at a constant rate equals to 1 mm/min. Then a dial gauge with a precision of 0.01 mm measured the vertical settlement. To achieve some degrees of confidence in the experiment results, in some cases, the experiments were repeated.

3. Experimental parameters and program

The variable parameters used in the experiments (in accordance with schematic diagram 1) and their values are shown in Table 4. Three series of tests have been carried out. First, the behavior of the circular footing resting on a uniform sand bed is investigated. Then, in the second and third series, the behavior of the circular foundation resting on the sandy bed with a weak and strong layer at different thicknesses and depths were investigated.

Table 4 Model test program

Type of test	Constant parameters	Variable parameters
Uniform sand	D_r = 41%, D_f = 0	---------
Uniform sand with weak layer	D_r = 41%, D_f = 0	Z_i/B=0, 0.5, 1, 2 t_i/B=0.1, 0.2
Uniform sand with strong layer	D_r = 41%, D_f = 0	Z_i/B=0, 0.5, 1, 2 t_i/B=0.1, 0.2

4. Results and discussion

Foundation bearing pressure-settlement curves were obtained from the results of the testing model. It is noticeable that the foundation settlement (S) is presented in dimensionless in terms of the foundation width (B) as the ratio (S/B, %).

4.1 Behaviour of the circular foundation resting on uniform sandy soil

The pressure-settlement curve of the circular foundation resting on uniform sandy soil is illustrated in Fig. 6. According to the figure, the value of ultimate bearing capacity is 183 kPa, and the value of settlement corresponding to the peak is 7.5 mm and the value of relative settlement (S/B, %) is 9.4%. For comparison and verification, the ultimate bearing capacity values by different researchers' analytical methods (Eqs. (1)- (5)) for the shear strength angle corresponding to the stress level of the model were calculated. The results of this comparison are presented in Table 5. It should be noted that due to the dryness of the sand, to calculate the ultimate bearing capacity, the cohesion of sand has been neglected. According to the results, the analytical values calculated by the methods of Meyerhof (1963), Vesic (1973), and Martin (2005) were in more agreement with the experimental results.

Comparing the results of analytical and experimental methods, the selection of the internal friction angle corresponding to the actual effective stress level in the small-scale physical model is confirmed. On the other hand, the results of analytical methods with 48 degrees of internal friction angle were in more agreement with the results of the experimental model.

$$q_u = 0.3\gamma B N_\gamma \quad (1)$$

$$N_q = tan^2\left(45 + \frac{\varphi}{2}\right) e^{\pi \tan\varphi} \quad (2)$$

$$N_\gamma = (N_q - 1)\, tan\, 1.4\varphi \qquad \text{(Meyerhof, 1963)} \quad (3)$$

$$N_\gamma = 2(N_q + 1)\, tan\, \varphi \qquad \text{(Vesic, 1973)} \quad (4)$$

$$N_\gamma = (N_q - 1)\, tan\, 1.32\varphi \qquad \text{(Martin, 2005)} \quad (5)$$

Table 5 Comparison of ultimate bearing capacity of circular footing with analytical relationships of various investigators

Angle of peak shear strength (degree)		Meyerhof (1963)	Vesic (1973)	Martin (2005)
48	N_γ	527	496	441
	q_u (kPa)	**197**	**186**	**165**

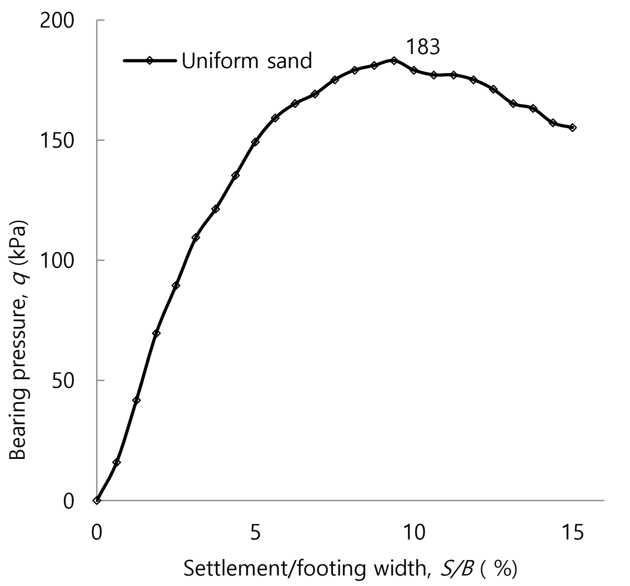

Fig. 6 Pressure-settlement curve of circular footing on uniform sand

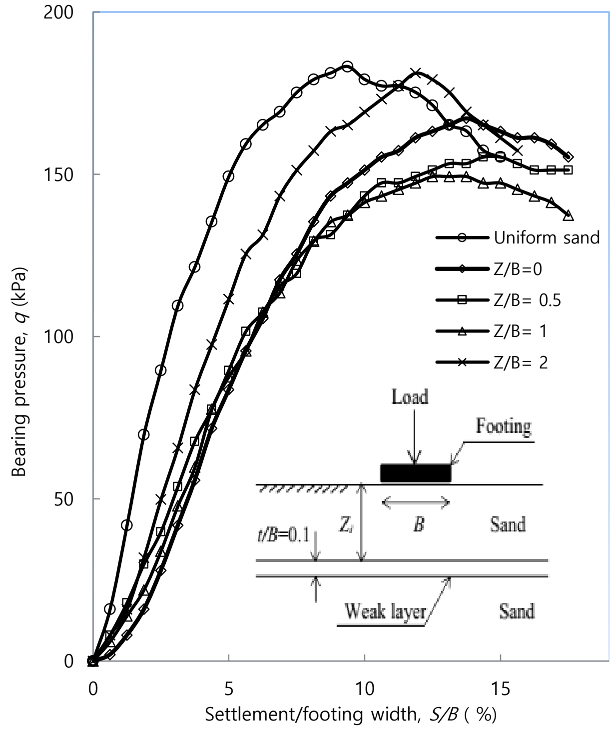

Fig. 7 Pressure-settlement curve of circular footing on sand with a weak layer for *t/B*=0.1

4.2 Behavior of the circular foundation resting on sandy soil with a weak thin layer

Bearing pressure-settlement curves of circular foundation resting on the sandy bed with a weak layer at thicknesses *t/B*=0.1 and *t/B*=0.2 are shown in Figs. 7 and 8, respectively. The results indicate that the weak thin layer decreases both the ultimate bearing capacity and stiffness of the soil-foundation system. The values of the ultimate bearing capacity for different states are compared in Fig. 9. Obviously, the effect of a thicker layer is more evident. The weak layer for the critical depth of 1*B* led to the most reduction in the ultimate bearing capacity by 26% (from 183 kPa to 135 kPa), while no effect was observed at the depth of 2*B*. According to the Fig. 10, depth (*D*) of the rupture zones is approximately equal to the width (*B*) of the footing. The contact of the weak layer with the failure surface at critical depth of 1*B* has caused the most reduction in the ultimate bearing capacity of the foundation and also because of reduction of the vertical pressure beneath of foundation up to 10% at depth 2*B*, the weak layer was ineffective.

According to Figs. 7 and 8, the stiffness of the soil-footing system, before approaching the peak, which is defined as $\Delta q/\Delta s$, in the case of using a weak thin layer is less than one corresponding to the uniform soil. It should be noted that the $\Delta q/\Delta s$ parameter is somehow the secant modulus in the bearing pressure-settlement curves that is defined based on the slope of a secant line.

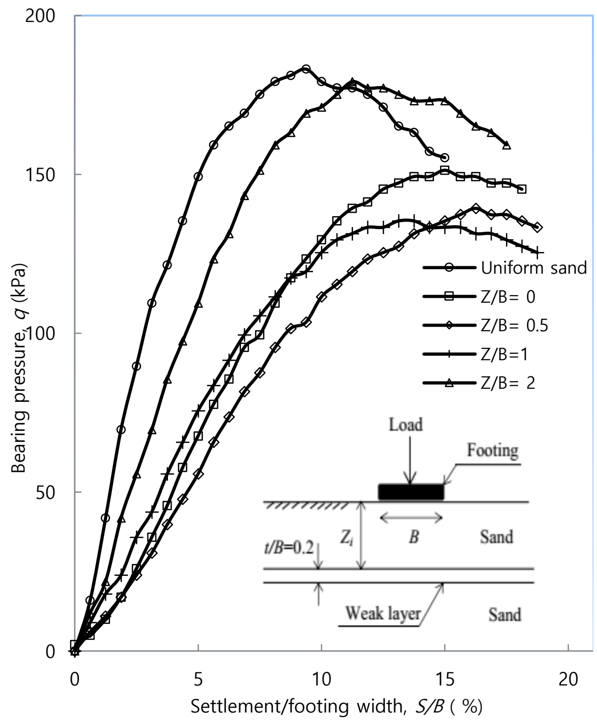

Fig. 8 Pressure-settlement curve of circular footing on sand with a weak layer for *t/B*=0.2

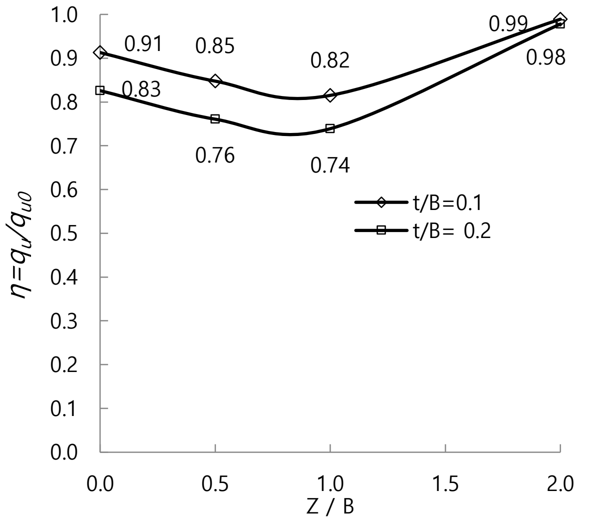

Fig. 9 Comparison of normalized ultimate bearing capacity q_u/q_{u0} against normalized depth of the weak layer *Z/B*

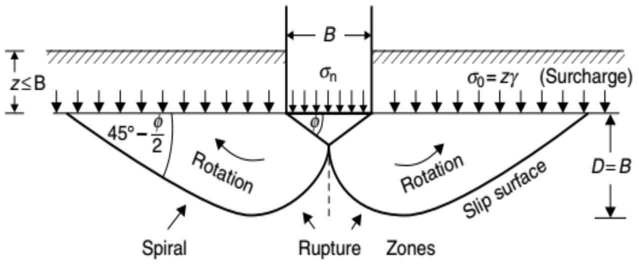

Fig. 10 Geometry of failure surface for Terzaghi's bearing capacity formulas (Bodó, 2013).

4.3 Behaviour of the circular foundation resting on sandy soil with a strong thin layer

Bearing pressure-settlement curves of circular foundation resting on the sandy bed with a strong thin layer at thicknesses *t/B*=0.1 and *t/B*=0.2 are shown in Figs. 11 and 12, respectively. The results indicate that the strong thin layer increases both the ultimate bearing capacity and stiffness of the soil-foundation system. The strong layer acts as a reinforcement layer, increasing both the ultimate bearing capacity of the foundation and the stiffness of the soil- foundation system.

The values of the ultimate bearing capacity for different states are compared in Fig. 13. It is quite clear that the effect of a thicker layer is more evident.

The strong layer for the state where this layer is just below the footing (*Z/B*=0), had the highest increase in ultimate bearing capacity by 329% (from 183 kPa to 603 kPa). For both strong thin layers (*t/B*=0.1 and *t/B*=0.2) at a depth of about 1.25*B*, it was ineffective.

According to Figs. 11 and 12, the stiffness of the soil-foundation system, before approaching the peak, which is defined as $\Delta q/\Delta s$, in the case of using a strong thin layer is more than one corresponding to the uniform soil.

The above results show the increasing effect of the presence of a strong thin layer on the ultimate bearing

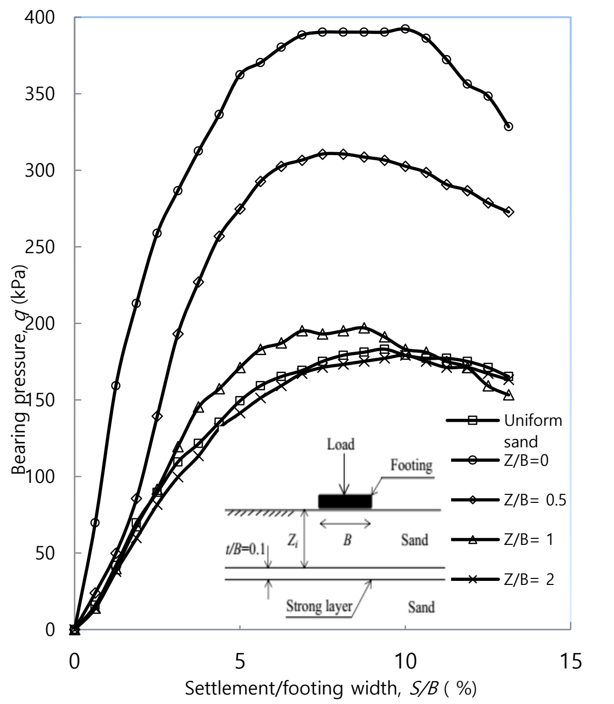

Fig. 11 Pressure-settlement curve of circular footing on sand with a strong layer for *t/B*=0.1

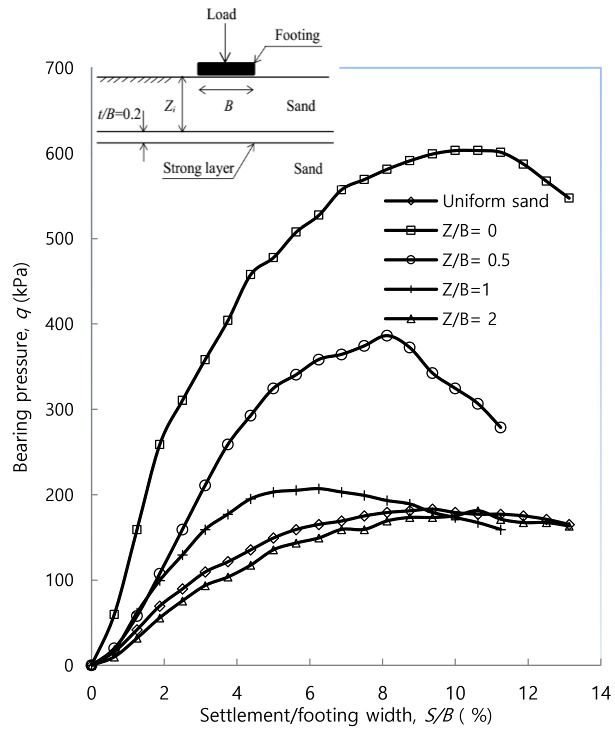

Fig. 12.Pressure-settlement curve of circular footing on sand with a strong layer for *t/B*=0.2

capacity of the foundation and the stiffness of the soil-foundation system. The effects of the strong thin layer generally are a function of factors such as the shear strength difference between the strong thin layer and the sandy bed, and the thickness and depth of the strong thin layer.

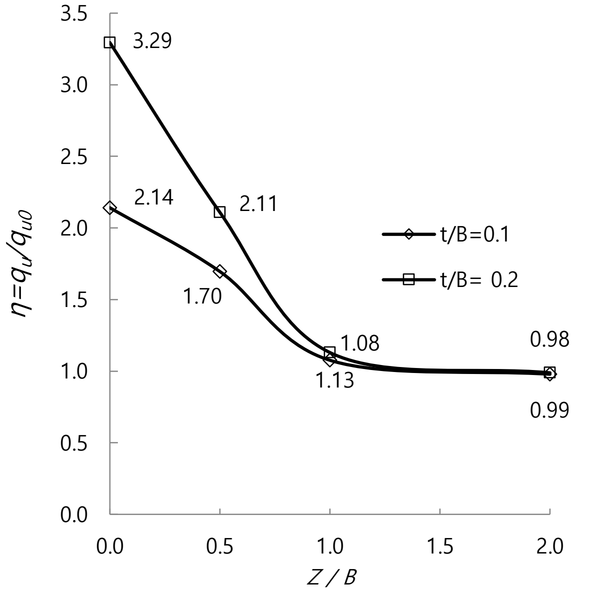

Fig. 13 Comparison of normalized ultimate bearing capacity q_u/q_{u0} against normalized depth of the strong layer *Z/B*

5. Conclusion

The circular footing resting behavior on the sand bed with weak and strong thin layer has been investigated by implicating a small-scale model experiment**.**The purpose of the present study was to evaluate the effects of thickness, depth of placement, and the type of horizontal thin layer (weak or strong) on the ultimate bearing capacity of the circular foundation resting on the sandy bed. Based on the experiment results, the conclusions are as follows:

- The horizontal weak thin layer decreases both the ultimate bearing capacity and stiffness of the soil-foundation system. The extent of this effect depends on the thickness and depth of the weak thin layer.
- The weak thin layer for the critical depth of 1*B* led to more reduction in the ultimate bearing capacity by 26% (from 183 kPa to 135 kPa). For both weak thin layers (*t/B*=0.1 and *t/B*=0.2) at a depth of about 2*B*, it was ineffective.
- The horizontal strong thin layer increases both the ultimate bearing capacity and stiffness of the soil-foundation system. The extent of this effect depends on the thickness and depth of the strong thin layer.
- The strong thin layer for the state where this layer is just below the foundation (*Z/B*=0), had the highest increase in the ultimate bearing capacity by 329% (from 183 kPa to 603 kPa). For both strong thin layers (*t/B*=0.1 and *t/B*=0.2) at a depth of about 1.25*B*, it was ineffective.
- Comparison of the results of the experimental model with the analytical results obtained by different researchers confirms the correct selection of the shear strength angle corresponding to the low-stress level.

It should be noted that due to the scale effects, the results of small-scale experiments are not applicable to real problems directly. One way to reduce the scale effects is to perform small-scale physical model experiments at high-stress levels. In addition, the main purpose of this study was to assess and predict the general trend of circular footing behavior with a thin layer and quantify the effect of different parameters on the ultimate bearing capacity results.

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Notation

B	footing width
c'	cohesion
C_c	coefficient of curvature
C_u	uniformity coefficient
D_{max}	maximum grain size
D_r	relative density
D_f	embedment depth of foundation
D_{10}	effective grain size
D_{30}	diameter corresponding to 30%
D_{50}	average grain size
D_{60}	diameter corresponding to 60% finer
G_s	specific gravity
N_γ, N_q	bearing capacity factors
q	bearing pressure
q_u	ultimate bearing capacity of uniform sand with thin layer
q_{u0}	ultimate bearing capacity of uniform sand
S	settlement of the foundation
R	footing radius
t_i	thickness of thin layer
Z_i	depth from the ground surface of thin layer
γ	unit weight
γ_d	dry unit weight
γ_{dmax}	maximum dry unit weight
γ_{dmin}	minimum dry unit weight
φ'	angle of internal friction
τ	shear stress
σ_n	normal stress
σ_v	vertical stress
η	ratio q_u/q_{u0}
$\Delta q/\Delta s$	variation of bearing pressure to variation of settlement ratio

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