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Experimental Study on the Effect of Eccentric Loads on the Bearing Capacity of Strip Footing Located on the Inclined Multi-Layer Soil Mass with a Weak Soil Layer

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ABSTRACT: Engineers often face challenges when designing foundations that are located over and near the slopes. By using a new small-scale laboratory model, the Effect of eccentric loading on the bearing capacity of a strip footing located on the inclined multi-layer soil mass with a weak soil layer was investigated as multi-effects. Thin layers have substantial effects on the ultimate bearing capacity, despite they seem to be insignificant. A series of laboratory model tests were performed on a rigid strip footing resting on surfaces with different layered slope foundations. The experimental program considered different foundation configurations by varying the footing distance from the slope's top and the inclination of the thin layer. It is found that the weak thin layer decreases the ultimate bearing capacity specifically. The laboratory results indicate that the value of eccentricity affects the final bearing capacity and increases this capacity by moving away from the weak layer and the slope. Also, The weak thin layer at the critical distance led to more reduction in the ultimate bearing capacity by 43%. The results were compared with analytical methods and the differences were 2 to 9.5%. Also, the numerical simulation of the physical data shows that the results can be developed into large-scale models as a prediction.

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1- Introduction

Footing is 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.

The behavior of shallow foundations in layered soils is quite complicated, and, therefore, has been a topic of interest for several decades. Initiated with Button (1953) in the form of different saturated clay layers, it has been enriched by several types of research through numerical modeling and/or laboratory physical tests indicating the influences of different parametric variations (Brown and Meyerhof (1969); Vesic (1973, 1975); Meyerhof (1974); Purushothamaraj, Ramiah and Rao (1974); Tournier and Milović (1977); Meyerhof and Hanna (1978); Pfeifle and Das (1979); Hanna and Meyerhof (1980); Kraft and Helfrich (1983); Siraj-Eldine and Bottero (1987); Madhav and Sharma (1991); Tani and Craig (1995); Burd and Frydman (1996); Cerato and Lutenegger (2006); Eshkevari et al. (2019); Hanna et al. (2020)).

The behavior of foundations on layered soils was discussed in different ways: for example, considering combinations of different soil types such as sand (or clay) overlaying clay (or sand) (Meyerhof (1974); Meyerhof and Hanna (1978); Hanna and Meyerhof (1980); Michalowski and Shi (1995, 1996); Burd and Frydman (1996); Kenny and Andrawes (1996); Michalowski (1997); Okamura, Takemura, and Kimura (1997)).

In general, physical model tests in varying configurations were the most common mode of study for the behavior of layered foundations; however, as compared to physical tests, analytical analyses are more competent to consider rigorous parametric variations (Mandel and Salencon (1972); Sloan and Randolph (1982); Madhav and Sharma (1991); Brocklehurst (1993); Frydman and Burd (1997); Yilmaz and Bakir (2009)).

The bearing capacity of the surface footing is one of the most investigated topics in the field of geotechnical engineering. To date, the literature is full of studies that have focused on the load–settlement response and the bearing capacity of surface footings placed over the level ground and near soil slopes (Keskin and Laman (2013); Keawsawasvong et al. (2021)). Hence, the probability of soil failure beneath the footing, considering a heterogeneous soil, is very high. Probabilistic analysis of various geomechanics problems (Liu et al. (2019); Krishnan and Chakraborty (2021); Wu et al. (2021b)) are carried out on spatially random soil. Many studies (Johari et al. (2017); Halder and Chakraborty (2020); Wu et al. (2020, 2021a)) reported the bearing capacity of footing due to spatial variability of soil under central vertical load. Some probabilistic studies (Soubra and Massih (2010); Massih et al. (2010); Al-Bittar and Soubra (2014)) considered either inclined or eccentric loading on the bearing capacity of

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the foundation.

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."

Valor *et al.* (2017) investigated the failure mechanism and the ultimate bearing capacity of strip foundations resting on a sandy bed with a weak layer. Based on this study at depths less than about 4*B* (*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%.

Oda and Win (1990) focused their attention on the ultimate bearing capacity of the foundation resting on a sandy bed with a saturated clay layer. Their study used a glass tank with internal dimensions of 40 cm length, 6 cm width, and 30 cm height. According to their study, a weak layer can affect the ultimate bearing capacity with a depth of up to 5*B* (*B* being the footing width). Several researchers have studied the bearing capacity reduction of a foundation that is due to the eccentricity of the load (Farzaneh et al. (2010); Michalowski & You (1998); Paolucci & Pecker (1997)).

Considering that due to the interaction between the constituents of the Earth's crust with external and internal deformation processes, various geological shapes and structures are created; in practice, in some projects, foundations may be placed on layered soil substrates or rocky substrates containing weak inclined soil layers. Therefore, in this research, the effect of the eccentricity of loading on the bearing capacity of the strip foundation located on the top of a slope is investigated.

Turker *et al*. (2014) examined final loads, rupture level, load-displacement diagrams, foundation period, etc. of a strip foundation by performing bearing capacity tests with off-center loading models on a footing located at two depths (D_f / B = 0, 0.25) and located near the slope of Geotextile-reinforced sand dunes. The main components of laboratory equipment include a chamber, model strip foundation, loading system, geotextile, sand, etc. (As shown in Fig.1).

Keskin and Laman (2013) with the experimental physical model investigated the effect of the parameters of foundation distance from slope crest, slope angle, the relative density of sand, and width of foundation on the final bearing capacity of strip foundation located on a sandy slope. In this research, a series of model experiments have been performed in a steel box with internal dimensions of 1.140 m (length), 0.475 m (width), and 0.5 m (depth) according to Figure 2.

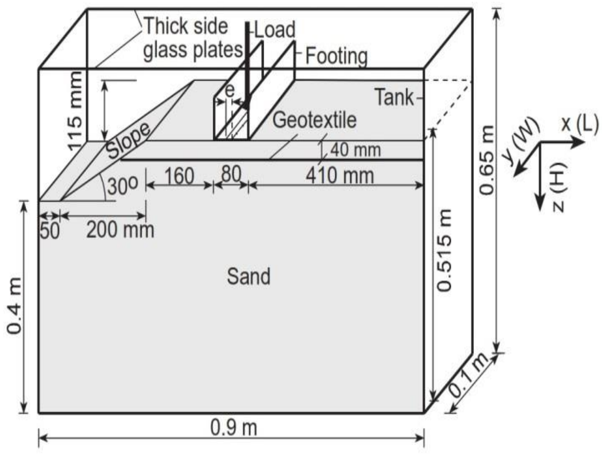

Fig. 1. 3D Scheme of the testing box (Turker et al. (2014))

To prevent lateral slippage when installing the soil and loading the foundation model, the floor and vertical walls of the box are rigid. Two walls of the test box were made of 20 mm thick glass to observe the sand sample during the preparation and deformation of the sand particles during the experiments. The box was sufficiently rigid to provide flat strain conditions in all model experiments. In addition to model experiments, for validation of laboratory results, a set of finite element analyses and slope modeling with full dimensions (full scale) were performed with Plaxis software and acceptable agreement and compatibility. Between laboratory results and finite element analysis in the load-sitting term the general behavioural trend is observed. Among the important results of these researchers, we can mention the following:

• The bearing capacity increases almost linearly by increasing the distance from the foundation to the ratio of the distance to the width of the foundation equal to 5. In conditions beyond this ratio, the final bearing capacity will remain constant and will be similar to the foundation located on the horizontal level.

• The bearing capacity of the strip foundation located on the sand slope depends significantly on the slope angle, relative sand density, and foundation width.

• The results clearly show that by increasing the slope angle, the final bearing capacity of the foundation decreases.

• Close agreement and compatibility between laboratory and analytical results have been observed in the general behavioral process, however, the final load capacity values obtained from finite element analysis have shown higher values than the model experiments.

• In previous studies, the impact of the presence of a weak

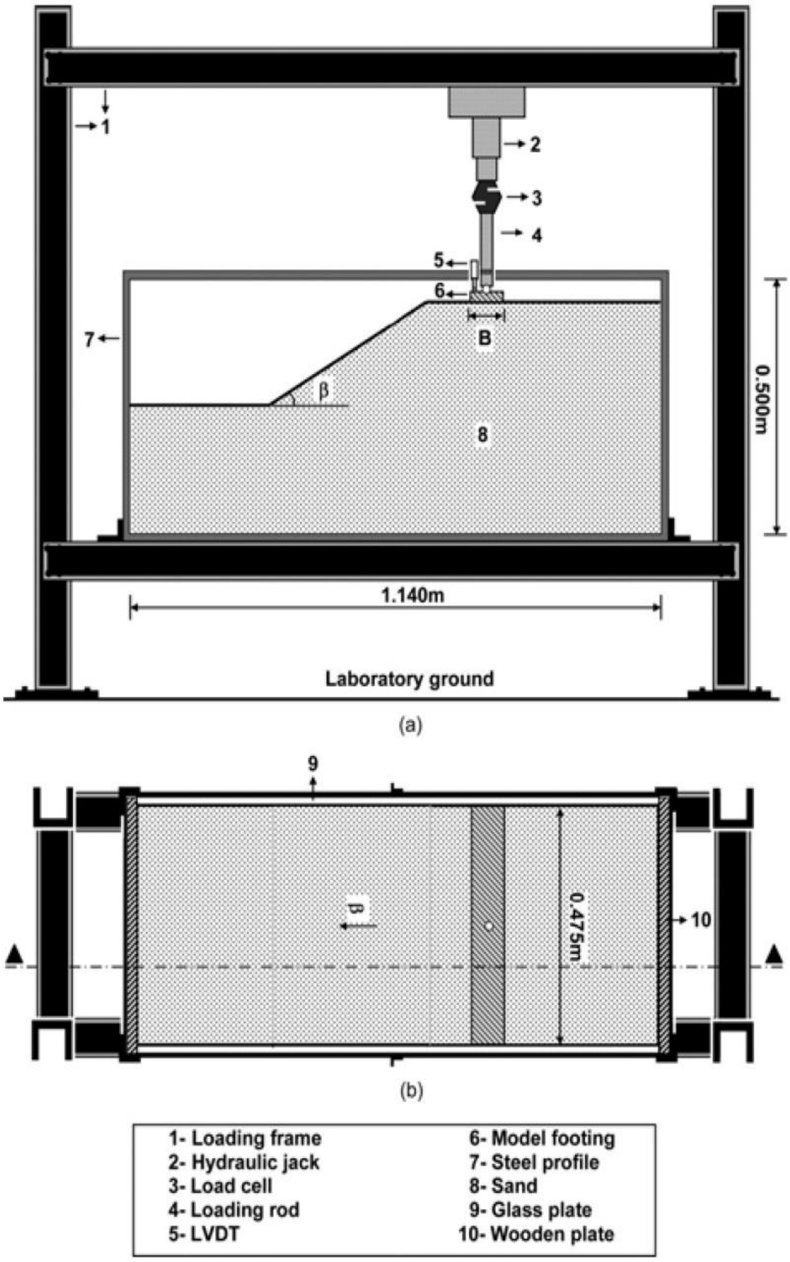

Fig. 2. Scheme of the testing equipment (Keskin and Laman, 2012)

layer in strip foundations on soil substrates mainly has been investigated. It is more important to explore the slopes and the effect of the presence of a weak layer in them on the capacity of the foundations, which was done in the present research. In addition to the slope of the soil layer, investigating the impact of eccentricity and its positive and negative effects on the bearing capacity of the foundation is also of particular importance.

The first innovation of this research is the assessment of the effect of loading eccentricity on the bearing capacity of a strip footing located on soil with a weak layer. The second objective also is to evaluate the effect of different horizontal distances of the foundation from the crest of the slope on the bearing capacity of the rigid strip foundation.

2- Experimental Modeling

2- 1- Experimental set-up and testing procedure

The geometry of the Soil-Strip Footing system is schematically illustrated in Fig. 3. The test is investigated under the uniaxial condition, and the Strip foundation is rigid.

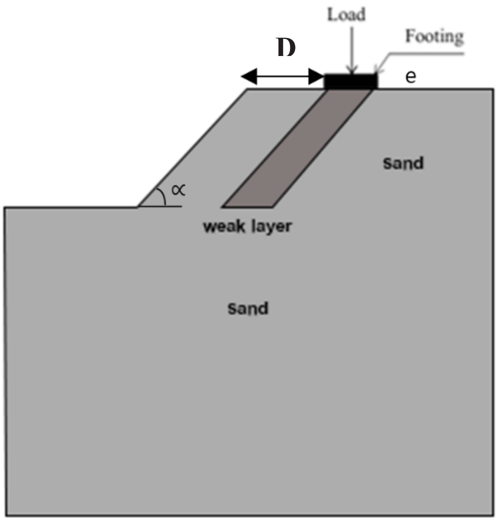

Fig. 3. Scheme of the study

This strip foundation is located on a slope, on the other hand, the initial depth of the depression is zero. Figure 3 shows a typical schematic of a foundation model on a sandy bed.

Studies were performed based on the loading eccentricity and footing distance from the slope crest changes. Medium-density crushed silica sand (SP) was used for the bed sand. For the thin layer, materials with weaker strength properties (compared to the sandy substrate) were used. To perform the experiments, a small-scale experimental model was designed and built. The details of these tests are shown in Figure 4.

Physical modeling and sample making of laboratory models have different stages that were done step by step. In the first stage, to avoid the effects of the test box wall conditions on the results, its net internal dimensions are equal to 100 cm (length), 70 cm (width), and 70 cm (height), and the model strip foundation is replaced with a rigid metal strip with a length of 70 cm and a width of 7 cm so that the experiments are not affected by the boundary constraints caused by the walls of the test box.

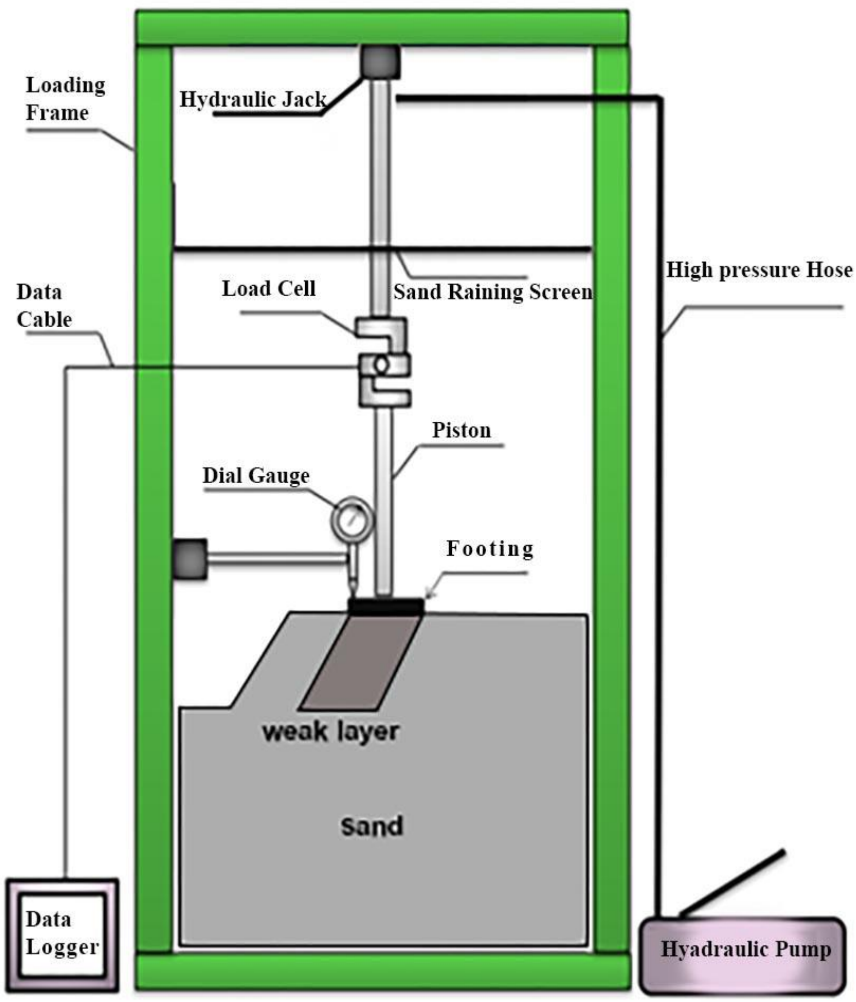

Fig. 4. Section view of the physical model

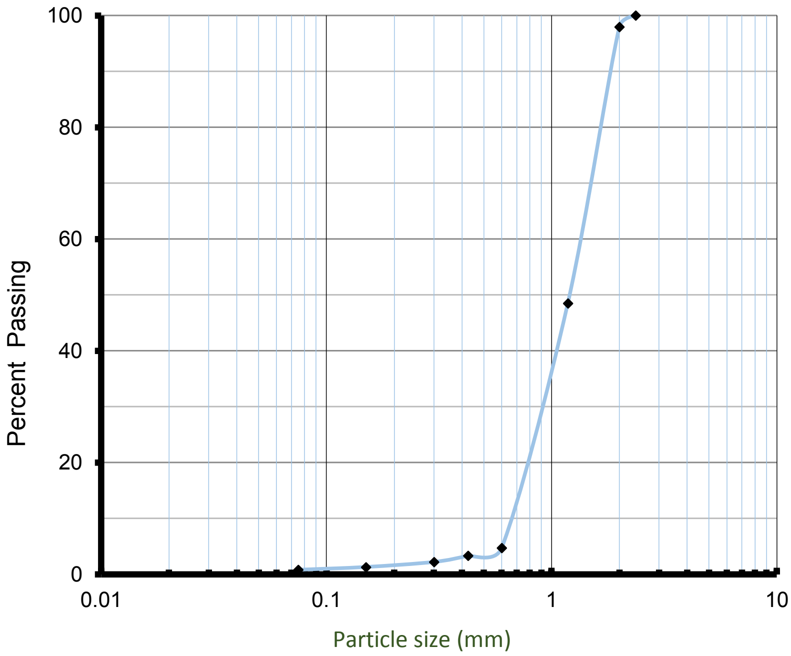

Fig. 5. Particle-size distribution curve for sand

Then each layer of soil with a thickness of 5 cm is poured into the box and compacted according to the desired relative density. These steps continue until the test box is filled to the level below the foundation.

2- 2- Test box, model foundation, and loading mechanism

In this investigation, a rectangular steel tank of size 1.0 m in length, 0.7 m in width, and 0.7 m in depth was chosen. The tests were conducted on a steel footing with 7 cm width, 70 cm length, and 3.5 cm thickness. The problem is investigated under plane strain conditions. To achieve the required density of sand, the foundation is poured in layers and compacted. The height of the foundation is 20 cm.

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 is 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.

It is noted that the use of a manual hydraulic jack for load application might cause a variation in the loading rate. However, under static loading conditions, the effect of **the** loading rate on the settlement, and the bearing capacity of the surface footing is insignificant (Bildik and Laman 2015). The data acquisition system, composed of a data logger and computer software, was used to extract the load and displacement data for analysis.

2- 3- Sand Properties

Sandy soil used in the model was provided by a silica sand factory located on the Firuzkuh road. The sand was used in air-dried conditions. In accordance with the Unified Soil Classification System (USCS), it is described as poorly graded sand (*SP*). Fig. 5 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. For each experiment, the box was emptied and refilled. 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 D4253 and D4253. 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 current physical model tests is low and due to the mineralogy and grading of the sand, particle crushing of sand during the experiments is negligible.

The shear strength parameters of the sand were determined by seven direct shear tests in accordance with ASTM D3080. The parameters of the shear strength of 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

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%	1.45	
Average grain size, D_{50} (mm)	1.25	
Diameter corresponding to 30%,	0.9	
Effective grain size, D_{10} (mm)	0.67	
Uniformity coefficient, C_u	2.16	
Coefficient of curvature, C_c	0.83	ASTM DC136
Specific gravity, G_s	2.66	ASTM D854
Maximum dry unit weight, γ_{dmax}	19.85	ASTM D4254
Minimum dry unit weight, γ_{dmin}	13.73	ASTM D4253
Dry unit weight, γ_d (kN/m^3)	15.71	
Relative density, D_r (%)	41	
Classification (USCS)	SP	ASTM D2487
Effective angle of internal	38	ASTM D3080
Effective cohesion (kg/cm^2)	0	ASTM D3080

is less than about 4 kPa. The result of the direct shear test corresponding to the model stresses level (1 kPa < σ_v < 4 kPa) is presented in Table 1.

2- 4- Weak layer properties

The slope weak layer is made of materials that have lower shear strength properties than the sandy bed. For the weak layer, compressible clay powder with CL classification was used. Clay powder with a natural moisture content of 5.5% was used continuously in all experiments. Some poor thin-layer engineering properties are shown in Table 2. Due to the low moisture content of the clay, there will be no pore pressure and therefore no additional pore pressure in the experiments.

Clay shear strength parameters were determined by seven direct shear tests, too. The results show that the shear strength parameters of weak thin film materials are not effective as a function of stress level. The result of the direct shear test related to the stress levels of the model (1 kPa<σ_v<4kPa) is presented in Table 2.

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
Effective angle of internal	28	ASTM D3080
Effective cohesion (kg/cm^2)	0.035	ASTM D3080

2- 5- Experimental method

At the first step of the test beginning, the sand-raining screen device was located directly above the sandbox. Then the following the sand was deposited in the 5 cm thick layers by using the raining method. During sand raining, sand density was controlled by placing the cans of specified volume in different locations of the box. Then the sand slope (α=45 degrees) was made with a defined angle using simple templates at the specified depths and thicknesses and also weak layer was made as the same (Fig. 6). Then the subsequent sand layers were poured into 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 equal to 1 mm/min. Then a dial gauge with a precision of 0.01 mm measured the vertical settlement. To achieve some degree 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 3. Two series of tests have been carried out. First, the behavior of the footing resting on a uniform sandy slope bed is investigated. Then, in the second series, the behavior of the foundation resting on the sandy slope bed with a weak layer was investigated. In these tests, the distance between the footing and the slope crest and also the eccentricity of the load varied.

Fig. 6. Geometry of the builted sandy slope

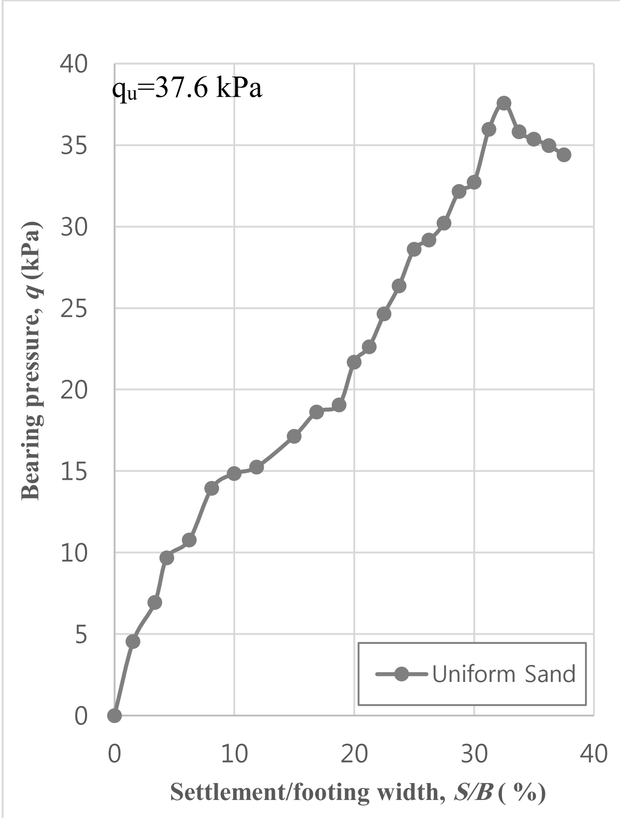

Fig. 7. Pressure-settlement curve of strip footing on uniform sand

Table 3. Model test program

Type of test	Constant parameters	Variable parameters
Uniform sand	$D_r = 41\%$, $D_f = 0$	---
Uniform sand with a weak layer	$D_r = 41\%$, $D_f = 0$ $\propto = 45^o$	$D=0,\ 0.5B,\ B$ $e=B/8\ ,B/6,\ B/4$

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 normalized respect to the foundation width (B) as the ratio (S/B, %).

The variable parameters of the experiment are exposed as e and D where the parameter e indicates the eccentricity of the load and the parameter D indicates the distance of the weak layer from the slope crest.

4- 1- Behaviour of the strip foundation resting on uniform sandy soil slope

The pressure-settlement curve of the strip foundation resting on uniform sandy soil is illustrated in Fig. 7. According to the figure, the value of ultimate bearing capacity is 37.6 kPa, and the value of settlement corresponding to the peak is 26 mm and the value of relative settlement (S/B, %) is 32.5%. For comparison and verification, the ultimate bearing capacity values by different researchers' analytical methods (Meyerhof (1963), Vesic (1973), and Hansen (1970)) 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 analytical methods were in good agreement with the experimental results.

One of the early sets of bearing-capacity equations was proposed by Terzaghi (1943). Terzaghi's equations were produced from a slightly modified bearing-capacity theory developed by Prandtl (1920) from using the theory of plasticity to analyze the punching of a rigid base into a softer (soil) material.

Meyerhof (1951,1963) proposed a bearing-capacity equation similar to that of Terzaghi but included a shape factor with the depth term. He also included depth factors and inclination factors for cases where the footing load is inclined from the vertical.

Hansen (1970) proposed the general bearing-capacity case. This equation is readily seen to be a further extension of the earlier Meyerhof (1951) work.

The Vesic (1973, 1915b) procedure is essentially the same as the method of Hansen (1961) with select changes. Vesic equation is somewhat easier to use than Hansen's. The shear

Table 4. Comparison of ultimate bearing capacity of strip footing with analytical relationships of various investigators

Meyerhof (1963)	Vesic (1973)	Hansen (2005)
36.7	41.1	29.6

strength angle corresponding to the stress level of the model is used to calculate the ultimate bearing capacity values by different analytical methods. The effect of sand cohesion is neglected due to the dryness of the sand during the experiment. The above-mentioned equations are listed below:

$$q_u = 0.5\gamma B N_\gamma \quad (1)$$

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

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

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

$$N_\gamma = 1.5\left(N_q - 1\right) tan\, \varphi \quad \text{(Hansen, 1970)} \quad (5)$$

$$N_\gamma = \left(\frac{K_{p\gamma}}{(cos\varphi)^2} - 1\right)\left(\frac{tan\,\varphi}{2}\right) \quad \text{(Terzaghi, 1943)} \quad (6)$$

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.

According to the results presented in this table, the values of bearing capacity of the theory obtained from the Meyerhof and Vesic's methods show values close to the laboratory results. So that the bearing capacity obtained through Meyerhof's theory method has only 2% difference from the amount of bearing capacity obtained in the laboratory. The Vesic's method then expresses more real values of final bearing capacity than the Hansen's method. In the Vesic's method, the difference with the experimental result is equal to 9.5% (Table 4).

4- 2- Behaviour of the strip foundation resting on sandy soil slope with a thin weak layer

Bearing pressure-settlement curves of strip foundation resting on the sandy slope bed with a weak layer (thicknesses *T=50 mm*) for different values of variable parameters in comparison with the one without any weak layer are shown in Fig. 8. The results indicate that even a thin weak layer decreases both the ultimate bearing capacity and stiffness of the soil-foundation system, noticeably. The same result was mentioned in the other research with the different rate (Askari et al., 2022 and Alejandro et al., 2023).

Based on the results, 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. 9 shows the layered soil rupture under the ultimate load. There are three different failure types in footing soils, and they are called as general, local, and punching shear failures. Which of the failure types occurs in the footing soil depends on relative depth (footing depth/footing width) and relative density.

According to Fig.10 and Fig. 9, toe failure was mobilized for the footing which is located close to the slope and for others tests, face failure were mobilized in this research.

4- 3- The effect of load eccentricity on bearing capacity of the strip foundation resting on sandy soil slope with a thin weak layer

To evaluate the effect of load eccentricity on the bearing capacity of a strip footing on a layered soil slope, several tests were performed with different load eccentricities. In these tests other parameters affecting the footing bearing such as the distance of footing from the slope crest were constant and the eccentricity in two directions (far from the slope crest (+) and toward the slope crest (-)) was considered.

Figs. 11, 12 and 13 show the results for D=0, D=0.5B and D=B and different load eccentricities, respectively.

Analysis of the laboratory results shown in the graphs indicate that the values of eccentricity affect the final bearing capacity of the foundation and increase the bearing capacity by moving away from the weak layer and the slope crest (positive values of e). Also, by increasing the amount of eccentricity to negative values (i.e., approaching the sloping crest), the bearing capacity decreases. In each figure, with changing the load eccentricity, the trend of soil pressure-settlement changes somewhat.

The values of the bearing capacity of the foundation per parameter D=0, in the maximum case, vary in the range of 20 to 25 kPa. These bearing capacity values have an average drop of 40% compared to the uniform sand state

Also, in laboratory conditions, six test modes have been performed for D=0, the highest amount of bearing capacity occurring for the highest positive amount of eccentricity, i.e., +B/4, and the lowest value occurring for the highest amount of eccentricity at the sloping crest (negative amount).

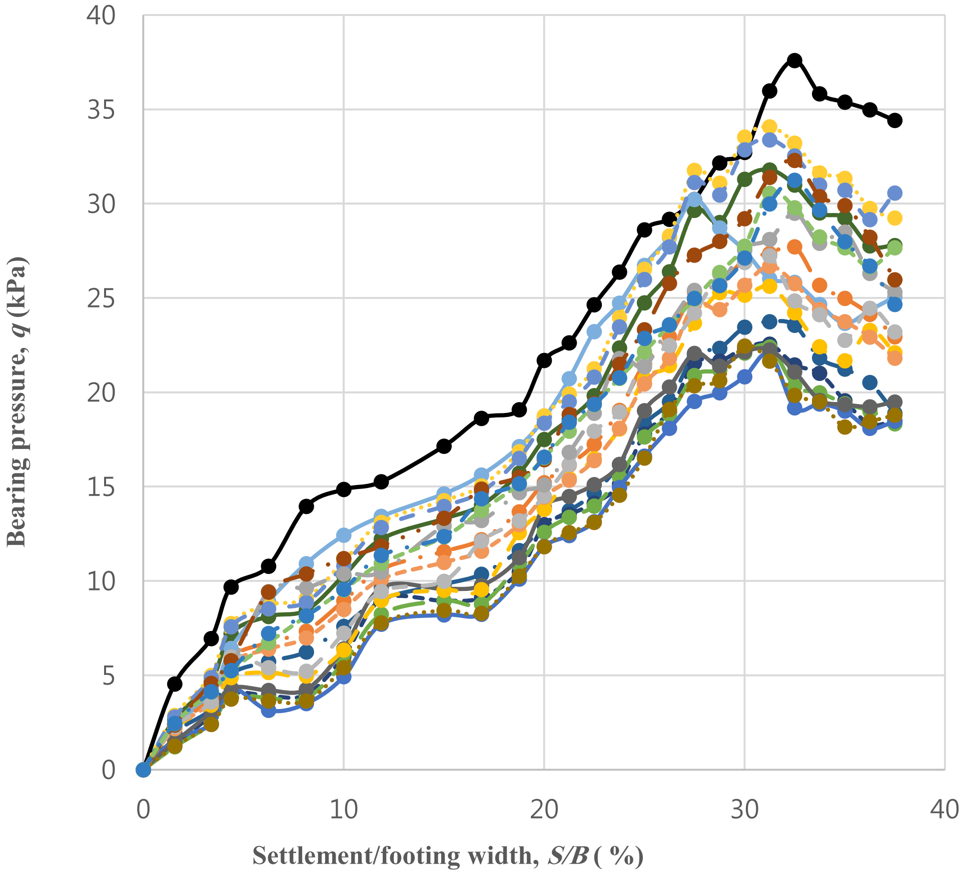

Fig. 8. Pressure-settlement curve of strip footing on uniform sand (black line) and sandy soil with a weak layer (colored lines)

4- 4- The effect of footing distance from slope crest on bearing capacity of the strip foundation resting on sandy soil slope with a thin weak layer

To assess the effect of footing and weak layer's distance from the slope crest, some tests were done. In these tests, the load eccentricity was constant and just this distance varied.

Fig. 14 shows the results of three tests with the same load eccentricity (e=+B/4) and different values of D (distance of footing to the slope crest).

By comparing the diagrams of Fig. 14, it is understood that by increasing the value of D, i.e., the distance of the strip foundation from the slope crest, the values of bearing capacity will increase, too. The lowest values of band bearing capacity occur for D=0 and the highest values occur for D=B. As the distance between the foundation and slope crest increases, 43% increase in the bearing capacity of the strip foundation (from 23.75 kPa to 34.07 kPa) occurs.

According to this figure, variations of the bearing capacity have similar trends and with increasing D parameter, both bearing capacity and stiffness values increase, too. This result was obtained for other load eccentricities, either.

Based on the results, the closest values of bearing capacity to the uniform sand state are when D=B (the distance from the foundation to the slope crest is equal to the width of the foundation). The lowest load capacity (largest difference with uniform sand state) also occurs when the foundation is located at the slope crest and D=0.

5- Numerical Simualtion

To complement the experimental findings, an extensive finite element analysis was conducted using the Geo-Studio software package. By employing a two-dimensional finite element model, the software enabled a comprehensive examination of soil mass loading and deformation behavior.

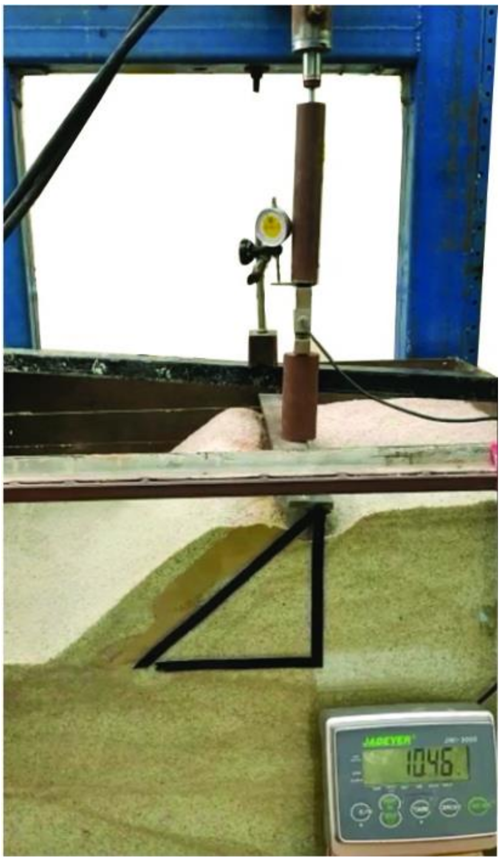

Fig. 9. Soil rupture beneath a strip footing on a sandy slope with a weak layer

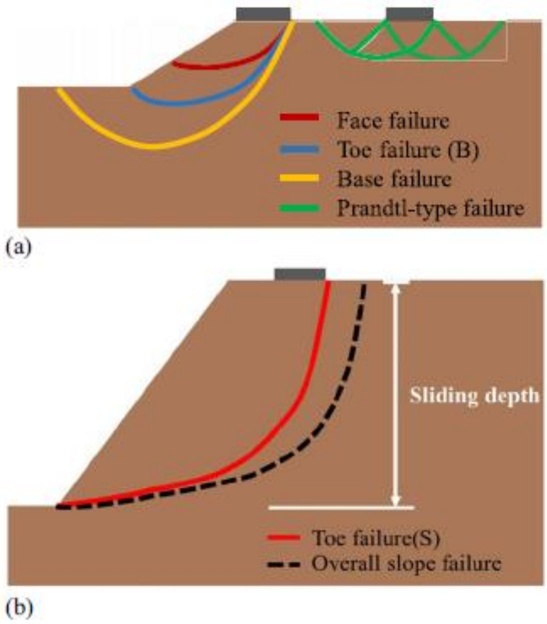

Fig. 10. Illustration of the potential failure mechanisms of footings on slopes according to Zhou et al. (2023): (a) bearing capacity failure mode; and (b) slope stability failure mode.

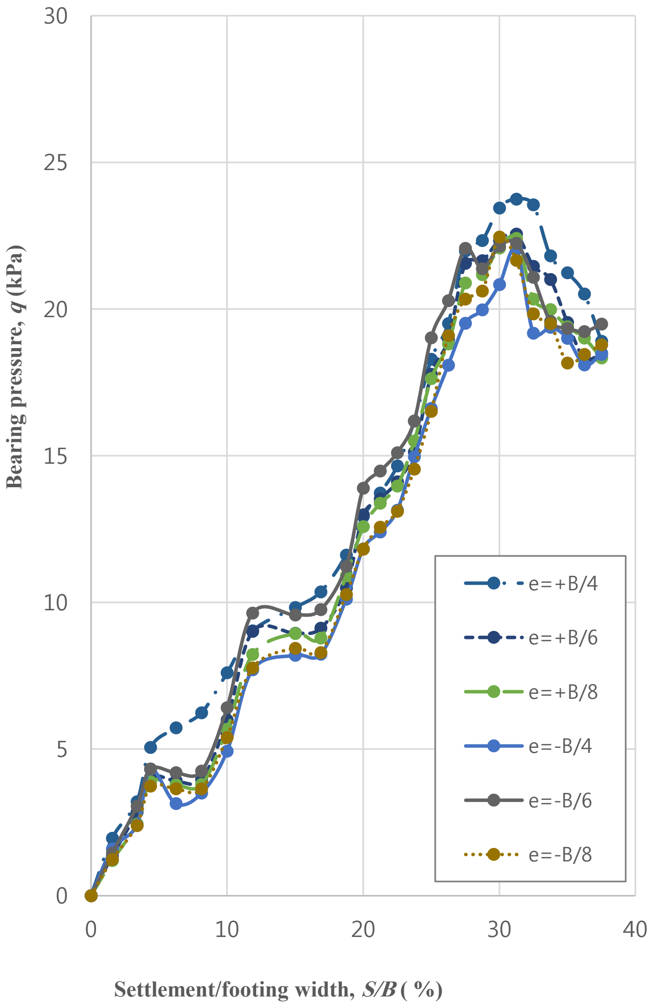

Fig. 11. Pressure-settlement curve of strip footing on sandy soil with a weak layer (D=0)

This numerical modeling approach, validated and calibrated using laboratory results, serves as a valuable tool in reducing the need for extensive experimental testing under different conditions.

Sigma/W module within the Geo-Studio software facilitated the visualization of load-settlement diagrams and determination of the maximum stress-induced allowable deformation, which correlates with the ultimate bearing capacity. The shear strength parameters obtained from direct shear tests, as presented in Tables 1 and 2, were utilized in defining the properties of the clay and sandy soils within the numerical models. A total of 19 numerical models were constructed in accordance with the specifications outlined in Table 5 to obtain the desired results.

Table 4 presents the numerical analysis results for strip footings on soils both with and without a weak layer, providing a comprehensive overview of the outcomes obtained from the numerical simulations. Additionally, Figures 15 illustrate the

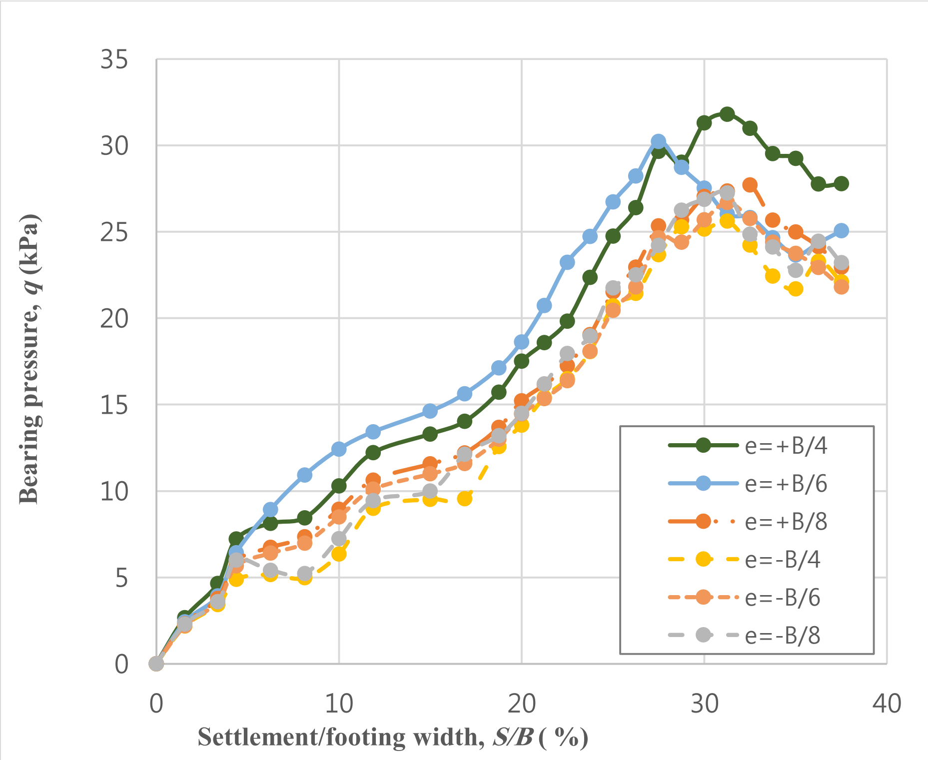

Fig. 12. Pressure-settlement curve of strip footing on sandy soil with a weak layer (D=0.5B)

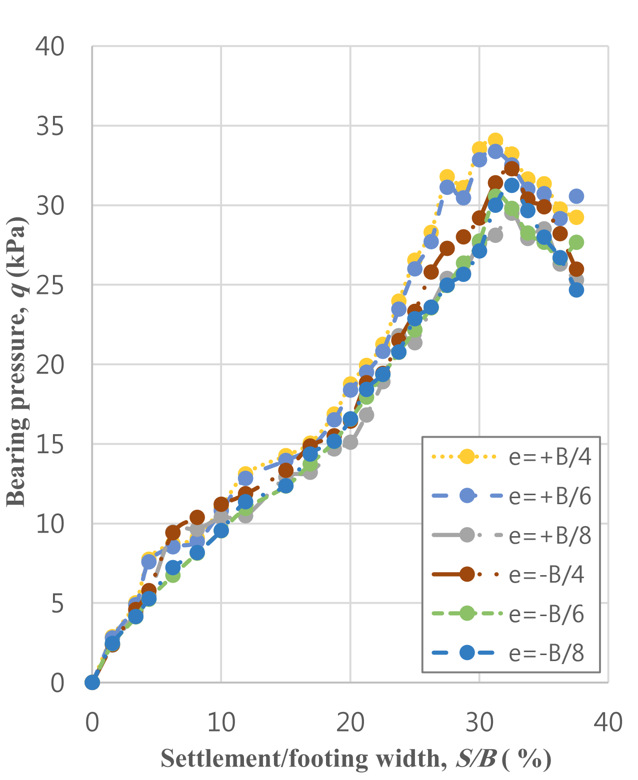

Fig. 13. Pressure-settlement curve of strip footing on sandy soil with a weak layer (D=B)

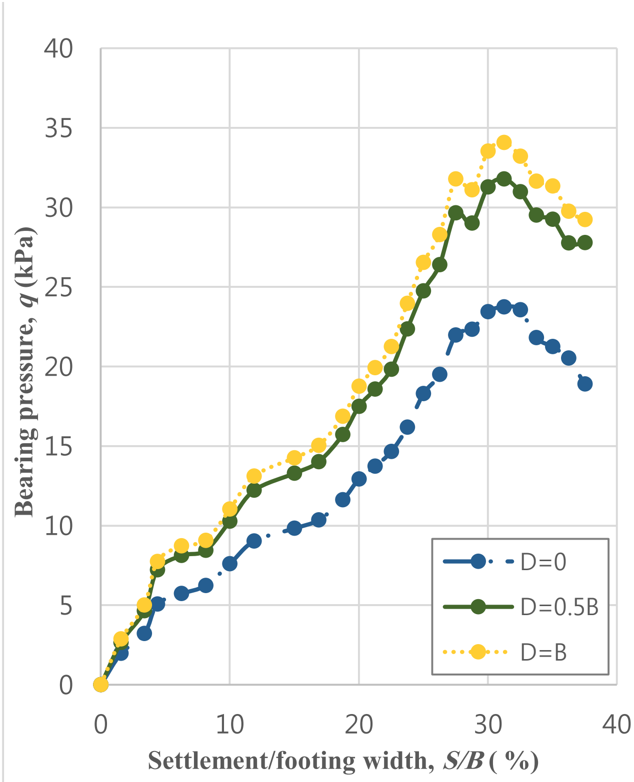

Fig. 14. Pressure-settlement curve of strip footing on sandy soil with a weak layer (e=+B/4)

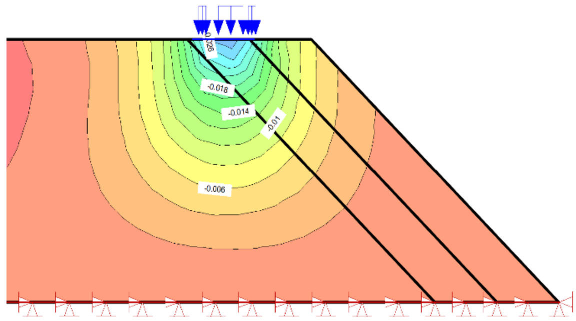

Fig. 15. Vertical displacement distribution result of strip footing Test No. 14 (Allowable settlement)

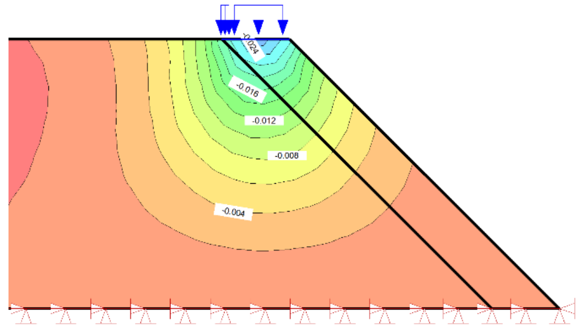

Fig. 17. Vertical displacement distribution result of strip footing Test No. 2 (Allowable settlement)

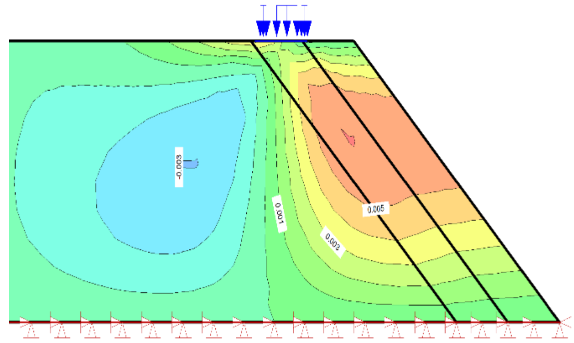

Fig. 16. Horizontal displacement distribution result of strip footing Test No. 14

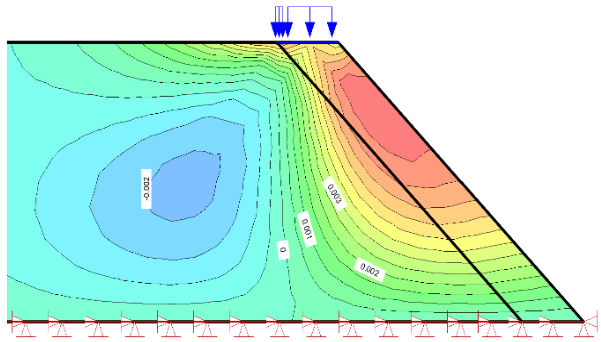

Fig. 18. Horizontal displacement distribution result of strip footing Test No. 14

load-settlement diagrams for strip footings with and without a weak layer. The comparison between the numerical results presented in Table 5 and the corresponding experimental evidence demonstrates the significant influence of weak clay layer thickness and depth on the bearing capacity of the layered soil. Figures 16 to 18 illustrate the displacement behavior of strip footings for Experiment No. 14 and No. 2, respectively.

The results reveal that the magnitude of overburden and the position of the weak layer exert a substantial influence on the ultimate bearing capacity of the foundation. For instance, within the scope of this study, the maximum bearing capacity exhibited an 11% reduction compared to Test No. 1, while the worst-case scenario within the test program displayed a significant 42% decrease in the bearing capacity of the strip foundation.

In general, the findings demonstrate that, akin to the uniform sand case, different tests were conducted for various values of the weak layer parameters, with corresponding numerical analysis employed to model these scenarios. As demonstrated in Table 4, the test group featuring a larger distance (B) compared to other values of the B parameter exhibited the highest bearing capacity values. Conversely, a decrease in this value, resulting in the weak layer being situated closer to the top of the slope, led to a reduction in the bearing capacity. The results are good agreement with experimental and numerical investigation of strip footing behavior on sand with a weak layer of varying thicknesses and overburden loads which is down by Hosseni Fani (Hosseni fani et al., 2024).

6- Conclusion

In the present research, the strip footing behavior resting on the sand slope bed with weak thin layer has been investigated by implicating a small-scale model experiment. The purpose of the present study was to evaluate the effects of eccentricity and footing distance from slope crest on the ultimate bearing capacity of the strip foundation resting on the sandy slope bed. Based on the experiment results, the conclusions are as follows:

Table 5. Ultimate bearing capacity for strip footings with weak layer (Numerical results)

Test data	Q_{ult} (KPa)
	Numerical Output
No 1	33.6
No 2	26.19
No 3	25.67
No 4	24.92
No 5	24.15
No 6	23.78
No 7	23.56
No 8	29.49
No 9	28.9
No 10	27.21
No 11	26.44
No 12	26.14
No 13	25.86
No 14	30.24
No 15	29.78
No 16	29.28
No 17	28.66
No 18	28.85
No 19	29.57

• The slope weak thin layer decreases both the ultimate bearing capacity and stiffness of the soil-foundation system. The extent of this effect depends on the eccentricity and footing distance from slope edge.

• The weak thin layer for the critical distance of D=0 led to more reduction in the ultimate bearing capacity by 43% (from 23.75 kPa to 34.07 kPa). The closest values of bearing capacity to the uniform sand state occurs when D=B. The lowest bearing capacity also occurs when D=0.

• 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.

• The values of the bearing capacity in the maximum case, vary in the range of 20 to 25 kPa. These bearing capacity values have an average drop of 40% compared to the uniform sand state. Also, in laboratory conditions, six test modes have been performed for each value of D, the highest amount of bearing capacity occurring for the highest positive amount of eccentricity and the lowest value occurring for the highest amount of eccentricity at the negative amount.

• By analyzing the results of theoretical relations, the values of bearing capacity obtained from the Meyerhof and Vesic's methods show closer values to the experimental results. The bearing capacity obtained through Meyerhof's theory method is only 2% different from the amount of bearing capacity obtained in the laboratory. The Vesic's method then expresses more real values of final bearing capacity than the Hansen's method. In the Vesic's method, the difference with the experimental result is equal to 9.5%.

• Bearing capacity increases by moving away from the weak layer and the slope crest. Also, by increasing the amount of eccentricity to negative values (i.e., approaching the sloping edge), the bearing capacity decreases.

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 strip footing resting on sand slope behavior with a thin weal layer and quantify the effect of different parameters on the ultimate bearing capacity results.

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NOTATIONS

B	footing width
e	eccentricity
$\propto$	slope angle
q	bearing capacity
c'	Effective cohesion
C_c	coefficient of curvature
C_u	uniformity coefficient
D	foundation distance from slope crest
D_f	embedment depth of foundation
D_{max}	maximum grain size
D_r	relative density
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
q	bearing pressure
q_u	ultimate bearing capacity
S	settlement of the foundation
T	thickness of thin layer
γ_d	dry unit weight
φ'	effective angle of internal friction
τ	shear stress
$\Delta q/\Delta s$	variation of bearing pressure to variation of settlement ratio

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