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# Experimental and numerical study of weak soil layer effects on ultimate bearing capacity of strip foundations resting on inclined layered soil masses

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**Abstract.** The construction of structures near slopes has nowadays become inevitable. and several theoretical models have been proposed to estimate the ultimate bearing capacity of foundations located on slops. However, slopes with inclined layered soils have so far remained insufficiently explored. This study examines the influence of slope angle and strip foundation location on the ultimate bearing capacity of such slopes through experimental and numerical analyses. The results indicate that a decrease in slope angle and an increase in setback distance (i.e., the horizontal distance from the foundation edge to the slope crest) enhance the ultimate bearing capacity. Additionally, compared to homogeneous slopes with similar dimensions and setback distances, slopes with a weak offset layer (a weak layer in the foreground) and those with a weak interlayer exhibit a reduction in ultimate bearing capacity. Specifically, for slopes with angles of 30°, 45°, and 60°, reductions of approximately 8%, 20%, and 31% were observed for weak offset layers, while reductions of 10%, 19%, and 28% were noted for weak interlayers. However, as the setback distance increases, these differences diminish following a quadratic function. At a distance of approximately four to six times the foundation width, the ultimate bearing capacity becomes comparable to that of a strip foundation situated on level ground.

**Keywords:** inclined layered soil; numerical modeling; physical modeling; strip foundation; ultimate bearing capacity; weak soil layer

## 1. Introduction

the behaviour of shallow foundations on soil. The ultimate bearing capacity of shallow footings has long been considered as a challenging topic among geotechnical engineers and researchers (Mandeel *et al*. 2020). Designing foundations requires a deep understanding of the geotechnical behavior of the subsoil. Determining the ultimate bearing capacity and subsoil settlement are key parameters that must be examined and analyzed during the process of designing foundations. The importance of precise recognition of foundation-subsoil interaction becomes more evident when limited access to flat and stable land, along with economic and architectural considerations, necessitates the construction of projects on sloping areas close to the crest. The ultimate bearing capacity of foundations adjacent to slopes might be dependent on the bearing capacity of subsoil or slope stability. Consequently, the interplay of these two factors complicates the investigation and analysis of the problem. Meyerhof (1957) was the first researcher to propose a hypothesis for determining the ultimate bearing capacity of foundations located on top or on the forehead of slopes by developing the theory of bearing capacity of foundations in flat and horizontal lands, and combining it with theories of slope stability. Meyerhof concluded that for foundations in such locations, a plastic zone forms, inclined toward the incomplete slope, which is smaller than the plastic zone under similar foundations on level ground. As a result, the final bearing capacity will be lower. In another research work, Naeini *et al.* (2012) investigated the load−settlement behavior and ultimate bearing capacity of strip foundations on clay slopes unreinforced and reinforced with geosynthetics. Based on the findings, they announced that the load-settlement behavior and the ultimate bearing capacity of the foundation are significantly improved by including the reinforcing layer. However, the use of more than one reinforcing layer does not significantly change the ultimate bearing capacity. Additionally, for both reinforced and unreinforced slopes, the bearing capacity increases with an increase in setback distance. In contrast, increasing the soil's friction angle reduces the efficiency of the reinforcement. Arvin *et al.* (2016) employed the theory of lower boundary shaker to evaluate the bearing capacity of strip foundations located on slopes and determined the reliability coefficient of the slopes using the method of

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reducing resistance under the effect of vertical repetitive dynamic loads. Their results demonstrated that both the foundation bearing capacity and the reliability coefficient of the slope are influenced by the dynamic characteristics of the slope and the imposed loads, with the lowest values occurring at resonance. Pusadkar *et al*. (2017) investigated the increase in strength and rigidity of sandy slope by using a new method of soil improvement with calcite deposition. After injecting S. Pasteurii bacteria and Urea + Ca Cl2 adhesive solution in the model slopes and curing for 14 and 28 days, the researchers conducted chemical tests in the laboratory and reported that the bearing capacity of the foundation of such slopes has increased significantly after bed improvement through this method such that the ultimate bearing capacity has been achieved in 28 days of curing. In a parametric study, Khattab *et al.* (2019) used the GEOSLOPE finite element program and evaluated the effect of rainfall intensity and duration, groundwater level, foundation width, and slope angle as parameters influencing the stability of unsaturated clay slopes. In addition, they provided diagrams for routine design and, as one of the important and clear results, declared that the ultimate bearing capacity increases as the underground water level decreases. Ramazan Burujerdi and Jiryaei Sharahi (2019) conducted a parametric study using the limited equilibrium method to investigate the effects of setback distance, slope angle, and foundation burial depth on the ultimate bearing capacity of foundations near slopes. Their findings showed that increasing the slope angle and reducing the setback distance lead to a decrease in ultimate bearing capacity, while increasing foundation burial depth results in an increase. In another parametric study, Anamika and Ragini (2021) investigated the effect of parameters such as setback distance, foundation width , inclination angle, internal friction angle, cohesion, and soil unit weight on the ultimate bearing capacity of slopes in some regions of India. They reported that the ultimate bearing capacity will decreases as a result of increasing the angle of inclination, but it increases as a result of increasing other parameters. Furthermore, increasing the setback distance beyond a certain threshold mitigates the slope's effect, causing the foundation's failure mechanism to become independent of the slope. Debnath (2021) investigated the seismic bearing capacity of shallow foundations near slopes by performing quasi-static limited equilibrium analysis. In addition to proposing a linear failure mechanism for determining bearing capacity coefficients, he reported that these coefficients decrease significantly with an increase in the seismic coefficient, and this reduction becomes more pronounced as slope inclination increases. Shukla and Jakka (2021) investigated the effects of slope on ultimate bearing capacity, slope factors, and failure mechanisms using limit analysis. After determining the lower and upper bound bearing capacities, they presented the average values. Their results indicate that bearing capacity increases with greater setback distance, foundation depth and soil internal friction angle but decreases as the slope angle increases. However, the slope factor decreases with increasing foundation depth, slope angle, and soil internal friction angle, while it increases with greater setback distance. Additionally, their study showed that the failure mechanism and slope factors change substantially with the increase of the internal friction angle of the soil and the slope angle, and the failure mechanism of the foundation changes from the bearing capacity to the combined state as a result of increasing the slope. Alamaar and Al-Jazaairry (2023) evaluated the bearing capacity of the foundation near sand slopes conducting an experimental study and reported that the bearing capacity of the foundation improves by increasing the horizontal distance between the foundation and the slope crest to foundation width ratio (b/B). This increase ends when b/B ratio reaches 2.5. They also observed that foundations placed closer to the slope edge exhibit lower bearing capacity and a higher likelihood of failure due to the influence of the slope. Conducting a numerical study on a shallow foundation on an unsaturated embankment using the Barcelona Foundation Model (BBM), Showkat and Babu (2023) investigated the effect of various factors affecting the bearing capacity during infiltration. Their results indicate that as the foundation distance increases from the crest (setback distance), the soil provides higher bearing capacity upon infiltration due to the confinement. Furthermore, they reported that the load-bearing capacity of slopes composed of clay and silt declines quickly as water infiltrates the soil. Conversely, sandy slopes exhibit a slight increase in load-bearing capacity under the same conditions. Kianpour *et al*. (2024) combined experimental and numerical analyses to investigate the behavior of strip foundations on sandy slopes with and without weak layers. Their findings demonstrated that adding a weak layer to the sandy embankment base significantly reduced both the bearing capacity and the stiffness of the soil-foundation system.

The review of related literature clearly shows that numerous studies have been carried out based on laboratory, analytical, and numerical examinations to evaluate the stability of slopes and the bearing capacity of foundations placed on slopes. However, the researchers have mainly focused on homogeneous slopes (mainly sandy), including unreinforced or reinforced horizontal layered soils and slopes stabilized or improved with chemical substances under the effect of static or seismic loads, as well as the effects of infiltration on unsaturated soil slopes (Madadzadeh Toulegilan *et al.* 2020, Mirnaghizadeh *et al.* 2020, Naderi *et al*. 2020, Zhou *et al.* 2020, Ebid *et al.* 2021, Hajiani Boushehrian 2021, Ramazan Borujerdi and Jiryaei Sharahi 2021, Sarkar and Chakraborty 2021, Tan and Vanapalli 2021, Alemyparvin and Kouhdaragh 2022, Mazouz *et al.* 2022, Shojaeian *et al*. 2022, Dilta and Shahram 2023, Luo *et al.* 2023, Susanti 2023). In contrast, natural and real conditions involve soil layers that deviate from the horizontal state and form inclined layered slopes. Therefore, this study investigates the effects of slope angle variations and the position of the foundation on the ultimate bearing capacity of strip foundations embedded in such slopes.

## 2. Materials and methods

In this study, the effects of slope angle variations and foundation position on the ultimate bearing capacity of strip

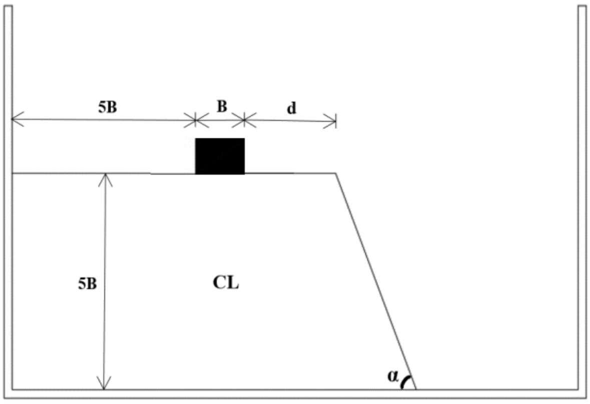

Fig. 1 The schematic models of homogeneous slopes

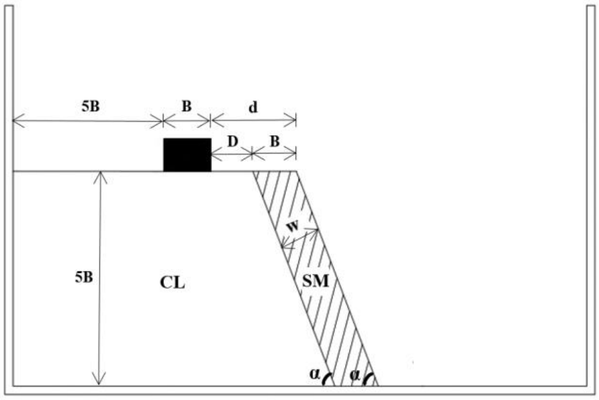

Fig. 2 The schematic models of slopes with weak offset layer

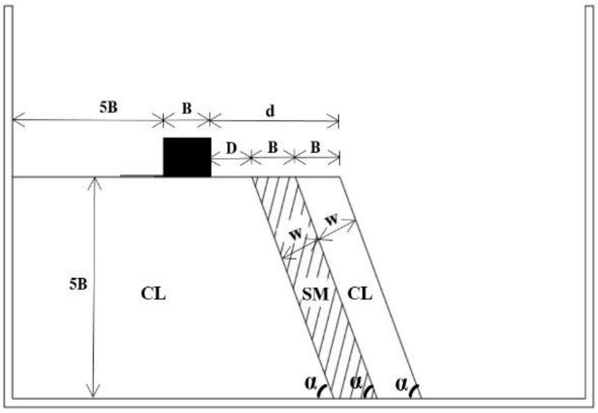

Fig. 3 The schematic models of Slopes with weak interlayer

Table 1 The status of considered parameters in homogeneous slopes

| α (deg) | B (cm) | d (cm) |
|---|---|---|
| 30 | | 0 |
| | | 5 |
| 45 | 5 | 10 |
| | | 15 |
| 60 | | 20 |

Table 2 The status of considered parameters in slopes with weak offset layer

| α (deg) | B (cm) | D (cm) | d (cm) |
|---|---|---|---|
| 30 | | 0 | 5 |
| 45 | 5 | 5 | 10 |
| | | 10 | 15 |
| 60 | | 15 | 20 |

Table 3 The status of considered parameters in slopes with weak interlayer

| α (deg) | B (cm) | D (cm) | d (cm) |
|---|---|---|---|
| 30 | | 0 | 10 |
| 45 | 5 | 5 | 15 |
| 60 | | 10 | 20 |

foundations rested on inclined layered soil slopes has been investigated using small-scale physical modeling. The schematic form of the models and the test program are presented in Figs. 1-3 and Tables 1-3, respectively.

### 2.1 Materials

The study of soil and rock samples through small-scale physical modeling has led to significant advancements and achievements in geotechnical engineering. The closer the boundary and initial conditions of the modeling are to real-world conditions, the more accurately the laboratory sample will replicate actual behavior. in this research, two soil samples with different geotechnical characteristics were selected as weak and strong soils. According to the Unified Soil Classification System, silty sand (SM) was used as the weak soil while clay with low plasticity properties (CL) was selected as strong soil. The technical specifications of these soils are provided in Table 4. For the strip foundation, specific design considerations were required to ensure sufficient bending stiffness, adherence to plane strain conditions, and minimal weight. so that in addition to being easy to move and operate, it would create small initial stress in the subsoil after being placed on the slope (Abrishami and Mir Mohammad Hosseini 2009). A piece of rigid aluminum with a length of 59.8 cm (2 mm shorter than the width of the chamber for convenience of embedding and avoidance of contact between the foundation edges and the chamber walls during model tests), a thickness and width of 5 cm, and a smooth bottom was selected following the laws of scale conversion, covered with a rigid steel belt in order to increase rigidity and prevent local crushing of the place where load is applied. It is noteworthy that in the center of the upper surface of the foundation model, a hole was created to provide the possibility of free rotation of foundation during loading by placement of a rigid and smooth steel ball bearing.

### 2.2 Preparation of soil samples

To achieve proper and uniform mixing of soil with optimum moisture content and to prepare the required soil

Table 4 Geotechnical properties of strong and weak soil layers

| Property | Amount of strong soil | Amount of weak soil |
|---|---|---|
| Liquid limit (LL) (%) | 34.2 | - |
| Plastic limit (PL) (%) | 11.6 | - |
| Plastic index (%) | 22.6 | - |
| Optimum moisture (%) | 17.8 | 13.6 |
| Soil dry density during test (g/cm$^3$) | 1.183 | 1.176 |
| Undrained cohesion (kg/cm$^2$) | 0.67 | 0.11 |
| Internal friction Angle (deg) | 13.1 | 22.2 |
| Elasticity coefficient (N/m$^2$) | 40000000 | 30000000 |
| Poisson's ratio | 0.3 | 0.25 |

Table 5 Different parts of the loading device

The main body (steel frame)
The test layered soil chamber
Load application electric motor
Loading bar (shaft)
Strain gauge
Electronic force gauge
Hand rammer and steel rigid plates for layers' compaction
Thin rigid and sharp steel blade with chamber for layers' cut with intended slope

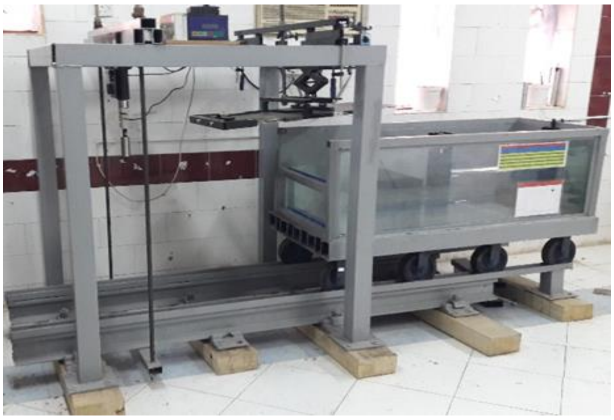

Fig. 4 Picture of physical model frame and loading machine apparatus in present study

samples, a progressive water sprinkler system and a large mixer were used. The prepared samples were immediately placed in thick vacuumed plastic bags and kept in a cold place. it is noteworthy that to ensure the uniform distribution of moisture in clayed soils, they were kept for 24 hours in the cold storage after being mixed and packed prior to application. However, the sand samples were prepared at the same day of performing test and kept in big vacuumed plastic bags in the considered place until application.

### *2.3 Physical modeling*

The various components of the loading device made for this research are presented in Table 5 and Fig .4.

The construction of the loading apparatus and the physical modeling were performed in sequential stages. After assembling the structural framework of the apparatus and embedding the load application equipment, the construction of test apparatus began. At this stage, the internal dimensions of the chamber, —150 cm in length, 60 cm in width, and 50 cm in height—were determined based on scale conversion rules to ensure simple strain conditions and avoid complications. The influence of the chamber walls on the experimental results was also considered. Subsequently, to enhance the accuracy and convenience in achieving the desired thickness of the condensed layers, the glass wall of the test chamber was marked with checkered lines in the form of 5-cm square grids. In the process of building model slopes, the amount of wet soil required for each layer was prepared based on the considered relative density and poured into the test chamber. Following initial leveling, the soil was compacted by a hand rammer and steel rigid plates until reaching a thickness of 5 cm (Fig. 5). After implementing five similar compacted soil layers and creating a bed with a thickness of five times the width of the foundation (25 cm) below it, the soil inside the chamber was cut diagonally using a sharp and rigid thin steel blade, a sample of which is represented in Fig. 6. it is noteworthy that in order to minimize the effect of the chamber wall and its rigid floor on the results, the distance of the edge and the foundation floor from the chamber wall and floor was considered to be five times greater than the width of the foundation. Furthermore, in order to reduce the friction and cohesion of the soil layers and the chamber wall, a thin coating of vaseline was applied on the walls of the chamber before making each slope model. Also, in

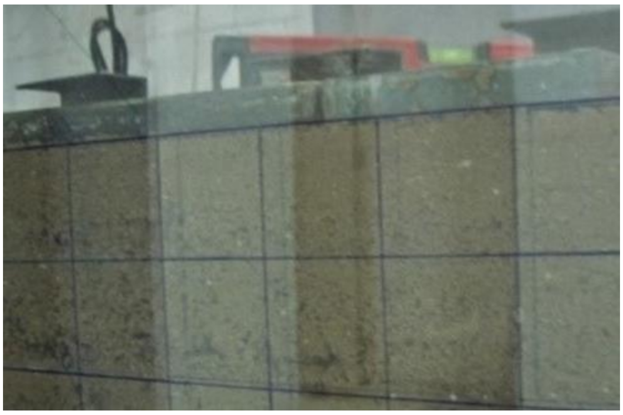

Fig. 5 Compaction and smoothing of soil with steel rigid plates and final leveling of the layers

Fig. 6 Preparing slopes using sharp edge blades in physical modeling

Fig. 7 Placement of the strip foundation model along with related equipment

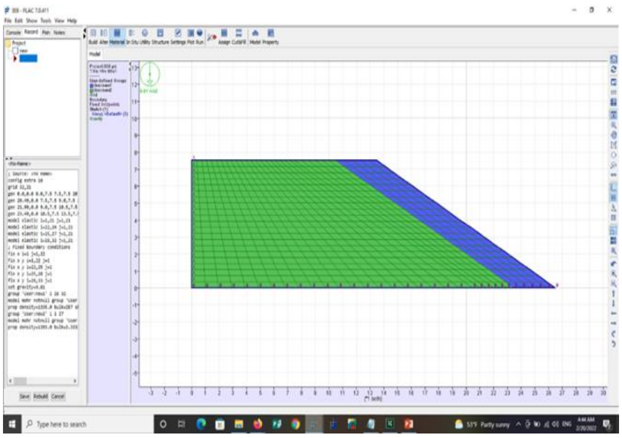

Fig. 8 A sample of the numerical model of a two-layered slope

the final stage of each test, after preparing the model and placing the strip foundation in the designated position, the loading and measuring equipment—including a force gauge and displacement gauge—were installed on the model foundation. Loading was applied at a predetermined rate of 1 mm/min until slope failure occurred (Fig. 7). Furthermore, to ensure the desired relative density and moisture in the test procedures, a small thin-walled steel mold with a certain volume was randomly embedded during the compaction operations in certain models. Measurements of specific weight and moisture content showed only minor, acceptable variations, confirming the consistency and reliability of the prepared soil samples.

### *2.4 Numerical modeling*

To evaluate the results of physical modeling, numerical simulations were conducted using the seventh version of Flac 2D finite element software. The real slopes modeled in the numerical analysis were scaled to 30 times the geometric dimensions of the physical models and analyzed under plane strain conditions. After applying boundary conditions and defining the necessary support constraints, the ultimate bearing capacity was examined and analyzed (Fig. 8).

Table 6 Scale coefficients (Muir Wood 2004)

| Parameter | Experimental Model (1 g) |
|---|---|
| Length | $1/n$ |
| Mass density | 1 |
| Stress | $1/n$ |
| Force | $1/n^3$ |
| Force in length | $1/n^2$ |

In numerical modeling, the Mohr-Coulomb plastic model, which is one of the most common applied models for soil environments, was used to define the soil layers in the slopes. This model effectively represents the failure behavior of soil. A beam element model with a flat bottom and no friction in contact with the subsoil was employed to stimulate the rigid concrete strip foundation. To simplify the numerical analysis, the interaction between strong and weak layers in layered slopes was neglected. In addition, as the bearing capacity cannot be directly calculated through Flac software, after the initiation of loading and applying stress in each analysis, the amount of load and stress was gradually increased and the corresponding displacement values were recorded. After drawing the foundation subsoil displacement-stress curve, the stress corresponding to the intersection of the tangent lines was determined as the ultimate bearing capacity of the foundation using the method of intersection of the tangent lines of initial and final parts of the diagram.

### *2.5 The effect of scale*

Physical modeling aims at scaling down the real sample with the desired scale; hence, the behavioral similarity of the model with the real sample requires correct dimensional analysis and compliance with the principles and rules of modeling in its design and construction. However, it should be acknowledged that the behavior of a physical model never matches that of the real sample, as differences—small or significant—are inevitable due to scaling effects. The effect of scale is particularly important, as it refers to how the reduction in size influences the behavior of a structure or mass (Fakher 2014). In small-scale modeling of soil masses, it is generally assumed that an infinite number of soil grains exist at the contact surfaces between different soil layers, the soil–structure interface, and the boundaries of the physical model. This assumption effectively creates a uniform contact surface, allowing the reduction in grain size to be ignored in soil models (Fakher 2014). In addition, El Sawwaf (2005) identified stress level differences as another major factor contributing to behavioral discrepancies between physical models and real samples in modelings under gravity acceleration (1 g). Based on prevailing conditions, he suggested that 1 g models should only be used to predict the general behavior of actual samples. Muir Wood (2004) introduced applicable scale coefficients in geotechnical engineering to expand the application scope of the physical modeling and generalize the results of physical models to real samples, using dimensional analysis and similarity equations. Table 6 presents a selection of the coefficients proposed by Muir Wood that are relevant to this research. Based on these principles, despite reducing the geometric dimensions of the

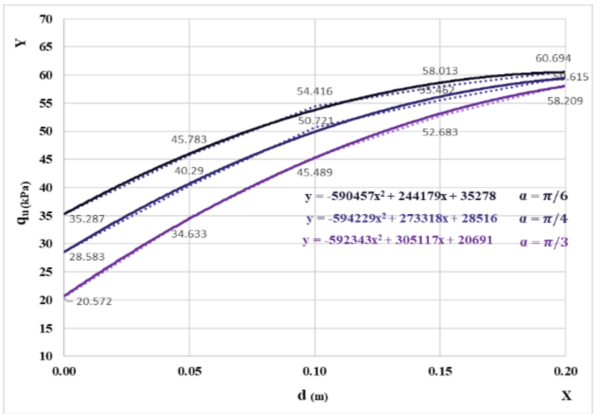

Fig. 9 Variations of the ultimate bearing capacity versus setback distance on homogeneous slopes in physical modeling

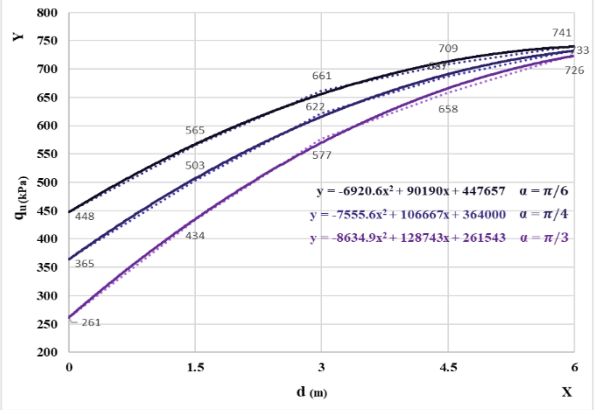

Fig. 10 Variations of ultimate bearing capacity versus setback distance on homogeneous slopes in numerical modeling

slopes and the model foundation with a scale reduction factor of n=30, the soil grain size in the physical sample and the real sample was kept the same in this research.

## 3. Results and discussion

In this study, small-scale model tests were conducted on homogeneous slopes, slopes with weak offset layer, and slopes with a weak interlayer at angles of 30, 45 and 60 degrees. The objective was to investigate the effect of the presence and location and of weak layers on the ultimate bearing capacity of strip foundations located on the mentioned slopes. In the second phase, in order to validate and evaluate the results obtained from laboratory modeling, full-scale numerical modeling and analysis were performed using FLAC 2D finite element software (version 7) to assess the ultimate bearing capacity of all corresponding physical models. This section presents and explains the results in detail.

### *3.1 Evaluating the effect of setback distance and slope angle of homogeneous slopes*

In the first stage of laboratory and numerical modeling, the behavior of homogeneous slopes was investigated and the related diagrams were drawn (Figs. 9 and 10) in order to obtain suitable basic equations for comparing and evaluating the effect of weak layers on the ultimate bearing capacity (Eqs. (1) to (6)).

$$q_u = -590457d^2 + 244179d + 35278 \quad \alpha = 30 \ _{(deg)} \tag{1}$$

$$q_u = -5942295d^2 + 273318d + 28516 \quad \alpha = 45 \ _{(deg.)} \tag{2}$$

$$q_u = -592343d^2 + 305117d + 20691 \quad \alpha = 60 \ _{(deg.)} \tag{3}$$

$$q_u = -6920.6d^2 + 90190d + 447657 \quad \alpha = 30 \ _{(deg.)} \tag{4}$$

$$q_u = -7555.6d^2 + 106667d + 364000 \quad \alpha = 45 \ _{(deg.)} \tag{5}$$

$$q_u = -8634.9d^2 + 128743d + 261543 \quad \alpha = 60 \ _{(deg.)} \tag{6}$$

The results of modeling and the corresponding graphs indicate that, at a constant setback distance, the ultimate bearing capacity decreases as a quadratic function with an increase in the slope angle. This finding clearly shows that the slope forehead, acting as a limiting boundary, prevents the sufficient development of the resistant area at the slope face, thereby reducing the lateral limitation and resistance of the subsoil against outward movement. In addition, it can be observed that at a constant slope angle, the ultimate bearing capacity obtained from the laboratory and numerical modeling increases as a quadratic function by increasing the setback distance, which indicates the significant effect of the foundation distance from the crest of the slopes in increasing the lateral restriction against the outward movement of the soil. Moreover, the results of numerical and physical modeling clearly show that, in homogeneous slopes, the ultimate bearing capacity increases by increasing the setback distance up to 4 to 4.5 times the width of the foundation, after which it stabilizes and becomes equivalent to the ultimate bearing capacity of the foundation placed on the level ground.

Meyerhof (1957) was the first to investigate the effects of foundation distance from the slope edge and slope angle on the bearing capacity of foundations on purely cohesive and non-cohesive slopes. He extended the bearing capacity theory for foundations on horizontal ground by incorporating slope stability theory, providing a foundation for subsequent studies in this field.. After conducting the desired studies and investigations, he announced that the bearing capacity of the foundations located at the top or at the forehead of the slopes is due to the decrease in the resistance of the soil against outward lateral movement, which is caused by the incomplete development of the resistant area near the forehead of the slope compared to the corresponding foundations located on the horizontal ground. His studies indicated that the bearing capacity of shallow foundations located near the slope decreased with the an increase in the inclination of the slope and increased with an increase in the foundation distance from the edge of the slope, up to a range of 2 to 6 times the width of the foundation (depending on the angle of soil internal friction and D/B ratio). Beyond that distance, the ultimate bearing capacity becomes independent of slope deviation, being equivalent to the ultimate bearing capacity of the foundations placed on the horizontal ground surface.

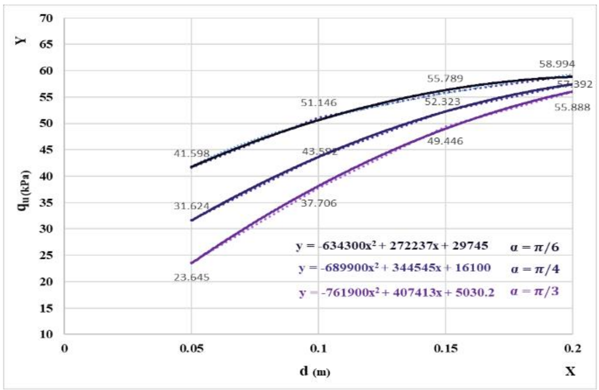

Fig. 11 Variations of ultimate bearing capacity versus setback distance on slopes with a weak offset layer in physical modeling

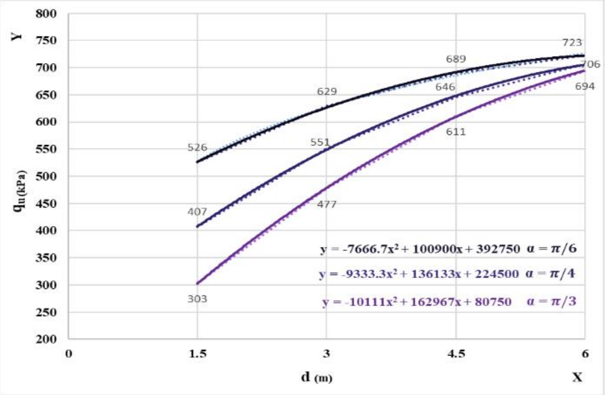

Fig. 12 Variations of ultimate bearing capacity versus setback distance on slopes with a weak offset layer in numerical modeling

Ramazan Burujerdi and Jiryaei Sharahi (2019) investigated the effect of the foundation distance from the crest, the slope angle and the buried depth of foundation on the bearing capacity of foundations near the slope in a parametric study using the limited equilibrium method. In their study, both the foundation floor and the studied soil were assumed to be homogeneous and isotropic, showing elastoplastic behavior and following a function of the Mohr-Coulomb failure criterion. Their results indicated that the ultimate bearing capacity coefficients increase with greater foundation depth and setback distance. However, when the distance exceeds five times the width of the foundation, the effect of the slope becomes insignificant, and the bearing capacity will be equivalent to the foundation capacity on the horizontal ground. Conversely, an increase in slope angle leads to a reduction in bearing capacity. Additionally, their findings showed that in slopes with a steep angle, the effect foundation distance from the crest is minimal compared to slopes with steeper angles.

An examination of these research findings confirms the overall validity of the present study's results regarding the behavior of strip foundations located on homogeneous slopes.

### 3.2 Evaluating the effect of setback distance and slope angle of slopes with weak offset layer

In the second stage of laboratory and numerical modeling, the behavior of slopes with a weak offset layer was investigated, and the results are presented in Figs. 11 and 12 along with Eqs. (7)-(12).

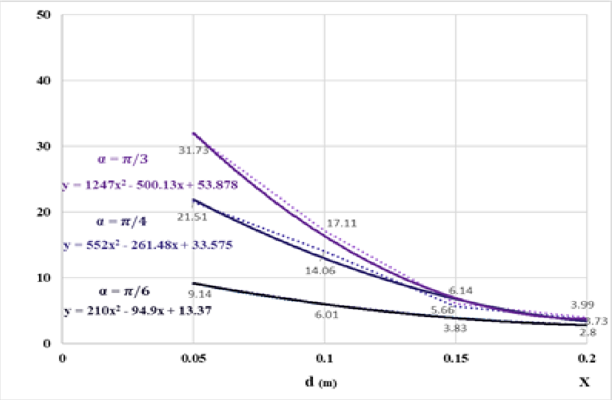

Fig. 13 Percentage of relative reduction of the ultimate bearing capacity versus setback distance on slopes with weak offset layer in physical modeling

$$q_u = -7666.7d^2 + 100900d + 392750 \quad \alpha = 30\ _{(deg.)} \tag{10}$$

$$q_u = -9333.3d^2 + 136133d + 224500 \quad \alpha = 45\ _{(deg.)} \tag{11}$$

$$q_u = -10111d^2 + 162967d + 80750 \quad \alpha = 60\ _{(deg.)} \tag{12}$$

The review of the results of modeling and the figures shows that in such slopes, at a fixed setback distance, the ultimate bearing capacity decreases as a quadratic function with an increase in the slope angle due to a decrease in the soil lateral resistance. In addition, in a fixed slope angle, the ultimate bearing capacity is noticeably increase with an increase in the setback distance, which clearly indicates the increase in the vertical resistant component of soil against the outward lateral movement with an increase in the foundation distance from the crest. Moreover, the results of numerical and physical modeling clearly show that in such slopes, the ultimate bearing capacity increases by increasing the setback distance up to 4.5 to 5 times the width of the foundation due to the low cohesion of the offset layer, subsequently becoming equal to the ultimate bearing capacity of the foundation placed on the level ground.

By observing the obtained graphs and the respective behavioral relationships (Figs. 13 and 14), it is clearly evident that the ultimate bearing capacity of strip foundations placed on such slopes, compared to homogeneous slopes, shows a significant decrease at a small setback distance due to the significant effect of low cohesion of the weak layer. This discrepancy becomes much more severe and noticeable with increasing the slope angle. Nevertheless, with increasing this distance, the existing difference decreases as a quadratic function and at distances greater than about five times the width of the foundation, it will be equal to the ultimate bearing capacity of flat and level ground (Eqs. (13)-(18)).

$$q_u = 210d^2 - 94.9d + 13.37 \quad \alpha = 30\ _{(deg.)} \tag{13}$$

$$q_u = 552d^2 - 261.48d + 33.575 \quad \alpha = 45\ _{(deg.)} \tag{14}$$

$$q_u = 1247d^2 - 500.13d + 53.878 \quad \alpha = 60\ _{(deg.)} \tag{15}$$

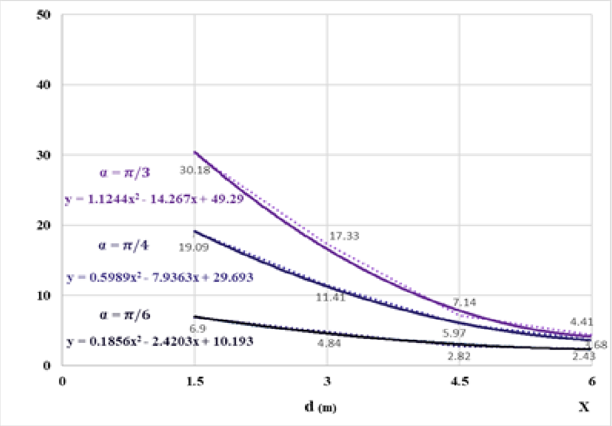

Fig. 14 Percentage of relative reduction of the ultimate bearing capacity versus setback distance on slopes with weak offset layer in numerical modeling

$$q_u = 0.1856d^2 - 2.4203d + 10.193 \quad \alpha = 30\ _{(deg.)} \tag{16}$$

$$q_u = 0.5989d^2 - 7.9363d + 29.693 \quad \alpha = 45\ _{(deg.)} \tag{17}$$

$$q_u = 1.1244d^2 - 14.267d + 49.29 \quad \alpha = 60\ _{(deg.)} \tag{18}$$

A review of the available studies shows that no study has so far dealt with the modeling of slopes having a weak offset layer for direct comparison with the results of the present research. In a parametric study, however, Anamika and Ragini (2021) investigated the effect of parameters such as the distance of the edge of the foundation from the crest of the slope, the width of the foundation, the angle of inclination, the angle of internal friction, cohesion, and the unit weight of soil on the bearing capacity of slopes in some regions of India. They reported that the ultimate bearing capacity decreases with an increase in the slope angle, but increases as a result of increasing other parameters. Also, increasing the setback distance beyond a certain limit eliminates the effect of reducing the slope, and the failure mechanism of the foundation will not be a function of the slope. Therefore, from the point of view of the influence of the parameters of shear resistance of soils on the bearing capacity, it can be confirmed that the general trend of the results of this study was inferred in relation to the slopes with a weak offset layer.

### *3.3 Evaluating the effect of setback distance and slope angle in slopes with a weak interlayer*

The third stage of laboratory and numerical modeling dealt with investigating the behavior of slopes with a weak interlayer, for which the results are presented in Figs. 15 and 16 along with Eqs. (19)-(24).

$$q_u = -496800d^2 + 242560d + 28425 \quad \alpha = 30\ _{(deg.)} \tag{19}$$

$$q_u = -417400d^2 + 269710d + 17661 \quad \alpha = 45\ _{(deg.)} \tag{20}$$

$$q_u = -693600d^2 + 410820d - 1574 \quad \alpha = 60\ _{(deg.)} \tag{21}$$

$$q_u = -6000d^2 + 87667d + 398000 \quad \alpha = 30\ _{(deg.)} \tag{22}$$

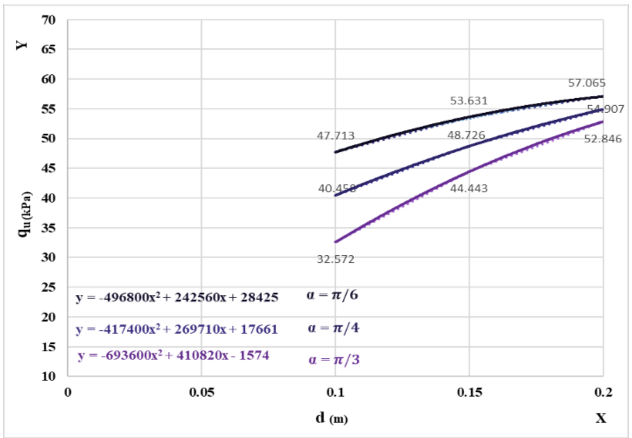

Fig. 15 Variations of the ultimate bearing capacity versus setback distance on slopes with weak interlayer in physical modeling

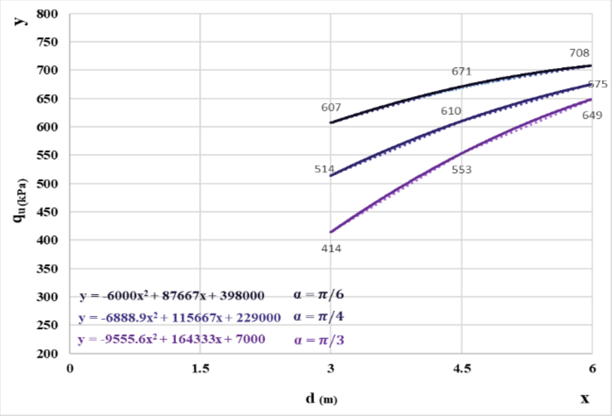

Fig. 16 Variations of the ultimate bearing capacity versus setback distance on slopes with weak interlayer in numerical modeling

$$q_u = -6888.9d^2 + 115667d + 229000 \quad \alpha = 45\ _{(deg.)} \tag{23}$$

$$q_u = -9555.6d^2 + 164333d + 7000 \quad \alpha = 60\ _{(deg.)} \tag{24}$$

The results of modeling such slopes clearly indicates that, at fixed setback distances, the ultimate bearing capacity decreases as a quadratic function with an increase in the slope angle, due to reduced soil resistance against the outward lateral movement. In fixed slope angles, however, the ultimate bearing capacity noticeably increase as a quadratic function by increasing the setback distance, which is consistent with previous cases, indicating the considerable effect of setback distance in making more lateral constraint against outward movement of the soil. Moreover, the results of numerical and physical modeling clearly show that in slopes with a weak interlayer, the ultimate bearing capacity increases by increasing the setback distance up to five to six times the width of the foundation, after which it becomes equal to the ultimate bearing capacity of the foundation placed on the level ground.

By observing the graphs and behavioral relationships obtained at this stage of the study (Figs. 17 and 18), it is clearly evident that the ultimate bearing capacity of strip foundations placed on such slopes, as compared to homogeneous slopes, shows a more significant reduction compared to slopes with a

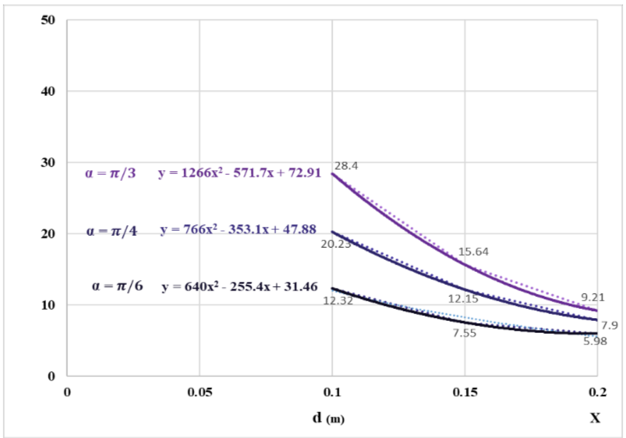

Fig. 17 Percentage of relative reduction of the ultimate bearing capacity versus setback distance on slopes with weak interlayer in physical modeling

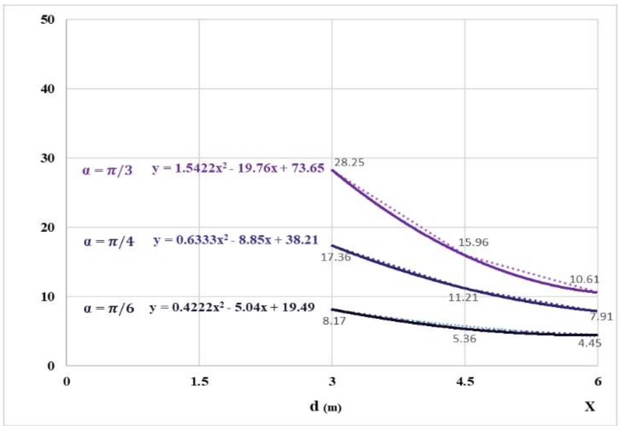

Fig. 18 Percentage of relative reduction of the ultimate bearing capacity versus setback distance on slopes with weak interlayer in numerical modeling

weak offset layer at small setback distance due to the significant impact of low cohesion of the weak interlayer and the increased potential for the collapse of the offset layer (layer located at the slope front). This difference becomes greatly severe and noticeable by increasing the slope angle. However, with increasing the setback distance, the existing difference decreases as a quadratic function and, at distances greater than about six times the width of the foundation, it will be equal to the ultimate bearing capacity of flat and level ground, as shown in Eqs. (25)-(30).

$$q_u = 640d^2 - 255.4d + 31.46 \qquad \alpha = 30\ _{(deg.)} \tag{25}$$

$$q_u = 766d^2 - 353.1d + 47.88 \qquad \alpha = 45\ _{(deg.)} \tag{26}$$

$$q_u = 1266d^2 - 571.7d + 72.91 \qquad \alpha = 60\ _{(deg.)} \tag{27}$$

$$q_u = 0.4222d^2 - 5.04d + 19.49 \qquad \alpha = 30\ _{(deg.)} \tag{28}$$

$$q_u = 0.6333d^2 - 8.85d + 38.21 \qquad \alpha = 45\ _{(deg.)} \tag{29}$$

$$q_u = 1.5422d^2 - 19.76d + 73.65n \qquad \alpha = 60\ _{(deg.)} \tag{30}$$

Al-Homoud and Tubeileh (1998)'s study focused on several cases of instability of failed slopes along highways with high traffic in Jordan, investigating the factors affecting their instability. They reported that the failure of the investigated slopes was due to the presence of steep weak cohesive layers (mainly clayey marl) occurring among stronger layers, along with relatively high piezometric levels in years with very heavy rainfall.

Examining the results of the mentioned research in the context of the effects of a weak layer placed among stronger layers clearly indicates the correctness of the general trend of the results of the present study concerning the slopes with a weak interlayer.

## 4. Conclusions

In this study, the effect of slope angle variations and the location of foundation on the ultimate bearing capacity of slopes containing inclined layers was investigated by conducting small-scale model tests and iteration of the numerical modeling with real dimensions using the seventh version of Flac 2D finite element software. The following are some of the key findings of this study:

- In all investigated cases, at a fixed setback distance, the ultimate bearing capacity decreases as the slope angle increases, following a quadratic function.
- In all investigated cases, at a fixed slope angle, the ultimate bearing capacity increases with an increase in the setback distance, also following a quadratic function.
- For slopes with a weak offset layer, the ultimate bearing capacity, compared to homogeneous slopes with similar dimensional coordinates and a setback distance equal to the width of the foundation decreases by approximately 8%, 20%, and 31% at slope angles of 30°, 45°, and 60°, respectively. However, these differences diminish as a quadratic function with a gradual increase in the setback distance and disappear at a distance of about four to five times the width of the foundation.
- For slopes with a weak interlayer, the ultimate bearing capacity, compared to homogeneous slopes with similar dimensional coordinates and a setback distance equal to twice the width of the foundation, decreases by approximately 10%, 20%, and 28% at slope angles of 30°, 45°, and 60°, respectively. Similarly, these differences decrease as a quadratic function with a gradual increase in the setback distance and disappear at a distance of about five to six times the width of the foundation.
- The results of this study demonstrate that physical modeling can be effectively utilized for the behavioral evaluation of both full-scale and prototype models.

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## Notations

| | |
|---|---|
| $B$ | Width of the foundation |
| $d$ | Setback distance (distance edge of foundation from the slope crest) |
| $\propto$ | Slope angle |
| $q_u$ | Ultimate bearing capacity |
| $C$ | Cohesion |
| $\varphi$ | Angle of internal friction |
| $LL$ | Liquid limit |
| $PL$ | Plastic limit |
| $PI$ | Plastic index |
| $\gamma$ | Unit weight |
| $\gamma_d$ | Dry unit weight |