# ASSESSMENT OF SETTLEMENT OF SHALLOW FOUNDATIONS ERECTED NEAR SLOPES OF SANDY SOIL

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## ABSTRACT

In this study, the behaviour of shallow foundations near slopes is studied using nonlinear elastic finite element analysis. Forty-four cases of strip footings resting on cohesionless soils that were studied by Sud (1984)[1] through model tests, have been analyzed. Pressure-settlement relations has been compared with experimental results of (Sud, 1984) [1], and a good agreement between the two has been observed. Ultimate bearing capacity of shallow foundations near slopes was evaluated using the intersection of two tangents of pressure-settlement curve. The values of ultimate bearing capacity agree well also with (Sud, 1984) [1].

A non-dimensional correlation has been developed between the settlement of footing erected near slope ($S_\beta$) and the settlement of footing resting on level ground ($S_o$). The relationship ($S_\beta/S_o$ versus De/B) can be expressed by a unique relation for different slope angles ($\beta$). This relation has been found to be dependent on

distance of the edge of the footing from slope shoulder; De, and angle of slope; β, while it is independent of the relative density of sand; $D_R$, and the factor of safety. By knowing the settlement of a footing resting on a level ground, the settlement of a footing erected near slope can be evaluated using this correlation.

**KEY WARDS**

Finite element, nonlinear, shallow foundation, slope, pressure-settlement, bearing capacity, relative density, sandy soil.

## INTRODUCTION

A foundation engineer frequently comes across the problems of foundations placed on slopes or near slope. The maximum value of bearing capacity of this problem can be obtained from foundation failure and from overall stability of slopes. In the case of sandy soils, the bearing capacity is always governed by foundation failure.

Meyerhof (1957)[2] extended his classical theory of bearing capacity of foundation on level ground and combined with the theory of the stability of slopes to cover the stability of foundation on slopes.(Sokolovsky[3],1960;Reddy and Mogaliah[4], 1975) solved this problem by using slip line approach. Limit equilibrium analysis was used by Mizuno et al[5]. 1960; Reddy and Mogaliah[6], (1976); Bowels[7], (1977) and Myslives and Kysela[8], (1978) to solve the problem of foundations near slopes. Chen[9] (1975) used the limit analysis approach to solve this problem. Sud[1], (1984) and Saran et al., (1989) [10] presented an analytical solution to obtain the bearing capacity of near slopes footing using limit equilibrium and limit analysis approaches. Saran et al[11]. (1988) developed a semi-empirical procedure to predict the settlement characteristics of actual footings resting on c-$\phi$ soil near slopes using nonlinear constitutive laws of soil.

In this study, an attempt has been made to investigate the pressure-settlement characteristics of shallow foundations resting on cohesionless soil and near the slopes, using nonlinear elastic finite element analysis. Also non-dimensional correlation is developed to find the settlement of the foundation near slopes.

## CASES CONSIDERED

Sud[1] (1984) performed plane strain model tests on sand to study the behaviour of footings near slopes. Different cases were studied (De/B = 0.5, 1.0, 1.5, 2.0, 2.5, 3.0 and 3.5); ($\beta$= 30$^o$, 26.6$^o$ and 20$^o$) and ($D_R$= 72% and 84%) where De is the distance from the edge of the foundation to the slope shoulder, B is the footing width, $\beta$ is the angle which the slope make with the horizontal and $D_R$ is the relative density of sand. Also two others cases where the foundation is resting on a horizontal ground level and with two different relative densities which are (72% and 84%). Properties of the footing, sand and tank considered through out this task were similar to those taken by Sud[1] (1984) in his experimental investigation, in an aim to match results of those obtained using finite element analysis, to those obtained from experimental investigation.

## Soil Properties

The soil used was dry sand. The physical properties are given in Table 1. Triaxial tests were performed by Sud[1] (1984) on dry sample of sand ($D_R$= 84 % and 72%), having corresponding angles of internal friction of 39$^o$ and 37.5$^o$ respectively. The parameters 'a' and 'b' of the hyperbola were correlated with the confining pressure (Duncan and Chang[12], 1970) for the given relative densities are shown in figures 1 and 2 respectively. Table 2 gives the values of constants; $A_1$, $A_2$, $K_1$ and $K_2$ for the Ranipur's sand.

## Footing and Testing Tank

Box type footing 100 mm high of aluminum plate of thickness 25 mm was used by Sud[1] (1984). The footing was 120 mm wide and 600 mm long. This length was equal to the width of the tank so as to give it an effect of the two dimensional loading.

The inside dimensions of the tank used were, 600 mm in width, 3000 mm in length and 900 mm in height.

## SOIL-FOOTING SYSTEM

A two dimensional, nonlinear finite element analysis software has been developed in this study. It makes use of numerically integrated isoparametric 2D finite elements and the program can handle plane strain and plane stress problems. It makes use of (Kondner's[13],1963 and Duncan & Chang[12], 1970) hyperbolic stress-strain approach as a nonlinear constitutive law to define the stress-strain behaviour of soil.

The forty-four cases were analysed using above nonlinear elastic finite element analysis software. The mesh has four (eight-nodded) isoparametric elements representing the footing and 225 (eight-nodded) isoparametric elements representing the soil mass. The finite element mesh used is shown in figure 3.

## RESULTS AND DISCUSSION

### Pressure-Settlement Relation

Figure 4 shows pressure-settlement characteristics for some typical cases of strip footings near slope for different relative densities, those obtained by finite element nonlinear elastic analysis. The results of Sud[1] (1984) are also shown on the corresponding figure. It is evident from these plots that the pressure-settlement characteristics match very well with the results of Sud[1] (1984). Similar trend was also observed in all other cases analysed in this study.

Figures 5 and 6 show the pressure-settlement relation of strip footing near slope for relative densities of sand equal to 84% and 72% respectively, those obtained by finite element nonlinear analysis.

## Evaluation of Ultimate Bearing Capacity

Figure 7 shows the pressure-settlement relation for strip footing resting on sandy soil with relative density equal to 72% ($\phi$=37.5$^o$), and erected near slope with $\beta$=30$^o$ and De=2.5B, using this plot, ultimate bearing capacity value ($q_u$) was obtained using the method of intersection of two tangents. The value of ultimate bearing capacity obtained from this plot is 83 kPa. The ultimate bearing capacity also can be obtained using the following equation (for surface footing resting on cohesionless soil):

$$q_u = \frac{1}{2}\gamma\ B\ N_\gamma \qquad (1)$$

Where $N_\gamma$ is bearing capacity factor corresponding to the case of a footing erected near slope. For $\phi$=37.5$^o$, $\frac{De}{B}=2.5$ and $\beta$=30$^o$, the value of $N_\gamma$ is 87.64 (Sud's[1] charts, 1984), and the value of $q_u$ from Eq. 1 workout as 83.87 kPa.

For all cases analyzed in this study, the ultimate bearing capacity were obtained using the relationship between pressure-settlement, (Figs. 5 and 6). Also for the same cases, the ultimate bearing capacity were obtained using Equation 1. Figure 8 shows the comparison of the values of ultimate bearing capacity those getting by two methods (from pressure-settlement relationship and from Equation 1) for all the cases which analysed in this study. A good agreement is shown between the two results, and in some cases the values of the ultimate bearing capacity evaluated in this study are greater than the values those getting by Equation 1, using Sud's[1] (1984) charts.

## NON-DIMENSIONAL CORRELATION ($S_\beta/S_o$)

For (De/B = 0.5, 1.0, 1.5, 2.0, 2.5 and 3.0), the values of settlements of 120mm wide footing have been obtained from nonlinear finite element analysis for ($\beta$ = 30°, 26.6° and 20°). The settlements were obtained for a factor of safety of 2.0 (i.e. $q = \frac{q_u}{2}$ ) and 3.0 (i.e. $q = \frac{q_u}{3}$) at relative densities equal to 84% and 72%.

The ratio ($S_\beta/S_o$) has been computed, where $S_\beta$ is the settlement of the footing for slope angle ($\beta$) and $S_o$ is the settlement of footing for the same width resting on level ground, the value of $S_o$ changes with the change in value of factor of safety and relative density. The ratio ($S_\beta/S_o$) computed for all parameters above were plotted against De/B as shown in Fig. 9 for three slope angles, 30°, 26.6° and 20° respectively. It is found that a unique curve is obtained for the relationship between ($S_\beta/S_o$) and (De/B), which is independent of factor of safety and relative density.

The relationship ($S_\beta/S_o$) versus (De/B) can be expressed by the following equation for different slope angles obtained by the method of least squares;

$$\frac{S_\beta}{S_o} = a_o \frac{De}{B} + a_1 \tag{2}$$

where $a_o$ and $a_1$ are constants which depend on the value of slope angle (β). The values of $a_o$ and $a_1$ are given in Table 3 for three slope angles. The equations for the values of $a_o$ and $a_1$ are obtained by plotting them against (β, in degrees) and are given as below:

$$a_o = 0.0608 + 0.0012\beta \tag{3}$$

$$a_1 = 0.9907 - 0.0136\beta \tag{4}$$

By substituting the values of $a_o$ and $a_1$ obtained from equations 3 and 4 into equation 2, equation 5 will be obtained,

$$\frac{S_\beta}{S_o} = \left[(0.0608 + 0.0012\beta)\frac{De}{B} + (0.9907 + 0.0136\beta)\right] \tag{5}$$

The settlement of footing resting near slope, $S_\beta$ for given $\beta$ and De/B can be evaluated using equation 5, provided that the settlement of the same footing resting on level ground, $S_o$ is known. The value of $S_o$ may be obtained by using the conventional plate load test data.

## CONCLUSION

**(i)** The pressure-settlement characteristics of shallow strip footings near slopes can be predicted satisfactorily by using the nonlinear elastic finite element analysis.

**(ii)** The ultimate bearing capacity of strip footing near slopes can be obtained from the pressure-settlement relations obtained in (i) above using the method of intersection of the two tangents.

**(iii)** Non-dimensional correlation of settlement of the footing near slope to the settlement of the same footing resting on level ground has been developed in the present study. From this relation the settlement of the footings erected near slopes can be evaluated by knowing the settlement of the same footing resting on level ground. It is found that this correlation is dependent upon edge distance factors, De/B and Slope angles, and it is independent of a factor of safety and a relative density of sand.

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**Table (1) Properties of Ranipur Sand (After Sud, 1984)**

| S. No. | Property | M agnitude |
|---|---|---|
| 1 | Type of soil | SP |
| 2 | Effective size ($D_{10}$) | 0.15 mm |
| 3 | Uniformity coefficient | 1.73 |
| 4 | Mean specific gravity | 2.646 |
| 5 | Minimum void ratio | 0.57 |
| 6 | Maximum void ratio | 0.88 |
| 7 | Average density in dense state | 16.3 $kN/m^3$ |
| 8 | Relative density in dense state | 84% |
| 9 | Average density in medium dense state | 15.95 $kN/m^3$ |
| 10 | Relative density in medium dense state | 72% |

**Table(2) Parameters of Constitutive Laws for Ranipur Sand (After Sud, 1984)**

| $D_R$ | $A_1$ | $A_2$ | $K_1$ | $K_2$ |
|---|---|---|---|---|
| 84% | 800 | 220 | 178.0 | 2.2 |
| 72% | 500 | 200 | 137.5 | 1.44 |

**Table (3) Values of $a_o$ and $a_1$**

| $\beta$ (degrees) | $a_o$ | $a_1$ |
|---|---|---|
| $30^o$ | 0.0974 | 0.5746 |
| $26.6^o$ | 0.0947 | 0.6405 |
| $20^o$ | 0.0853 | 0.7144 |

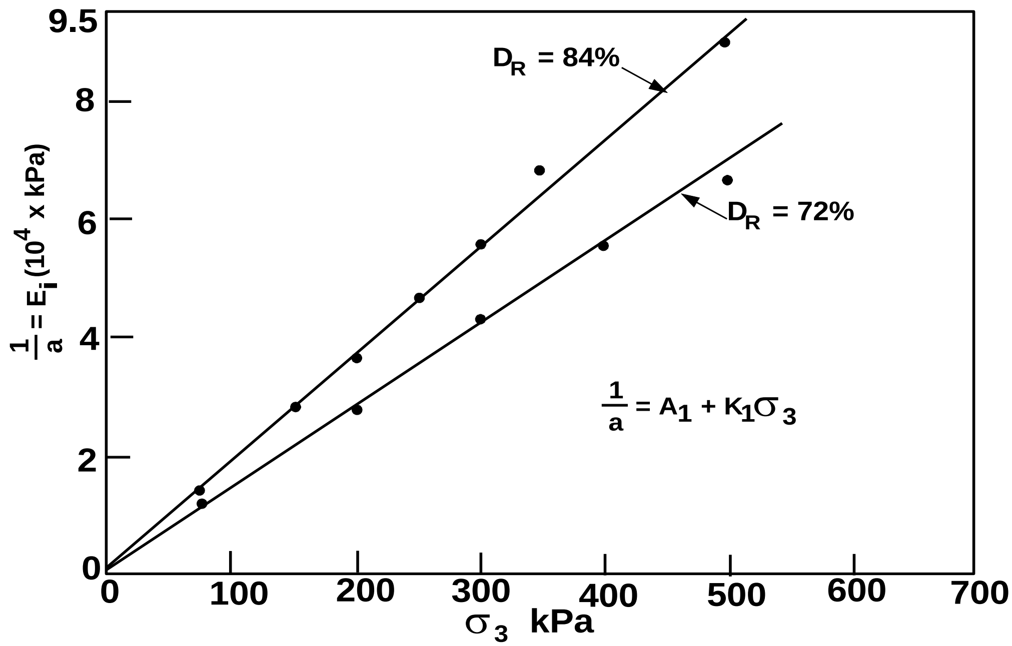


**Fig. 1 Variation of Ei (1/a) w.r.t confining pressure for Ranipure sand (After Sud, 1984)**

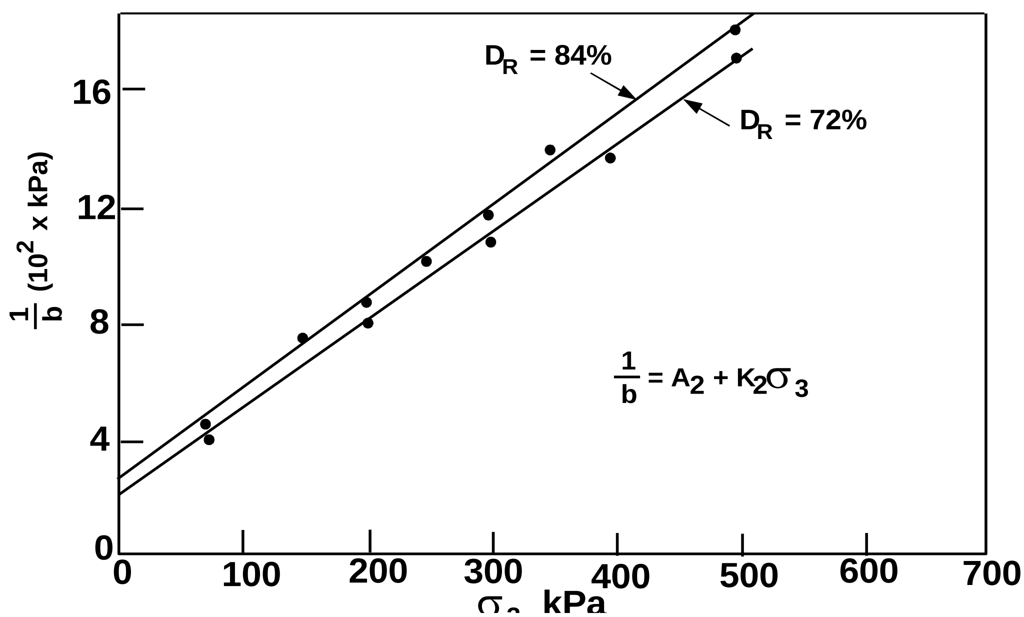


**Fig. 2 Variation of Konder's (1/b) w.r.t confining pressure for Ranipure sand (After Sud, 1984)**

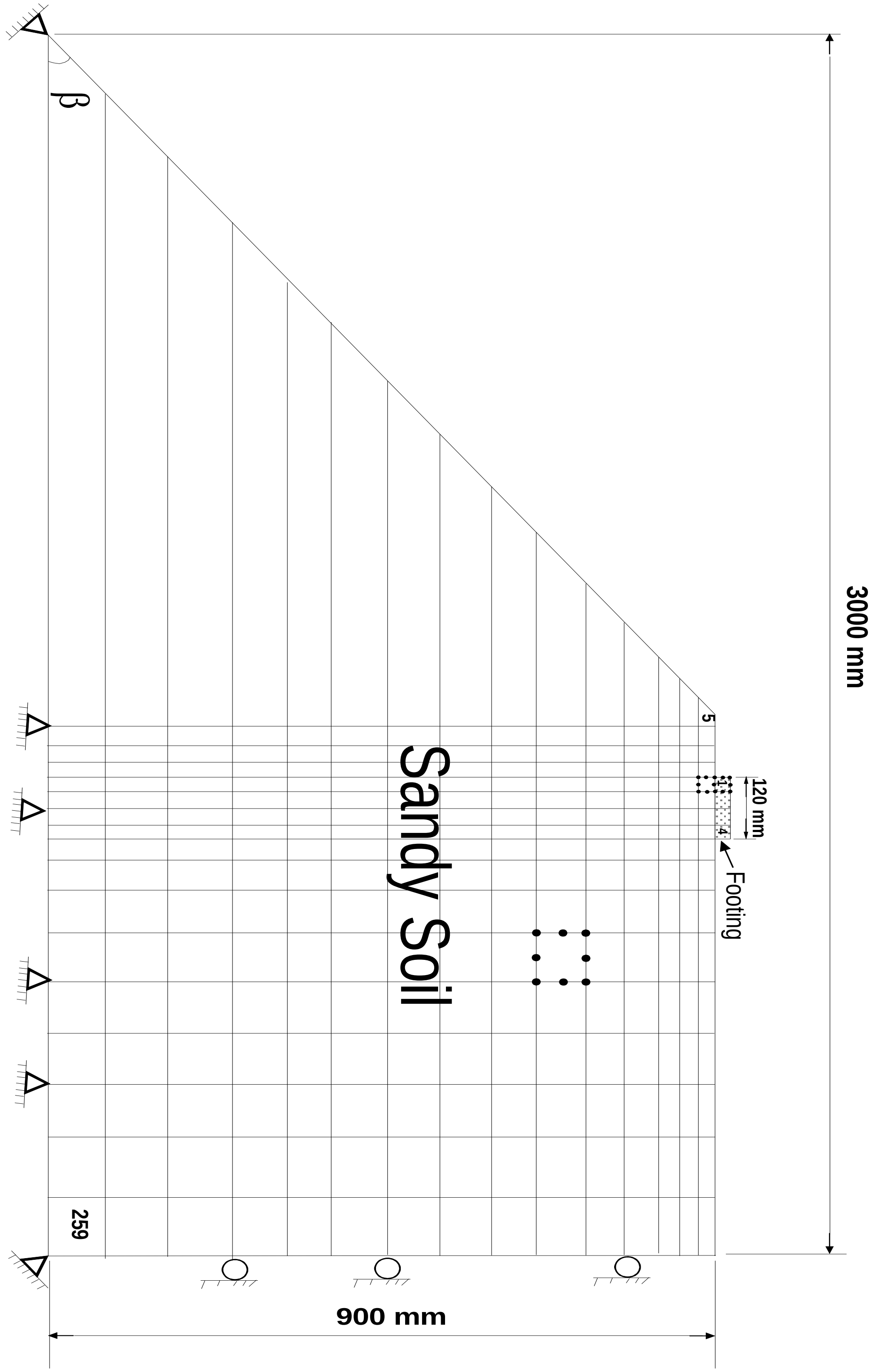


**Fig. 3 F.E. Mesh representing footing –soil system (not to scale)**

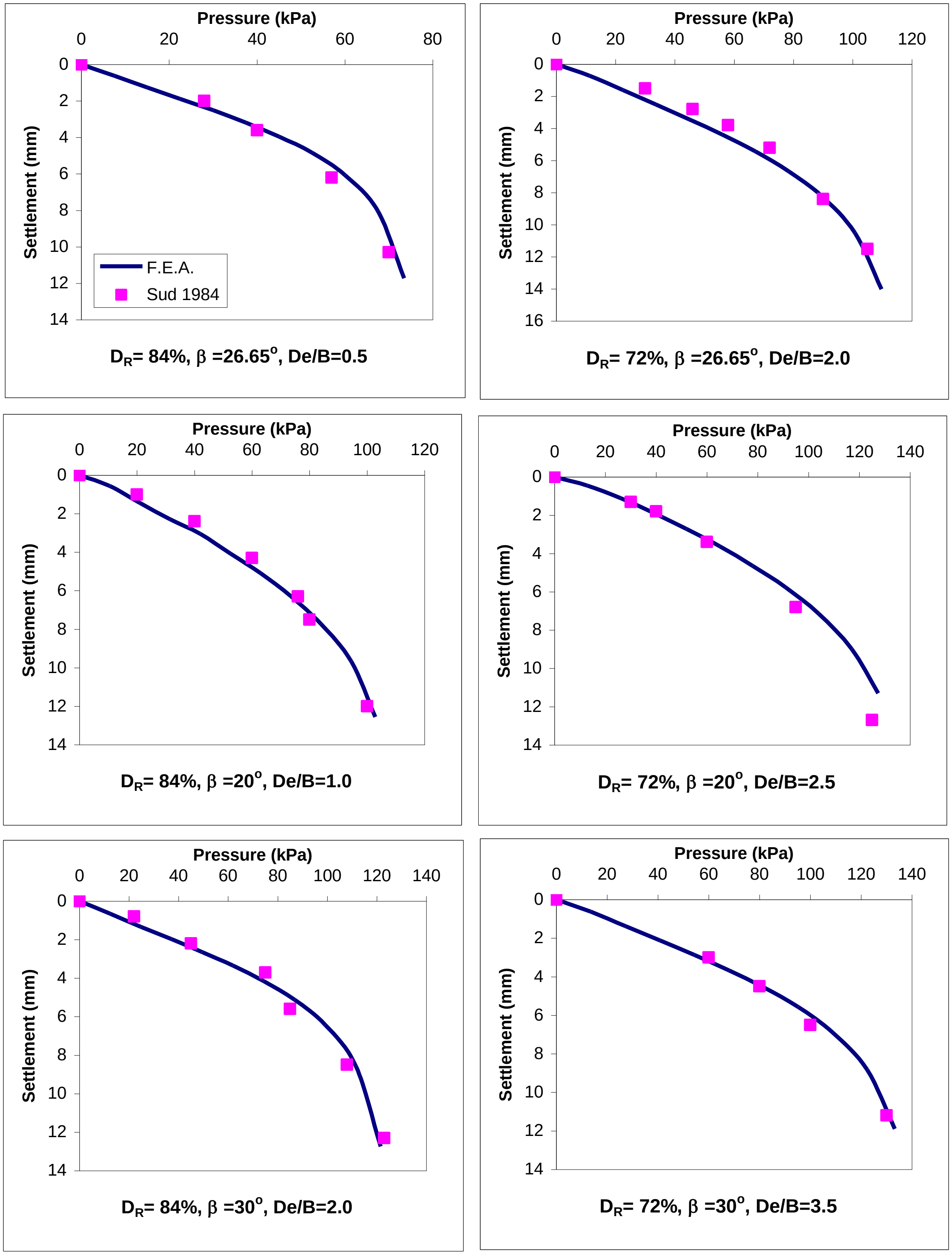


**Fig. 4 Pressure –settlement characteristics of strip footing (120 mm width)**

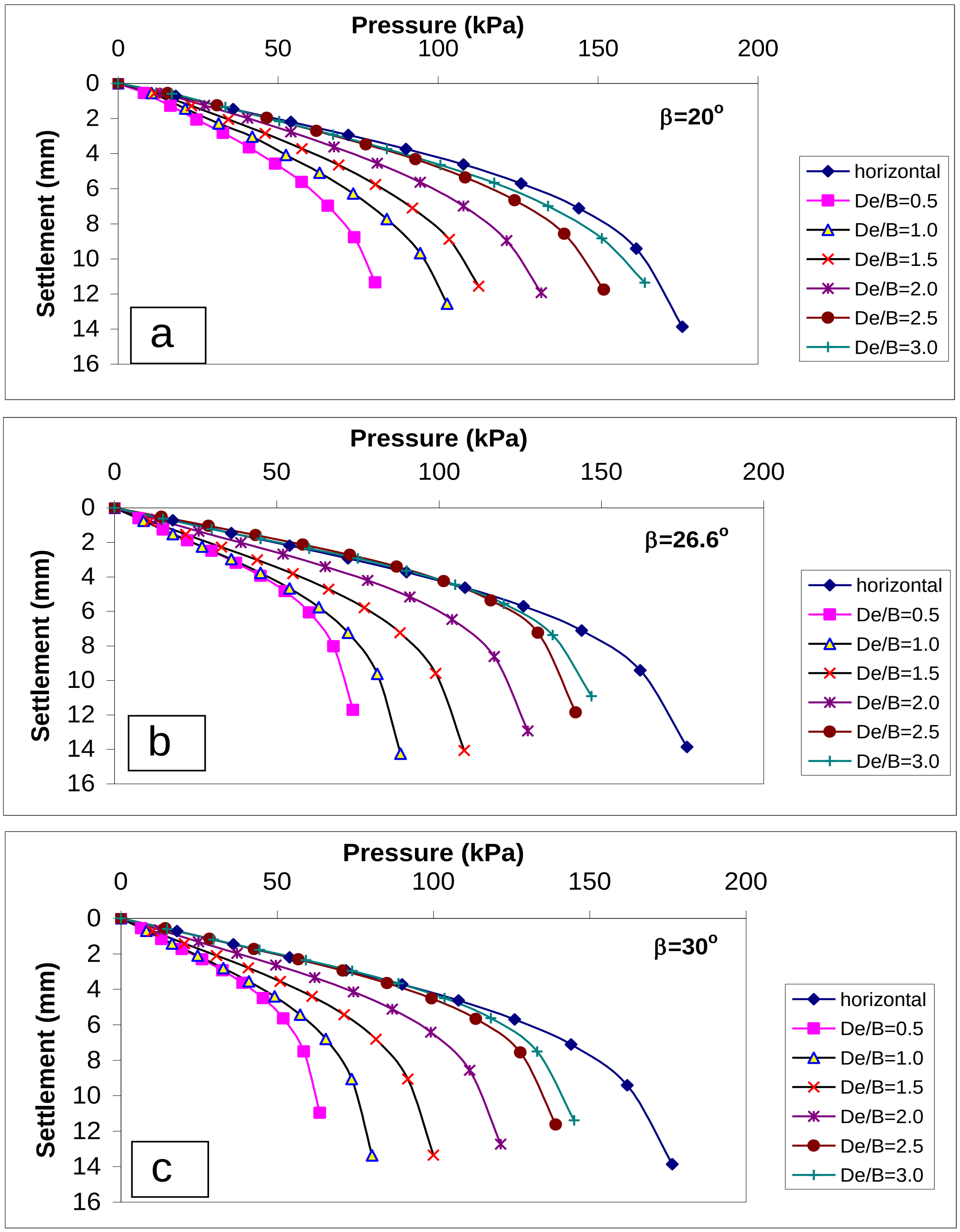


**Fig. 5 Pressure –settlement curve of the cases analyzed ($D_R$=84%)**

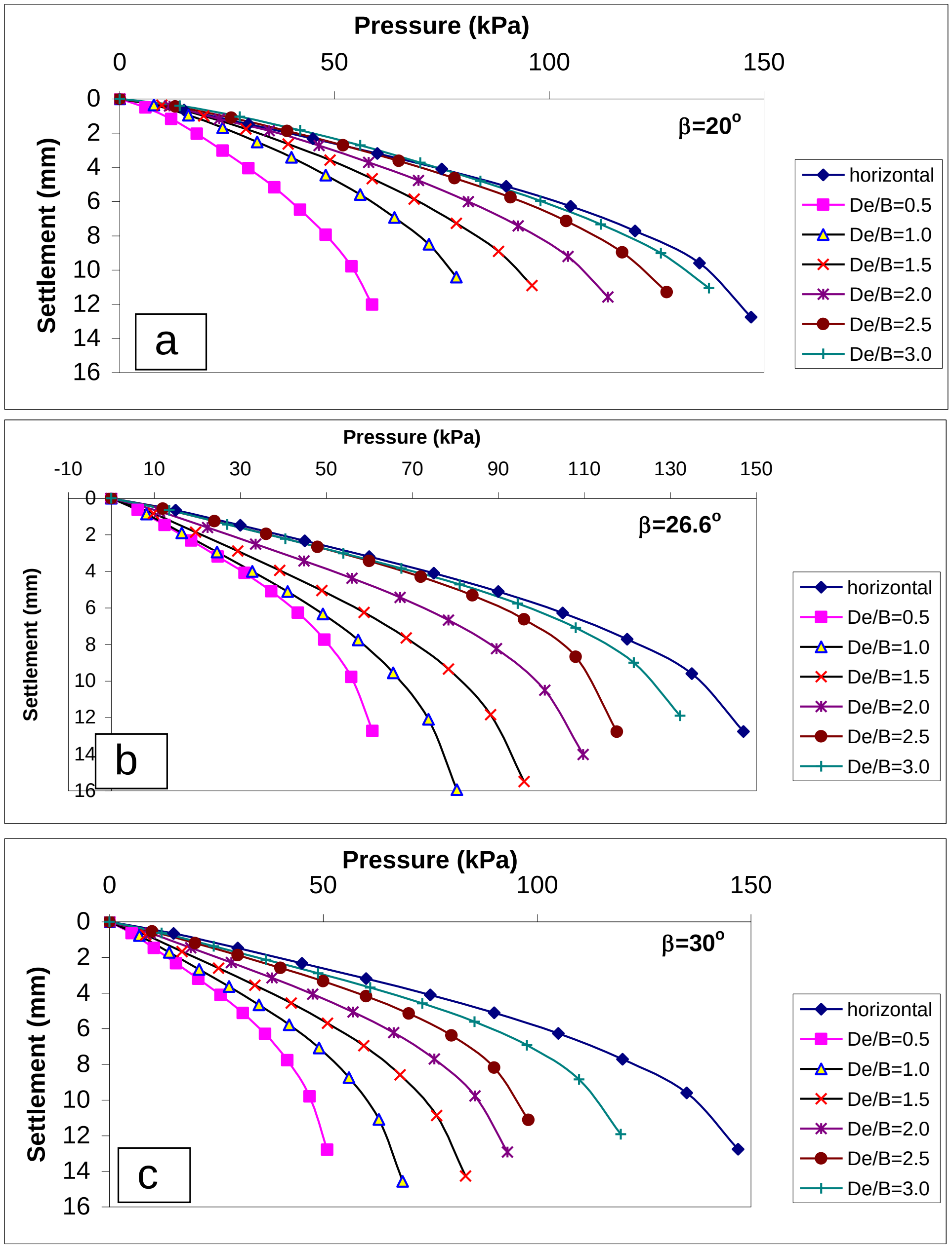


Fig. 6 Pressure –settlement curve of the cases analyzed (DR= 72%)

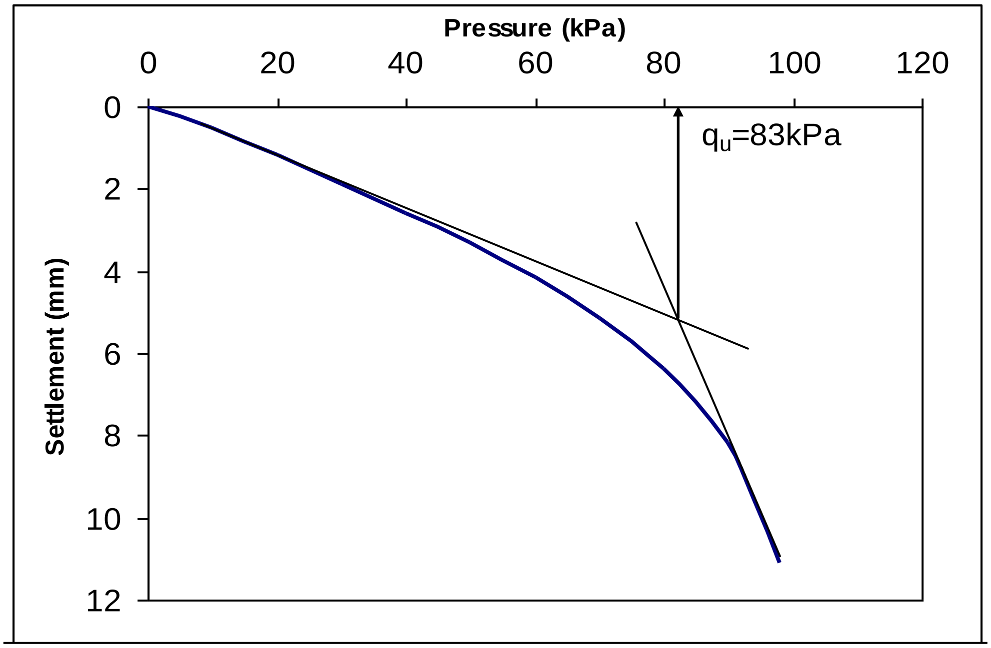


**Fig. 7 Evaluation of ultimate bearing capacity $D_R$= 72%, β=30$^0$, De/B=2.5**

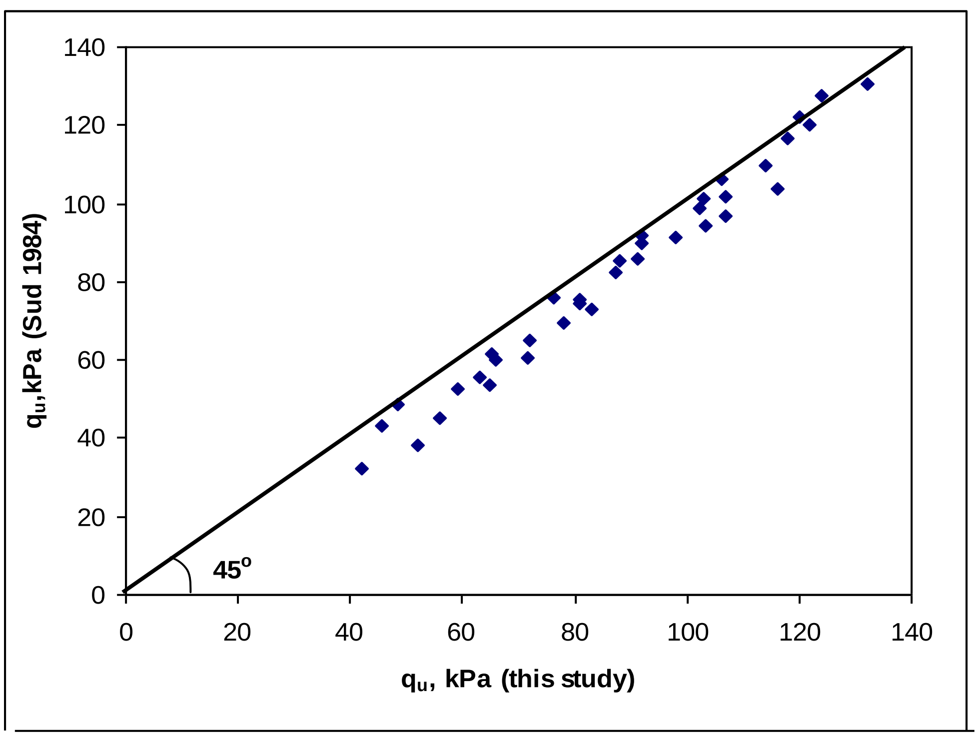


**Fig. 8 Comparison of $q_v$ (present study) with $q_v$ (Sud, 1984) for strip footing adjacent to slopes**

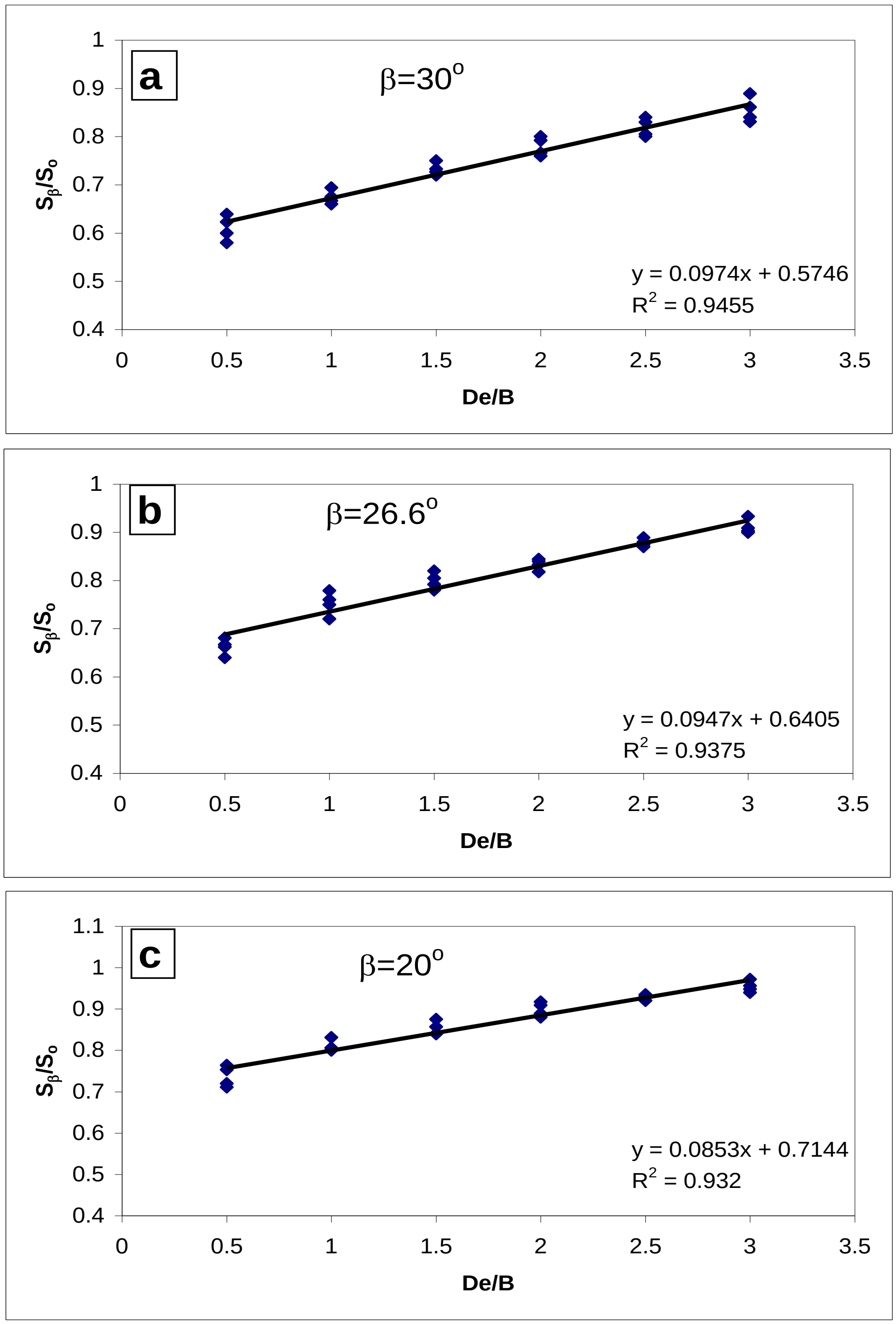


**Fig. 9 Variation of (Sβ/S0) with (De/B) ratio**

# حساب الهبوط للأسس الضحلة المقامة على التربة الرملية والقريبة من المنحدرات

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**مدرس**

**قسم الهندسة المدنية– جامعة تكريت**

**الخلاصة**

الهدف من هذا البحث هو دراسة سلوك الاساسات الضحلة و القريبة من المنحدرات باستخدام طريقة العناصر المحددة. حيث تم تحليل اربع واربعين حالة لاساس شريطي يستند على تربة رملية والتي تم دراستها (من قبل Sud عام 1984 من خلال تجارب انموذجية). تمت مناقشة العلاقة بين الضغط و الهطول من خلال النتائج التي تم الحصول عليها وتشير نتائج التحليل الى تقارب النتائج المستحصلة مع النتائج التي حصل عليها Sud عام 1984 مختبريا. وكذلك تم احتساب مقدار اجهاد التحمل الأقصى للتربة تحت الاساس باستخدام تقاطع مماسي المنحني الخاص بالـ (ضغط–هطول) الاساس والتي تم الحصول عليه لجميع الحالات في هذه الدراسة، و قد بينت النتائج بان هذه القيم للأجهاد الاقصى للتربة مقاربة للنتائج التي حصل عليها Sud عام 1984.

تم كذلك ايجاد علاقة رياضية يمكن باستخدامها احتساب مقدار الهبوط للأساس القريب من المنحدرات اذا تمت معرفة مقدار الهبوط لنفس الاساس الذي يستند على ارض مستوية. و قد وجد ان بعد الاساس عن المنحدر و زاوية ميل المنحدر يؤثران في هذه العلاقة، في حين لاتتأثر هذه العلاقة بعامل الامان والكثافة النسبية للتربة.

**الكلمات الدالة**

العناصر المحددة، لاخطي، الأساسات الضحلة، المنحدر، ضغط–هبوط، اجهاد التحمل، الكثافة النسبية، التربة الرملية.