NUMERICAL MODELING OF THE EFFECT OF SAND CUSHION ON EXPANSIVE SOILS HEAVE

Ahmed Amr Darrag[1], Tamer Yehia Elkady[2]
and Youssef Gomaa Nile[3]
[1]Professor, Faculty of engineering, Cairo University, Cairo, Egypt
[2]Assistant Professor, Faculty of engineering, Cairo University, Cairo, Egypt
[3]Assistant Lecturer, Faculty of engineering, Fayoum University, Fayoum, Egypt

ملخص البحث باللغة العربية:

يعتبر استخدام الإحلال أسفل الأساسات من أكثر الطرق استخداما لتجنب تأثير التربة الانتفاشية على الأساسات سواء كان الإحلال لطبقة التربة الانتفاشية بكامل عمقها أو لجزء منها. ومع ذلك لا توجد قواعد واضحة لتحديد عمق الإحلال والامتداد الجانبي له في حالة الإحلال الجزئي للتربة الانتفاشية. وفى الناحية العملية فان معظم المهندسين يختارون عمق الإحلال بناء على الخبرة دون اخذ العمق الفعال لمنطقة الانتفاش في الاعتبار ويرجع ذلك لان تحديد العمق الفعال لمنطقة الانتفاش يعتبر صعب من الناحية العملية. وخلال هذا البحث تم عمل دراسة لتأثير الإحلال على سلوك التربة الانتفاشية باستخدام برنامج عناصر محددة. وقد تم أدارج نموذج رياضي مرن غير خطي للتربة الانتفاشية غير المشبعة في برنامج عناصر محددة وهو برنامج (CRISP). وقد تم دراسة انتفاش التربة نتيجة حدوث التغيرات المناخية. وقد استخدام خصائص التربة المعروفة باسم (Regina Clay) نظرا لتوفر خصائصها المطلوبة لهذا النموذج الرياضي. وقد شملت الدراسة التي تم إجرائها عمق الإحلال والامتداد الجانبي للإحلال والكثافة النسبية للإحلال.

ABSTRACT

One of the most common mitigation methods for founding on expansive soils is the full or the partial removal of expansive soils and replacement with non-expansive soils. In case of partial removal of expansive soils (sand cushion), there are no definitive guidelines for estimating the depth and lateral extent of sand cushion. In practice, most engineers suggest some arbitrary thickness for the sand cushion without consideration to the depth of the zone of potential volume change which in itself is difficult to determine. A parametric study was performed using a two-dimensional finite element program to investigate the effect of sand cushion parameters on the swelling behavior of expansive soils under climate change conditions. The finite element program used is CRISP modified to include a nonlinear elastic constitutive soil model developed by Fredlund (1993). Soil considered in this analysis was Regina Clay. Sand cushion parameters considered include depth, lateral extension, and relative density.

Keywords: Expansive, Sand Cushion, Heave, Finite Element.

1. INTRODUCTION

Volume change of expansive soils upon wetting may cause extensive damage to structures, in particular, light buildings and pavements. Climate variations cause cyclic water content changes resulting in edge movement of structures. Also, the changes in depth to the water table lead to changes in soil water content.

Full and partial removal of expansive soils and replacement with non-expansive soils is one the most common methods to minimize the effect of heave. In case of partial removal of expansive soils (sand cushion), there are no definitive guidelines for estimating the depth and lateral extent of sand cushion. Zeitlen, Snethen and Chen have suggested removal of expansive soil fully in case of shallow thickness or partially when it extends to considerable depth to counteract the anticipated heave with an applied load [1-2-3]. They reported that the depth to which non-expansive backfill should be placed will be governed by the weight necessary to restrain the expected swelling pressures and the ability of the backfill to mitigate differential displacements. Chen recommends a minimum of 1.00 to 1.30 m for thickness of soil replacement [3]. Therefore, most of the foundation engineers often suggest some arbitrary thickness for the sand cushion without consideration to the depth of the zone of potential volume change which itself is difficult to determine.

This study provides a numerical model to investigate the effect of sand cushion parameters on the swelling behavior of expansive soils subjected to changes in soil suction profiles due climate variations.

2. Finite Element Program and Parametric Study

The finite element program used in this study is CRISP (Critical State Program), which introduced by Britto and Gunn [4]. The source code was rewritten and amended to include a nonlinear elastic constitutive unsaturated soil model developed by Fredlund [5]. This model characterize the mechanical behavior of unsaturated soil with five soil parameters; elasticity parameter for the soil structure with respect to a change in the net normal stress, E, elasticity parameter for the soil structure with respect to a change in matric suction, H, water volumetric modulus associated with a change in the net normal stress, E_w, volumetric modulus associated with a change in matric suction, H_w, and Poisson's ratio, ν. Sand cushion parameters considered in this study include sand cushion thickness, lateral extension and relative density. The relative density, *R.D.*, of sand cushion is modeled to represent loose, medium and dense sand. In addition, the model assumes a footing of width equal to 1.0 m and variable footing pressure resting on top of the expansive soil layer. The parameters used in this study are shown in Fig. 1. Graphical representation of finite element model dimensions as well as different parameters considered in this parametric study is shown in Fig. 2.

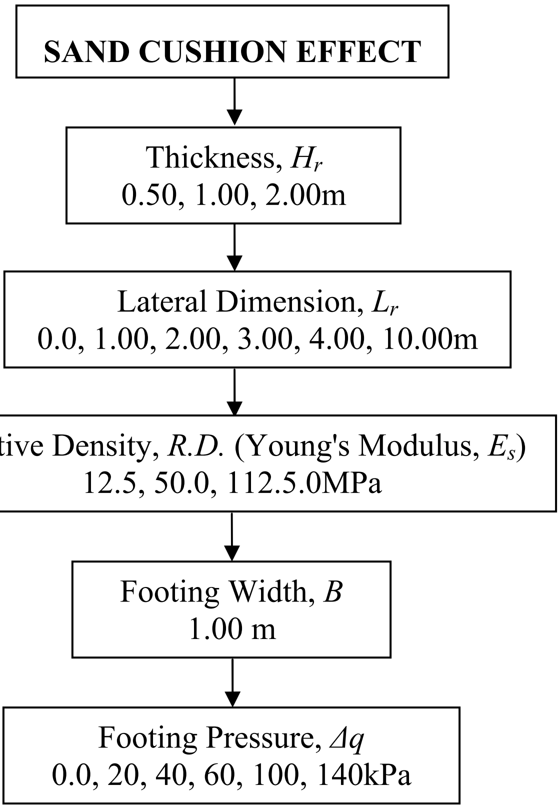

Fig. 1: Sand Cushion Parametric Study

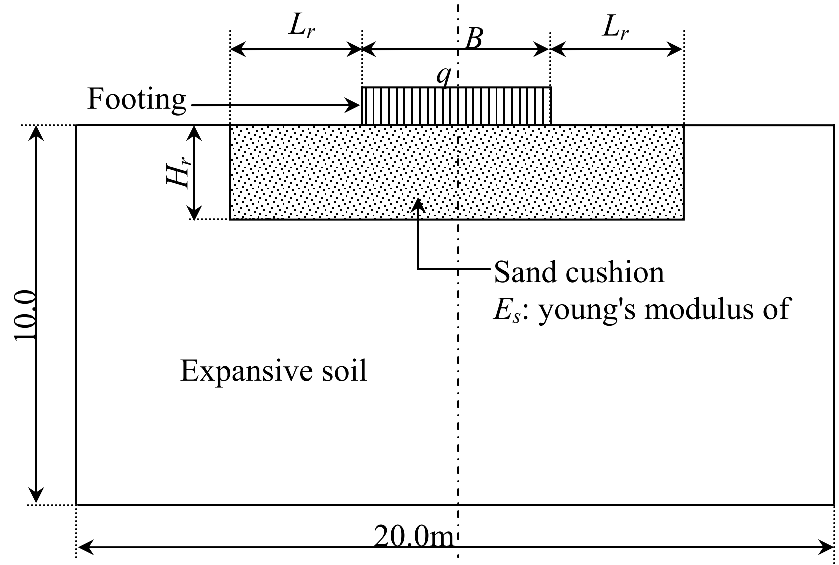

Fig. 2: Finite Element Dimensions and Parameters Considered

3. Model parameters

Soil properties adopted in the finite element analysis is that for Regina clay. Regina Clay is highly expansive, post-glacial lake deposit found beneath the city of Regina, Saskatchewan. Regina clay was selected because of abundance of data on properties that were measured under different stress state variables with accuracy. Mechanical properties of Regina Clay considered in this analysis are provided in Table 1.

Table 1: Mechanical and Physical Properties of Regina Clay

No.	Properties	Symbol	value	units	Ref.
1	Unit weight	γ_b	18.88	kN/m^3	[6]
2	At rest earth pressure coefficient	K_o	0.667	-	[6]
3	Poisson's ratio	ν	0.40	-	[6]
4	The elasticity parameter function with respect to changes in normal stress	E	$28.11(\sigma_{av} - u_a)$	kN/m^2	[6]
5	The elasticity parameter function with respect to changes in normal stress	H	$140.5(u_a - u_w)$	kN/m^2	[6]

The sand cushion in this study is modeled as a linear elastic material defined by modulus of elasticity, E_s and a Poisson's ratio, ν, equals to 0.30. The effect of relative density of sand cushion on heave behavior of expansive soils was modeled by varying the modulus of elasticity of sand. Values of modulus of elasticity representing loose, medium and dense sand were obtained from the Egyptian Code of Practice, Part 3, 2001 as shown in Fig. 1.

4. Climate Conditions

As stated earlier, the effect of sand cushion parameters on the swelling behavior of expansive soils was investigated as consequences to the change in soil suction profiles due to climate variations. Amount and periods of precipitation and evaporation greatly influence the magnitude of soil suction change and depth of seasonal moisture fluctuation zone, Z_s. The remaining subsections describes of climate conditions considered in this study.

4.1 Depth of Seasonal Moisture fluctuation zone, Z_s

The depth of seasonal moisture fluctuation zone, Z_s, is defined as the least soil depth near the surface in which the water content varies due to climate after construction of foundation. The deeper seasonal moisture fluctuation zone is, the larger the region over which soil expansion can occur and thus the larger the potential for heave due to soil expansion. The depth of seasonal moisture fluctuation zone is related to the climate and clay soil properties. Fityus et al. [7] have correlated the depth of seasonal moisture fluctuation zone, Z_s, to the Thornthwaite Moisture Index (TMI) as shown in Table 2. In current research, the depth of seasonal moisture fluctuation zone is assumed to be 3.00 m, which the maximum expected value for depth of seasonal moisture fluctuation zone.

Table 2: Depth of Seasonal Moisture fluctuation zone Based on TMI Values [8]

Climate classification	Thornthwaite Moisture Index, TMI	Depth of seasonal moisture fluctuation, Z_s (m)
Wet (Coastal/Alpine)	>40	1.50
Wet temperate	10 to 40	1.50 to 1.80
Temperate	-5 to 10	1.80 to 2.30
Dry temperate	-25 to -5	2.30 to 3.00
Semi-arid	< -25	3.0

4.2 Soil Suction Change due to Climate Conditions

Variations in climate conditions produce changes in suction distribution, which in turn result in shrinking or swelling of the soil deposit. Soil suction distribution with depth can take on a wide variety of shapes as a result of climate changes as shown in Fig. 3. The change in suction profile due to climate can be assumed to decrease linearly with increasing depth below ground surface and becoming zero at end of seasonal moisture fluctuation zone, Z_s [8]. Recommended soil suction change values at ground surface, S for various locations in Australia are given in Table 3.

Table 3: Soil Suction Change for various Location in Australia (AS 2870) [8]

Location	Change in soil suction at The soil surface, S (pF)
Albury/Wodonga	1.20
Brisbane/Ipswich	1.20
Hobart	1.50
Hunter Valley	1.50
Newcastle/Gosford	1.50
Sydney	1.50

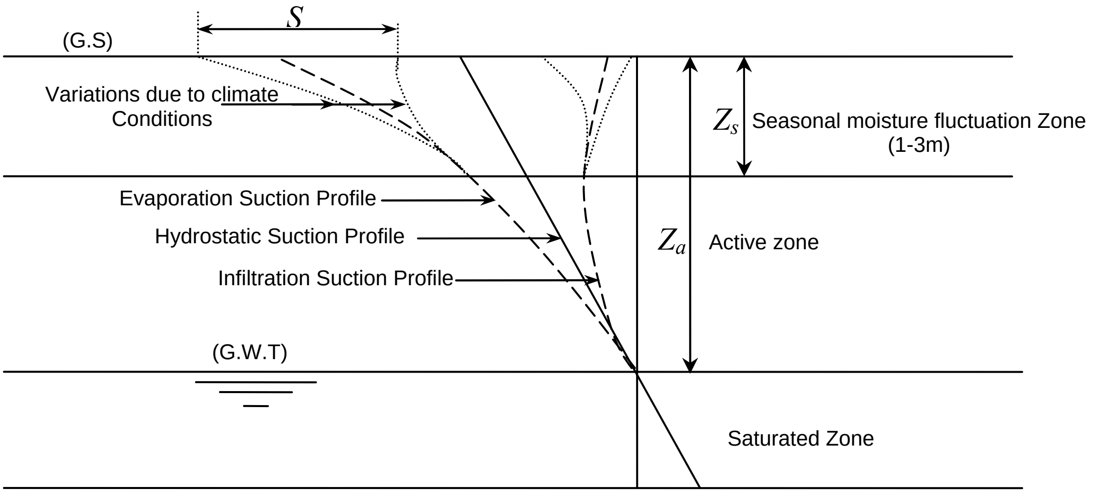

Fig. 3: Change in Soil suction profiles due to Environmental Conditions

The Australian standards (AS 2870) estimated the soil moisture conditions in terms of soil suction, (u_a-u_w) with units of pF. When a soil is saturated, it has a relatively low suction value of 3.2 pF (158kPa) or less which increases to 4.2 pF (1585kPa) when soil dries to the wilting point of vegetation [8].

The suction profile used in this study will be estimated from data available in the literature. The suction change at ground surface, *s*, is selected to be 1.50 pF. The final soil suction is assumed to be hydrostatic with soil suction value of 3.2 pF (150kPa) at ground surface which simulates wet conditions in winter as illustrated before in Fig. 4. The initial soil suction is estimated by subtracting the soil suction change from final soil suction. The idealized profile used in analysis of climate effect through this research is shown in Fig. 4.

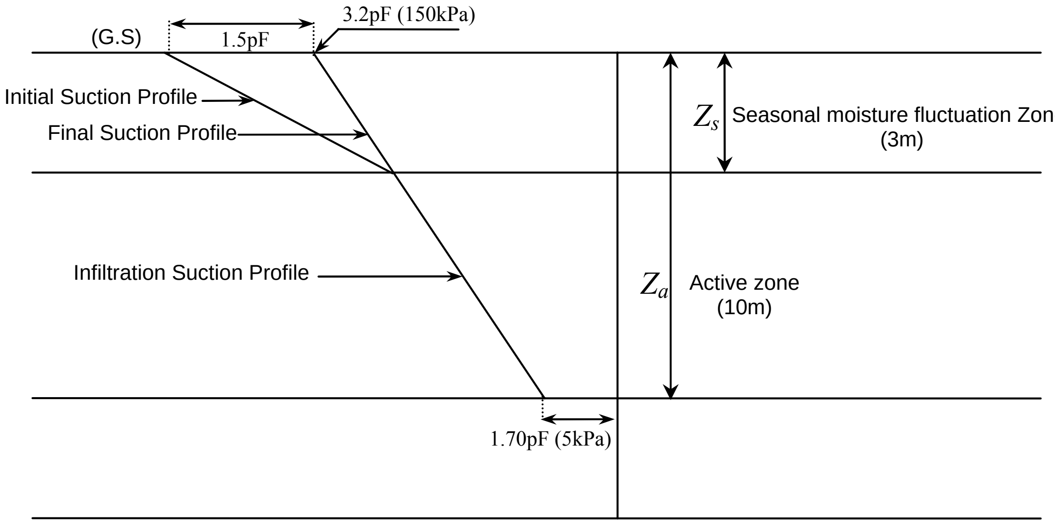

Fig. 4: The Idealized Soil Suction Profile Used in the Analysis

5. Results of Analysis

The research investigates the effect of sand cushion parameters on footing heave. Results of analysis for the effect of sand cushion parameters: thickness, lateral extension and relative density are presented in the following sections

5.1 Effect of Sand Cushion Depth, H_r

Fig. 5 and Fig. 6 summarize the results of finite element analysis performed for a 1.00 m footing width resting on expansive soil. Fig. 5 presents the variation of footing settlement with sand cushion thickness as a result of footing pressure prior to variation in soil suction; while, Fig. 6 presents variation of soil heave with sand cushion due to change (decrease) in soil suction.

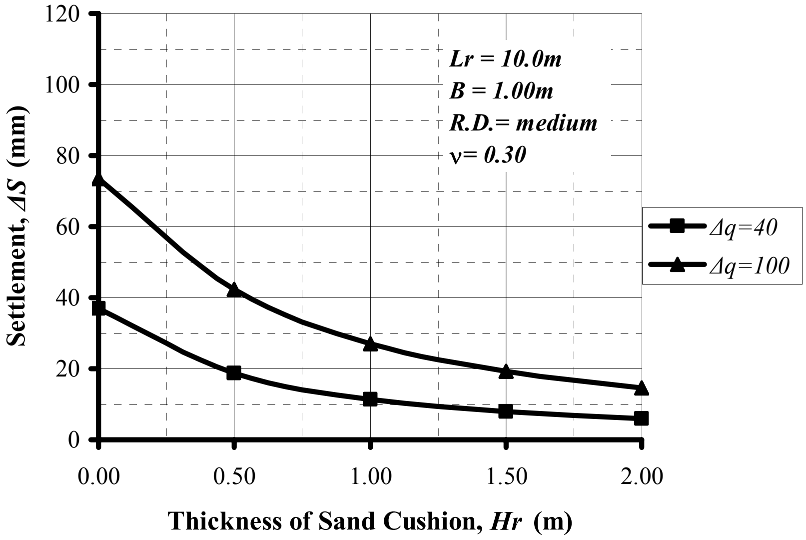

Fig. 5: Effect of Sand Cushion Thickness on Footing Settlement

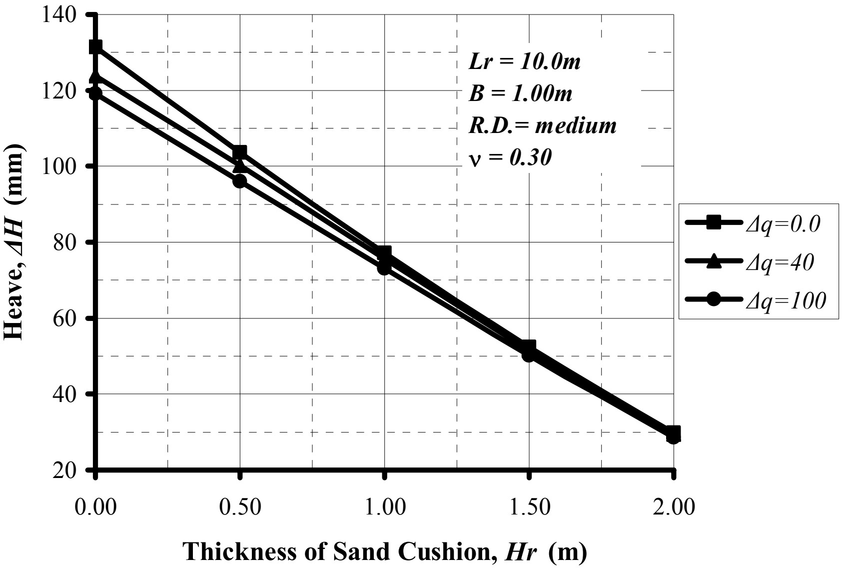

Fig. 6: Effect of Thickness of Sand Cushion on Footing Heave

From the previous results, it is clear that the sand cushion thickness has a significant effect on decreasing soil heave and soil settlement. In other words, increase in sand cushion thickness results in decrease footing heave magnitude attributed to decrease in depth of seasonal moisture fluctuation zone. Magnitude of heave decreases by 21% when using 0.50 m thickness sand cushion and by 41% when using 1.00 m thickness sand cushion as shown in Fig. 6.

5.2 Effect of Lateral Extension of Sand Cushion, L_r

Fig. 7, Fig. 9 and Fig. 11 illustrate the effect of lateral extension on footing settlement for 0.50, 1.00 and 2.00 m sand cushion thickness; respectively. Similarly, Fig. 8, Fig. 10 and Fig. 12 present the effect of lateral extension on footing heave for 0.50, 1.00 and 2.00 m sand cushion thickness; respectively.

Based on these figures, it is apparent that the lateral extension of sand cushion has a significant effect on the settlement of footing. For 1.00 m sand cushion thickness and under 20 kPa footing pressure, the settlement of footing decreases by about 36.5% when lateral extension increases from zero to 1.00 m as shown in Fig. 9. If the lateral extension is greater than two times the depth of sand cushion, further decrease of settlement will not be noted. Therefore, increasing lateral extension more than twice the depth of sand cushion is not recommend. The effect of lateral extension on footing settlement decreases with increase of sand cushion depth. For 2.00 m depth sand cushion, the decease in settlement is about 17.5% when lateral extension increases from zero to 1.00 m under 20 kPa footing pressure (compared to 36.5% for 1.00 m sand cushion depth) as shown in Fig. 11.

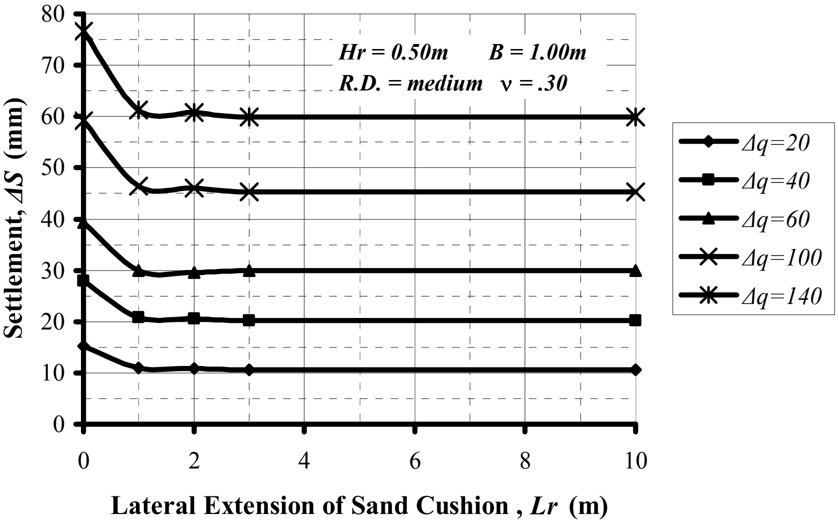

Fig. 7: Footing Settlement for Different Lateral Extensions

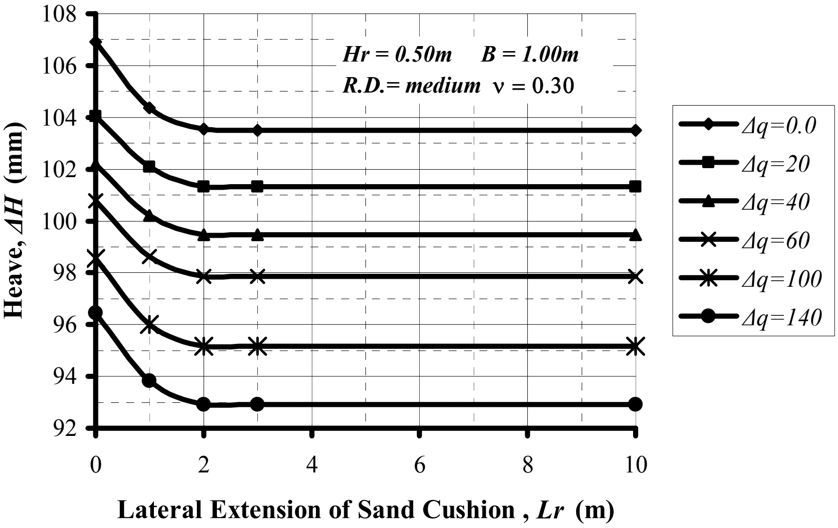

Fig. 8: Footing Heave for Different Lateral Extensions

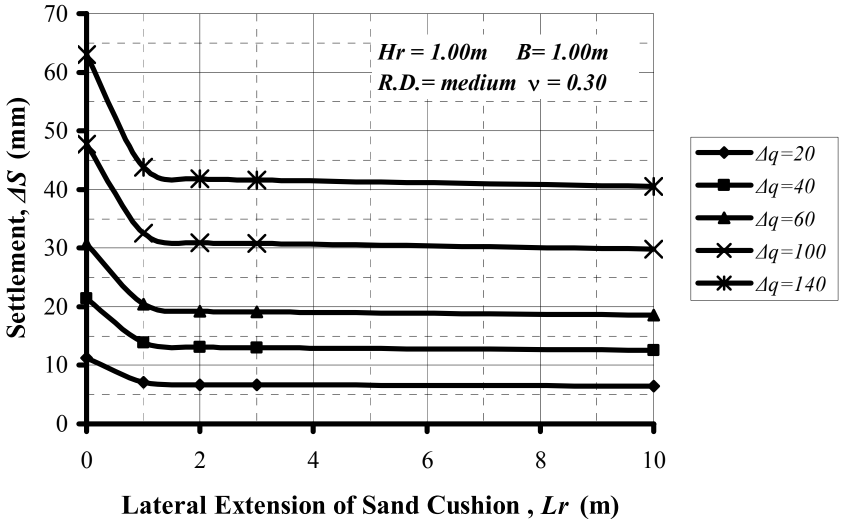

Fig. 9: Footing Settlement for Different Lateral Extensions

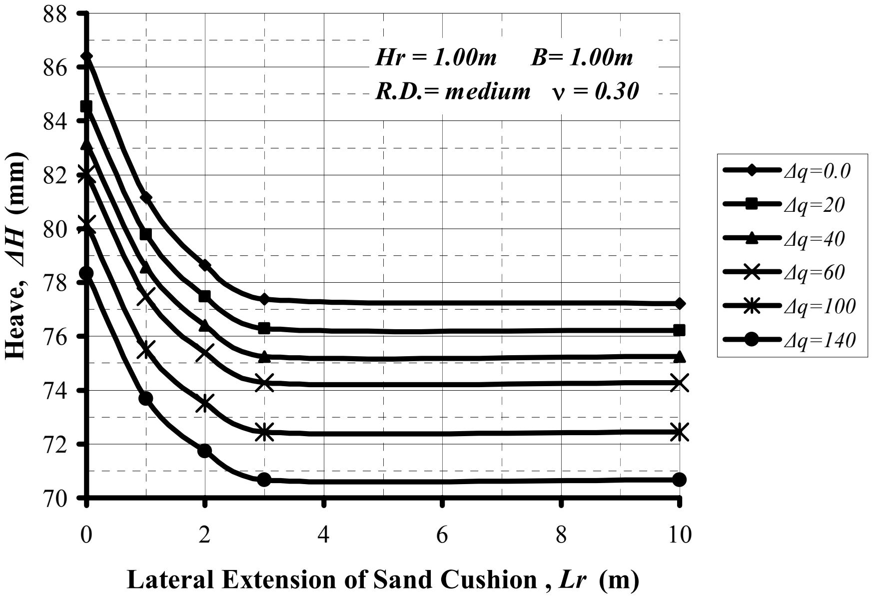

Fig. 10: Footing Heave for Different Lateral Extensions

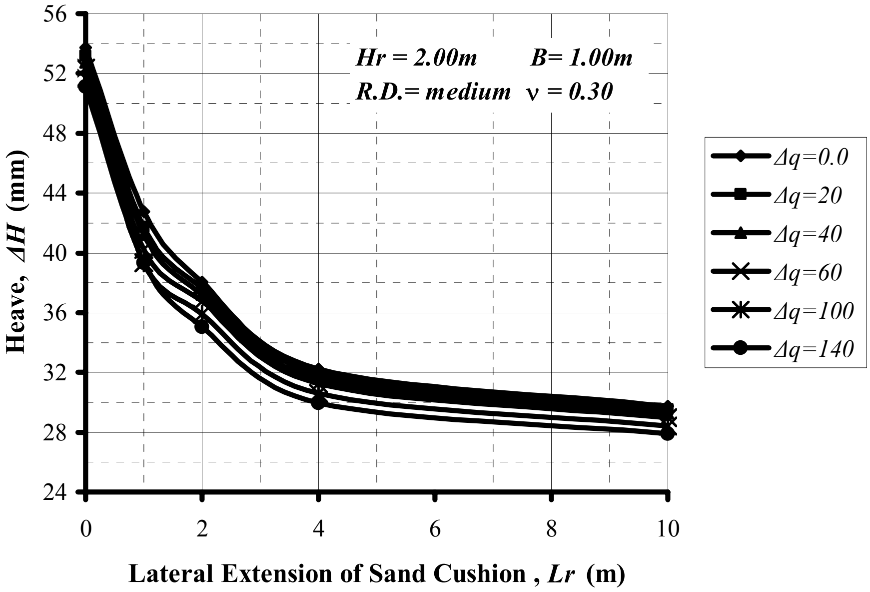

Fig. 11: Footing Settlement for Different Lateral Extension of Sand Cushion

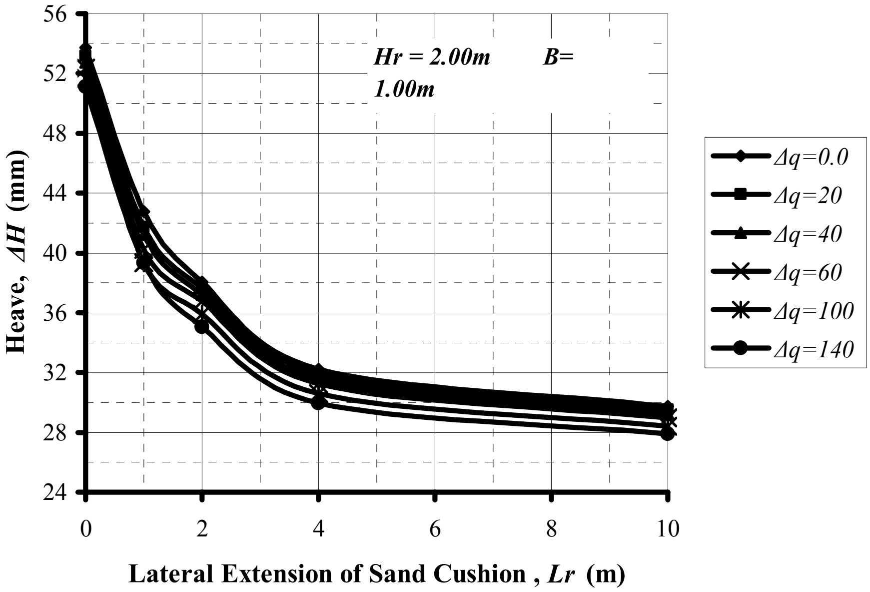

Fig. 12: Footing Heave for Different Lateral Extension of Sand Cushion

As shown in Fig. 8, Fig. 10 and Fig. 12, the lateral extension of sand cushion has less significant effect on footing heave than its effect on footing settlement. For sand cushion thicknesses smaller than 1.00 m, the effect of lateral extension is insignificant. For 0.50 m sand cushion thickness and under 20 kPa footing pressure, decrease in heave is estimated to be 2% when the lateral extension increases from zero to 1.00 m as shown in Fig. 8. Furthermore, the effect of lateral extension on footing heave increases with increase of sand cushion depth. The heave magnitude of the model footing resting on 1.00 m thick sand cushion decreases by 6%, when lateral extension increases from zero to 1.00 m under 20 kPa footing pressure as shown in Fig. 10 (compared to 2% for 0.50 sand cushion depth).

5.3 Effect of Sand Cushion Relative Density

Fig. 13 and Fig. 14 present the variation of model footing settlement with modulus of elasticity of sand cushion for 0.50 m and 2.0 m thickness; respectively. Similarly, Fig. 15 and Fig. 16 present the relationship between model footing heave and modulus of elasticity of sand cushion for 0.50 m and 2.0 m thickness; respectively.

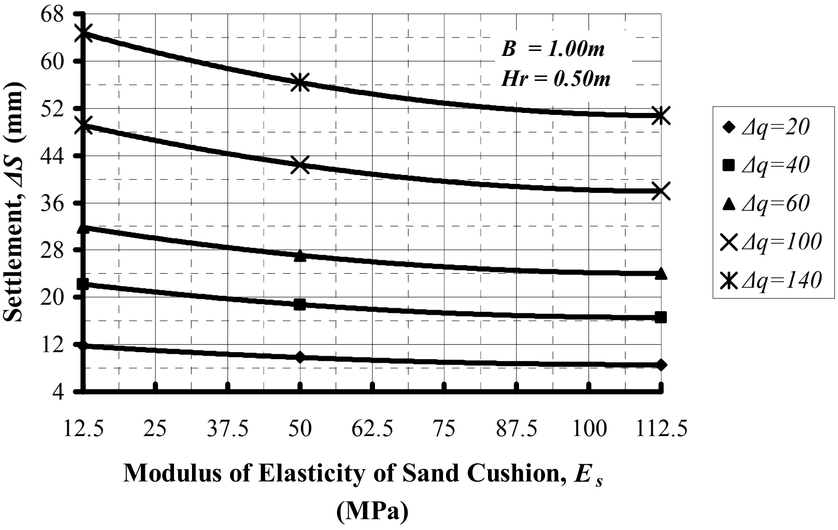

Fig. 13: Effect of Elasticity Modulus of Sand Cushion on Footing Settlement

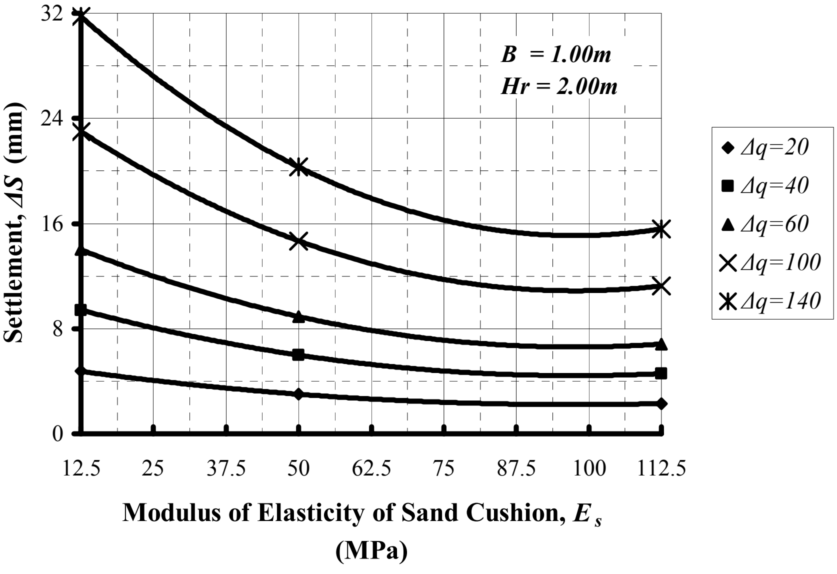

Fig. 14: Effect of Elasticity Modulus of Sand Cushion on Footing Settlement

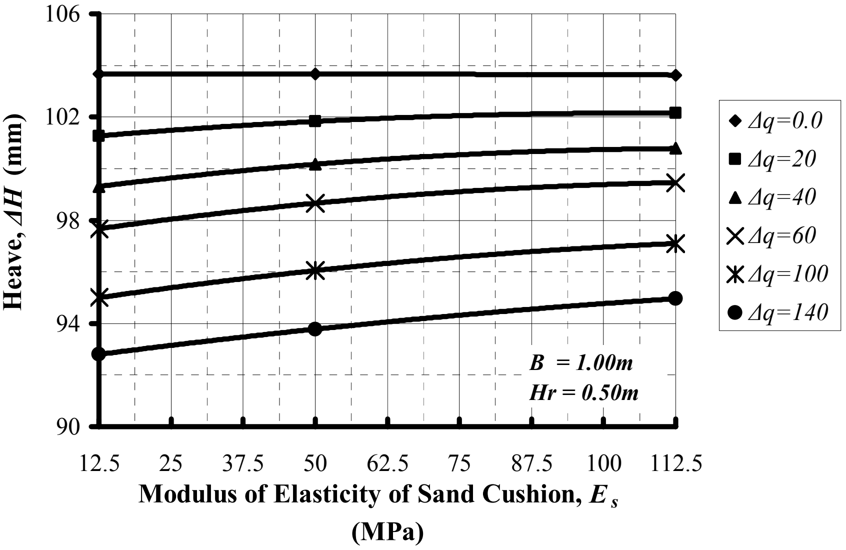

Fig. 15: Effect of Elasticity Modulus of Sand Cushion on Footing Heave

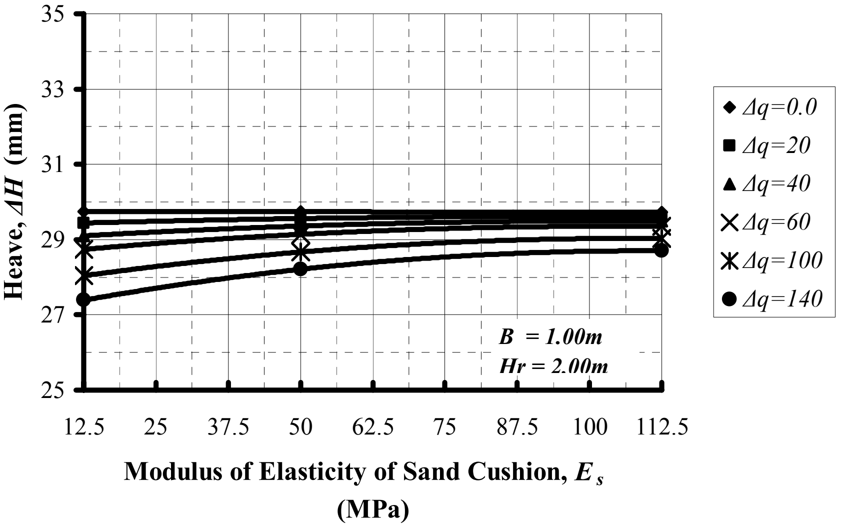

Fig. 16: Effect of Elasticity Modulus of Sand Cushion on Footing Heave

Effect of modulus of elasticity of sand cushion on footing settlement is significant. Settlement decreases with increase of modulus of elasticity of sand cushion as shown in Fig. 13 and Fig. 14. This effect increases with increase of footing pressure. On the other hand, effect of modulus of elasticity of sand cushion on footing heave is considered negligible as shown in Fig. 15 and Fig. 16. It is important to note that increase of modulus of elasticity leads to increase of footing heave however this increase is considered insignificant. This means that increase of relative density of sand cushion causes increase of footing heave. This increase of heave due to increase of modulus of elasticity of sand cushion is attributed to increase in rigidity of sand cushion to adapt its volume due to heave.

6. Conclusions

The analysis presented herein provides considerable insight into the effect of sand cushion as mitigation method on the behavior expansive soils. Conclusions from this research may be summarized as follow:

1. Sand cushion depth, H_r, has a significant effect on decreasing footing heave and footing settlement.
2. The lateral extension of sand cushion has a significant effect on the settlement of footings. However, increasing lateral extension more than twice the depth of sand cushion is insignificant on footing settlement.
3. Lateral extension of sand cushion has a moderately significant effect on footing heave than its effect on footing settlement. The effect of lateral extension of sand cushion on footing heave is negligible for sand cushion depths less than 1.00 m. The effect of lateral extension of sand cushion on footing heave increases with increase of sand cushion depth.
4. The optimum lateral extension of sand cushion required to be placed under a footing resting on expansive soils increases with increase of sand cushion depth. The optimum lateral extension for 0.50, 1.00, 2.00 m sand cushion thickness are depth are 1.00, 3.00, 6.00 m respectively. This is far from the criteria of the lateral extension being one time the sand cushion thickness; typically proposed in practice.
5. Relative density of sand cushion has a significant effect on footing settlement. Settlement decreases with increase of relative density of sand cushion.
6. Conversely, the relative density of sand cushion on footing heave is negligible. Increase of sand cushion relative density leads to slight increase in footing heave. Thus, loose sand is more suitable for heave conditions.
7. It is good practice to select the relative density (degree of compaction) of sand cushion to minimize the effect of heave without violating the requirements of settlement and bearing capacity of footings.

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