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Foundation Failures Mitigation under Expansive Clay by Using Granular Pile Anchor System

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Abstract: Expansive soils are found in typical areas in the world especially in arid and semi-arid regions. The problems associated with this type of soil drive geotechnical engineers to invent new technologies as remediation's such as physical and chemical treatments. Innovative foundation techniques were also suggested for remedying the swell-shrink problems of the expansive soil. The granular pile anchor (GPA) is relatively a more favorable technique indebted to its cost-effective, easy and fast to assemble and most importantly was found to be more efficient in remedying the expansive soil. Despite the extensive studies on the expansive soil remedies, yet the granular pile anchor system requires more comprehensive and in-depth investigations. This study is aimed at developing a model with granular piles of various length and diameter extended to the stable zone to investigate the heave and uplift pressure in the expansive soil. For this purpose, experimental and numerical analysis were conducted in a small and in a full scale model respectively. A significant improvement was attained in heave reduction and an increment of uplift capacity. The findings also show that heave decreased significantly when the length and diameter of the GPA increases while the uplift capacity increased. However, it was noted that the extension of length to the stable zone resulted in insignificant changes. Therefore, it can be concluded that the maximum length of 6 m is the ideal length for GPA with different diameters according to foundations design requirement for this particular type of soil.

Keywords: Expensive soil, uplift pressure, granular pile anchor, heaves

1 Introduction

Expansive soils are found in typical areas in the world especially in arid and semi-arid regions. These soils owe their expansion property to the presence of swelling clay minerals; smectite clay minerals such as montmorillonite. The soil swells when clay minerals absorb water molecules and, conversely, shrinks when losing it leaving large voids in

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the soil. Therefore, damage or distress of structures (i.e. light building) can be triggered due to the large repeated volume changes. The repairing cost of this damage urged for more viable remedies during the foundation design. Innovative foundation techniques suggested for remedying the swell-shrink problems can be categorized as physical alteration (i.e. soil replacement), chemical alteration (i.e. chemical binders; cement and lime) and tension-resistant foundations (i.e. granular pile anchor) [1]. The granular pile anchor (GPA), shown in Fig. 1, is relatively a more favorable technique indebted to its cost-effective, easy and fast to assemble and most importantly was found to be more efficient in remedying the expansive soil. Previous studies were conducted to investigate the effects of granular pile system on expansive soil. Various researchers [1]-[5] investigated the pullout behavior and found that the pullout forces increased as the surface area of the granular pile anchor increased. Similarly, researchers has investigated the heave behavior [6], heave and pullout [7], heave and shrinkage [8,9] uplift force [10] and found that the granular pile anchor is effective in improving the soil condition. In this paper, study focus to find best depth of granular pile anchor to extend from active zone to stable zone to control the heave and uplift pressure.

2 Concept of Granular Pile Anchor

Fig. 1 shows the concept of a granular pile anchor system and the existing forces acting in the system. The system comprises essentially of soil medium in which granular column with steel anchor attached to a foundation base. The swelling represented by the uplift force acting on the base of the foundation in the vertical direction is due to the exerted pressure of the expansive soil. With application of granular pile anchor, this uplift force is resisted by the weight of the granular pile acting in the downward direction and the friction mobilized along the pile-soil interface between the bed granular fill and the bed soil. The incorporation of the anchor steel rod enhances the tension resistance, which is lacking in the congenital granular pile (stone column). Moreover, the uplift resistance is further increased by the lateral swelling pressure, which confines the granular pile anchor radially increasing the friction hence preventing the pile from being uplifted easily.

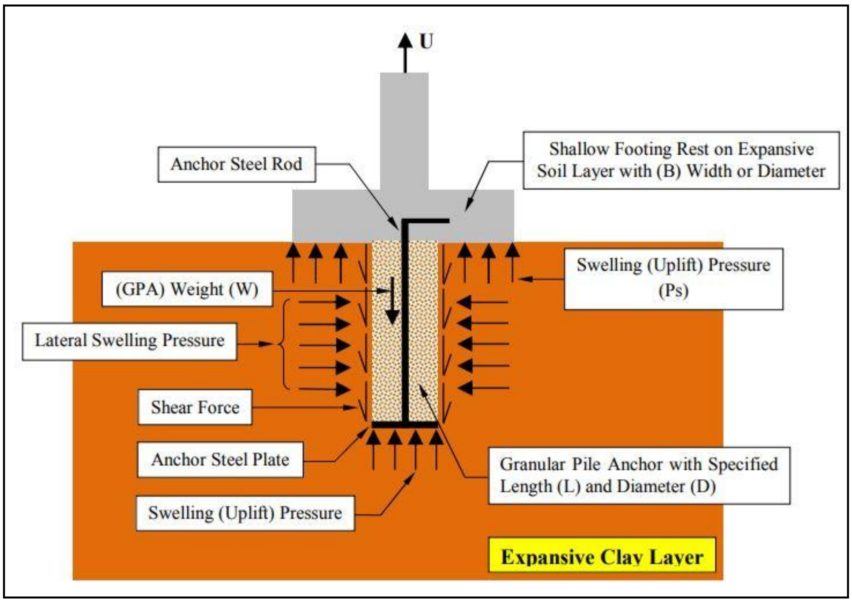

Fig. 1 - Concept of granular pile anchor foundation system

3 Materials and Methods

The investigated soil in this study is Iraqi expansive soil in Babylon state collected within 1 to 1.5 m below the ground level. The properties of these soils are presented in Table 1 while the properties of the GPA fill materials are shown in Table 2. It is obvious that the expansive soils have high percentages of clay content and classified as high plasticity soil. On the other hand, the fill material for the GPA is coarser to give more friction while resisting the uplift movement.

3.1 Laboratory Design

Series of laboratory tests were carried out on the expansive soil to obtain physical and mechanical properties as summarised in Table 1 and Table 2 respectively. The preparation of the material and set up of the physical model experiment is as specified in the author's previous work [11]-[15]. The laboratory work for heave was performed in metal container of 30 diameter and 50 cm height as shown in Fig. 2. The heave tests were conducted on expansive soil with and without GPA. For convenience, two dial gauges were mounted on the top of the footing to monitor the upward movement. The internal surface of the container was lubricated to minimise friction effects along the container interface. The expansive soil maximum dry unit weight of (16.33 kN/m³) and optimum moisture content of (21.5 %) were prepared based on standard compaction test. The maximum heave was obtained at 70 % saturation. Therefore, the degree of saturation was set as 70 % for both laboratory and numerical work.

The expansive soil was placed in layers in the mould and each layer (5 cm) was compacted until obtaining the total depth of expansive soil inside the model container of 40 cm. The uniformity in the soil bed is checked by measuring the unit weight and moisture content at various depths of the soil bed. A pit was made in the centre of the expansive soil by driving a steel pipe gradually in specified diameter up to the required depth. The anchor rod with the bottom anchor plate of specified diameter and depth was placed vertically in the hole. Simultaneously, the hole was filled with fill material gradually and compacted gently using steel tamping rod in required relative density 75 %. The GPA length was fixed at 20 cm and the diameter as 4 cm, 6 cm, 8 cm, 10 cm to give a different ratio of L/D 2-5 to study both of lengths and diameters effect to minimize the heave and uplift pressure in active zone and stable zone. A circular mild steel plate of 20 cm diameter was used as the surface shallow footing for the heave tests.

Table - 1 Properties of expansive soils

Particle density	2.74
Liquid limit, %	60
Plastic limit, %	23
Plasticity index, %	37
Gravel, %	0
Sand, %	5
Silt, %	43
Clay, %	52
Soil classification	CH
Optimum moisture content, %	21.5
Maximum dry density, KN/m³	16.3

Table - 2 Properties of fill material

Particle density		2.68
Organic Matter Content (%)		0.31
Gypsum Content (%)		0.78
Total Soluble Salts Content (%)		0.86
Sulphate (SO3) Content (%)		0.34
Grain size analysis sieve analysis	D_{10},mm	0.177
	D_{30},mm	0.309
	D_{60},mm	0.5
	Coefficient of Uniformity (Cu)	2.793
	Coefficient of Curvature (Cc)	1.07
	Classification System (USCS)	SP
Maximum Unit Weight (γ_{max}), kN/m³		18
Minimum Unit Weight (γ_{min}), kN/m³		13.4
Experimental Relative Density (Dr)		75
Experimental Unit Weight (γ_{dry}), kN/m³		17
Cohesion (c), kPa		3
Angle of Shearing Resistance (ϕ)°		42

Fig. 2 - Experimental model

3.2 Numerical Design

The performance of GPA in expansive soil is also investigated by conducting numerical study on large-scale model. PLAXIS 3D program is used to model the effects of GPA on heave, shrinkage and uplift pressure for GPA at different length and diameters. The simulated expansive soil layer is located above a layer of saturated stable clay with 16 m thickness. The active zone of the expansive soil was fixed as 4 m. At this depth, the water table rises causing a considerable swelling in expansive soil. The footing diameter was fixed at 2 m, and the GPA lengths were 2 m, 4 m, 6 m, 8 m and 10 m with diameters of 0.4 m, 0.6 m, 0.8 m and1 m as shown in. Therefore, the ratio of length to diameter was ranged as 2 - 25 while the ratio of the area replacement varied between 0.04-0.25. The average element size and the number of triangular elements depend on the global coarseness setting. The simple global finite element mesh of model was generated using the coarse setting to allow for more accurate stress distribution as shown in Fig. 3. The properties of the simulated soils and pile anchors are shown in Table 3 and Table 4 respectively.

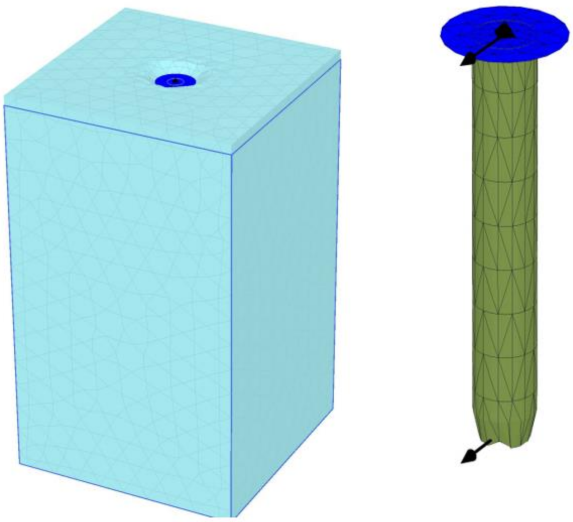

Fig. 3 - Modelling mesh type in PLAXIS 3D

Table 3 - Material properties used in numerical modelling

Sand	Expansive soil	Model Parameters
17	16.33	γ_{usat} (KN/m3)
20	19	γ_{sat}(KN/m3)
3	30	C' (KN/m2)
42	22	ϕ'
-	6.6	Volumetric strain%(swelling)
-	1.7	Volumetric shrinkage%

Table 4 - Properties of plate and anchor used in numerical model

Model Type	Model parameters	Shallow footing	Anchor plate
		Steel	Steel
Linear	E (kN/m2/m)	23.5 x 106	23.5 x 106
Elastic	v	0.15	0.15

4. Results and Discussion

3.3 Heave

The results of the numerical analysis of heave behavior for each length and diameter is shown in Fig. 4. For any given length of the examined piles which are 2, 4, 6, 8 and 10 m, it is obvious that the heave decreased when the pile diameter (0.4 m, 0.6 m, 0.8 m and 1 m) increased. The obtained maximum heave for all piles at given configuration of piles is shown in Fig. 5. The maximum heave for the natural soil without granular pile was found to be 263.15 mm which is equivalent to 6.6 % of the total bed thickness of soil. On the other hand, the maximum heave for reinforced soil with granular pile anchors decreased with increasing both length and diameter. However, the maximum heave increased significantly with 2, 4 and 6 m of length. Beyond that, the maximum heave seemed to increase marginally.

Therefore, it can be interpreted that the effective length for granular pile anchor is up to 6 m. The maximum heave for L = 2 m, 4 m, 6 m, 8 m, 10 m and diameter 1 m are 173.63, 73.14, 23.80, 14.44 respectively. The heave reduction was attributed to the uplift resistance that was mobilized within the pile-soil interface. The high frictional angle of the granular material affects the generation of resistance to uplift along the outer pile-soil interface. Thus, the larger the surface area is the higher the uplift resistance. Reduction in heave of GPA can be attributed to the GPA weight, the frictional resistance mobilized along the GPA-soil interface [9]-[12]. The maximum heave decreases with increasing (L/D) ratio due to increasing (GPA) length. This means that the (GPA) movement is strongly dependent on the (GPA) size; the ability of the system to resist various rates of swelling seems to improve with increasing the (GPA) size. As interpreted previously in the experimental works, this is attributed to the anchorage action (GPA) that resulting from (GPA) weight and shear stress mobilized along (GPA) body, of them increases when (GPA) size increases. The effect of anchorage produced from the GPA causes to resist the uplift force applied on the foundation. In addition, the developed lateral uplift pressure resulting from surrounding expansive soil confines the GPA radially and increases the upward resistance. This finding agrees with the results reported by [1], [7], [16] for GPAs installed in expansive clay beds.

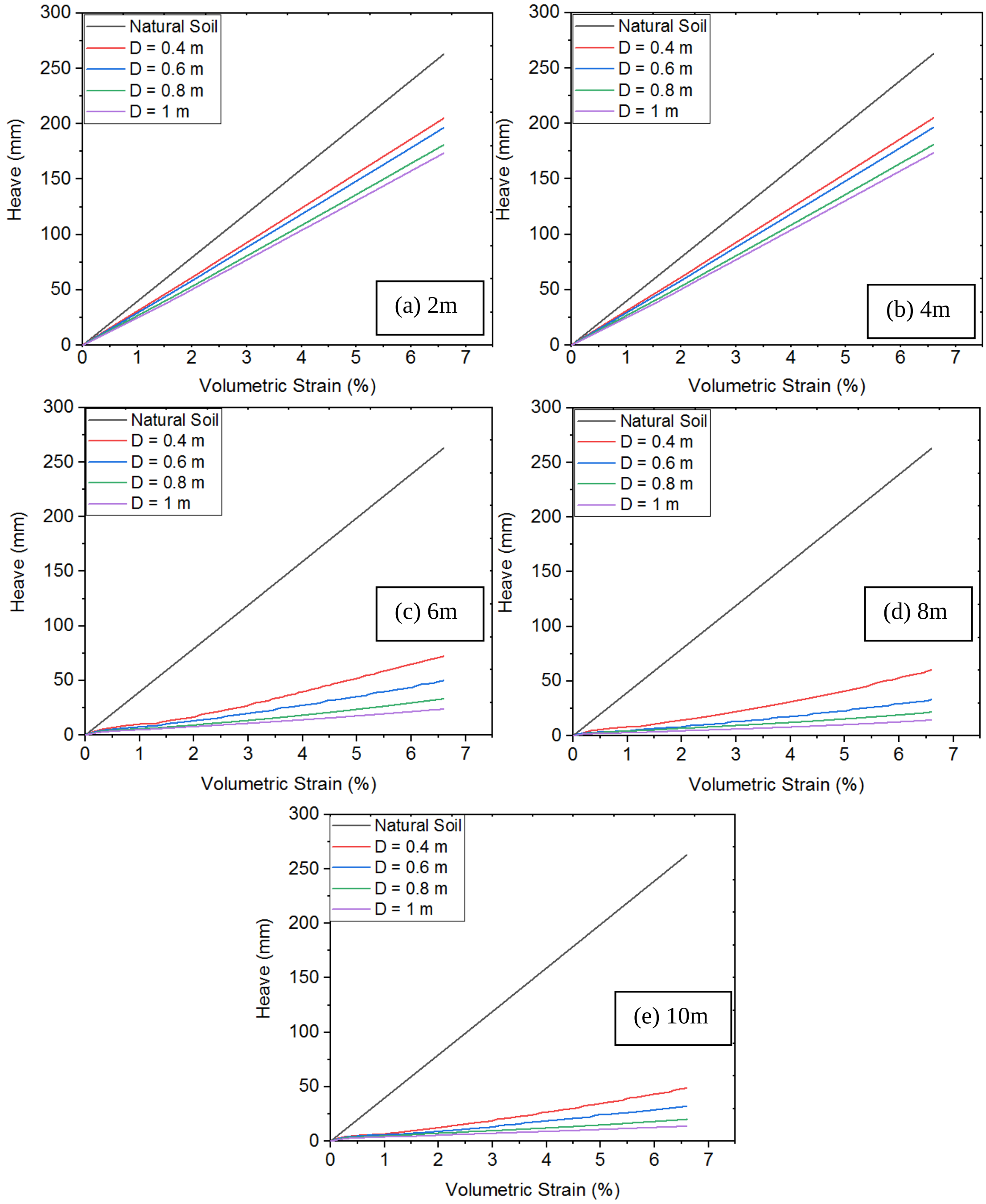

Fig. 4 - GPA heave vs volumetric strain at different pile length

Knowing that the expansive soil bed in full-scale model was 6 m, 8 m and 10 m pile were extended to the stable zone. The degree of improvement in terms of maximum heave is shown in Fig. 6. The maximum improvement for each pile at maximum diameter (1m) was 34 %, 72 %, 91 %, 95 %, 95 % for 2 m, 4 m, 6 m, 8 m and 10 m respectively.

It is obvious that the increment of the GPA length reduces the heave significantly which can reach up to 95 % for 8 m and 10 m. It is worth mentioning that the improvement was almost identical when the lengths were 8 m and 10 m. Therefore, it can be concluded that degree of improvement was more pronounced in GPAs with lengths in the expansive soil up to 6 m whereas the pile extension to the stable zone resulted in insignificant improvement in heave.

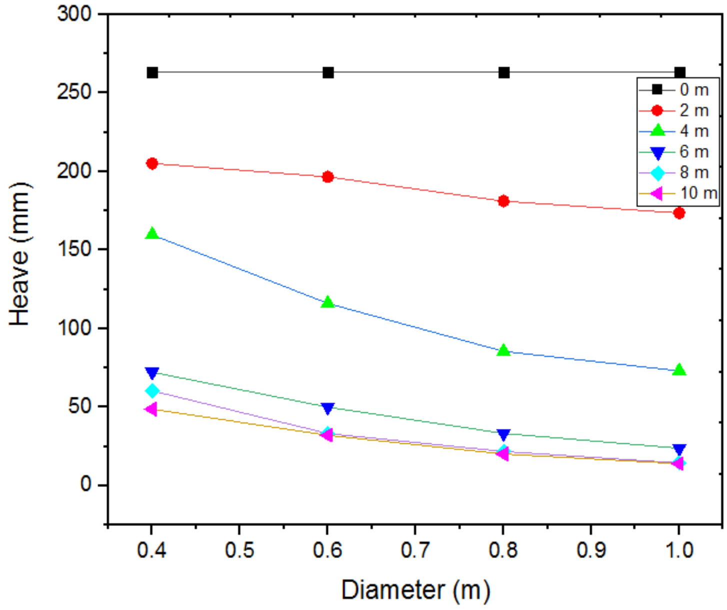

Fig. 5 - Maximum heave for all piles

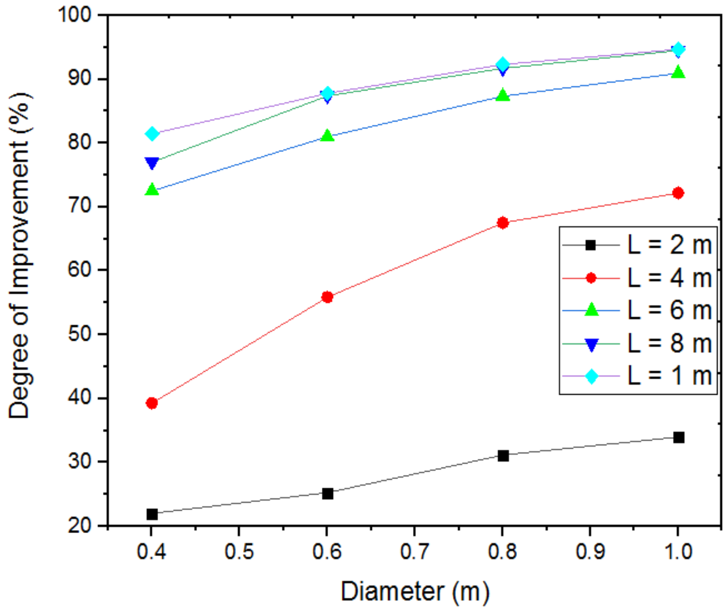

Fig. 6 - Degree of improvement in heave for all GPA

3.4 Uplift Pressure

The configuration of uplift pressure is illustrated in Fig. 7. The results of uplift pressure tests on GPA are discussed in terms of ultimate uplift capacity with length and diameter of the tested piles. The uplift pressure results are plotted graphically against the diameter of piles in Fig. 8. For any given length of piles, generally, the ultimate uplift capacity increased as the diameter increased. All piles were tested up to failure. It is obvious that the ultimate pullout capacity increased with increasing length of the GPA up to certain length. Similar to that in the heave behavior, ultimate pullout capacity was more obvious as the length increased from 2-8 m. After that, the effect of pile length became less. The developed uplift capacity was caused by the effect of anchorage and also because of the shear resistance mobilized along the cylindrical pile-soil outer interface. Hence, the uplift resistance depends upon the frictional characteristics of the fill material and the surface area of the interface. The higher the surface area of the interface is, the greater the uplift resistance. The figure presents the effect of the diameter (D) on the uplift pressure response of (GPA Foundation System), it can be seen that for a given diameter, the maximum uplift pressure decreases with increasing diameter due to increasing footing diameter (area of replacement ratio). The reason of this behaviour can be understood as the following: when the GPA diameter decrease with constant footing diameter, the annular area of the footing on which the swelling pressure acts is increased resulting increases in the heave and uplift pressure of the (GPA-Foundation System) by [1]-[8].

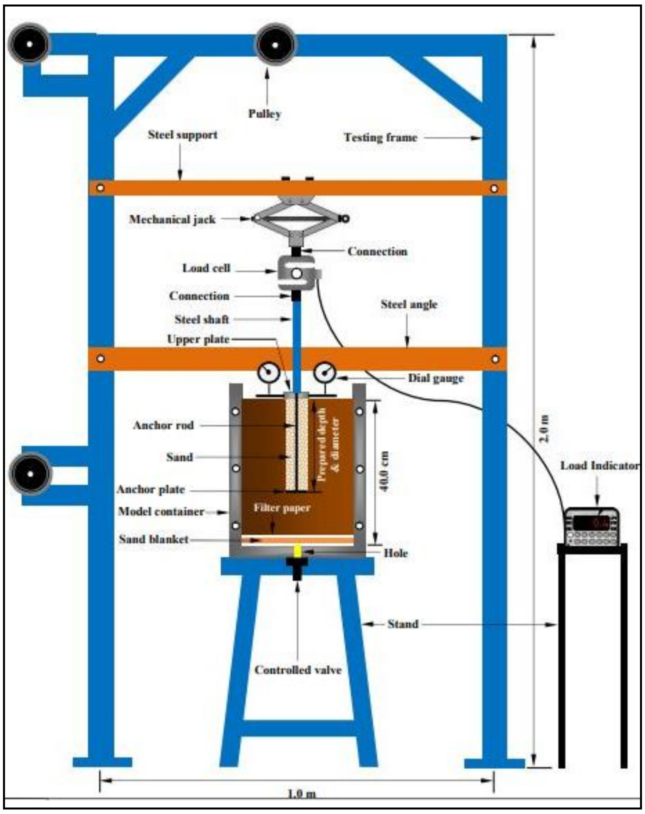

Fig. 7 - Configuration of capacity uplift pressure

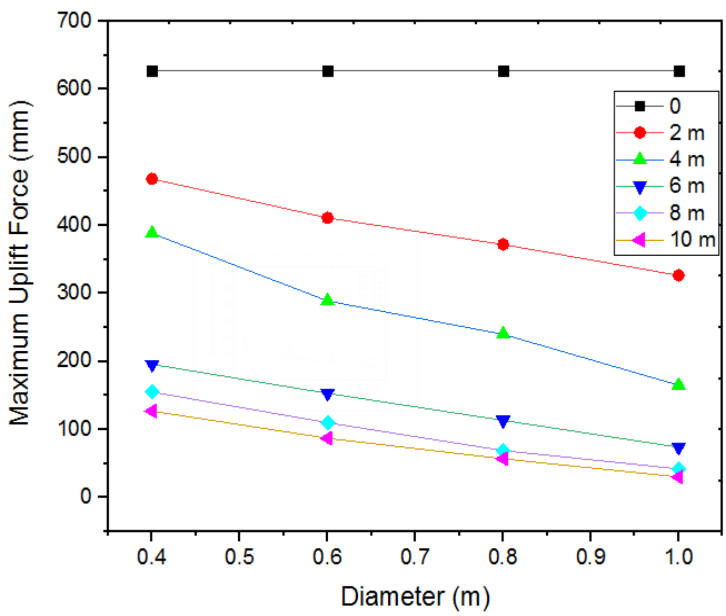

Fig. 8 - Ultimate uplift force capacity

3.5 Results Validation

The accuracy of the proposed numerical modelling in PLAXIS 3D was validated by comparing the laboratory results of GAP system performed on expansive soils. Small scale model in laboratory was conducted on a single pile with dimensions 20 cm length and varied diameter 4 cm, 6 cm, 8 cm and 10 cm. Fig. 9 shows the similarity between the experimental and numerical results in terms of heave while the uplift pressure similarity is show in Fig. 10. A good agreement between the laboratory and experimental results were obtained with an average 10 % error which is due to the factors that may affect the setup and performance of the laboratory work.

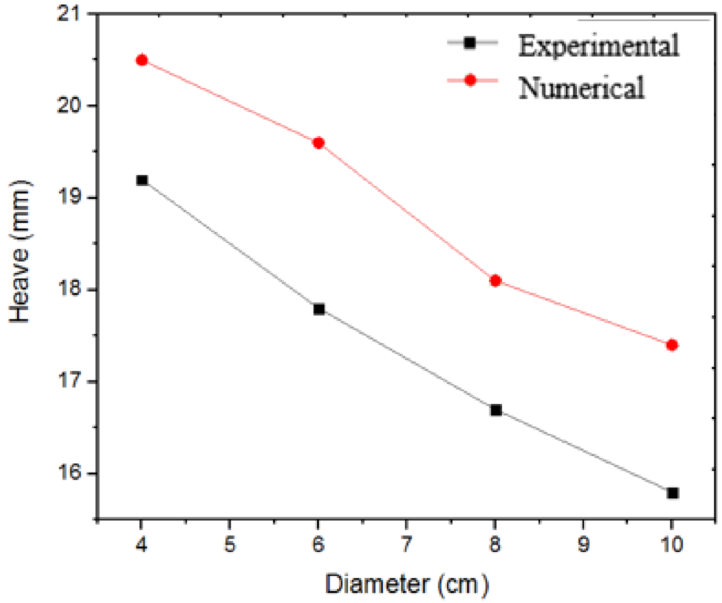

Fig. 9 - Validation of heave measurement

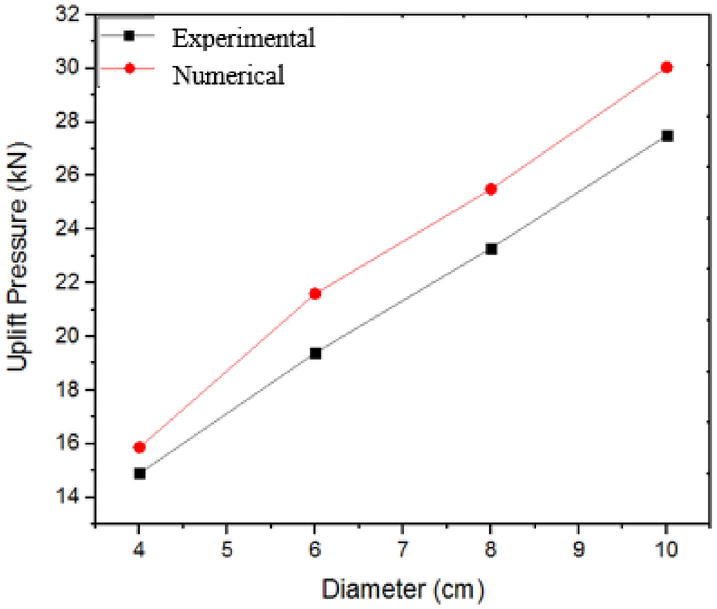

Fig. 10 - Validation of uplift pressure measurement

4. Conclusion

This study is conducted to investigate the efficiency of granular anchor system to reduce the heave and increase the uplift pressure capacity in expansive soil. Experimental and numerical work was conducted for various lengths and diameters of granular anchor piles. The obtained results showed that the heave decreased significantly with application of granular pile anchor while the pullout increased significantly. This indicates that the surface area of the granular pile anchor system influences the resistance of the upward force encountered in the expansive soils. The results also revealed that when the length of GPA was extended beyond 6 m to the stable zone, there was no major contribution to the soil stability in terms of heave and uplift pressure. Therefore, it can be concluded that the maximum length of 6 m is the ideal length for GPA for this particular type of soil.

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