Heave Behavior of Granular Pile Anchor-Foundation (GPA-Foundation) System in Expansive Soil

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ABSTRACT: Granular Pile Anchor (GPA) is one of the innovative foundation techniques, devised for mitigating heave of footing resulting from the expansive soils. This research attempts to study the heave behavior of (GPA-Foundation System) in expansive soil. Laboratory tests have been conducted on an experimental model in addition to a series of numerical modelling and analysis using the finite element package PLAXIS software. The effects of different parameters, such as (GPA)length (L) and diameter (D), footing diameter (Df), expansive clay layer thickness (H) and presence of non-expansive clay are studied. The results proved the efficiency of GPA in reducing the heave of expansive soil and showed that the heave can be reduced with increasing length and diameter of GPA. The heave of (GPA-Foundation System) is controlled by three independent variables these are (L/D) ratio, (L/H) ratio and (Df/D) ratio. The heave can be reduced by up to (38 %) when (GPA) is embedded in expansive soil layer at (L/H=1) and reduced by about (90 %) when GPA is embedded in expansive soil and extended to non-expansive clay (stable zone) at (L/H=2) at the same diameter of GPA and footing. An equation (mathematical mode1) was obtained by using the computer package (SPSS 17.0) for statistical analysis based on the results of finite element analysis relating the maximum heave of (GPA-Foundation System) as a function of the above mentioned three independent variables with coefficient of regression of (R^2 = 92.3 %).
Keywords: Expansive Soil; Sand; Heave; Granular Pile Anchor (GPA); Foundation; PLAXIS; Finite Element.

INTRODUCTION

Many plastic types of clay swell considerably when water is added to them and then shrink with loss of water. Foundations constructed on such clays are subjected to large uplifting forces caused by swelling. These forces induce heaving, cracking, and the breakup of both building foundations and slab-on-grade members (Das, 2011). Expansive soil is a term applied to any soil that undergo detrimental changes in volume because of variations in moisture content. These soils subject to cycles of wetting-drying and swell when taking up water during wet seasons and shrink because of evaporation of water in dry spells (Chen, 1988, Nelson - Miller, 1992). Such soils are considered natural hazards that pose challenges to civil engineers, construction firms, and owners. Based on (Chen, 1988) the six major natural hazardous are earthquakes, landslides, expansive soils, hurricanes, tornados and floods. Over the last four decades, relentless efforts were made to understand and solve the problems associated with engineering on expansive soils. Several methods can be used to minimize the effect of the damage caused by expansive soils. These include soil replacement, physical & chemical treatment and use of special techniques. The application of these methods will keep intact over a long period of time. Many of them, however, have certain limitations and may be very costly (Dafalla and Shamrani, 2012). Keeping these shortcomings in view, an attempt to develop a simple, easy to install and cost-effective alternative foundation system, this research presents a simple foundation technique in the name of GPA foundation system as a dependable solution to suppress or tolerate heaving developed by expansive soils.

Concept of (GPA-foundation system)

GPA is an innovative foundation technique, devised for mitigating heave of expansive clay and improving their engineering behaviour. It is a modification of the conventional granular pile, wherein an anchor is provided in the pile to render it tension-resistant. Granular piles are a well-known ground improvement technique used for reducing the settlement and increasing load-carrying capacity of soft clay beds (Hughes and Withers, 1974). In a granular pile anchor, the foundation is anchored at the bottom of the granular pile to an anchored steel plate with the help of a mild steel road. This renders the granular pile tension-resistant and enables it to offer resistance to the uplift force exerted on the foundation by the swelling soil (Phanikumar, 1997, Phanikumar et al., 2004, Rao et al., 2007, Phanikumar et al., 2008). Figure 1 shows a typical schematic representation of the fundamental concept of

GPA and the various forces acting on the foundation. The uplift force (P_{Uplift}) acting on the base of the foundation in the vertical direction is due to the swelling pressure (P_s) of the expansive soil. This uplift force is resisted by the weight of the granular pile (W) acting in the downward direction. The friction mobilized along the pile-soil interface also resists the upward movement of the foundation. This friction is generated mainly because of the anchor in the system. The upward resistance is further augmented by the lateral swelling pressure, which confines the granular pile anchor radially, increases the friction along the pile-soil interface, and prevents it from being uplifted (Phanikumar, 1997, Phanikumar et al., 2004, Rao et al., 2007, Phanikumar et al., 2008).
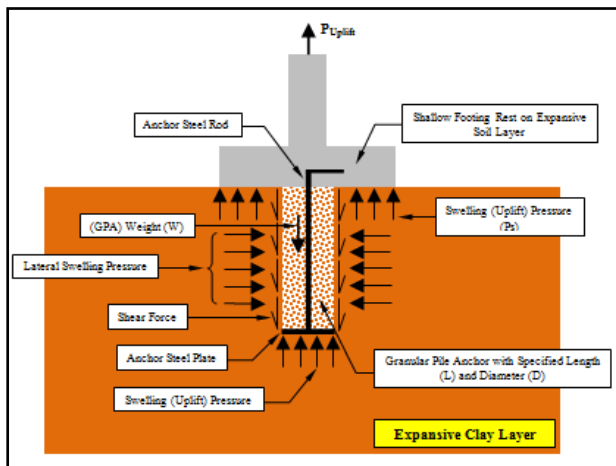

Figure 1. Concept of Granular Pile Anchor Foundation System and Forces acting on a Granular Pile Anchor (GPA) (After Rao et al., 2007)

Objectives

Due to limited knowledge currently available in the literature about GPA, the present study is an attempt aiming at insight understanding to the behavior and performance of GPA in expansive soils in reduce the heave. The following aspects are covered:

1- The behaviour of GPA-Foundation System under heave.

2- The validity and suitability of GPA as a dependable solution for problems in expansive soils.

Different parameters will be investigated that would be count for in the design of GPA, such as GPA length (L), diameter (D), expansive soil layer thickness (H), shallow footing diameter (Df), (L/D) ratio, (L/H) ratio, (Df/D) ratio and presence of non-expansive soil.

MATHERIALS AND METHODS

The study is divided into two phases including:

1- Experimental Phase: A cylindrical physical steel model with (30 cm) diameter and (50 cm) height has been built up and planned experimental laboratory testing program has been performed on expansive soil bed prepared from silty clayey soil.

2- Numerical Phase: A numerical model has been used and solved to analyze the described problem in the field. A software finite element program PLAXIS 2D-Version 8.2 packages is used to solve such problem

depending on the adopted non-linear elastoplastic models.

Experimental Works

The expansive clay used in this investigation was collected from Al-Wahda Discrete at Al-Mosul governorate in the north of Iraq, from a depth of about (1-1.5) m below the ground level. A series of rotten laboratory tests was carried out on the expansive soil samples to obtain physical, mechanical, and swelling soil properties. Table 1 and Figures 2 - 7 shows the properties of expansive soil used.

The granular material used for the installation of the granular piles was dense sand with (75 %) relative density. Table 2 and Figures 8 and 9 show the properties of sand used.

Table 1. Summary of Physical, Mechanical & Chemical Properties of Expansive Soil Used

Soil Property	Standard	Grades
Specific Gravity (Gs)	ASTM D-854	2.73
Liquid Limit (L.L) %		59
Plastic limit (P.L) %	ASTM D-4318	23
Plasticity Index (P.I) %		36
% Clay		51
% Silt	ASTM D-422	42
% Sand		7
% Gravel		0
Unified Soil Classification System (USCS)	ASTM D-2484	CH
Maximum Dry Density (γ_{dry}), kN/m³	ASTM D-1557	16.3
Optimum Moisture Content (O.M.C)%		21.5
Initial Void Ratio (eo)		0.674
Unconfined Compressive Strength (q_u), kPa	ASTM D-2216	165
Undrianed Cohesion (c_u), kPa	ASTM D-2850	70
Undrained Angle of Internal Friction (φ_u)°		10
Drained Cohesion (c'), kPa	ASTM D-3084	5
Drained Angle of Internal Friction (φ')°		24
Compression Index (Cc)		0.332
Swelling Index (Cs)	ASTM D-4546 Method (A)	0.076
Free Swelling (%)		6.5
Swelling Pressure (kPa)		170
Organic Matters Content (%)		1.9
Gypsum Content (%)	BS 1377: 1990 Part 3	1.8
Total Soluble Salts Content (%)		1.05
Sulphate (SO₃) Content (%)		0.86

Table 2. Summary of Physical, Mechanical & Chemical Properties of Sand Dunes Used

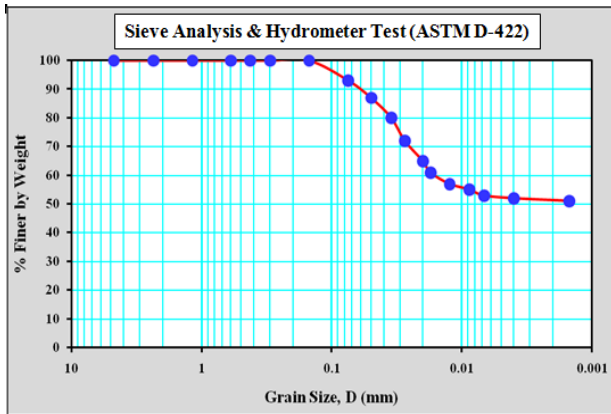| Soil Property	Standard	Grades
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Figure 2. Grain-Size Analysis Plot for Expansive Soil Used According to (USCS)
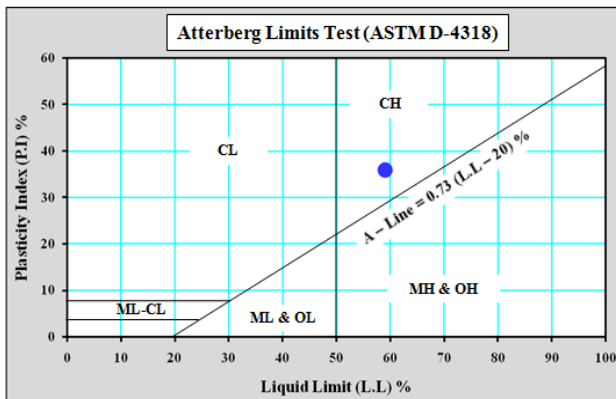

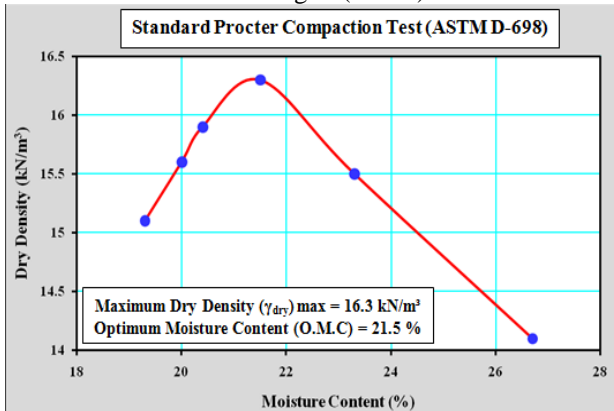**Figure 3.** Plasticity Chart Plot of Expansive Soil Used According to (USCS)

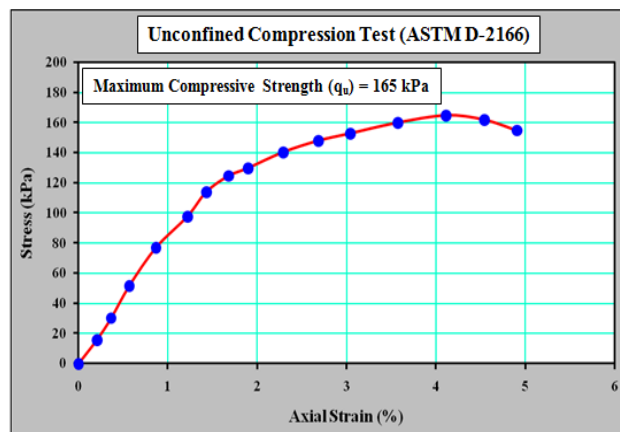**Figure 4.** Dry Density versus Moisture Content Plot for Expansive Soil Used

Figure 5. Vertical Stress versus Axial Strain Plot for Expansive Soil Used
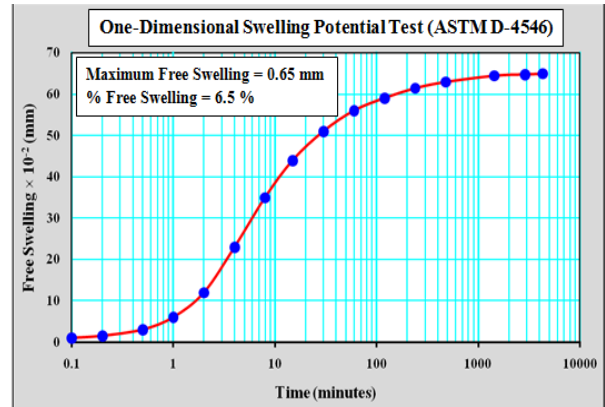

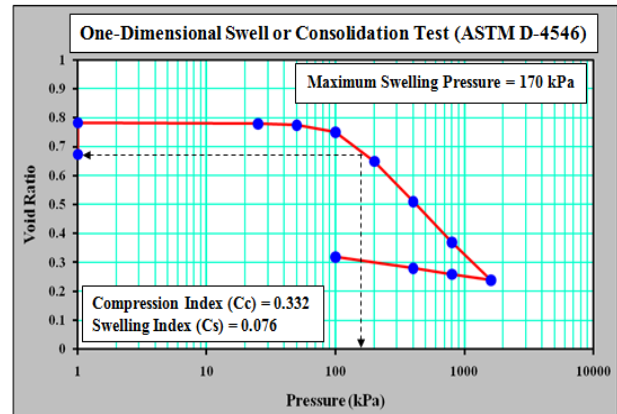**Figure 6.** Time-Swell Plot for Expansive Soil Used (Free Swelling Test)

Figure 7. Void Ratio versus Log Pressure Plot for Expansive Soil Used (Swelling Pressure & Consolidation Test)
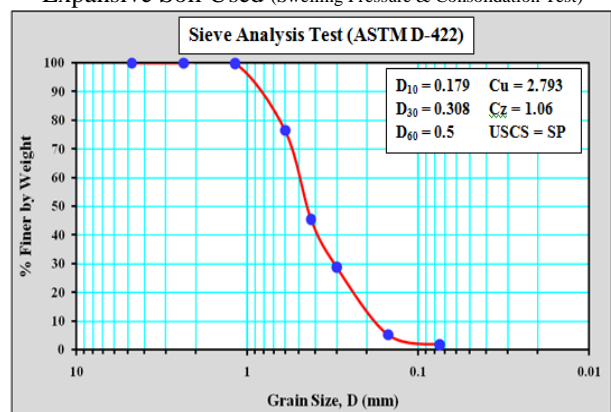

Figure 8. Grain-Size Analysis Plot for Sand Used According to (USCS) Expansive Soil Used
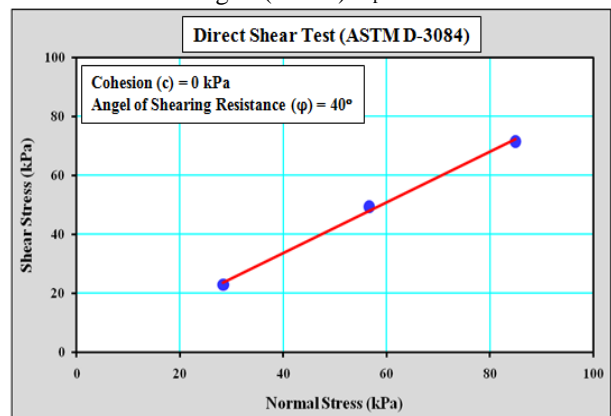

Figure 9. Shear Stress versus Normal Stress Plot for Sand Used

Heave tests were performed in metal cylindrical container of (0.3 m) diameter and (0.5 m) height. The expansive soil bed is prepared firstly by laying a filter paper covered with thin layer (30 mm) of poorly graded sand, as a drainage layer. All internal sides of container are covered with petroleum jelly to diminish friction effect. After thorough mixing with water, the soil lumps are spread inside the model container at maximum dry unit weight of (16.3 kN/m³) and optimum moisture content of (21.5 %) which is obtained using standard compaction test in form of eight layers. Each layer have a compacted thickness of (5 cm) and contain (5.76 kg) of soil to give the total depth and weight of expansive soil inside the model container of (40 cm) and (46 kg). The uniformity in the soil bed is checked by measuring the unit weight and moisture content at various depths of the soil bed. The (GPA) installed in expansive soil bed by made a hole in the centre of the expansive soil bed surface by driving a steel pipe gradually in specified diameter up to the required depth. The unit of anchor rod with the bottom anchor plate of specified diameter and depth is placed vertically in the hole. Simultaneously, the hole is filled with poorly graded sand gradually and compacted gently using steel tamping rod in required relative density (75 %). Finally, GPA is formed in specified depth and diameter at an average dry unit weight of (16.9 kN/m³). The GPA length was varied as (10, 20, 30, and 40) cm and the diameter as (1, 2, 3, and 4) cm to give a different ratios of (L/D). A circular mild steel plate of (20 cm) diameter was used as the surface shallow footing in the heave tests. A total of (16) test was conducted for studying the heave behaviour of (GPA-Foundation System). Figures 10 and 11 show the experimental setup of heave test.
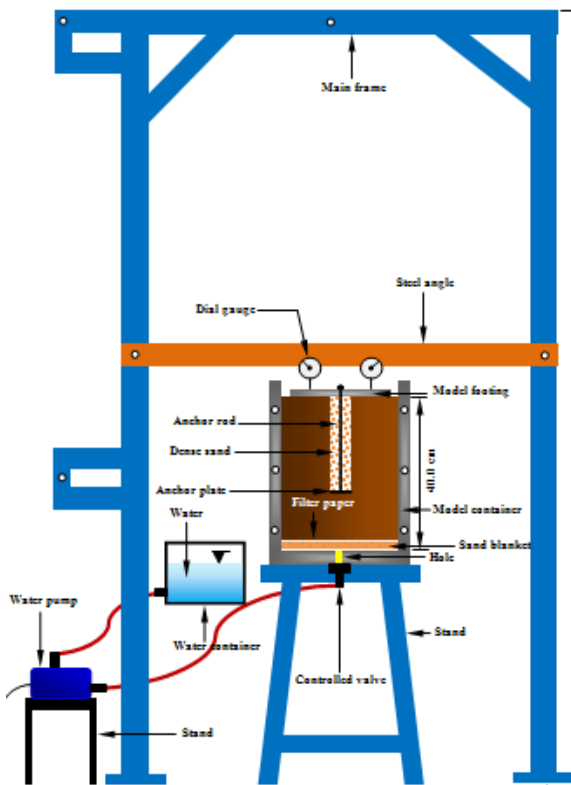

Figure 11. Plate of (GPA-Foundation System) under the Heave

The soil bed is wetted gradually by adding the water from the top and continuously pumping water from the base of model container using water pump and controlled valve. Water pump system is used as a vacuum to accelerate the saturation of expansive soil bed by continuously suction the water from model container. The model was left under the saturation and amount of heave is measured and continuously monitored with time until there is no further swelling. At this stage, saturation of soil bed is conformed and the test is completed.

RESULTS AND DISCUSSIONS

The results of unreinforced and reinforced expansive soil bed with (GPA) are obtained as shown in Table 3 and Figures 12 - 15. Generally, the heave response appears non-linear behavior and increases continuously with time until reach the equilibrium after (7) days for unreinforced expansive soil bed and (4) days for reinforced expansive soil bed with GPA. The results showed that the unreinforced expansive soil attained a final heave of (26 mm) and the heave of GPA-Foundation System decreases with installation of GPA in expansive soil. This may indicate the efficiency of (GPA) in reducing the heave. This is in agreement with findings of Phanikumar (1997), Phanikumar et al. (2004), Rao et al. (2007), Phanikumar et al. (2008), Ismail and Shahin, (2011), Krishna et al. (2013).

Table 3. Summary of the Maximum Heave of Expansive Soil Reinforced with (GPA) Models at Different Lengths

(GPA) Diameter (cm)	(GPA) Length (cm)	(L/D) Ratio	(L/H) Ratio	(Df/D) Ratio	Maximum Heave (mm)
1	10	10	0.25	20	24.0
	20	20	0.5		23.2
	30	30	0.75		22.4
	40	40	1		21.2
2	10	5	0.25	10	23.1
	20	10	0.5		22.7
	30	15	0.75		21.6
	40	20	1		19.2
3	10	3.3	0.25	6.6	22.0
	20	6.6	0.5		21.0
	30	10	0.75		19.2
	40	13.3	1		17.1
4	10	2.5	0.25	2.5	21.0
	20	5	0.5		20.1
	30	7.5	0.75		18.3
	40	10	1		16.1

Figure 10. Schematic Details of Heave Test of Reinforced Expansive Soil Bed with (GPA) Models
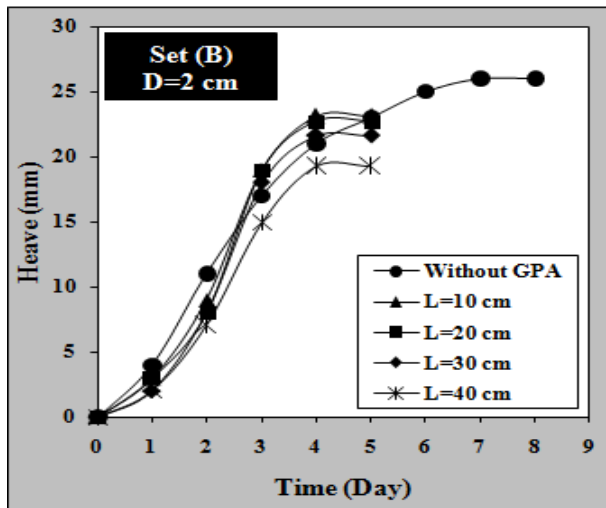
Figure 12. Heave–Time Relationship for Reinforced Expansive Soil with (GPA) at 1 cm Diameter
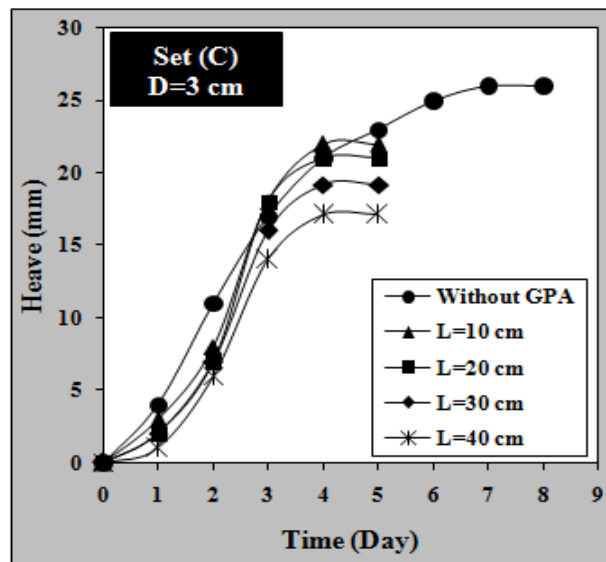

Figure 13. Heave–Time Relationship for Reinforced Expansive Soil with (GPA) at 2 cm Diameter
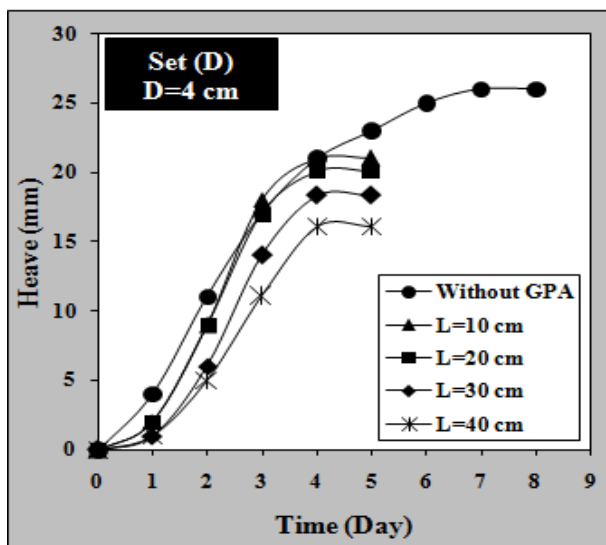

Figure 14. Heave–Time Relationship for Reinforced Expansive Soil with (GPA) at 3 cm Diameter
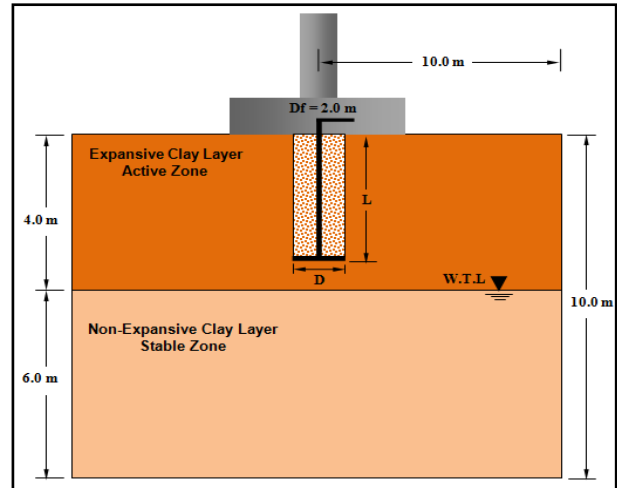

Figure 15. Heave–Time Relationship for Reinforced Expansive Soil with (GPA) at 4 cm Diameter

The results showed that, there are three main variables controlling heave behavior of GPA-Foundation System that can be categorized as [(L/D) ratio, (L/H) and (Df/D) ratio]. The heave of GPA-Foundation System is affected by one or all theses variable, the heave reduction and degree of improvement increases with increasing (L/D) ratio, (L/H) ratio and decreases with increasing (Df/D) ratio at a given two variables. The percentage heave reduction and degree of improvement can be expressed as a percentage from the maximum heave without (GPA) by the following equation:

$$\text{Degree of Improvment (\%)} = \left(\frac{H_{vo} - H'_{v}}{H_{vo}}\right) \times 100$$

(1)

Where:

H_{vo}: is the maximum heave of footing without (GPA) reinforcement.

H'_{v}: is the maximum heave of footing with (GPA) reinforcement.

It can be noted that, slightly reduction in heave was observed at [(L/D=10), (L/H=0.25) and (Df/D=20)] with (7.8 %) degree of improvement, while higher reduction in heave was observed at [(L/D=10), (L/H=1) & (Df/D=2.5)] with (38.1 %) degree of improvement. This reflects the ability and efficiency of a single (GPA) in reducing the heave when embedded in an expansive soil and anchored to the shallow footing. This performance agrees with the results obtained from researchers (Phanikumar, 1997; Phanikumar et al., 2004; Rao et al., 2007; Phanikumar et al., 2008; Krishna et al, 2013). The results of GPA-Foundation System showed that, there is a great effect on the time of heave development. The time period required for attaining the final amount of heave in the case of reinforced expansive soil with GPA was (4/7) of that for unreinforced expansive soil. This performance agrees with the results obtained from researchers (Phanikumar, 1997; Phanikumar et al., 2004; Phanikumar et al., 2008).

Numerical modelling of heave of (GPA-foundation system)

In this study, PLAXIS 2D-Version 8.2 program is used in numerical modelling and analysis of heave problems of GPA-Foundation System. The problem

deals with shallow circular footing rest on the expansive soil layer reinforced with GPA models with different length and diameter. For comparison, the circular footing rest on the expansive soil without GPA is also modelled here. The purpose of the problems is to calculate the maximum heave under the footing. The expansive soil layer is located above a layer of saturated stable clay with (6 m) thickness. The active zone of the expansive soil is chosen to be (4 m); at this depth, the water table rising causes a considerable swelling in expansive soil. Figure 16 shows the sketch of described problem. Axisymmetric type model is chosen, it is the best option for circular models. The soil parts are modelled using 15-node triangular element. The shallow footing and anchor plate are modelled using plate element, while the anchor rod is modelled using node-to-node element. The footing diameter was fixed at (2 m), and the GPA length was varied from (2-8) m and diameter was varied from (0.2-0.8) m. So, the ratio of length to diameter was ranged as (2.5 to 40) and the ratio of the footing diameter to GPA diameter varied as (2.5 to 10). The thickness of expansive clay layer is fixed at (4 m) and thickness of non-expansive clay layer is fixed at (6 m), so, the ratio of GPA length to expansive soil thickness was varied as (0.5-2).

The boundary conditions are assumed using standard fixity. This means a full fixity at the base of the geometry and, roller conditions at the vertical sides. Figure 17 shows the finite element model of heave problems. The clay of expansive and non-expansive soil layers are modelled using Mohr-Coulomb (MC) model, assumed to behave in an undrained manner. The granular pile sand is modelled using Mohr-Coulomb (MC) also. It is assumed to behave in a drained manner. The rigid steel is used as a material for both anchor plate, anchor rod and shallow footing and assumed as linear elastic model. The flexural rigidity of anchor plate, anchor rod and footing assumed as very high to avoid unnecessary buckling and deformation. All materials and models with set of parameters are listed in Tables 4 and 5.
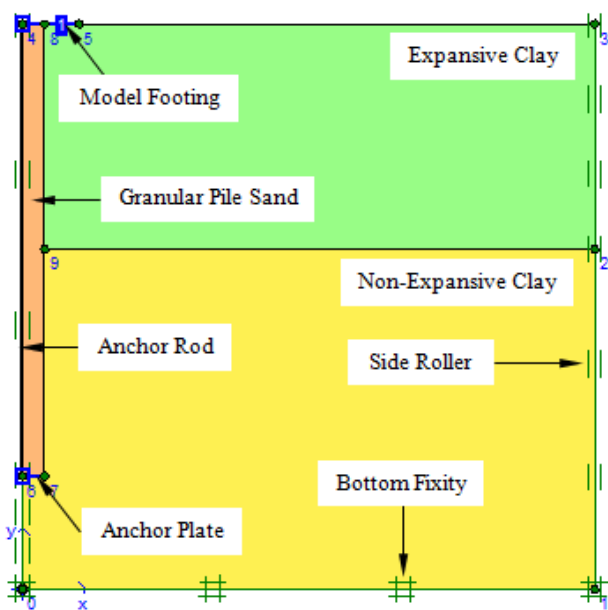

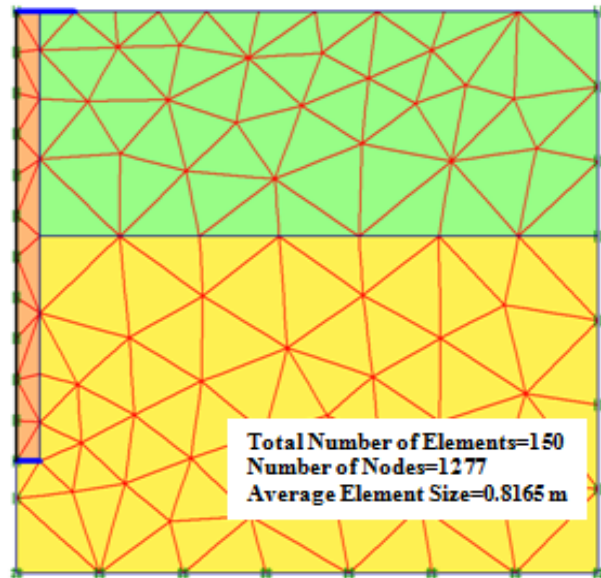**Figure 16.** Descriptive Sketch of Large Scale Heave Problems

Figure 17. 2D-Axisymmetric Model, (GPA) Extend to the Non-Expansive Clay Layer

Table 4. Soil Parameters set Considered for Heave Response Problems

Model Type	Model Parameters	Expansive Clay Undrained Method (A)	Granular Pile Sand Drained ---	Non-Expansive Clay Undrained Method (A)
Mohr-Coulomb (MC) Model	γ_{usat} (kN/m³)	16	17	16
	γ_{sat} (kN/m³)	19	20	19
	E_{ref} (kPa)	5000	50000	5000
	c_{ref} (kN/m²)	5	0.1	5
	$\varphi°$	24	40	24
	$\psi°$	0	0	0
	ν_{nu}	0.35	0.3	0.35

Table 5. Steel Properties set Considered for Heave Response Problems

Model Type	Model Parameters	Footing Model Steel	Anchor Plate Steel	Anchor Rod Steel
Linear Elastic	EA (kN/m²)	$5×10^6$	$5×10^6$	$2×10^6$
	EI (kN/m²/m)	$4×10^4$	$1×10^4$	-
	ν	0.15	0.15	0.15

The simple global finite element mesh of model is generated using the coarse setting to allow a more accurate stress distribution as shown in Figures 18. The swelling of expansive soil layer is modelled by applying a positive volumetric strain of (6.5 %) to the expansive clay cluster. In reality, the rate at which expansive clay would normally swell depends on the location from the source of moisture and magnitude of overburden pressure. However, for simplicity, in the analyses presented herein, the volumetric strain was applied uniformly across the full thickness of the expansive soil layer.

The numerical results of heave of unreinforced and reinforced expansive clay with (GPA) are obtained as shown in Table 6, and Figures 19 - 21.

The results reflect the efficiency of GPA to reduce the heave GPA-Foundation System. The maximum heave of footing resting on unreinforced expansive soil with GPA is observed as (260 mm). In case of footing resting on reinforced expansive soil with GPA models, i.e. GPA-Foundation System, the results showed that the maximum heave of footing decrease with increasing the GPA size, the heave decrease with increasing (GPA)

length and diameter due to anchorage action of (GPA) and there are three main variables controlling behaviour of GPA-Foundation System under the heave. These variables are (L/D) ratio, (Df/D) ratio and (L/H) ratio, this performance in agreement with the experimental modelling. The results also showed that, the (GPA) could be extended to the non-expansive soil layer or stable zone at sufficient depth to provide the anchorage zone help the GPA to resist the heave. (69%) reduction in heave when single GPA embedded in the expansive soil depth layer and (90.4 %) reduction in heave can be obtained when single GPA embedded in expansive clay layer and extended into non-expansive clay layer at the same embedded length.

Table 6. Summary of the Maximum Heave of Unreinforced & Expansive Soil Reinforced with (GPA) Models at Different Lengths and Diameters

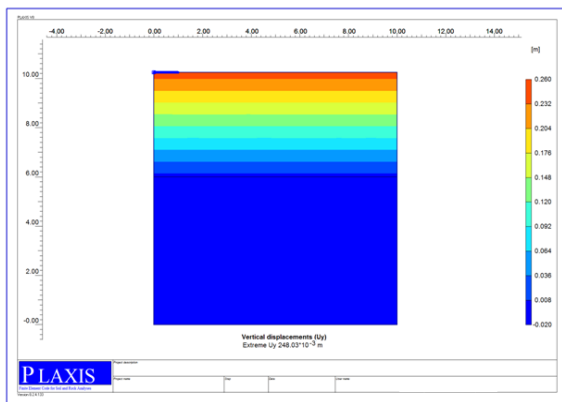| (GPA) Diameter (m)	(GPA) Length (m)	(L/D) Ratio	(L/H) Ratio	(Df/D) Ratio	Maximum Heave (mm)
Footing Resting on Unreinforced Expansive Soil with (GPA)					260
0.2	2	10	0.5	10	225
	4	20	1		189
	6	30	1.5		130
	8	40	2		115
0.4	2	5	0.5	5	215
	4	10	1		170
	6	15	1.5		100
	8	20	2		84
0.6	2	3.3	0.5	3.3	209
	4	6.6	1		124
	6	10	1.5		56
	8	13.3	2		40
0.8	2	2.5	0.5	2.5	204
	4	5	1		81
	6	7.5	1.5		38
	8	10	2		25

Figure 19. Shading Diagram of the Vertical Displacement Distribution Resulting from the Heave for Unreinforced Expansive
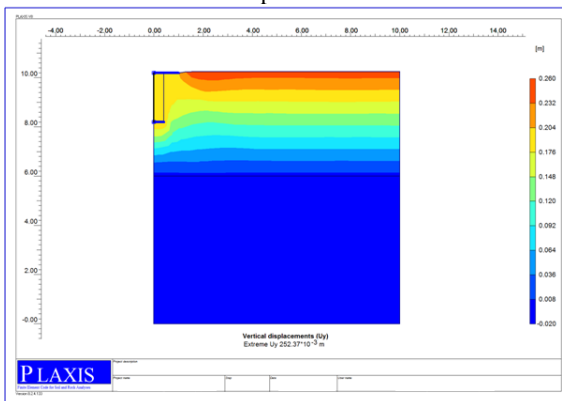

Figure 20. Shading Diagram of the Vertical Displacement (m) Distribution Resulting from the Heave for (GPA at L=2 m & D=0.8 m)
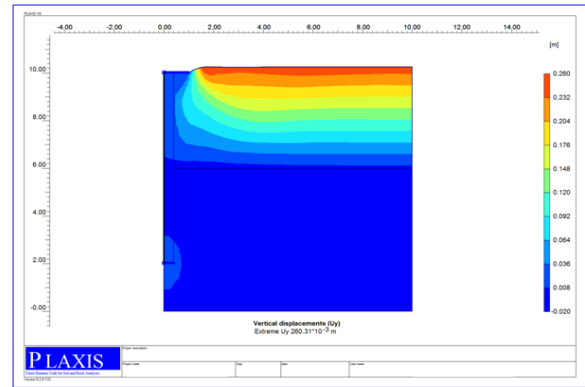

Figure 21. Shading Diagram of the Vertical Displacement (m) Distribution Resulting from the Heave for (GPA at L=8 m & D=0.8 m)
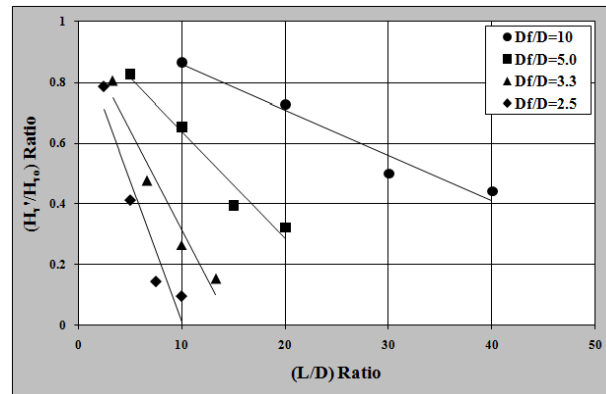

Figure 22. Relationship between the Normalized Maximum Heave (H_v'/H_{vo}) & (L/D) Ratio of (GPA) for Different Ratios of (Df/D) - (L/D) Ratio Effect
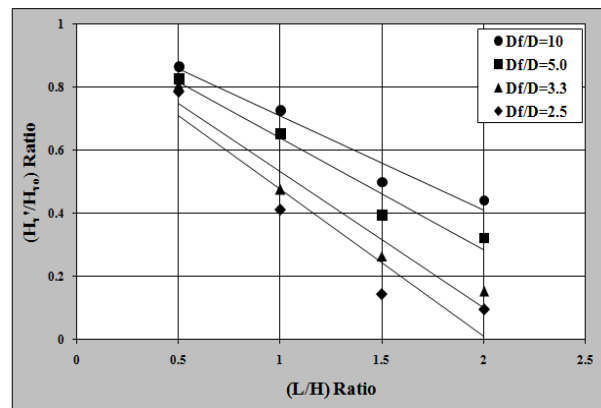

Figure 23. Relationship between the Normalized Maximum Heave (H_v'/H_{vo}) & (L/H) Ratio of (GPA) for Different Ratios of (Df/D) - (L/H) Ratio Effect

The efficiency of the (GPA-Foundation System) in arresting the heave induced by expansive soil layer is illustrated in Figure 22. The figure relates the normalized maximum heave ratio (H_v'/H_{vo}) with (L/D) ratio of GPA for different ratios of (Df/D), where (H_v') represent the maximum heave of footing with (GPA) reinforcement, while (H_{vo}) represent the maximum heave of footing without GPA reinforcement. It can be noted that for a given (Df/D) ratio, the maximum heave decrease with increasing (L/D) ratio due to increasing (GPA) length. This means the (GPA) movement 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 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 heave can be reduced from (260 mm to 25 mm) at (L=8 m & D=0.8 m) i.e., (L/D=10) with (90.4 %) reduction in heave.

Figure 23 displays the relationship between normalized maximum heave ratio (H_v'/H_{vo}) with (L/H) ratio for different (Df/D) ratios. It can be seen that for a given (Df/D) ratio, the heave decreases when (L/H) increases due to increasing the (GPA) length. Dramatic reducing in heave was observed when (GPA) penetrated in non-expansive clay layer at sufficient length, this means the (GPA) can be penetrate the non-expansive clay layer (stable zone) to provide a sufficient anchorage in the base of (GPA) help it in arresting the heave. This behaviour can be attributed to increase the shear resistance in circumference of penetrate length of (GPA). The results showed that, the (GPA) could be extended to non-expansive clay layer with thickness not less than thickness of expansive clay layer thickness to provide a sufficient anchorage at (GPA) base. The heave dropped from (260 mm) to (25 mm) when (L/H=2) at (D=0.8 m & L=8 m) with (90.4 %) reduction in heave, while, the heave reduced to (204 mm) when (L/H=0.5) and to (81 mm) when (L/H=1) at the same size of GPA with (21.54 %) & (69 %) reduction in heave respectively.

Figure 24 shows the relationship between normalized maximum heave ratio (H_v'/H_{vo}) and (Df/D) ratio for different ratios of (L/H). The figure presents the effect of the footing diameter (Df) on the heave response of (GPA- Foundation System). It can be seen that for a given (L/H) ratio, the maximum heave increases with increasing (Df/D) ratio due to increasing footing diameter. The reason of this behaviour can be understood as the following: when the footing diameter increases with constant (GPA) diameter, the annular area of the footing on which the swelling pressure acts is increased resulting increases in the heave of the (GPA-Foundation System). Dramatic reduction in heave can be obtained at (Df/D=2.5), where the heave reduced from (260 mm to 25 mm) with (90.4 %) reduction in heave.

Mathematical Modelling of Heave of (GPA-foundation system)

An attempt is made to develop a mathematical modelling relate the heave of footing resting on reinforced expansive soil with a single (GPA) with three effective variables (L/D), (Df/D) and (L/H). The results of finite element analysis are merged and entered in a multiple linear regressions statistical analysis using SPSS Statistics 17.0 to develop a mathematical model that relates the ratio of (H_v'/H_{vo}) as a dependent variable to (L/D), (Df/D) and (L/H) as independent variables. A general equation relates all variables were obtained in the following form with very good degree of correlation ($R^2=0.923$):

$$\frac{H_v'}{H_{vo}} = 0.94 + 0.011 \left(\frac{L}{D}\right) + 0.008 \left(\frac{Df}{D}\right) - 0.5 \left(\frac{L}{H}\right)$$

Where:

H_{vo}: Maximum heave without (GPA) reinforcement
H_v': Maximum heave of with (GPA) reinforcement
L: Length of (GPA)

D: Diameter of (GPA)
H: Depth of expansive soil layer
Df: Diameter of shallow footing

The derived equation is valid within the ranges of the variables they were developed from. The ranges of variables can be seen in Table 7. To verify the validity of the equation, the predicted values of heave are compared with observed values obtained previously from laboratory test results as shown in Table 8 and Figure 25. It can be seen that, the values agree well with (98 %) degree of correlation and consider under estimation, conforming the validity of derived equation.

Table 7. Variables Limitation for the Heave Equation

Variable	Minimum	Maximum
(L/D) Ratio	2.5	40
(Df/D) Ratio	2.5	10
(L/H) Ratio	0.5	2

Table 8. Comparison between the Predicted and Observed Heave

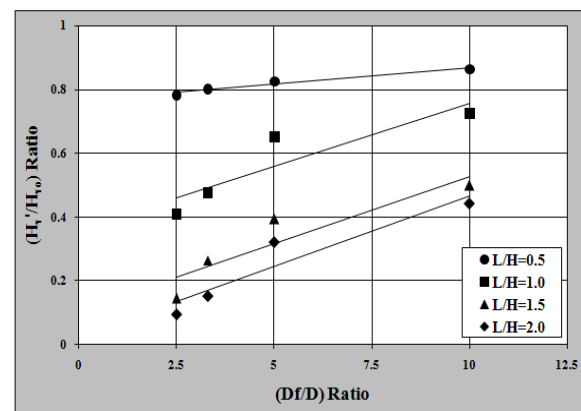| (GPA) Diameter (cm)	(GPA) Length (cm)	(L/D) Ratio	(L/H) Ratio	(Df/D) Ratio	Predicted Heave (mm)	Observed Heave (mm)
2	20	10	0.5	10	22.88	22.7
	30	15	0.75		21.06	21.6
	40	20	1		19.24	19.2
3	20	6.67	0.5	6.67	21.24	21.0
	30	10	0.75		18.94	19.2
	40	13.33	1		16.64	17.1
4	20	5	0.5	5	20.41	21.1
	30	7.5	0.75		17.87	18.3
	40	10	1		15.34	16.1

Figure 24. Relationship between the Normalized Maximum Heave (H_v'/H_{vo}) & (Df/D) Ratio of (GPA) for Different Ratios of (L/H) - (Df/D) Ratio Effect
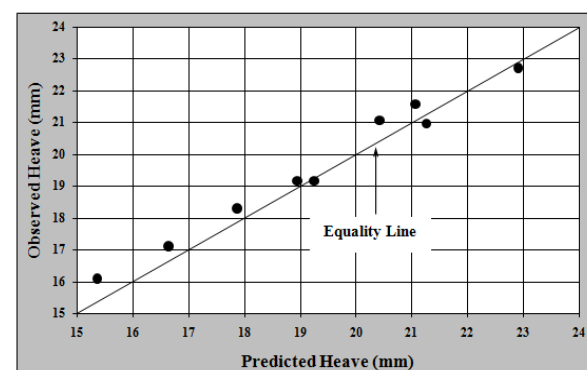

Figure 25. Relationship between the Predicted & Observed Heave of (GPA-Foundation System)

CONCLUSION

An extensive laboratory testing and numerical modelling and analysis was conducted to study the performance of Granular Pile Anchor (GPA) in expansive soil. The research work focuses on studying the efficacy and ability of the innovative (GPA) system in minimizing heave of foundations laid on expansive clay. The conclusions drawn from the different aspects of the study in this paper may be summarized as follows:

1- Installation of (GPA) in expansive soil reduces the amount of heave effectively. Of the various combinations of length (L) and diameter (D) of (GPA), the amount of heave reduces with increasing both length and diameter.

2- The maximum heave of (GPA-Foundation System) is controlled by three main independent variables, (GPA) length to diameter (L/D) ratio, (GPA) length to expansive soil active thickness (L/H) ratio and footing diameter to (GPA) diameter (Df/D) ratio.

3- The efficacy of (GPA) in reducing the heave can be improved when (GPA) embedded in expansive soil layer and extend to non-expansive clay layer (stable zone) at sufficient depth. The maximum of about (38 %) reduction in heave is observed when (GPA) embedded in expansive soil layer at (L=H) and reaches to (90.4%) at (L=2H) i.e. (GPA) extend to stable zone at length equal to thickness of expansive soil layer, this performance was observed at (L/D=10) and (Df/D=2.5).

4- Reduction in (GPA-Foundation System) can be attributed to the (GPA) weight, the frictional resistance mobilized along the (GPA)-soil face, the effect of anchorage which made the (GPA) to resist the uplift force applied on the foundation. In addition, the developed lateral swelling pressure resulting from surrounding expansive clay which confines the (GPA) radially increases the upward resistance.

5- Installation of (GPA) in expansive soil reduces the time of heave and the rate of heave become faster. The expansive soil reinforced with (GPA) adjusted quickly to moisture changes because of the higher permeability of the granular material. The high permeability characteristics of (GPA) allowed a quick circulation and absorption of water and the path of radial inflow of water became shorter, which led to a rather quick attainment of the final heave.The time period required for attaining the final amount of heave in the case of reinforced expansive soil with (GPA) was (3/7) of that for unreinforced expansive soil.

6- An equation is obtained to calculate the maximum heave of (GPA-Foundation System). The equation is derived basing on statistical analysis of the obtained analysis results.

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