Heave Behavior of Granular Pile Anchor-Foundation System (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 modeling and analysis using the finite element package PLAXIS software. The effects of different parameters, such as (GPA) length (L) and diameter (D), footing diameter (B), 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 (B/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), PLAXIS, foundation, finite element.

سلوك الانتفاخ لمنظومة (اساس - ركيزة رملية مربوطة) في التربة الانتفاخية

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الخلاصــة

تعتبر الركائز الرملية المربوطة المسماة بـ (GPA) احدى الطرق المبتكرة والحديثة المستخدمة للحد من الرفع او الازاحة العامودية الحاصلة في الاساس والناتجة من الترب الانتفاخية. هذا البحث يهدف الى دراسة مدى استجابة وسلوكية منظومة الاساس الجديدة تحت تأثير الانتفاخ وتعيين كفاءة وقدرة الركائز الرملية المربوطة في تقليل الازاحة العامودية الحاصلة في الاساس. تضمنت الدراسة انجاز عمل مختبري على موديل مختبري مصغر تم ابتكاره لهذا الغرض بالاضافة الى اجراء سلسلة من من النمذجة والتحليلات بأستخدام نظرية العناصر المحددة بأستخدام برنامج البلاكسس (PLAXIS) تم اعداده لهذا الغرض. تم دراسة عدة متغيرات مثل طول وقطر الركائز الرملية المربوطة, قطر الاساس, سمك طبقة التربة الانتفاخية بالاضافة الى تأثير طبقة التربة الطينية الغير منتفخة. لقد اثبتت النتائج كفاءة وقدرة الركائز الرملية المربوطة في تقليل الازاحة العامودية الحاصلة في الاساس وقد تبين ان الازاحة العامودية للاساس تقل بزيادة طول و قطر الركائز الرملية المربوطة وان هذه الازاحة تتأثر بثلاثة متغيرات رئيسية وهي نسبة الطول المدفون الى القطر للركائز الرملية المربوطة (L/D), نسبة الطول المدفون الى سمك طبقة التربة الانتفاخية (L/H) ونسبة قطر الاساس الى قطر الركيزة الرملية المربوطة (B/D). وقد تبين ان الازاحة العاموية للاساس تقل بنسبة (38%) عندما تدفن الركائز الرملية المربوطة بطول مساوي الى سمك طبقة التربة الانتفاخية وتقل بنسبة تصل الى (90%) عندما تدفن في التربة الانتفاخية وتمتد الى تربة طينية غير انتفاخية بطول مساوي الى

ضعف سمك طبقة التربة الانتفاخية بسبب الحصول على مقدار ازاحة ضئيل للاساس. تم استنباط معادلة احصائية وتكوين موديل رياضي تم الحصول عليه بأستخدام البرنامج الاحصائي المعروف بـ (SPSS 17) بالاعتماد على النتائج المستحصلة من التحليل بأستخدام نظرية العناصر المحددة بحيث يمكن ايجاد اقصى ازاحة عامودية لمنظومة الاساس الجديدة تحت تأثير الانتفاخ بدلالة المتغيرات الثلاثة التي ذكرت سابقا بدرجة عالية مقدارها (92.3%).

1. 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** and **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 and 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 Granular Pile Anchor (GPA) foundation system as a dependable solution to suppress or tolerate heaving developed by expansive soils.

2. CONCEPT OF (GPA-FOUNDATION SYSTEM)

The granular pile anchor (GPA) is an innovative foundation technique, devised for mitigating heave of expansive clay and improving their engineering behavior. 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** and **Phanikumar et al., 2008)**. **Fig. 1** shows a typical schematic representation of the fundamental concept of a granular pile anchor (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 and Phanikumar et al., 2008**.

3. 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 behavior 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 account for in the design of (GPA), such as (GPA) length (L), diameter (D), expansive soil layer thickness (H), shallow footing diameter (B), (L/D) ratio, (L/H) ratio, (B/D) ratio and presence of non-expansive soil.

4. METHODOLOGY

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.

5. EXPERMINTAL 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** 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** shows the properties of 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 testin 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 holein the center 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, granular pile anchor (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). **Fig. 2** and **3** show the experimental setup of heave test. 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.

6. RESULTS AND DISCUSSIONS OF EXPERMINTAL WORKS

The results of unreinforced and reinforced expansive soil bed with (GPA) are obtained as shown in **Table 3** and **Fig 4** to **7.** 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 in agreement with **,Phanikumar, 1997, Phanikumar et al., 2004, Rao et al., 2007, Phanikumar et al., 2008, Ismail** and **Shahin, 2011 and Krishna et al, 2013**. 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 (B/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 (B/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:

$$\text{Degree of Improvment (\%)} = \left(\frac{\mathrm{H_{vo}} - \mathrm{H_v'}}{\mathrm{H_{vo}}}\right) \times 100 \qquad (1)$$

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 (B/D=20)] with (7.8 %) degree of improvement, while higher reduction in heave was observed at [(L/D=10), (L/H=1) and (B/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, **Phanikumar, 1997, Phanikumar et al., 2004, Rao et al., 2007, Phanikumar et al., 2008,**and **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,**Phanikumar, 1997, Phanikumar et al., 2004** and **Phanikumar et al., 2008.**

7. 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. **Fig. 8** 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. **Figs. 9, 10** and **11** show the finite element models 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**. The simple global finite element mesh of model is generated using the coarse setting to allow a more accurate stress distribution as shown in **Figs. 12** and **13.** 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.

8. RESULTS AND DISCUSSIONS OF NUMERICAL MODELING

The numerical results of heave of unreinforced and reinforced expansive clay with (GPA) are obtained as shown in **Table 6**, and **Figs. 14, 15** and **16**. 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 behavior of (GPA-Foundation System) under the heave. These variables are (L/D) ratio, (B/D) ratio and (L/H) ratio, this performance in agreement with the experimental modeling. 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. The efficiency of the (GPA-Foundation System) in arresting the heave induced by expansive soil layer is illustrated in **Fig. 17**. The figure relates the normalized maximum heave ratio (H_v'/H_{vo}) with (L/D) ratio of (GPA) for different ratios of (B/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 (B/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 and D=0.8 m) i.e., (L/D=10) with (90.4 %) reduction in heave. **Fig. 18** displays the relationship between normalized maximum heave ratio (H_v'/H_{vo}) with (L/H) ratio for different (B/D) ratios. It can be seen that for a given (B/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 behavior 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 and 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 %) and (69 %) reduction in heave respectively. **Fig. 19** shows the relationship between normalized maximum heave ratio (H_v'/H_{vo}) and (B/D) ratio for different ratios of (L/H). The figure presents the effect of the footing diameter (B) 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 (B/D) ratio due to increasing footing diameter. The reason of this behavior 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 (B/D=2.5), where the heave reduced from (260 mm to 25 mm) with (90.4 %) reduction in heave.

9. 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), (B/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), (B/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):

$$\frac{\mathbf{H_v'}}{\mathbf{H_{vo}}} = \mathbf{0.94 + 0.011\left(\frac{L}{D}\right) + 0.008\left(\frac{B}{D}\right) - 0.5\left(\frac{L}{H}\right)} \qquad (2)$$

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
B: 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 **Fig. 20**. It can be seen that, the values agree well with (98 %) degree of correlation and consider under estimation, conforming the validity of derived equation.

10. CONCLUSIONS

An extensive laboratory testing and numerical modeling 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 (B/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 (B/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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NOMENCLATURE

ASTM	American society for testing and materials
B	Footing width or diameter
Cc	Compression Index
Cc	Coefficient of curvature
Cs	Swelling index
Cu	Coefficient of uniformity
c	Soil cohesion
CH	Clay with high plasticity
D	Diameter of granular pile anchor
D_r	Relative density of soil
B/D	Ratio of footing diameter to granular pile anchor diameter
E	Modulus of elasticity
e	Void ratio of soil
e_o	Initial void ratio
e_{max}	Maximum void ratio
e_{mim}	Minimum void ratio
Gs	Specific gravity of soil
GPA	Granular pile anchor
H	Expansive soil layer or bed thickness
H_{vo}	Maximum heave of footing without reinforcement with (GPA)
H_v'	Maximum heave of footing with (GPA) reinforcement
L	Length of granular pile anchor
L/D	Ratio of length to diameter of granular pile anchor
L/H	Ratio of length of granular pile anchor to expansive soil layer or bed thickness
L.L	Liquid limit
MC	Mohr-coulomb
O.M.C	Optimum moisture content
PLAXIS	Finite element code for soil and rock
Ps	Swelling pressure
P.L	Plastic limit
P.I	Plasticity index
USCS	Unified soil classification system
W	Granular pile anchor weight
ΔH	Heave or shrinkage
ϕ^o	Angle of internal friction of soil
ψ^o	Dilatancy angle
ν_u	Undrained poison's ratio
γ_{unst}	Unsaturated unit weight
γ_{sat}	Saturated unit weight
γ_{dry}	Dry unit weight

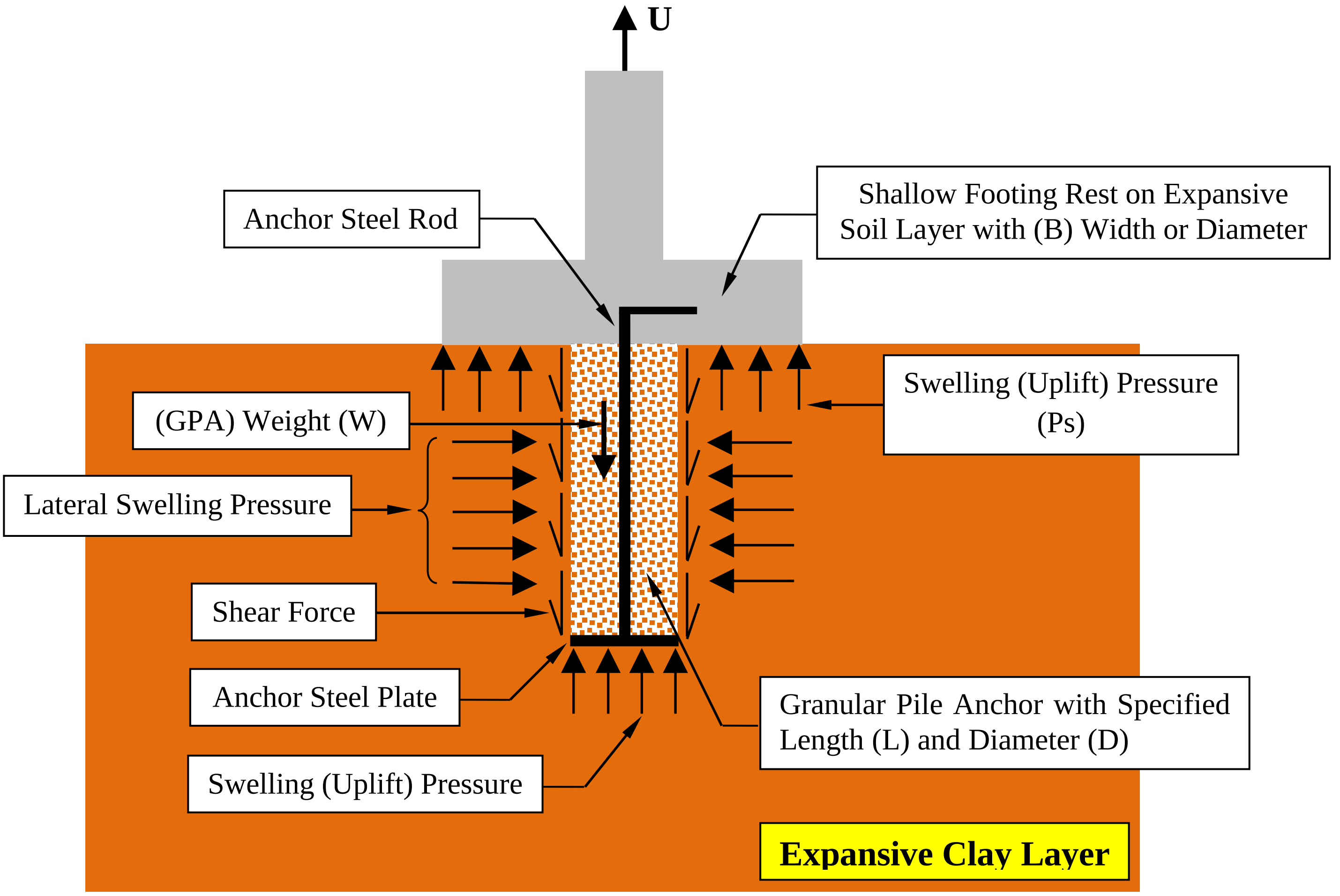

Figure 1. Concept of Granular Pile Anchor foundation system and forces acting on a Granular Pile Anchor (GPA) (After Rao et al., 2007).

Table 1. Summary of physical, mechanical and chemical properties of expansive soil used.

Test Name	Standard	Soil Property	Value
Specific Gravity	(ASTM D-854)	Specific Gravity (Gs)	2.73
Atterberg Limits	(ASTM D-4318)	Liquid Limit (L.L) %	59
		Plastic limit (P.L) %	23
		Plasticity Index (P.I) %	36
Grain Size Analysis Hydrometer	(ASTM D-422)	% Clay	51
		% Silt	42
		% Sand	7
		% Gravel	0
		Unified Soil Classification System (USCS)	CH
Standard Compaction	(ASTM D-1557)	Maximum Unit Weight (γ_{dry}), kN/m³	16.3
		Optimum Moisture Content (O.M.C)%	21.5
		Initial Void Ratio (eo)	0.674
Unconfined Compression	(ASTM D-2216)	Unconfined Compressive Strength (q_u), kPa	165
Undrained Unconsolidated	(ASTM D-2850)	Undrianed Cohesion (c_u), kPa	70

Triaxial (UU)		Undrained Angle of Internal Friction (ϕ_u)°	10
Direct Shear at (0.02 mm/min) adjusted Velocity	(ASTM D-3084)	Drained Cohesion (c'), kPa	5
		Drained Angle of Internal Friction (ϕ')°	24
One-Dimensional Swell or Consolidation	(ASTM D-3084) Method (A)	Compression Index (Cc)	0.332
		Swelling Index (Cs)	0.076
		Free Swelling (%)	6.5
		Swelling Pressure (kPa)	170
Chemical Properties	BS 1377: 1990 Part 3	Organic Matters Content (%)	1.93
		Gypsum Content (%)	1.85
		Total Soluble Salts Content (%)	1.05
		Sulphate (So_3) Content (%)	0.86

Table 2. Summary of physical, mechanical and chemical properties of sand used.

Test Name	Standard	Property	Value
Specific Gravity	(ASTM D-854)	Specific Gravity (Gs)	2.66
Grain Size Analysis Sieve Analysis	(ASTM D-422)	D_{10}	0.179
		D_{30}	0.308
		D_{60}	0.5
		Coefficient of Uniformity (Cu)	2.793
		Coefficient of Curvature (Cc)	1.06
		Unified Soil Classification System (USCS)	SP
Maximum Unite Weight	(ASTM D-253)	Maximum Unit Weight (γ_{max}), kN/m³	18.1
Maximum Unite Weight	(ASTM D-4254)	Minimum Unit Weight (γ_{min}), kN/m³	13.6
Chosen	---	Experimental Relative Density (Dr) %	75
Calculated	---	Experimental Unit Weight (γ_{dry}), kN/m³	16.72
Calculated	---	Maximum Void Ratio (e_{max})	0.956
Calculated	---	Minimum Void Ratio (e_{mim})	0.469
Calculated	---	Experimental Void Ratio (e_o)	0.591
Direct Shear	(ASTM D-3084)	Cohesion (c), kPa	0
		Angle of Shearing Resistance (ϕ)°	40
Chemical Properties	(BS 1377: 1990 Part 3)	Organic Matters Content (%)	0.31
		Gypsum Content (%)	0.78
		Total Soluble Salts Content (%)	0.88
		Sulphate (So_3) Content (%)	0.36

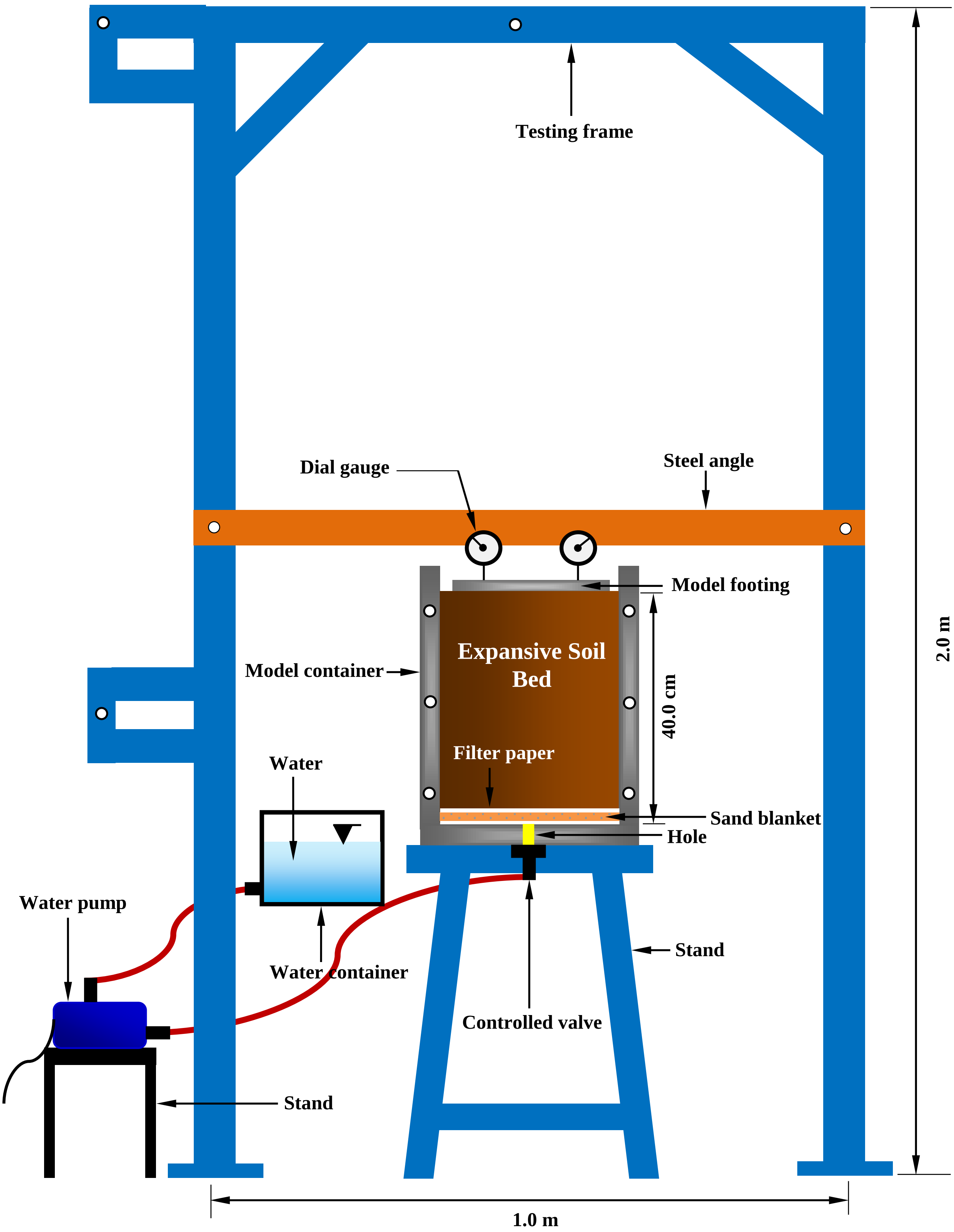

Figure 2. Schematic details of heave test of unreinforced expansive soil bed.

Figure 3. Plate of (GPA-Foundation System) under the heave.

Table 3. Summary of the maximum heave of expansive soil reinforced with (GPA) models at different lengths and diameters.

(GPA) Diameter (cm)	(GPA) Length (cm)	(L/D) Ratio	(L/H) Ratio	(B/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

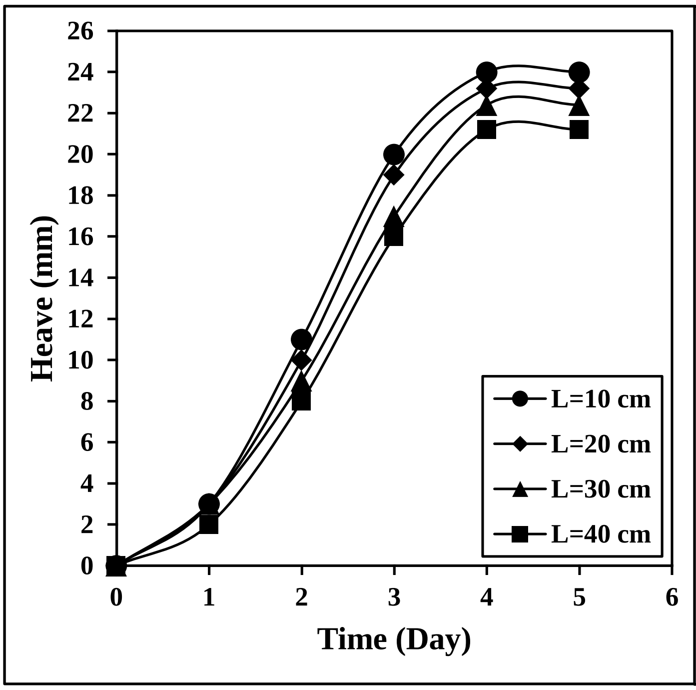

Figure 4. Heave–time relationship for reinforced expansive soil with (GPA) at 1 cm diameter.

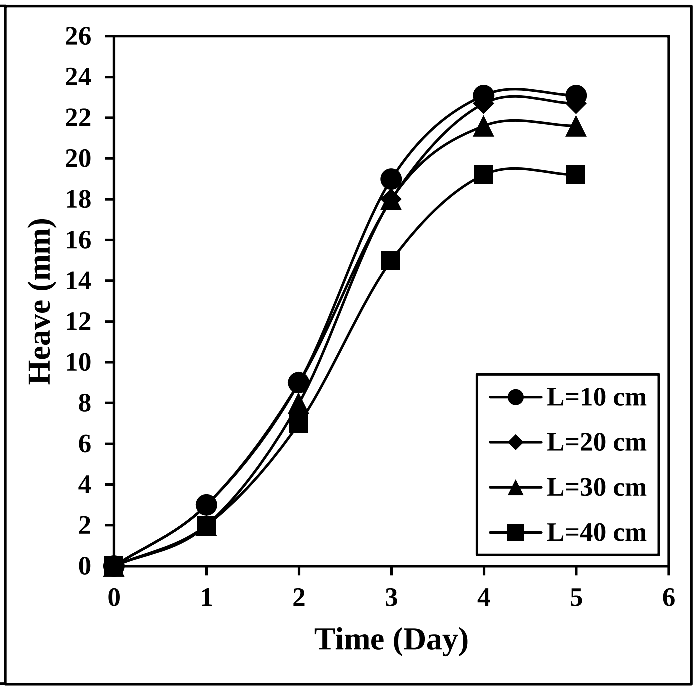

Figure 5. Heave–time relationship for reinforced expansive soil with (GPA) at 2 cm diameter.

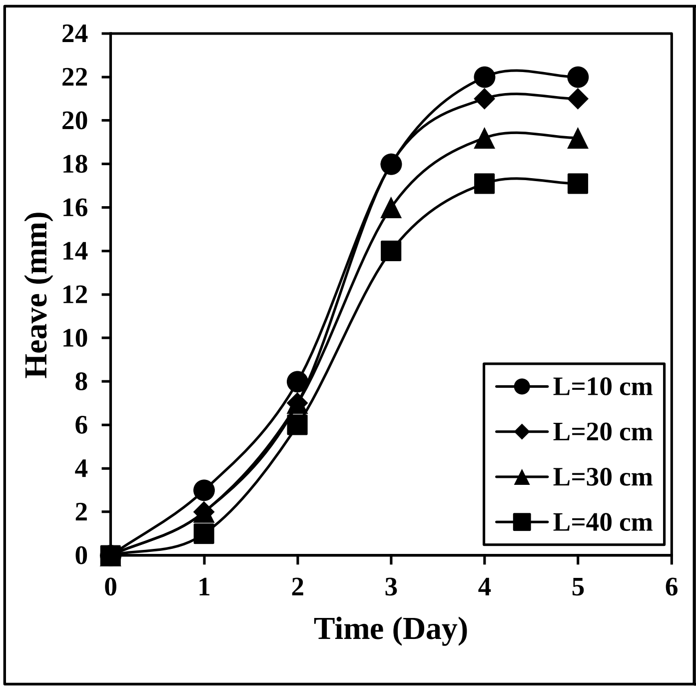

Figure 6. Heave–time relationship for reinforced expansive soil with (GPA) at 3 cm diameter.

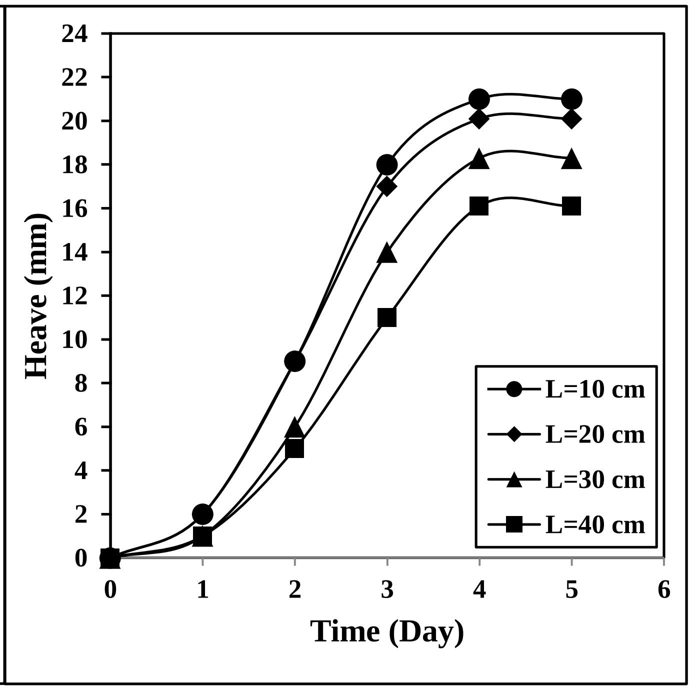

Figure 7. Heave–time relationship for reinforced expansive soil with (GPA) at 4 cm diameter.

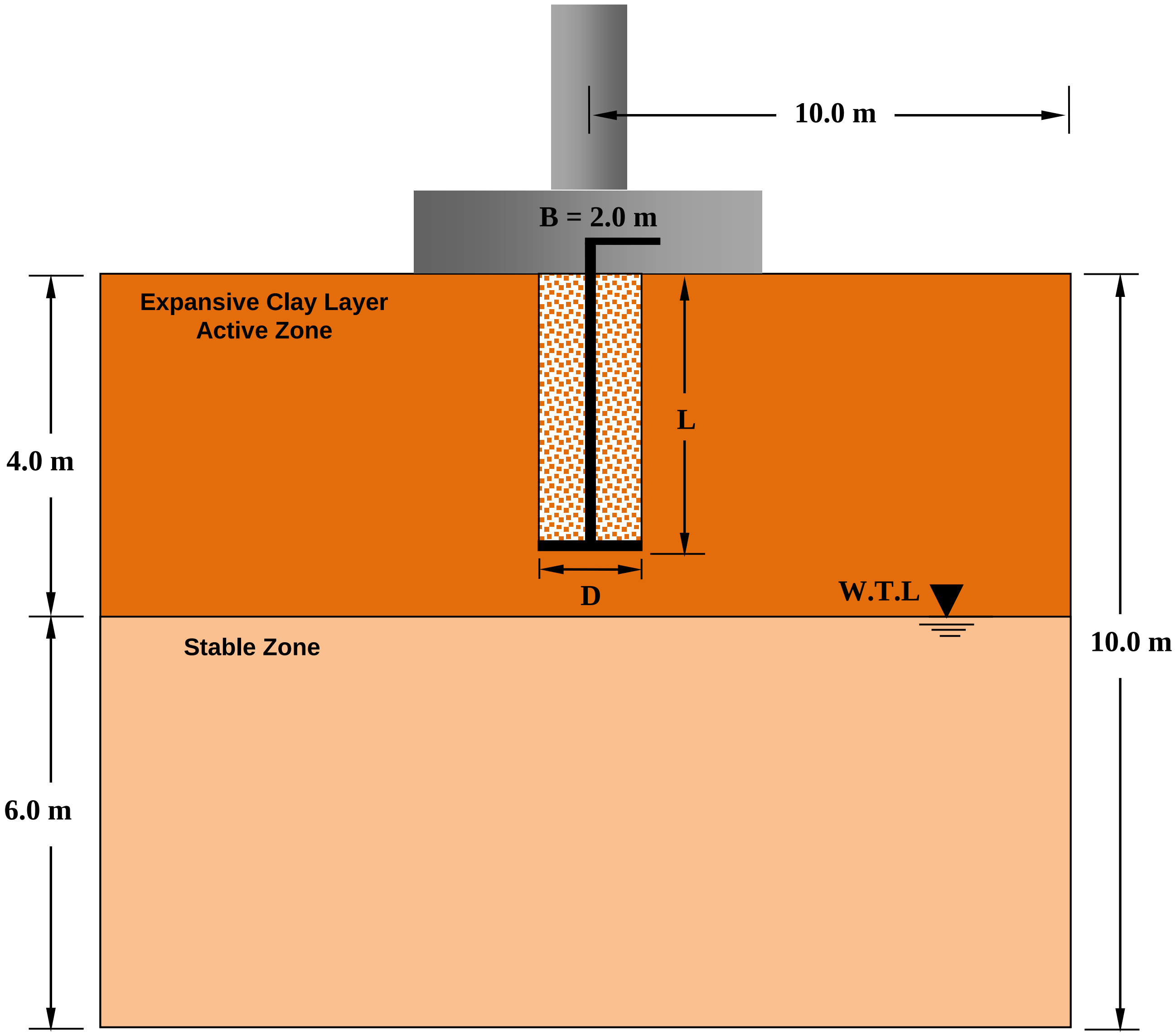

Figure 8. Descriptive sketch of large scale heave problems.

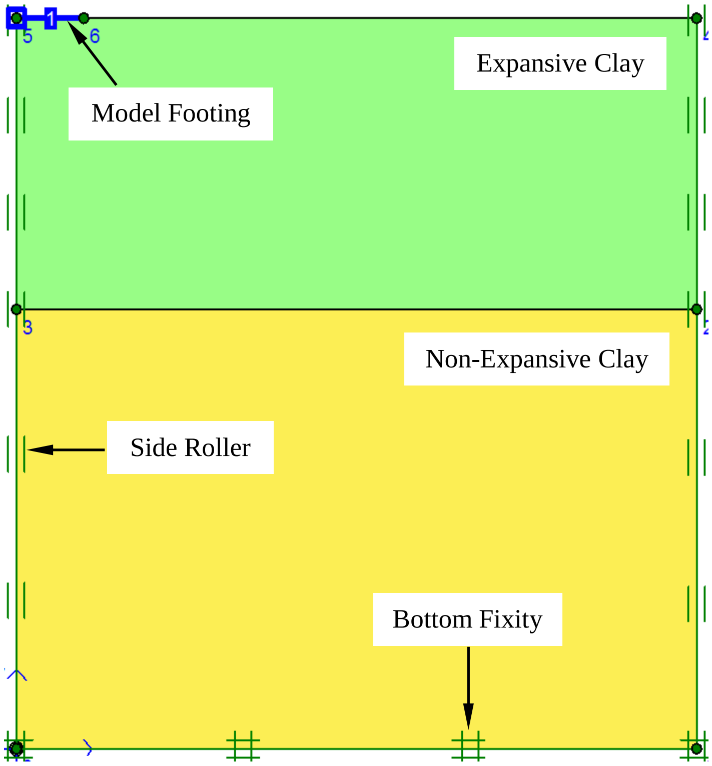

Figure 9. 2D-Axisymmetric model, unreinforced expansive clay.

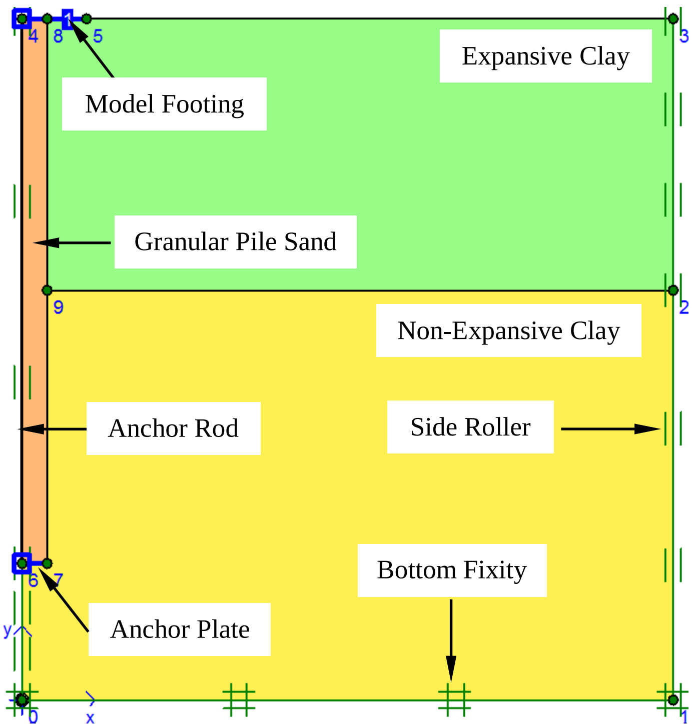

Figure 11. 2D-Axisymmetric model, (GPA) extended to the non-expansive clay layer.

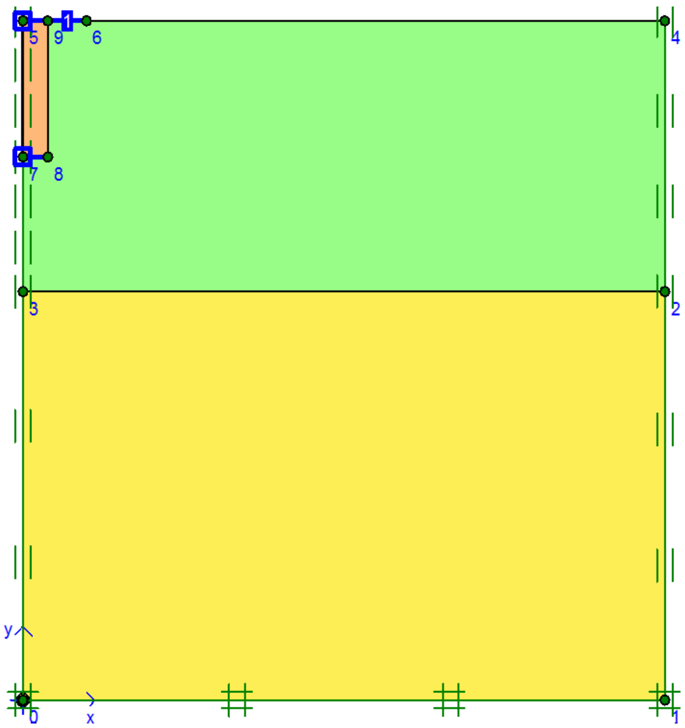

Figure 10. 2D-Axisymmetric model, (GPA) within the expansive clay layer.

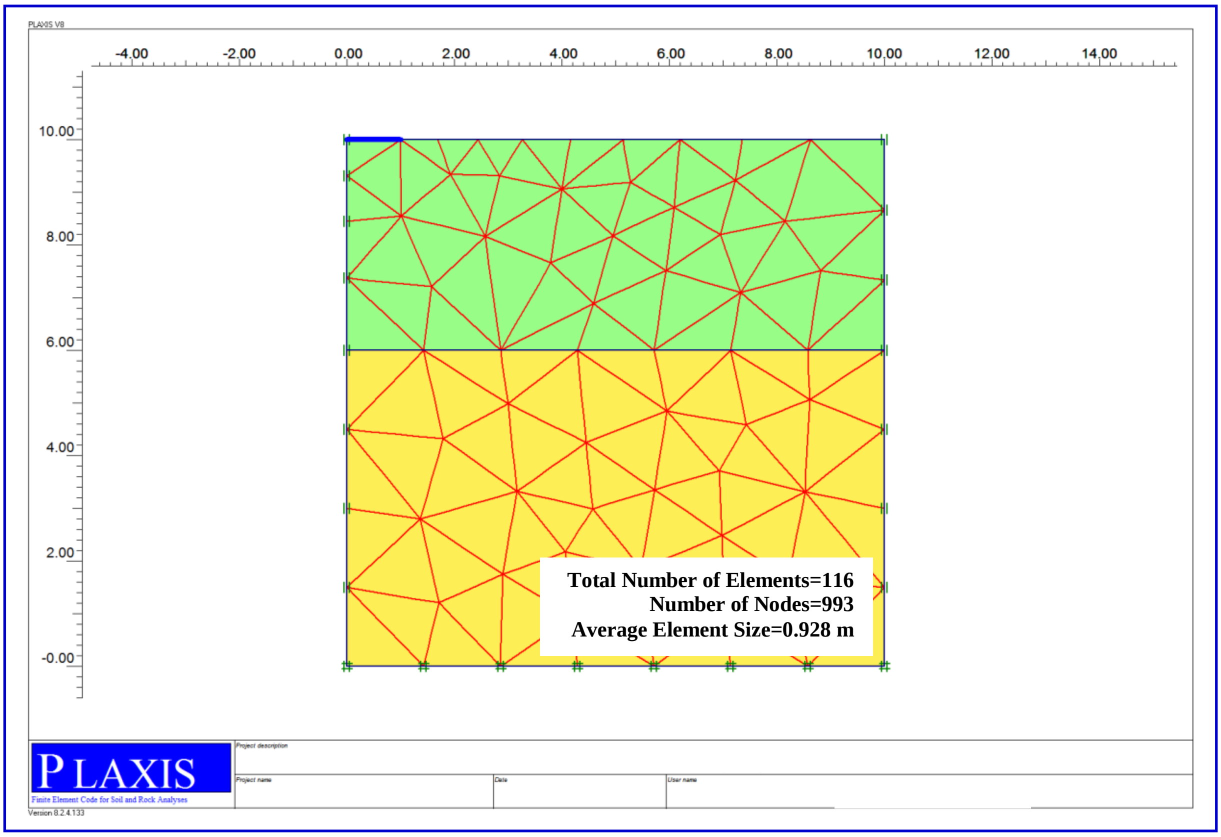

Figure 12. Finite element mesh of foundation system without (GPA).

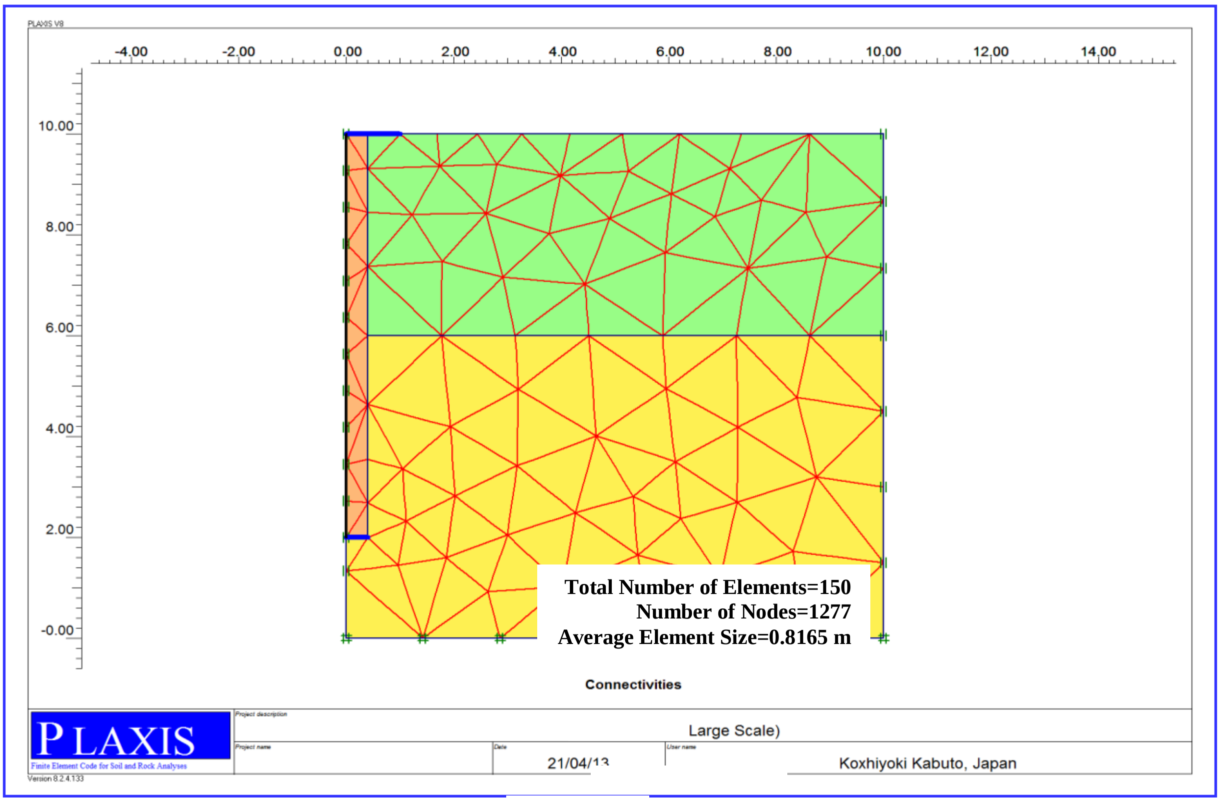

Figure 13. Finite element mesh of (GPA-Foundation System), GPA extended to the non-expansive clay layer.

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/m^2)	5	0.1	5
	ϕ'^{o}	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	Anchor Plate	Anchor Rod
		Steel	Steel	Steel
Linear Elastic	EA (kN/m^2)	5×10^6	5×10^6	2×10^6
	EI (kN/m^2/m)	4×10^4	1×10^4	-
	ν	0.15	0.15	0.15

Table 6. Summary of the maximum heave of unreinforced and expansive soil reinforced with (GPA) models at different lengths and diameters.

(GPA) Diameter (m)	(GPA) Length (m)	(L/D) Ratio	(L/H) Ratio	(B/D) Ratio	Maximum Heave (mm)
Footing Resting on Unreinforced Expansive Soil					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

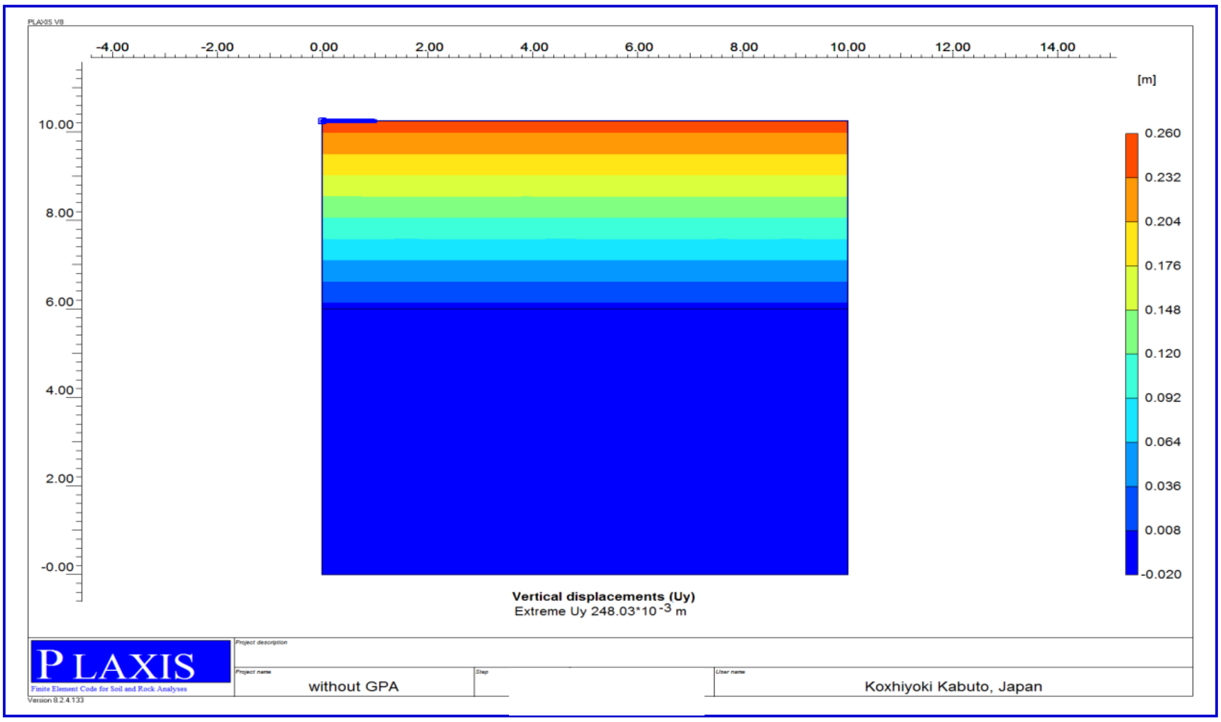

Figure 14. Shading diagram of the vertical displacement distribution resulting from the heave for unreinforced expansive clay in (m).

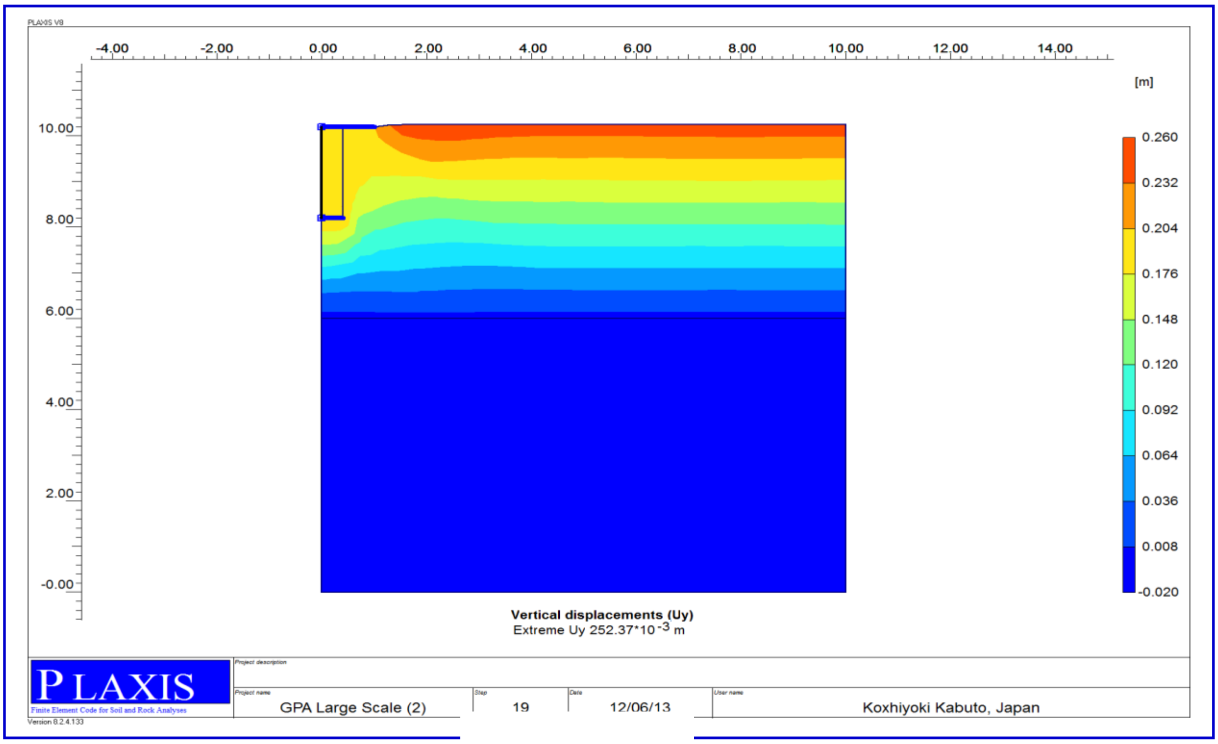

Figure 15. Shading diagram of the vertical displacement distribution resulting from the heave for (GPA at L=2 m and D=0.8 m) in (m).

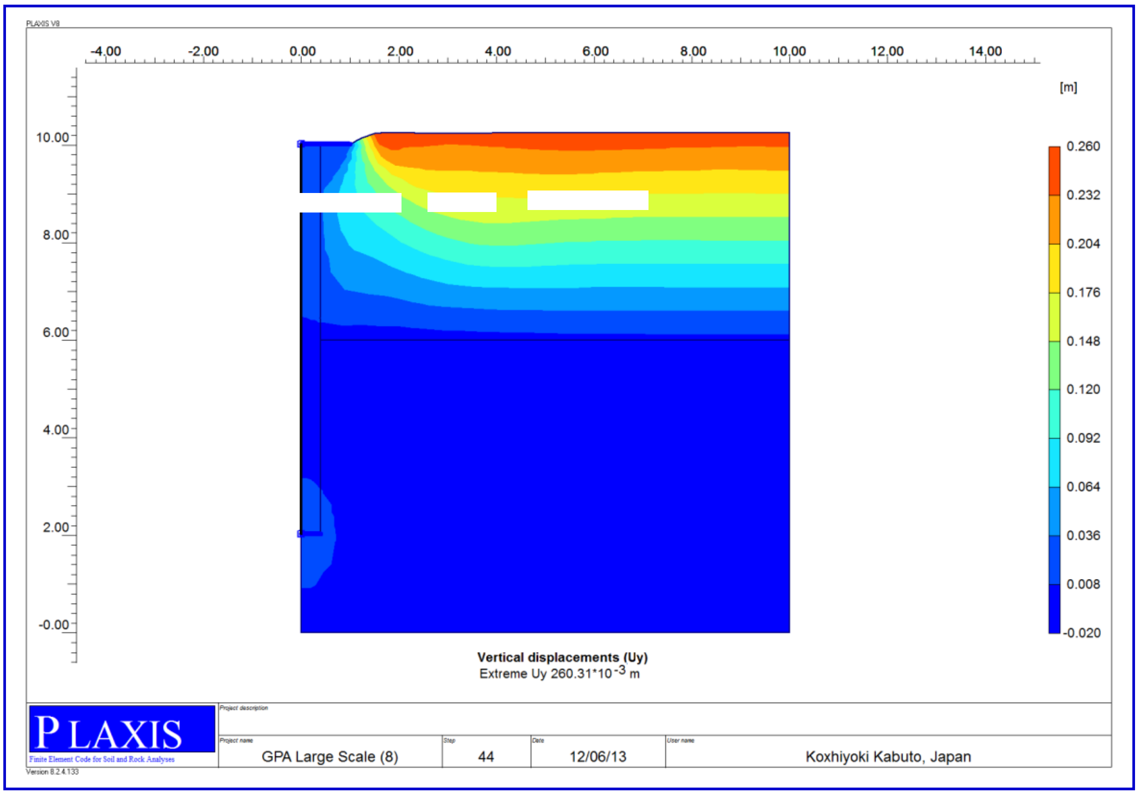

Figure 16. Shading diagram of the vertical displacement distribution resulting from the heave for (GPA at L=8 m and D=0.8 m) in (m).

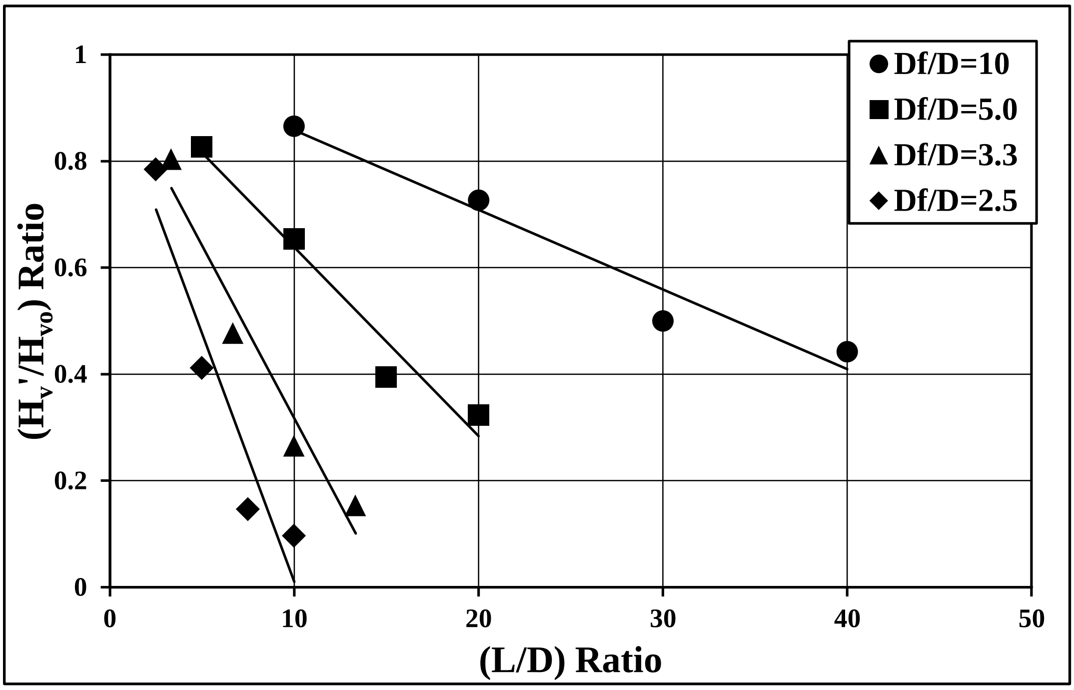

Figure 17. Relationship between the normalized maximum heave (H_v'/H_{vo}) and (L/D) ratio of (GPA) for different ratios of (B/D) - (L/D) ratio effect.

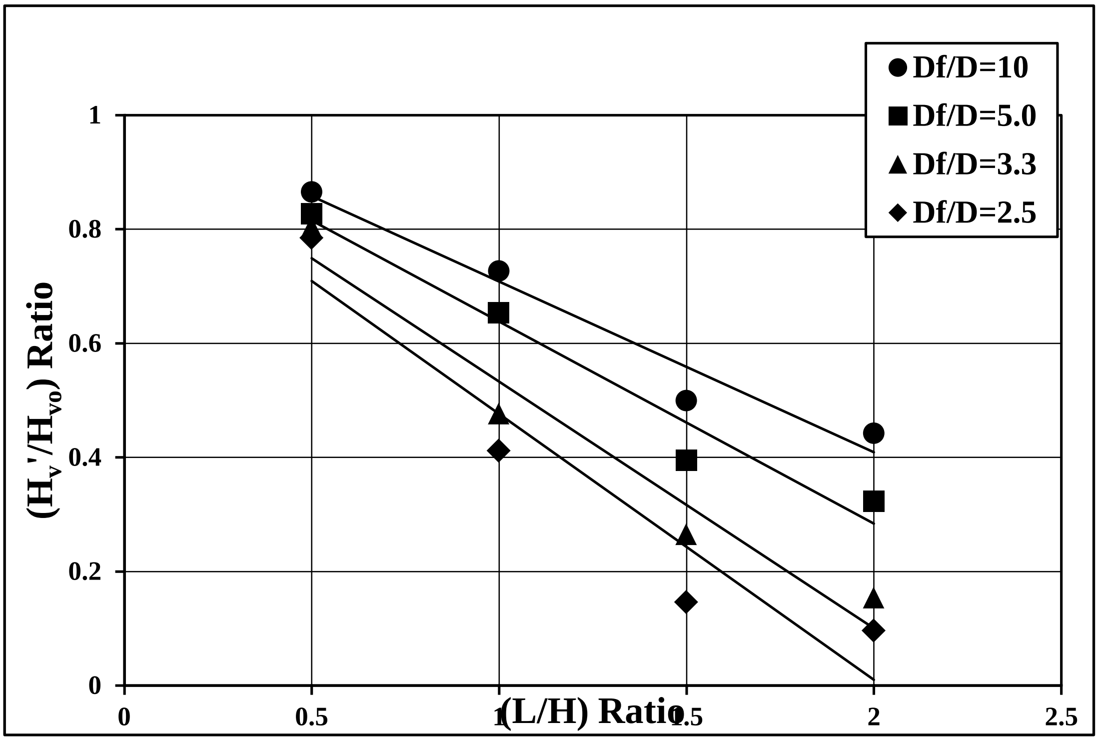

Figure 18. Relationship between the normalized maximum heave (H_v'/H_{vo}) and (L/H) ratio of (GPA) for different ratios of (B/D) - (L/H) ratio rffect.

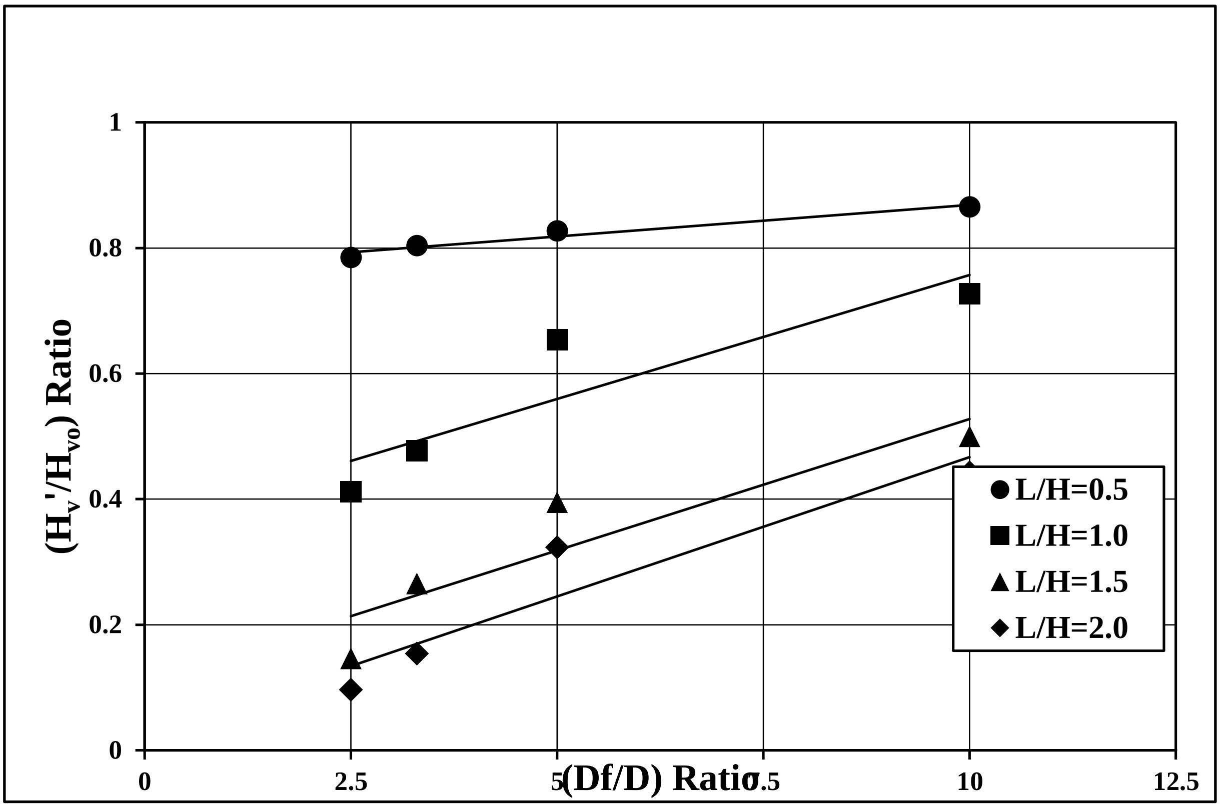

Figure 19. Relationship between the normalized maximum heave (H_v'/H_{vo}) and (B/D) ratio of (GPA) for different ratios of (L/H) - (B/D) ratio effect.

Table 7. Variables limitation for the heave equation.

Variable	Minimum	Maximum
(L/D) Ratio	2.5	40
(B/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	(B/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

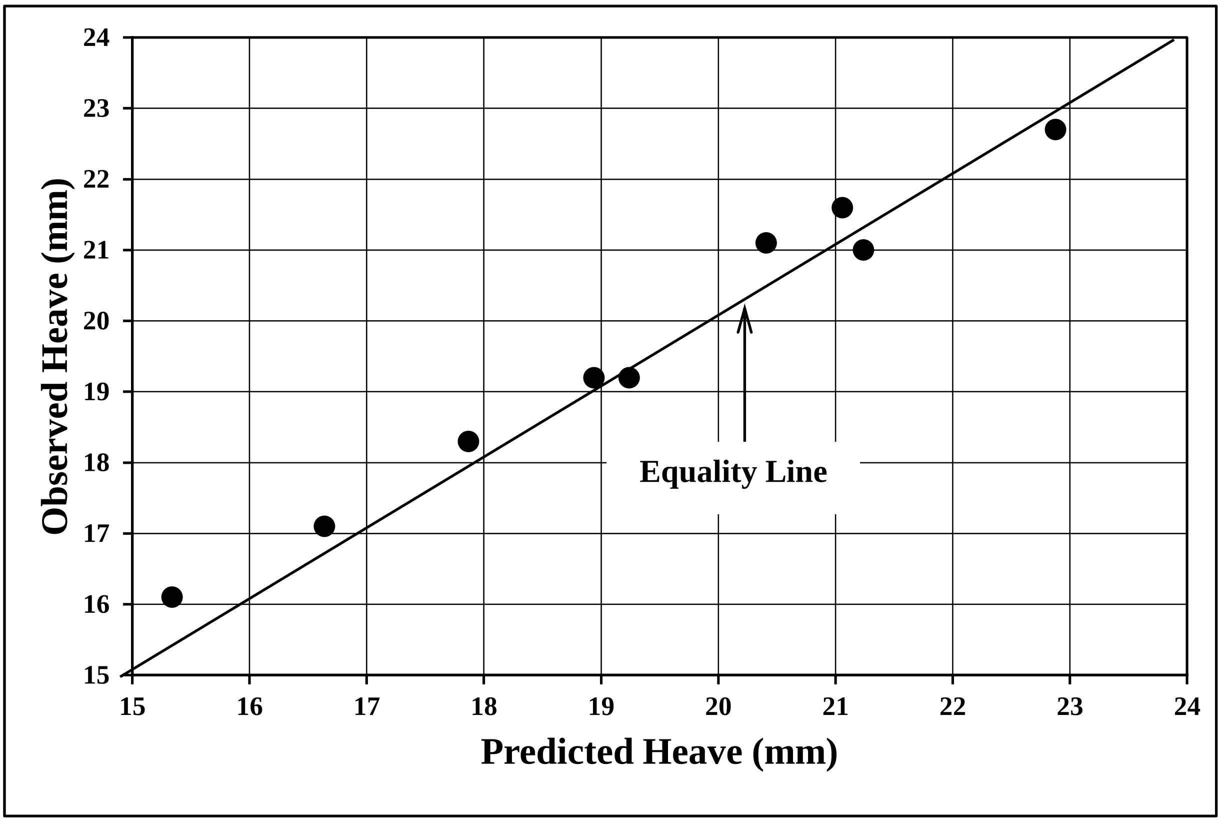

Figure 20. Relationship between the predicted and observed heave of (GPA-Foundation System).