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*«Орталық Азия академиялық ғылыми орталығы» ЖШС «ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналының Web of Science-тің жаңаланған нұсқасы Emerging Sources Citation Index-те индекстелуге қабылданғанын хабарлайды. Бұл индекстелу барысында Clarivate Analytics компаниясы журналды одан әрі the Science Citation Index Expanded, the Social Sciences Citation Index және the Arts & Humanities Citation Index-ке қабылдау мәселесін қарастыруда. Web of Science зерттеушілер, авторлар, баспашылар мен мекемелерге контент тереңдігі мен сапасын ұсынады. ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы Emerging Sources Citation Index-ке енуі біздің қоғамдастық үшін ең өзекті және беделді геология және техникалық ғылымдар бойынша контентке адалдығымызды білдіреді.*

*ТОО «Центрально-азиатский академический научный центр» сообщает, что научный журнал "Известия НАН РК. Серия геологии и технических наук» был принят для индексирования в Emerging Sources Citation Index, обновленной версии Web of Science. Содержание в этом индексировании находится в стадии рассмотрения компанией Clarivate Analytics для дальнейшего принятия журнала в the Science Citation Index Expanded, the Social Sciences Citation Index и the Arts & Humanities Citation Index. Web of Science предлагает качество и глубину контента для исследователей, авторов, издателей и учреждений. Включение Известия НАН РК. Серия геологии и технических наук в Emerging Sources Citation Index демонстрирует нашу приверженность к наиболее актуальному и влиятельному контенту по геологии и техническим наукам для нашего сообщества.*

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# DEVELOPING PREDICTION EQUATION FOR THE SWELLING AND SWELLING PRESSURE OF SWELLABLE CLAY BASED ON EXPERIMENTAL DATA

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**Abstract.** Swellable soil is the type of soil that undergoes significant volumetric change upon changing the moisture content of the soil that takes place in the field due to seasonal changes and elevating the water table level. The granular pile anchor (GPA) is a cost-effective and efficient foundation used to mitigate swellable soil's heave and uplift forces. The main purpose of this study is to introduce new prediction equations for the swelling and uplift pressure of the swellable clays based on previous numerical modelling results in order to reduce the effort, energy, materials, and time, which are usually required to conduct full-scale research on investigating the efficiency of GPA. In this study, numerical analyses were performed using Plaxis 3D software on models of GPA embedded in swellable soil at different GPA lengths, diameters, and number of piles (for group piles). The results of heave and uplift forces were then used to develop empirical equations that can predict heave and uplift forces based on variables proven by previous studies to be significantly influential. Statistical analysis and checks were performed to validate the accuracy of the developed equation. Despite the fact that this study through its finding emphasised the importance of GPA in reducing the swelling and uplift pressure, it was concluded that the developed equations are reliable and applicable for certain GPA length and diameter ranges.

**Key words:** swellable clay; granular pile anchor (GPA), uplift force; empirical equation; statistical analysis

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# ТӘЖІРИБЕЛІК ДЕРЕКТЕР НЕГІЗІНДЕ ІСІНЕТІН САЗДЫҢ ІСІНУІ МЕН ІСІНУ ҚЫСЫМЫН БОЛЖАУ ТЕҢДЕУІН ЖАСАУ

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**Аннотация.** Ісінетін топырақ – маусымдық өзгерістерге және су деңгейінің көтерілуіне байланысты танапта болатын топырақтың ылғалдылығы өзгерген кезде айтарлықтай көлемдік өзгеріске ұшырайтын топырақ түрі. Түйіршікті қада анкері (GPA) ісінетін топырақтың көтерілу және көтерілу күштерін азайту үшін қолданылатын үнемді және тиімді іргетас болып табылады. Бұл зерттеудің негізгі мақсаты, әдетте, GPA тиімділігін зерттеу бойынша толық ауқымды зерттеулер жүргізу үшін талап етілетін күш, энергия, материалдар және уақытты азайту үшін алдыңғы сандық модельдеу нәтижелеріне негізделген ісінетін саздардың ісінуі және көтерілу қысымының жаңа болжау теңдеулерін енгізу болып табылады. Бұл зерттеуде әртүрлі GPA ұзындықтарында, диаметрлерінде және қадалар санында (топтық қадалар үшін) ісінетін топыраққа ендірілген GPA үлгілерінде Plaxis 3D бағдарламалық құралының көмегімен сандық талдаулар жүргізілді. Содан кейін көтерілу және көтеру күштерінің нәтижелері айтарлықтай әсер ететін алдыңғы зерттеулермен дәлелденген айнымалыларға негізделген көтерілу және көтеру күштерін болжай алатын эмпирикалық теңдеулерді әзірлеу үшін пайдаланылды. Жасалған теңдеудің дұрыстығын растау үшін статистикалық талдаулар мен тексерулер жүргізілді. Бұл зерттеу өз нәтижелері арқылы GPA-ның ісіну мен көтерілу қысымын төмендетудегі маңыздылығын атап көрсеткеніне қарамастан, әзірленген теңдеулер сенімді және белгілі GPA ұзындығы мен диаметрі диапазондары үшін жарамды деген қорытындыға келді.

**Түйін сөздер:** ісінетін саз, түйіршікті қада анкері (GPA), көтеру күші, эмпирикалық теңдеу, статистикалық талдау.

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# РАЗРАБОТКА УРАВНЕНИЯ ПРОГНОЗИРОВАНИЯ НАБУХАНИЯ И ДАВЛЕНИЯ НАБУХАНИЯ НА ОСНОВЕ ЭКСПЕРИМЕНТАЛЬНЫХ ДАННЫХ

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**Аннотация.** Набухающие грунты — это тип грунтов, претерпевающих значительные объемные изменения при изменении влажности почвы, происходящем в полевых условиях из-за сезонных колебаний и повышения уровня грунтовых вод. Гранулярная анкерная свая (ГАС, англ. GPA) — это экономичный и эффективный тип фундамента, используемый для снижения сил пучения и подъёма набухающих грунтов. Основная цель данного исследования — разработка новых уравнений для прогнозирования давления пучения и подъёма набухающих глин на основе результатов предыдущих численных исследований. Это позволит сократить затраты ресурсов (сил, энергии, материалов и времени), обычно требуемых для проведения полномасштабных исследований эффективности ГАС. В данном исследовании численный анализ проводился с помощью программного обеспечения Plaxis 3D на моделях ГАС, заглубленных в набухающие грунты, при различных длинах, диаметрах и количестве свай (для групповых свай). Результаты расчётов сил пучения и подъёма были затем использованы для разработки эмпирических уравнений, позволяющих прогнозировать силы пучения и подъёма на основе переменных, значительное влияние которых доказано предыдущими исследованиями. Для подтверждения точности разработанных уравнений был проведён статистический анализ и проверки. Несмотря на то, что данное исследование подчеркнуло важность ГАС в снижении давления набухания и подъёма, сделан вывод о том, что разработанные уравнения надёжны и применимы для определённых диапазонов длины и диаметра ГАС.

**Ключевые слова:** набухающая глина, гранулярная анкерная свая (GPA), подъёмная сила, эмпирическое уравнение, статистический анализ

**Introduction.** The GPA is an advanced foundation system that was presented to mitigate the effect of swellable soil heave on footings and raft foundations and helps to improve their engineering behaviour. GPA is a modified form of the conventional granular pile at which an anchor is added to provide tension resistance for the pile (Miao et al, 2020; Chittoori et al, 2010; Alhani et al, 2020; Choudhary et al, 2018).

The addition of the anchor rod increases tensile resistance, while the force acting downward such as the pile weight and the friction along the pile-soil interface both counteract the swelling force exerted beneath the foundation's base due to swelling.

Additionally, the heave of swellable soil that creates lateral swelling pressure further increases GPA's resistance to the uplift force by confining the granular pile anchor radially and raising friction, which makes it more difficult for the pile to be easily lifted (Gedik et al, 2005; Santhosh et al, 2012; Albadri et al, 2018; Jotisankasa et al, 2016).

The GPA must be designed to withstand the uplift force exerted by the swellable soil. However, factors include GPA length, diameter, L/D ratio, and properties of granular fill material (Vahneiki et al, 2024; Lim et al, 2022; Vanapalli and Fredlund, 2000).

(Ismail, and Shahin, 2011) figured out two modes of GPA failure under pullout load: pile failure mode and bulging failure mode. Additionally, they emphasized that greater ultimate pullout capacity was mobilized by the bigger surface area attained by increasing the length and (or) diameter. Additionally, they proposed that the primary failure mode of GPA is governed by the L/D ratio. A laboratory investigation was conducted by (Albadri et al, 2021; Rao et al, 2007) on GPA installed in swellable soil to examine the pullout forces developed by the heave of swellable soil at different GPA lengths, diameters, and the physical properties of the filling material. The results indicated that as the length and diameter of the GPA increased, the ultimate pullout load also increased in all cases

Based on the findings of finite element analysis using Plaxis software, (Rao, et al, 2007; Bulut, et al, 2001) examined the behavior of a footing reinforced with a single and group GPA at various diameters. The findings indicated that as the GPA's diameter increases, its resistance to the heave of expanding soil appears to improve. In this study, empirical equations to predict swellable soil's heave and uplift forces were developed based on results obtained from numerical modelling using Plaxis 3D. This study aims to reduce the effort, energy, materials, and time, which are usually required to conduct full-scale research on investigating the efficiency of GPA.

**Materials and Methods.** Plaxis 3D was used to simulate swellable soil's volume change and obtain heave and uplift force data for GPA-reinforced swellable soil at different GPA dimensions and numbers of piles. All results were processed and analysed using Design-Expert software, which utilises response surface methodology (RSM) for analysing the data, developing an empirical equation, and validating the accuracy of the developed equation. The key steps to conduct this study are summarised below:

• Initial modelling, including finite element formulation, mesh generation, selecting modelling method, and numerical model generation.

• Running the model to obtain heave and uplift force results for the GPA-reinforced swellable soil.

• Develop the prediction equations after categorising the selected parameters into dependent and independent variables

• Checking the accuracy of the developed equations

**Results and discussion**.

**Numerical Modelling**

The Finite Elements Method (FEM) was used by using PLAXIS 3D to model the swelling of swellable soil through applying positive volumetric strain to the soil model. The finite element equations for distortion theory, consolidation theory, and seepage theory, that were essential during the modelling process, are well defined and presented in PLAXIS Manual. Standard fixity is used to assume the boundary conditions. Which means the horizontal and vertical displacements are both zero.

The essential components of Granular Pile Anchored foundation (GPA) are the top foundation that connected to the underneath rod, then the rod that links the foundation above the ground level with the bottom plate, the filling material around the rod to increase the uplift resistance by the frictional resistance developing between the coarse filling material and the surrounding clay. And lastly, the bottom plate that works as platform for the whole foundation system. In this study, two rods lengths were considered to evaluate the performance of GPA at different lengths.

The swellable and non- swellable soil (underneath the swellable soil) were modelled using the Hardening Soil (HS) model and assumed to behave in undrained conditions. Anchor plates, anchor rods, and shallow footing are made of rigid steel, which is thought to be a linear elastic (LE) model. To prevent needless buckling and deformation, it is believed that the anchor plate, anchor rod, and footing have extremely high flexural stiffness. However, Mohr-Coulomb (MC) is used to represent the granular pile (sand). It was thought to act in a depleted state. Following several tests and sensitivity analysis using the hardening soil model, the Mohr-Coulomb model was chosen. The best model for sand soil is the Mohr-Coulomb model. Figure 1 displays the 3D-PLAXIS modeling of GPA in all of its components.

The global medium option determines the number of triangular elements and the average element size. To enable more precise stress distribution, the medium setting is taken into consideration while creating the model's basic global finite element mesh. A patching test and several experiments with the various medium settings in 3D-PLAXIS were used to choose the medium mesh setting. For medium mesh, the relative element size factor of 1 was selected.

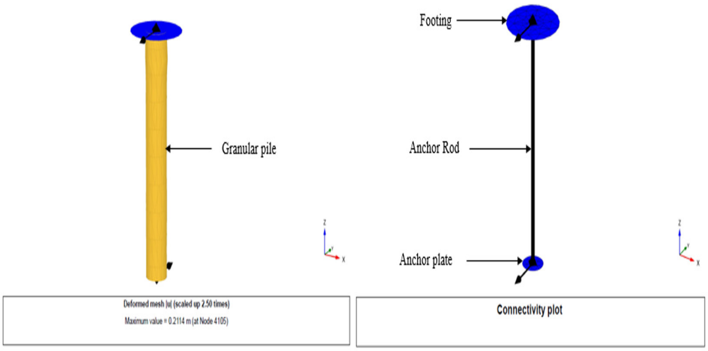


Figure 1. Components of GPA modelled by PLAXIS 3D

The swellable clay is subjected to a volume change of 6.6% in order to simulate the expansion of the Swellable soil layer. Using the Oedometer test, the free swelling test result for swellable soil yielded the same value.

The location of the moisture supply and the amount of overburden pressure determine how quickly swellable clay would normally swell. However, in order to reduce the complexity of the modelling process, the values of volumetric strain and swelling index were applied for the whole layer of the swellable soil. In these situations, the interface between the clay and sand layers at the GPA side will be utilized since $R_{inter}$ = 0.97. Likewise, finite element computations were used to determine the heave, which was then referred to as the heave phase. At this stage, the expanded clay cluster's positive volumetric strains become active.

The reference point for calculating heave is the top head of GPA in the center of the model footing. When positive volumetric strains are applied to the swellable clay without loading activation, GPA becomes lodged in the swellable clay layer and experiences swelling. Because the base plate of GPA was modeled as a fixed end, the volumetric change in swellable clay will cause the footing to raise, and the heave will produce tension force in the anchor.

**Running the Model**

The actual finite element computations have been carried out following the completion of the finite element modeling for the challenges that have been outlined. For these kinds of issues, heave was determined by finite element computations and referred to as Heave Phase. At this stage, the swellable clay cluster's positive volumetric strains are activated.

Additionally, the reference point for calculating heave is the top head of the GPA in the center of the footing model. Lastly, staged construction and plastic computation were also chosen to determine the final heave in the chosen point (A).

The GPA undergoes uplift force at stage two and swelling at stage one when implanted in an expanding layer of clay. The expanding clay's volumetric change will cause the footing to rise, and the heave will provide tension force in the anchor. The ultimate pull-out load resistance of GPA is determined by the anchor's tension value. By computing the stress in the anchor from the node-to-node anchor, the pull-out force is determined at the reference point at the GPA head.

The modelling showed how the heave will create and produce uplift force when the unsaturated soil begins to absorb water. The following relationship can be used to determine the uplift force for any given GPA:

$$F_p = F_s - F_r$$

Where:

$F_p$ = Net uplift force of GPA-reinforced soil

$F_s$ = Uplift force in swellable soil without GPA

$F_r$ = Resistance of uplift force by GPA

According to (Zhan, et al, 2004), the GPA becomes resistant to the uplift force caused by the friction between the soil and the granular interface. The GPA resistance increases with the size of the frictional resistance area. Additionally, the GPA's overall resistance was influenced by the swellable soil's lateral expansion, which placed lateral stresses on the GPA and raised its frictional resistance.

The uplift force results in Tables 1 and 2 show that as the GPA length and diameter rose, the uplift forces and heave in GPA-reinforced soil reduced. The granular pile's weight, the friction generated between the coarse filling material and the swellable clay along the pile-soil interface, and the lateral heaving force developed by the surrounding swellable clay, which cause lateral confinement to the GPA , were some of the factors stated by (Alhani, et al, 2018; Sun, et al, 2008; Alhani, et al, 2021; Salas, et al, 2009; Nelson, et al, 2018) as the causes of this behavior.

However, because the GPA length piercing the non- swellable soil layer loses the strength acquired by the lateral pressure of swellable soil, the rate of GPA resistance to soil swelling reduced for the GPA lengths that exceeded the thickness of the swellable layer.

Table 1. Summary of swelling and swelling pressure results with respect to length and diameter of piles

| Length (m) | Diameter (m) | Swelling (mm) | Swelling Pressure (kN) |
|---|---|---|---|
| 1 | 0.4 | 191 | 485.9 |
| | 0.6 | 149 | 451.2 |
| | 0.8 | 84 | 258.9 |
| | 1 | 67 | 204.2 |
| 3 | 0.4 | 183 | 459 |
| | 0.6 | 118 | 351.2 |
| | 0.8 | 58 | 202.9 |
| | 1 | 46 | 153.2 |

| | | | |
|---|---|---|---|
| 5 | 0.4 | 175 | 413.8 |
| | 0.6 | 92 | 286.8 |
| | 0.8 | 44 | 156.1 |
| | 1 | 30 | 94.5 |
| 7 | 0.4 | 173 | 371 |
| | 0.6 | 73 | 212.2 |
| | 0.8 | 27 | 99.1 |
| | 1 | 20 | 21.5 |

Table 2. Summary of swelling and swelling pressure results with respect to length and number of piles for group pile configuration

| Length (m) | Number of Pile | Swelling (mm) | Swelling Pressure (kN) |
|---|---|---|---|
| 3 | 2 | 135 | 557.60 |
| | 3 | 114 | 380.90 |
| | 5 | 94 | 274.80 |
| 5 | 2 | 60 | 261.10 |
| | 3 | 41 | 178.00 |
| | 5 | 33 | 89.40 |
| 7 | 2 | 60 | 191.30 |
| | 3 | 33 | 103.20 |
| | 5 | 22 | 86.00 |

**Development of Equation**

Prediction model was developed to predict the swelling and swelling pressure by using regression analysis. A statistical tool named RSM (Response Surface Methodology) was used for this purpose. The inputs used for the model are the ratio between length and diameter of the pile, the number of piles, the ratio between the length of pile and the height of swellable layer and the cross-sectional ratio. The outputs should be the swelling (heave of soil) and the swelling pressure (uplift pressure).

The assumption of linearity is checked using the relationship between the uplift force's actual and expected values. The link between the linear model's actual and anticipated values is shown in Figure 2. Because the values were evenly spread around the fitted line, the findings demonstrated a very high degree of agreement between the actual and anticipated values. Thus, the linearity assumption is satisfied. As seen in Figure 3, there was a high correlation between the expected and actual values of heave, and the linearity conditions were also satisfied. The following is the expression for the uplift force prediction linear model:

$$\frac{F_p}{F_s} = 0.62\frac{L}{D} + 0.012N + 0.02A_r - 0.308 - 0.063\frac{L}{H}$$

The linear model for the heave prediction is expressed as:

$$\frac{H_p}{H_s} = 0.091 + 0.0255\frac{L}{H} + 0.0092N - 0.442\frac{L}{D} - 0.056A_r$$

Where:

$F_s$: Ultimate swelling force for non-GPA-reinforced soil

$F_p$: Ultimate swelling force for GPA-reinforced soil,

$H_s$: Ultimate swelling for non-GPA-reinforced soil

$H_p$: Ultimate swelling for GPA-reinforced soil

L: Pile length,

D: Pile diameter,

H: Thickness of swellable soil layer, and

$A_r$: Area ratio (which defined as the ratio of footing area to the cross-sectional area of GPA).

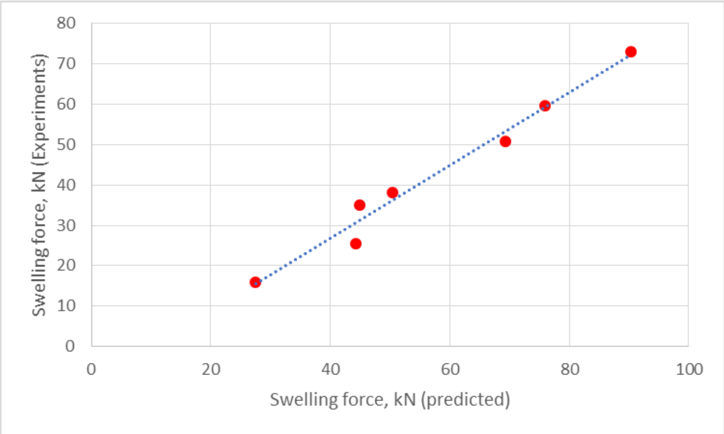


Figure 2. The relationship between the actual and the predicted values of swelling pressure

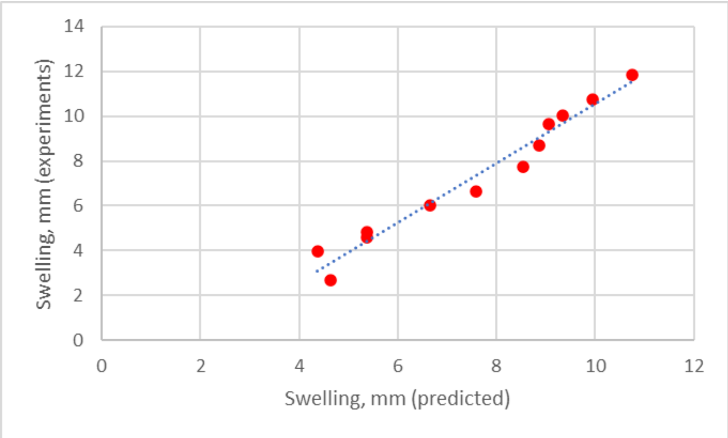


Figure 3. The relationship between the actual and predicted values of soil swelling

**Validating the Accuracy of Equation**

For the data analysis, linear regression was taken into consideration. The following assumptions were examined in order to determine whether the linear models were adequate:

• Linearity to examine the correlation between the response and the components,

• Normality assumption to verify that the data has a normal distribution,

• The distribution of the data around the zero was examined using the equal variance assumption, and

• The autocorrelation between the independent and dependent variables was confirmed using the independence assumption.

The distribution of the residual data was examined using the error distribution of the residuals plot (normal probability). The difference between the actual and anticipated values was used to calculate the residuals. The residuals' normal distribution suggests that the model does a good job of fitting the data. The distribution of residuals along the straight line indicates the presence of a normal distribution. The residuals are not normally distributed, as evidenced by the other distributions, which include S, left and right skews, and long and short tails.

In other words, the model is inappropriate for describing the relationship between the causes and the responses; instead, nonlinear models should be changed to get the typical relationship. As can be seen in Figure 4, the normalcy assumption is satisfied because the residuals are distributed regularly along the linear straight. However, because the linear model's assumptions were confirmed, as illustrated in Figure 5, the linear model's effectiveness and capacity to forecast the Hp/Hs were guaranteed.

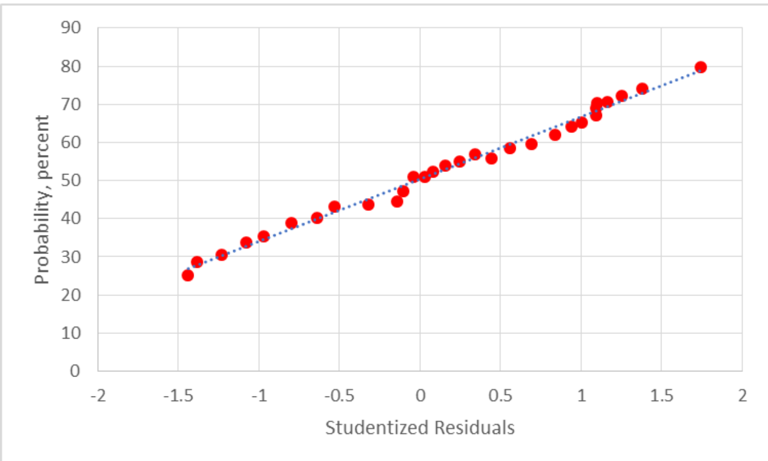


Figure 4. Regression analysis plot of swelling pressure

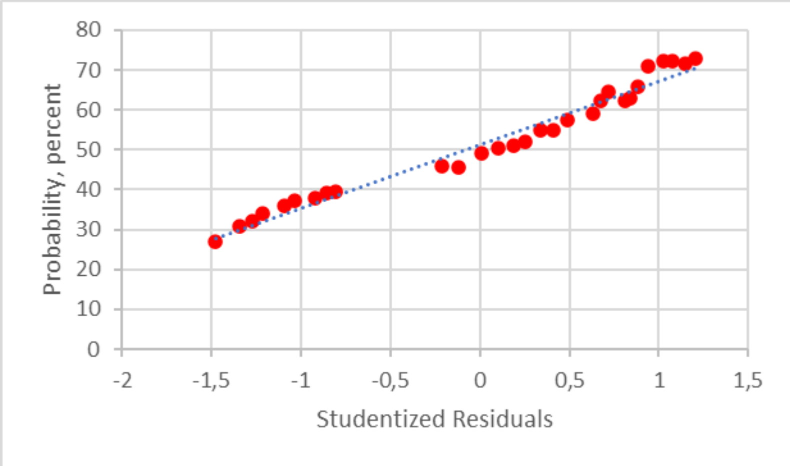


Figure 5. Regression analysis plot of soil swelling

Plotting the residuals against the anticipated values allowed for the investigation of the homoscedasticity (equal variance) assumption for both dependent variables ($F_p/F_s$ and $H_p/H_s$), as illustrated in Figures 6 and 7, respectively. The symmetrical distribution of the expected values suggests that the linear model accurately describes the facts.

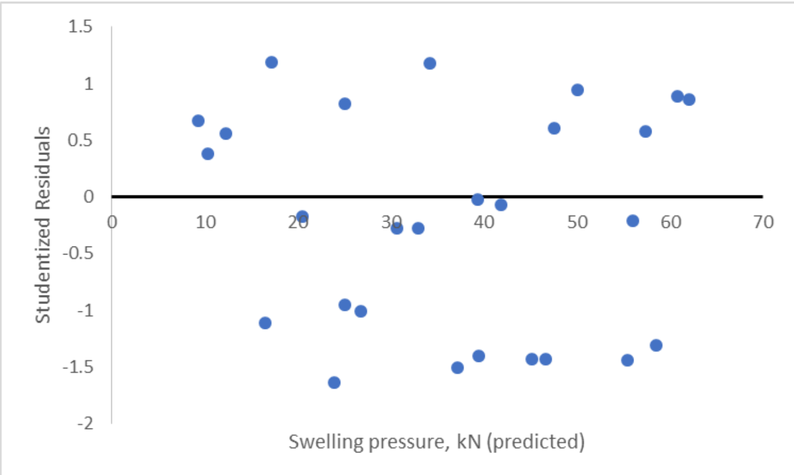


Figure 6. The predicted values versus the studentized residuals for swelling pressure values

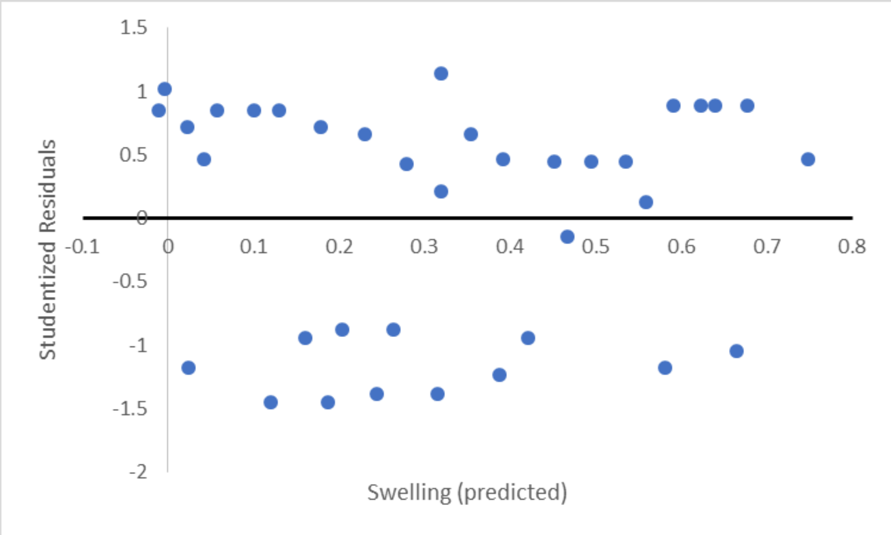


Figure 7. The predicted values versus the studentized residuals for soil swelling values

Around the regression line, the gap between the actual and anticipated values are dispersed. Normality assumption was confirmed since the linear model was found suitable for data fitting. Additionally, charting the anticipated values versus the studentized residuals was very helpful for evaluating the assumption of homoscedasticity.

Heteroscedasticity, or asymmetrical patterns, show that the studentized residuals differ proportionately from the expected values. On the other hand, homoscedasticity is satisfied when the pattern is symmetrical. This symmetry adds more evidence that the data is well represented by the linear model. Additionally, the symmetrical distribution and random dispersion of data points around zero verify that the premise of equal variance is maintained.

Figure 8 demonstrates that the run number values were randomly distributed as an examination of the assumption of independence, suggesting that the linear model is appropriate for predicting the $F_p/F_s$. Furthermore, there is no autocorrelation shown by the values assigned to the positive and negative sides. As a result, the independence assumption is satisfied. Since it was demonstrated that there are no autocorrelations between the values to forecast the $H_p/H_s$, as illustrated in Figure 9, similar behavior was recorded.

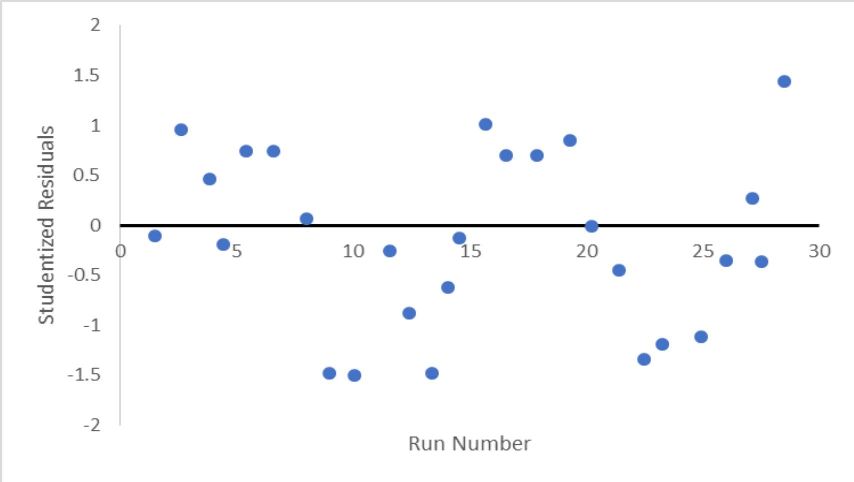

Figure 8. The run number versus studentized residuals plot for swelling pressure

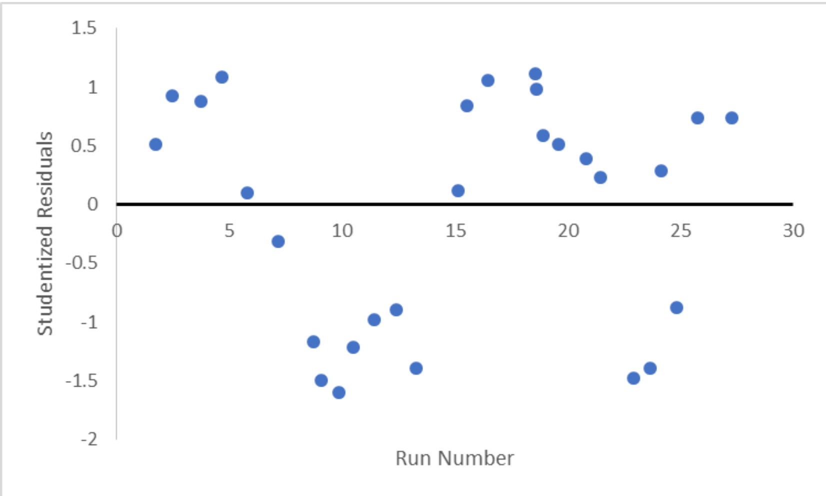

Figure 9 The run number versus studentized residuals plot for soil swelling

Only the ranges of the variables listed allow the developed equation to be used. Table 5 presents the variable ranges. Therefore, further study and investigation are required to check the applicability of the developed equations for a broader range of data.

Table 5. Variables limitation for the heave and uplift pressure equations

| Variable | Minimum | Maximum |
|---|---|---|
| (L/D) Ratio | 1.5 | 20 |
| (L/H) Ratio | 0.7 | 2 |
| Pile Number, N | 1 | 5 |
| $A_r$ | 3 | 22 |

**Conclusions.** The following conclusions were drawn from the obtained results

1. The granular pile anchor (GPA) is a cost-effective and efficient type of foundations that mitigate swellable soil's heave and uplift forces
2. The results showed that the performance of GPA in decreasing the heave and uplift force is highly affected by the diameter and length of GPA as well as the number of piles. Larger diameter and longer GPA contribute to higher performance of GPA
3. In certain cases where increasing the pile length and diameter is not possible, using group GPA connected by top pile cup showed significant results in decreasing the heave and uplift force of swellable soil
4. The predicted values heave and uplift force that obtained from developed prediction equations were found reliable after comparing the predicted values with those obtained from the numerical modelling.
5. The regression analysis performed to validate the accuracy of the predicted values showed a high level of accuracy and proved the applicability of the developed equations
6. It was reported that the developed equations are not applicable for certain GPAs due to some limitations related to GPA length, diameter, and number of piles (for group GPA).

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