Computational Engineering and Physical Modeling 5-3 (2022) 64-81

Contents lists available at **CEPM**

Computational Engineering and Physical Modeling

Journal homepage: www.jcepm.com

# Finite Element Based Investigation of Belled Piers in Expansive Soils

**Gideon Amha Gebremedhin**[1*], **Henok Fikre Gebregziabher**[2]

1. Lecturer, School of Civil and Environmental Engineering, Addis Ababa Institute of Technology, Ethiopia
2. Associate Professor, School of Civil and Environmental Engineering, Addis Ababa Institute of Technology, Ethiopia

Corresponding author: *gideon.amha@aait.edu.et*

https://doi.org/10.22115/CEPM.2023.364210.1223

## ARTICLE INFO

Article history:
Received: 03 October 2022
Revised: 20 April 2023
Accepted: 22 April 2023

Keywords:
Expansive soils;
Belled piers;
FEM;
Parametric investigation;
Cost comparison.

## ABSTRACT

To address previous limitations of belled piers embedded in expansive soils, a numerical investigation is performed using the finite element-based software Abaqus. A parametric study, cost comparison, and trend line development (for design) were conducted. The parametric investigations indicated that when designing belled piers in expansive soils, increasing the shaft diameter is preferred to increasing the length, or the bell size; the limiting diameter for belled piers is much higher than that for straight shaft piers; most belled piers in expansive soils in Ethiopia do not need tensile reinforcement; and the applied load needed to fully eliminate tensile stresses in belled piers is less than that needed in straight shaft piers. The cost comparison indicated that for smaller values of the swelling pressure and the depth of the swelling zone, straight shaft piers are more cost-effective; while for medium to large values of the swelling pressure and the depth of the swelling zone, large bell size belled piers are more cost-effective. The trend lines indicated that in Ethiopia belled piers with the minimum sizes can be used.

How to cite this article: Gebremedhin GA, Gebregziabher HF. Finite element based investigation of belled piers in expansive soils. Comput Eng Phys Model 2022;5(3):64–81. https://doi.org/10.22115/cepm.2023.364210.1223

## 1. Introduction

Expansive soils exist throughout the world; as an example, considering the authors' country, the distribution of expansive soils in Ethiopia is presented in Fig. 1. Consequently, and, with the rapid development of urban infrastructure, expansive soil related problems have become more evident. There is therefore a need to address the problems associated with these soils [1]. One solution is to use belled pier foundations.

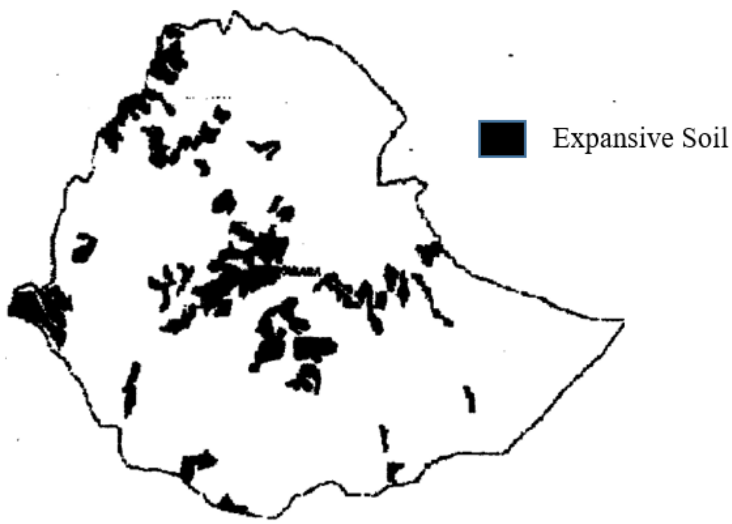


**Fig. 1.** Distribution of expansive soils in Ethiopia [2].

Various research and books have investigated and reported on the behavior of straight shaft piers in expansive soils [3–13]. However, very few investigations exist concerning belled piers in expansive soils. Though some design approaches exist [3,4,14], the only in-depth investigation of the behavior of belled piers in expansive soils was presented by [3], who considered the soil as an elastic medium known as the elastic pier approach. This approach was later somewhat modified by [7] and [10] to make it more easily usable by the design engineer.

[15] investigated the performance of straight shaft piles/piers and under-reamed/belled piles/piers embedded in expansive soils. Pile upward movement due to soil swelling is reduced to about (20%-30%) when using under-reamed piles with one base bulb instead of conventional straight shaft piles, deeper piles showed more resistance to upward and downward movement than shallower piles [15]. Pile uplift force due to soil swelling is reduced to about (10%-20%) when using under-reamed piles instead of conventional straight shaft piles [15]. The use of under-reamed piles instead of straight shaft piles for the same pile length to pile diameter ratio increases the pull-out capacity of the piles by (12.5% -38.46%) for unwetted soil state, and about (14.26% - 80%) for wetted soil state [15].

The most common design approach for belled piers in expansive soils is the approach by [14]. This approach has the following limitations: (1) pier heave is considered to be zero. If some pier heave were to be allowed, more economical designs can be obtained, (2) no soil-pier slip is considered. But, some soil-pier slip is certain to exist in the actual soil-pier interaction, (3) bell friction is neglected, (4) interface shear stress is considered as a constant maximum value throughout the length of the belled pier in the swelling zone, (5) for large bell sizes, increase in shaft diameter does not reduce the corresponding required length for a safe design. This results in uneconomical designs for large bell-size belled piers, and (6) does not enable the determination of the maximum tensile stresses developed inside the belled piers accurately.

The elastic pier approach investigation [3,7,10] in relation to belled piers in expansive soils has the following limitations: (1) the plastic behavior of the soil is not considered, (2) investigations are presented for belled piers with bell sizes of a bell to shaft diameter (db/d) of 2 only, (3) relationships with time have not been investigated, (4) bell friction is neglected, (5) no suggestions have been given on whether to use small bell sizes or large bell sizes, and (6) the interface shear stress between the pier and the soil is an approximation.

This research is therefore conducted to address these limitations of both the design approach proposed by [14] and the elastic pier approach investigation [3,7,10].

## 2. Research significance

Belled pier foundations are rational and reliable solutions to combat the problem of expansive soils [4]. However, very few investigations exist that study the behavior of these foundations. The only in-depth investigation here is the elastic pier approach which has limitations and is majorly focused on straight shaft piers. Concerning the design of belled piers in expansive soils, the rigid pier method is commonly used but is generally not cost-effective. To address these limitations and to study belled piers embedded in expansive soils, a finite element-based investigation is performed.

## 3. Modelling of the soil and pier

Belled piers are modeled in expansive soil using the FEM software Abaqus CAE. Abaqus/Standard (static analysis) is used in the simulation considering the complexity of the problem. A hypothetical ground condition (site) is modeled. A general condition is assumed instead of a specific one. The belled piers are fully embedded in clay soils. The model is prepared based on an actual ground condition. The GWT is just below the swelling zone. Soil properties are determined from laboratory tests performed on samples taken from the actual site.

## 4. Formulation of the finite element model in Abaqus

As shown in Fig. 2, the finite element model in Abaqus has three parts; namely, the belled pier, the swelling zone, and the non-swelling zone. Since these parts are symmetric with respect to both actions on them and their shape, axisymmetric modeling is chosen where one-half of the belled pier-soil combination is modeled in two dimensions. The dimensions of the soil are chosen in a way that the boundary effect on the belled pier behavior is minimized; the width of the soil is taken to be 10.5db and the length to be L + 10db where db is the diameter of the base of the belled pier and L is the length of the belled pier [16]. The Boundary Conditions represent the field conditions with restrained movement and water flow. The Axisymmetric Boundary

Condition restrains movement along the horizontal plane and rotation along the vertical plane and a plane in the third dimension.

The belled pier is assumed to have elastic properties only while the soil has elastic, plastic, and swelling properties. The elastic properties of the belled pier and the soil in Abaqus are defined by specifying Young's modulus and Poisson's ratio of the two materials. The elastic behavior for both the belled pier and the soil is assumed to be linear and isotropic. The total stress is defined from the total elastic strain as $\sigma = D^{el}\varepsilon^{el}$ where $\sigma$ is the total stress ("true," or Cauchy stress in finite-strain problems), $D^{el}$ is the fourth-order elasticity tensor, and $\varepsilon^{el}$ is the total elastic strain (log strain in finite-strain problems).

The plastic property of the soil is modeled in Abaqus using the modified Drucker-Prager (Cap plasticity) model by specifying the Cap plasticity model parameters. The Cap plasticity model can be used in conjunction with the elastic material model in Abaqus and is intended to model cohesive geological materials that exhibit pressure-dependent yields, such as soils and rocks. It is appropriate to model soil behavior because it is capable of considering the effect of stress history, stress path, dilatancy, and the effect of the intermediate principal stress. The Cap plasticity model

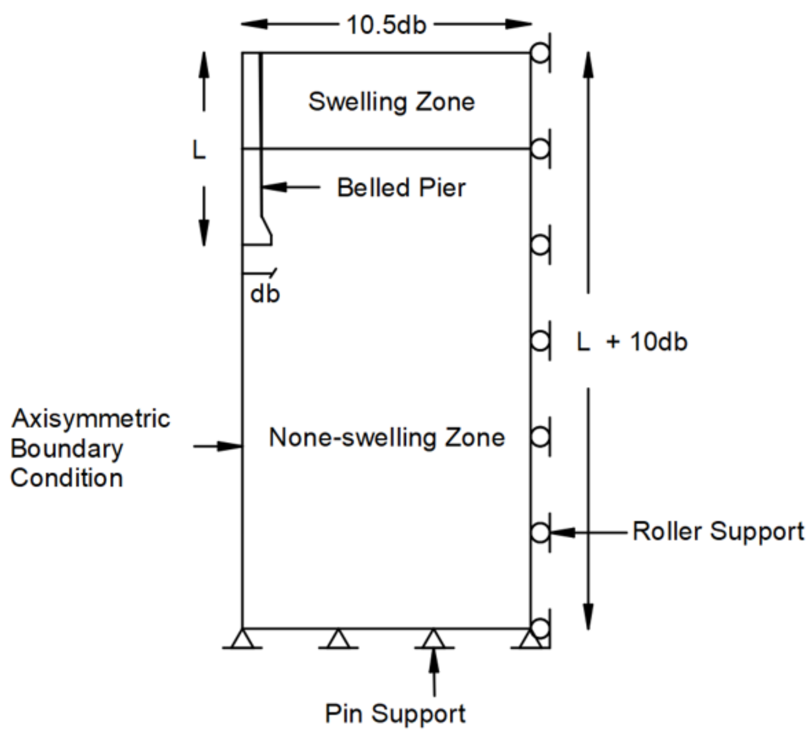


**Fig. 2.** Model, parts, and boundary conditions in Abaqus.

considers the addition of a cap yield surface to the Drucker-Prager plasticity model. The addition of the cap yield surface to the Drucker-Prager model serves two main purposes: it bounds the yield surface in hydrostatic compression, thus providing an inelastic hardening mechanism to represent plastic compaction; furthermore, since softening is provided as a function of the inelastic volume increase that occurs when materials yield on the Drucker-Prager shear failure surface during shear, this helps to manage volume dilatancy. As shown in Fig. 3, the yield surface of the modified Drucker–Prager/cap plasticity model consists of three parts: a Drucker–Prager shear failure surface, an elliptical cap, which intersects the mean effective stress axis at a right angle, and a gradual interface region between the cap and the shear failure surface.

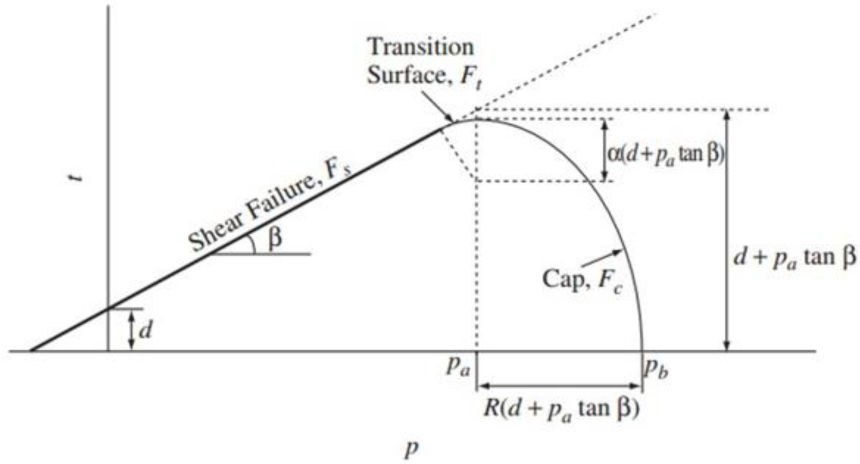


**Fig. 3.** Yield surfaces of the modified Cap plasticity model in the p–t plane [17].

The swelling property of the soil is modeled in Abaqus using the Moisture Swelling model in conjugate with the Sorption model by considering coupled pore fluid diffusion (stress) analysis. The moisture swelling model defines the saturation-driven volumetric swelling of the solid skeleton of a porous medium in partially saturated flow conditions. The moisture swelling model assumes that the volumetric swelling of the porous medium's solid skeleton is a function of the saturation of the wetting liquid in partially saturated flow conditions. The porous medium is partially saturated when the pore pressure is negative. The swelling behavior is assumed to be reversible. The logarithmic measure of swelling strain is calculated with reference to the initial saturation. The Sorption model represents the suction-saturation relationship of the soil and defines a porous material's absorption (exsorption) behavior under partially saturated flow conditions. A porous medium becomes partially saturated when the total pore pressure becomes negative. Negative values of pore pressure represent capillary effects in the medium. The transition between absorption and exsorption and vice versa takes place along "scanning" curves. Only adsorption behavior is considered for the modeling of the swelling property.

The pier-soil contact was modeled using Coulomb frictional model in conjugate with the "hard" contact model by considering the contact pairs algorithm, finite sliding, and node-to-surface contact. Pier-soil slip is allowed. As per the recommendations of [16], and by considering the soil to be clay soil, the tangential behavior is modeled in the Coulomb frictional model by providing a very high value of the frictional coefficient, μ, but the interface shear stress was limited by providing a limit shear stress value. The limit shear stress value is dependent on the cohesion in the non-swelling zone and on the swelling pressure in the swelling zone. A more comprehensive form of the traditional isotropic Coulomb friction model is provided in Abaqus for use with all contact analysis capabilities. The extensions include an additional limit on the allowable shear stress, anisotropy, and the definition of a "secant" friction coefficient. The standard Coulomb friction model assumes that no relative motion occurs if the equivalent frictional stress is less than the critical stress, which is proportional to the contact pressure. It is possible to put a limit on the critical stress. If the equivalent stress is at the critical stress, slip can occur. Therefore, this particular way of contact modeling in allows for pier-soil slip. The contact relationship known as "hard" ensures that there is minimal penetration of the slave surface (such as soil) into the master surface (such as a pier) at constraint locations, and it also prevents the transfer of tensile stress across the interface. When surfaces are in contact, any contact pressure can be transmitted between them. The surfaces separate if the contact pressure reduces to zero. Separated surfaces come into contact when the clearance between them reduces to zero. See Fig. 4.

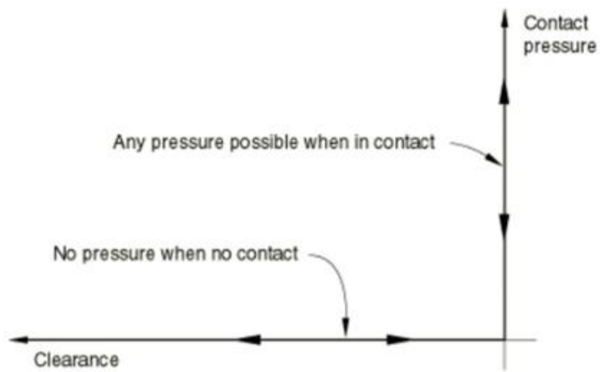


**Fig. 4.** Default pressure-overclosure relationship [17].

Four-node axisymmetric quadrilateral, bilinear displacement, and bilinear pore pressure (CAX4P) mesh elements are used for the soil (both swelling and non-swelling zone) based on recommendation of [16]. The mesh elements used for the pier are four-node bilinear axisymmetric quadrilateral (CAX4) elements. In both cases, first-order mesh elements are used. A mesh sensitivity study was conducted as shown in Fig. 5 and a minimum mesh element size (near the piers) of 0.51 m by 0.51 m was used.

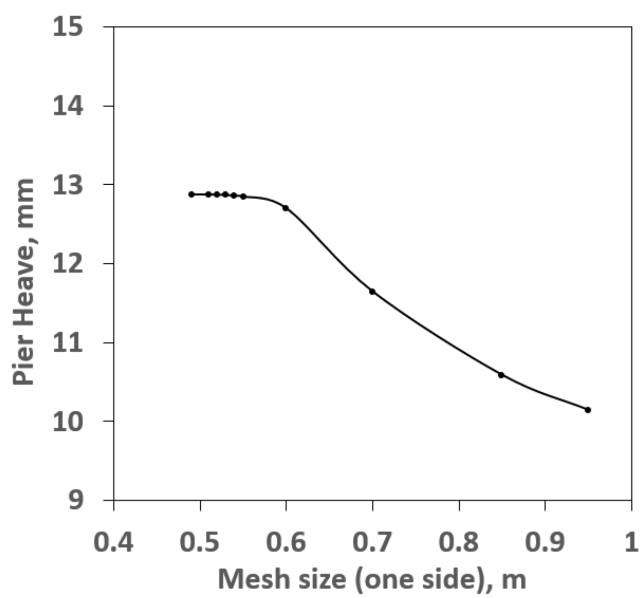


**Fig. 5.** Mesh sensitivity study result.

The finite element analysis is run in two steps. In the first step, a geostatic stress field procedure is invoked; while in the second step, a coupled pore fluid diffusion/stress analysis is invoked. Geometric nonlinearity is considered in both steps to account for large displacements. A geostatic stress field procedure is used to verify that the initial geostatic stress field is in equilibrium with gravity loads and boundary conditions and to iterate, if necessary, to obtain equilibrium. The procedure guarantees that the initial stress state of an element in a clay layer is contained within the yield surface of the cap model. Here, self-weight (gravity load) is applied by using the body force option in Abaqus. In this option, the unit weight is specified for every point on the model and the self-weight (gravity load) is calculated by multiplying the specified unit weight by the depth of every point as measured from the top of the model; i.e., the self-weight (gravity load) will be the overburden pressure. Considering the complexity of the problem, equilibrium is established by making Abaqus compute the initial stress state itself by invoking the enhanced procedure; where the tolerable displacements are taken to be $10^{-5}$ m (default value).

Fig. 6 shows an example of stresses computed by Abaqus in units of kPa for a belled pier in expansive soil in the geostatic stress field procedure. Considering the height of the model (19 m), the heights of the swelling and non-swelling zones of 3 m and 16 m respectively, and saturated unit weight of 17.6 kN/m$^3$ for the swelling zone and the submerged unit weight of 7.79 kN/m$^3$ for the non-swelling zone, the stress computed by Abaqus at the bottom of the model is 175 kPa which closely agrees with the actual overburden at this point of 177 kPa (17.6 kN/m$^3$ $*$ 3m + 7.79 kN/m$^3$ $*$ 16m). Fig. 7 shows an example of deformations computed by Abaqus in units of meter for a belled pier in expansive soil in the geostatic stress field procedure. As it is observed, the deformations are very small and can be approximated to be equal to zero; proving that equilibrium was established.

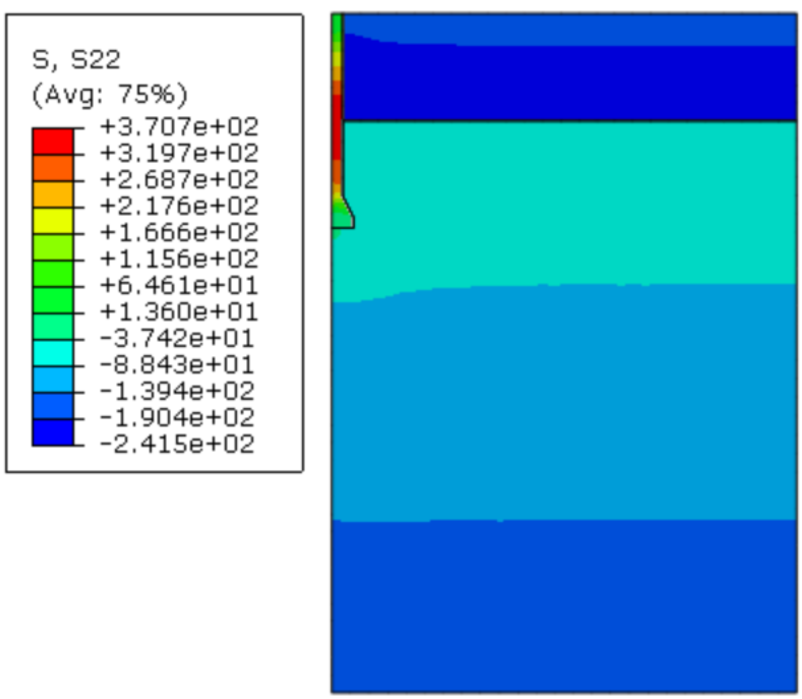


**Fig. 6.** Initial Stress State as computed by Abaqus in the geostatic stress field procedure.

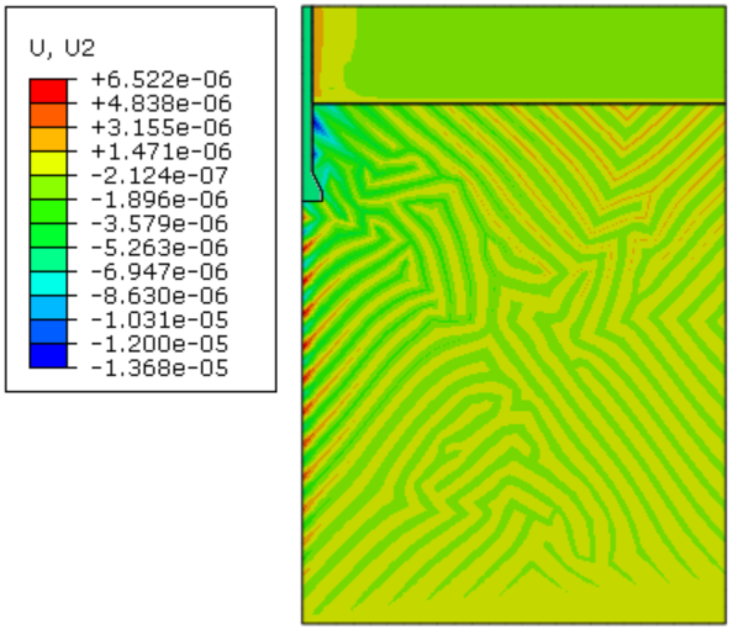


**Fig. 7.** Deformations as computed by Abaqus in the geostatic stress field procedure.

A coupled pore fluid diffusion/stress analysis is used to model single-phase, partially, or fully saturated fluid flow through porous media. A porous medium is modeled by a conventional approach that considers the medium as a multiphase material and adopts an effective stress principle to describe its behavior. The porous medium modeling provided considers the presence of two fluids in the medium. One is the "wetting liquid," which is assumed to be relatively (but not entirely) incompressible. Often the other is a gas, which is relatively compressible. An example of such a system is soil containing groundwater. When the medium is partially saturated, both fluids exist at a point; when it is fully saturated, the voids are completely filled with the wetting liquid. The horizontal boundary at the top of the swelling zone is made permeable to allow for the saturation of the swelling zone. This will initiate the swelling process in the swelling zone since the soil here has a swelling behavior defined by the Moisture Swelling model in conjugation with the Sorption model. The swelling process continues until the entire depth of the swelling zone is at a saturation level of 100%; a sufficient step time is specified to allow for this. The step considers the transient analysis where the backward difference operator is used to integrate the continuity equation, this operator provides unconditional stability so that the only concern with respect to time integration is accuracy. Loads on the belled pier, if any, are also applied in this step.

## 5. Model validation

The credibility and accuracy of the formulated finite element model in Abaqus is evaluated using the following comparisons. Fig. 8 uses the following symbols: $\rho_o$ = field heave, $\rho_p$ = pier heave, $P_{max}$ = maximum tensile force in the belled pier, $F_{um}$ = 0.01$Es$, $Es$ = modulus of elasticity of the soil, $d$ = shaft diameter, and $Cu$ = undrained cohesion.

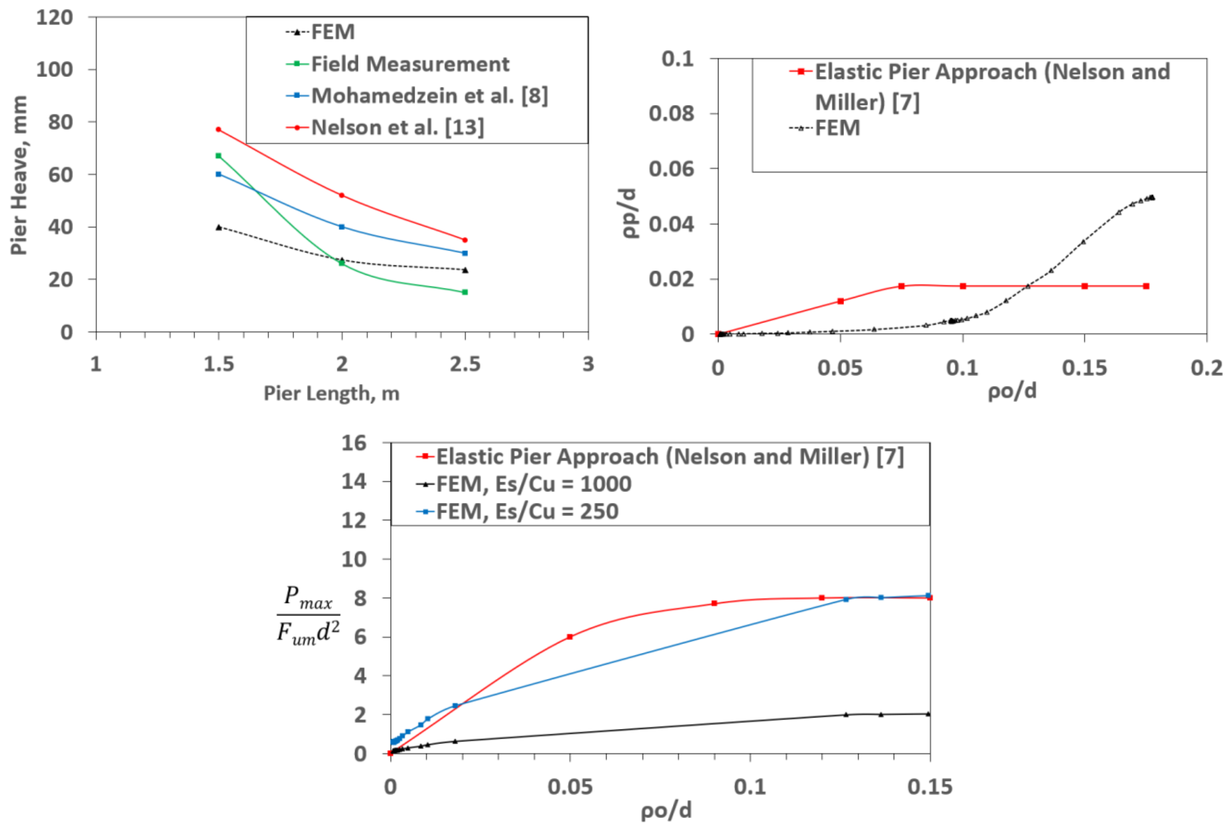


**Fig. 8.** Comparison of the FEM to other models and results.

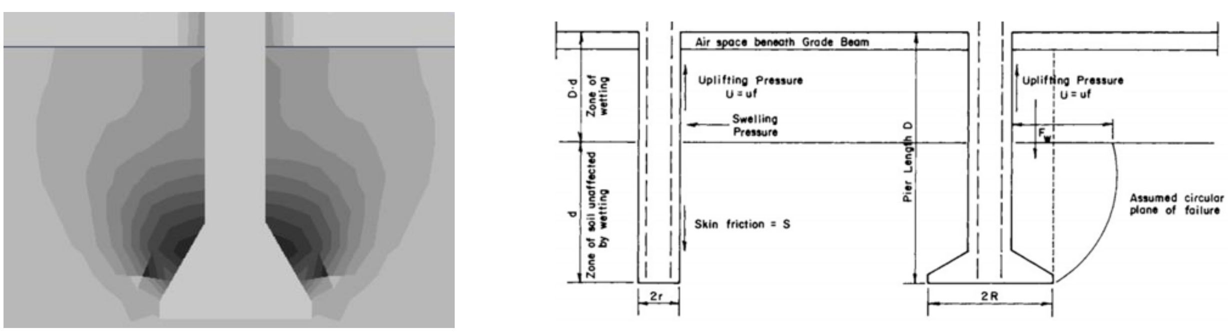


**Fig. 9.** Failure Plane observed in the FEM (left) and Failure Plane Assumed by [4] (right).

It is observed from Fig. 8 that the pier heave computed in the finite element analysis is in close agreement with the field-measured pier heave, especially when the pier length is large. Furthermore, the pier heave computed by the finite element analysis agrees closely with the field-measured pier heave as compared to the pier heave computed by [8] or the one computed by [13].

Moreover, the solutions from the finite element analysis closely match the solutions from the elastic pier approach [7] when pier heave is considered. Small differences seem to arise because the elastic pier approach doesn't consider the plastic behavior of the soil. The differences suggest that the finite element analysis gives conservative values as compared to the elastic pier approach. When considering the maximum tensile force developed in the piers, the solutions presented by the finite element analysis closely match the solutions from the elastic pier approach [7] especially when smaller values of the ratio Es/Cu are considered.

Fig. 9 shows the failure plane observed in the vicinity of the enlarged base. The concentration of strains, which indicates the failure plane, observed in the finite element model closely resembles the failure plane assumed by [4].

## 6. Parametric study

The effects of different parameters that can affect belled pier behavior in expansive soils are investigated. These parameters are the length of the pier, shaft diameter of the pier, time of saturation of the expansive soil, and applied loads on the pier. The soil swelling pressure is considered to be 500 kPa and the depth of the swelling zone is taken to be 3 m. The parametric study (considering all the above parameters) was also conducted for 300 kPa, 750 kPa swelling pressures, and 4.5 m depth of the swelling zone and similar results were obtained.

According to Fig. 10, when the belled pier length increases, which also means the length of embedment of the belled pier in the non-swelling zone increases, the belled pier heave decreases. This demonstrates the importance of providing adequate anchorage length. However, increasing the belled pier length also increases the tensile stresses developed inside the belled pier. This means more cost to provide tensile reinforcement. This should be noted when designing belled piers and selecting the appropriate lengths for a safe design.

The decrease in the belled pier heave mentioned above is observed to be less and less sensitive to the increase in belled pier length. For example, when length increased from 6 m to 7 m, which is an increment of 1 m, the heave decreased by 5 mm. However, when the length increased from 7 m to 8 m, which is again an increment of 1 m, the heave decreased only by 1 mm. The same observation can be made about the increase in tensile stress and its sensitivity to the increase in length, i.e., sensitivity becomes less and less as length increases.

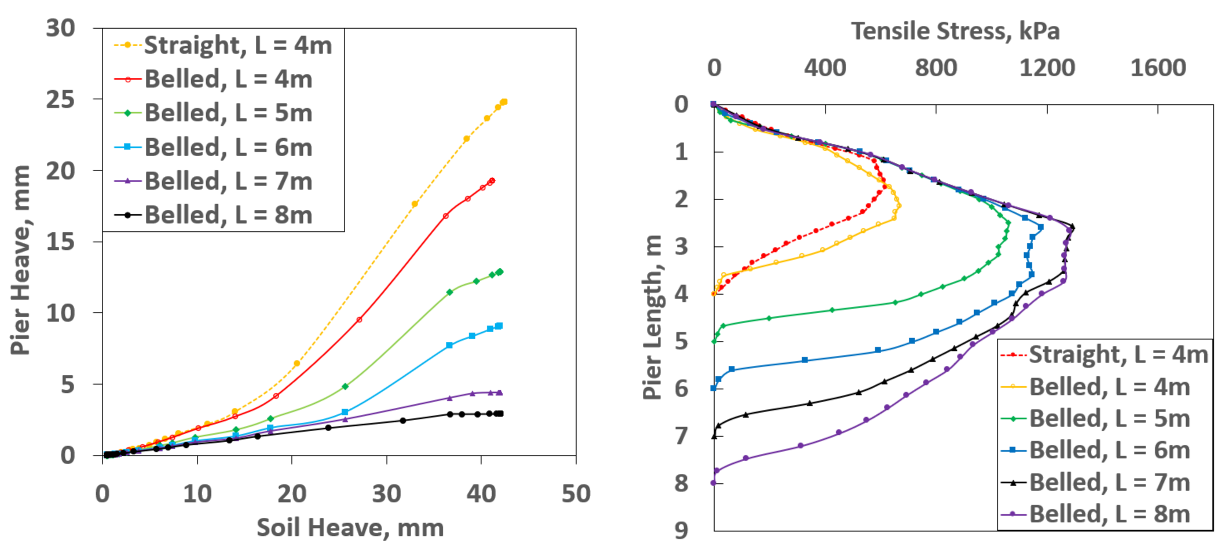


**Fig. 10.** Effect of Length on Belled Pier Heave and Tensile Stresses developed.

The location of the maximum tensile stress along the length of the belled piers is another observation that can be made. For the shorter belled piers, this location is around L/2, while for the longer belled piers, it's around L/3 from the pier top. This means, as the length of the belled pier increases, the location of the maximum tensile force shifts upward from the center.

Based on these observations, relationships between straight-shaft piers and belled piers can be established. The pier heave to soil heave relationship is similar, but, for the same length, belled piers exhibit a much smaller heave than straight shaft piers. The tensile stress to length relationship (tensile stress distribution) is also similar, but, for the same length, more tensile stresses develop in belled piers than in straight shaft piers.

Considering Fig. 11, it is observed that as the shaft diameter increases both the belled pier heave and the tensile stresses developed inside the belled piers decrease. This is different from the effect of length, where increasing length decreased pier heave but increased tensile stresses developed. Therefore, it may be better to increase the shaft diameter rather than the length to obtain safe designs when designing belled piers in expansive soils.

The decrease in heave mentioned above gets less and less sensitive to the increase in shaft diameter. The same observation was made for the effect of length. For example, as the shaft diameter increased from 0.6 m to 0.8 m (an increase of 0.2 m), the belled pier heave decreased by about 10mm, while, as the shaft diameter increased from 1.5 m to 1.8 m (an increase of 0.3 m), the pier heave decreased by just about 0.1mm.

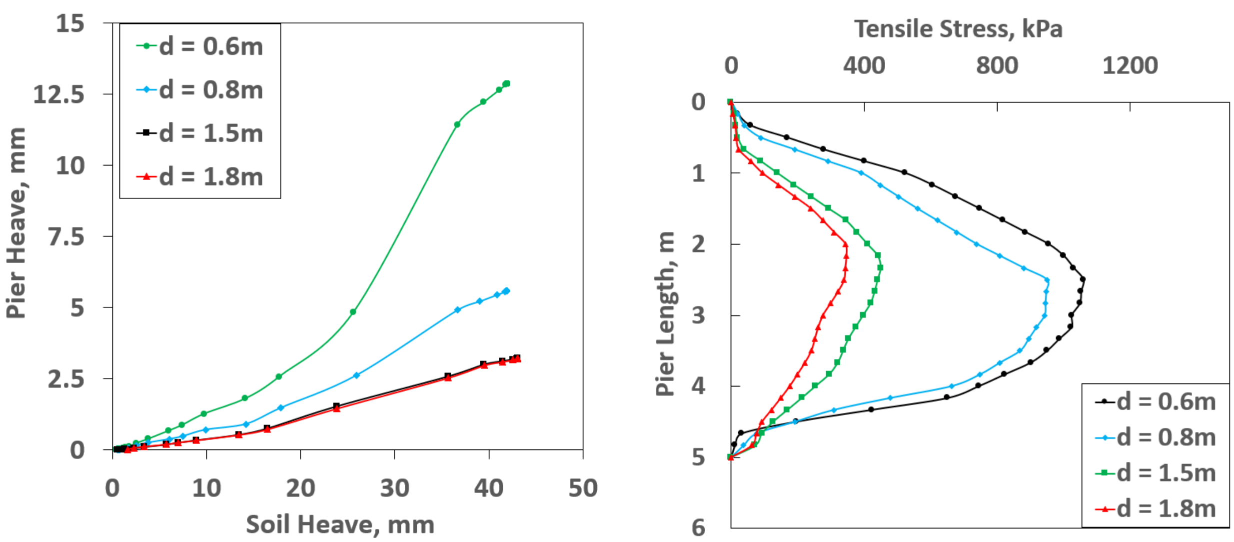

**Fig. 11.** Effect of Shaft Diameter on Belled Pier Heave and Tensile Stresses developed.

This sensitivity concept was investigated for straight shaft piers by [12] and [7]. Both concluded that there is a limiting value of the diameter after which its increase will have no effect on pier heave reduction. For [12], this value was found to be d/L = 0.04. For [7], this value was found to be d/L = 0.03. An attempt was made to investigate if there is such a limiting value for belled piers. The result is presented in Fig. 12.

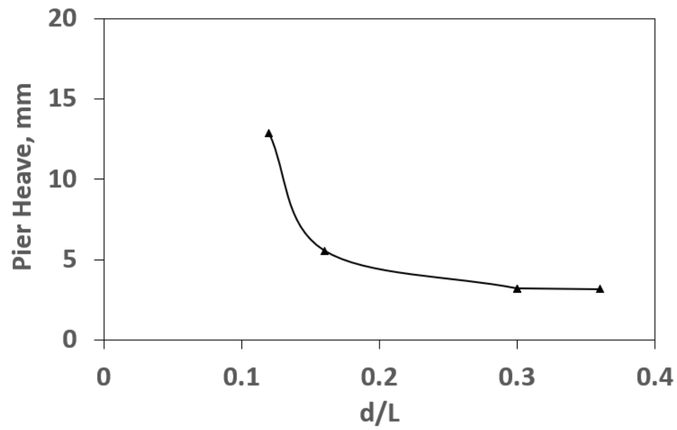


**Fig. 12.** Belled Pier Limiting Diameter.

Fig. 12 shows that the limiting diameter for belled piers is 0.3 which is a much higher value than the ones observed for straight shaft piers. This means increasing the shaft diameter to obtain safe designs is more effective in belled piers than in straight shaft piers.

Considering Fig. 13, soil heave, belled pier heave, and tensile stress all attain their maximum values in about 7 *months* of continuous Saturation.

It is particularly interesting to note that, whereas soil heave begins almost immediately after the saturation process has begun, belled pier heave does not begin until sometime later. This is because some amount of soil heave needs to develop before the heaving soil can cause the heave of the belled pier. The same phenomenon was observed by [10] for straight shaft piers.

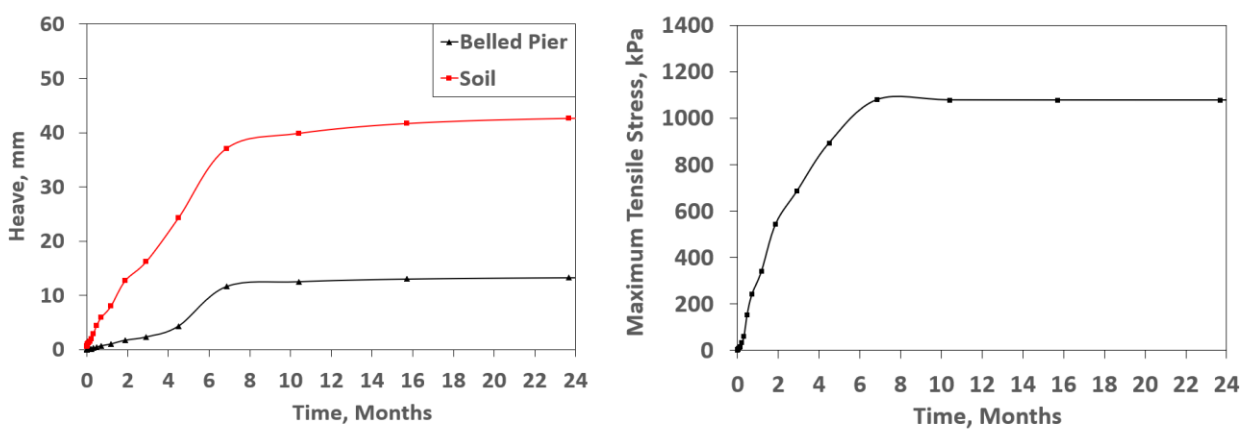


**Fig. 13.** Effect of Time of Saturation on Belled Pier Heave, Soil Heave, and Tensile Stress developed.

A Belled pier of length of 6 m, shaft diameter of 0.6 m, and bell-to-shaft ratio of 2 is considered in this investigation (Fig. 13). The initial saturation level of the soil is considered to be 52 %.

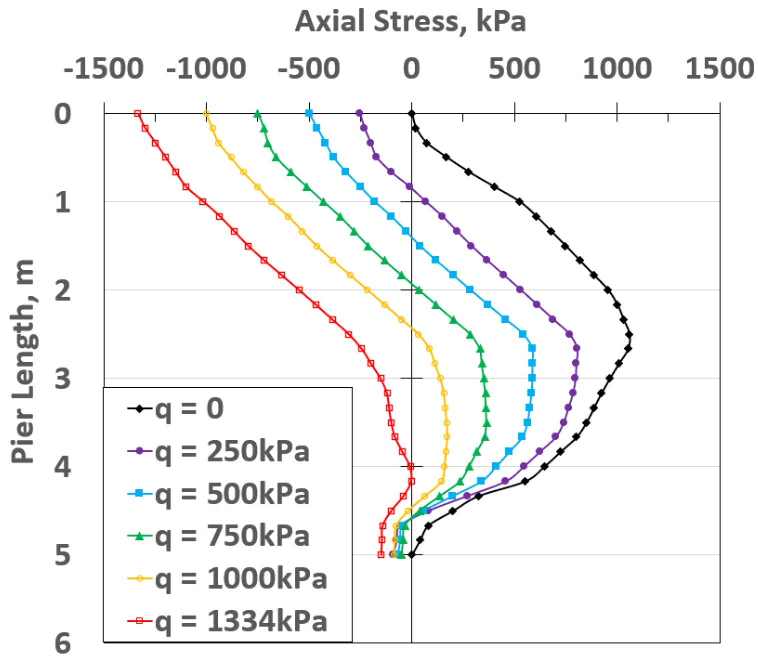


**Fig. 14.** Effect of Applied Loads on Axial Stresses developed in Belled Piers.

Fig. 14 shows that the applied load pressure needed to fully eliminate tensile stresses in belled piers is 1.2 times the maximum tensile stress in the corresponding free-belled pier. This value is less than that observed for straight shaft piers by [12] where the value was 2.5 times the maximum tensile stress in the corresponding free straight shaft pier.

## 7. Cost comparison

In the design of piers embedded in expansive soils, one can select straight shaft piers and small bell size piers with longer lengths or large bell size piers with shorter lengths depending on the amount of the cost. To check which selection is better, a cost comparison is conducted. To conduct this cost comparison, the costs of piers with the same heave are considered. The costs considered are concrete cost, reinforcement steel cost (Rebar cost), shaft drilling cost, and bell drilling cost.

Costs are considered considering the construction market in Ethiopia in the year 2017 (G.C.) considering the local currency, Birr (ETB). Nevertheless, one can easily apply the data for general cost evaluation.

Concrete cost is considered to be 3800 ETB/m$^3$ considering concrete of cylindrical strength of fck of 30 MPa. Reinforcement steel cost is considered to be 42 ETB/kg considering Grade 60 steel. Shaft drilling cost is considered to be 2500 ETB/m$^3$ considering a shaft diameter of 0.6 m. Bell drilling cost is considered to be 3000 ETB for large bell sizes, 2000 ETB for medium bell sizes, and 1000 ETB for small bell sizes.

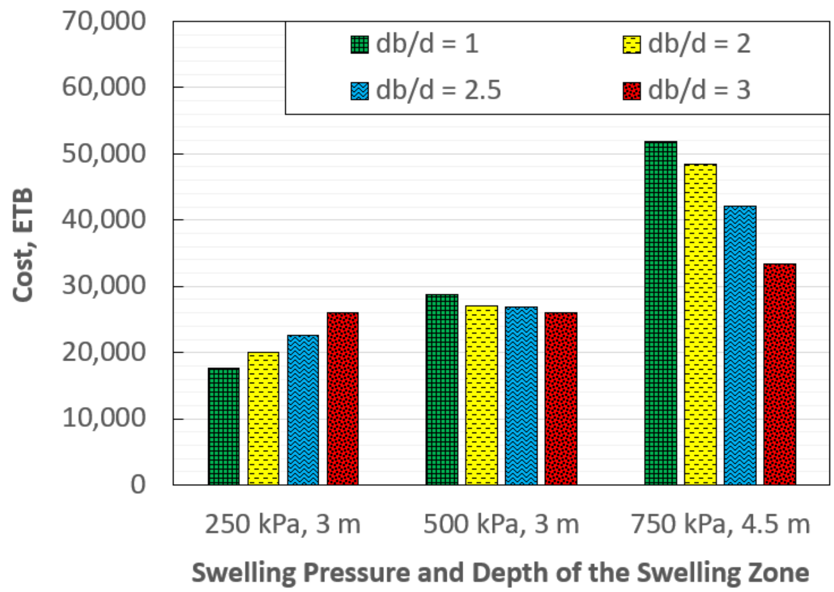


**Fig. 15.** Cost Comparison of Piers.

Fig. 15 shows that for smaller values of the swelling pressure and the depth of the swelling zone, straight shaft piers are more cost-effective; while for medium to large values of the swelling pressure and the depth of the swelling zone, large bell-size belled piers are more cost-effective.

## 8. Trend lines

Considering the aforementioned limitations of previous methods, Trend Lines which can be upgraded to design charts are presented to be used for the design of belled piers in expansive soils. These Trend Lines were produced from the relationships obtained in the abovementioned parametric study.

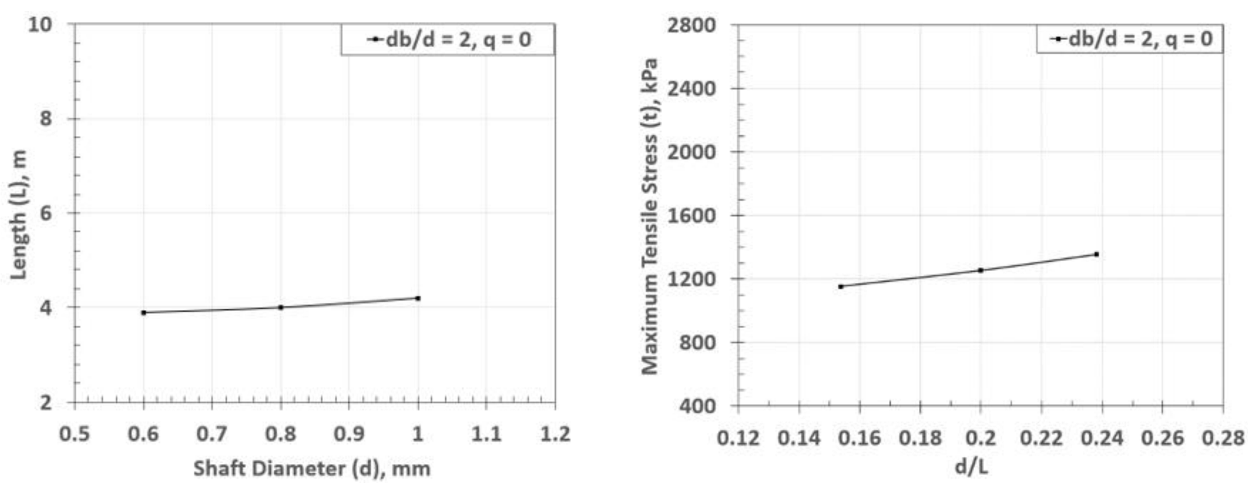


**Fig. 16.** Trend Lines for Shaft Diameter, Length, and Maximum Tensile Stress for 3 m depth of the swelling zone and 750 kPa swelling pressure.

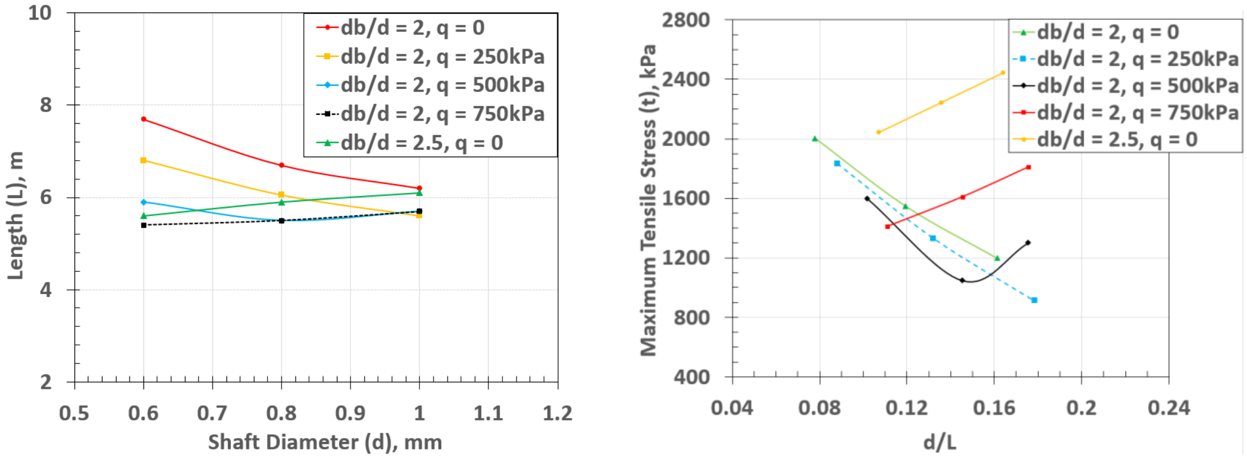


**Fig. 17.** Trend Lines for Shaft Diameter, Length, and Maximum Tensile Stress for 4.5 m depth of the swelling zone and 750 kPa swelling pressure.

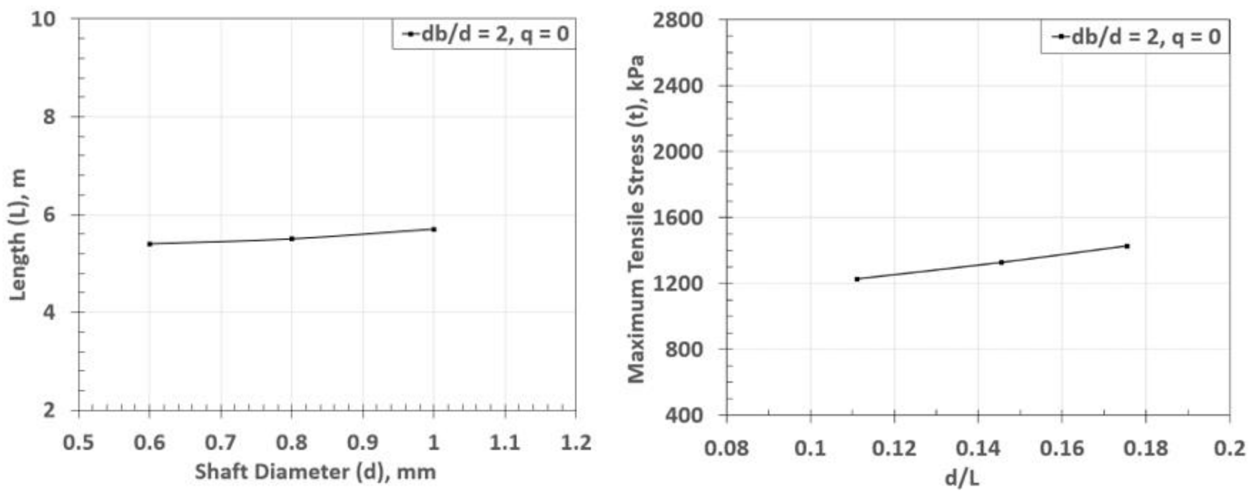


**Fig. 18.** Trend Lines for Shaft Diameter, Length, and Maximum Tensile Stress for 4.5 m depth of the swelling zone and 500 kPa swelling pressure.

The following points should be noted when using the proposed trend lines (Fig. 16 to Fig. 18): (1) allowable heave is taken to be 50 *mm* as per the recommendations of [10], (2) it is suggested to reduce the applied dead load pressures by a factor of *k as* per the recommendations of [14] to account for the establishment of structural continuity, (3) the trend lines must be used for belled piers fully embedded in hard, inorganic clay soils (CH according to the USCS); this is mostly the case for belled piers embedded in expansive soils, (4) it is assumed that the most important parameters to consider in the design of belled piers in expansive soils are the depth of the swelling zone, the swelling pressure and the applied loads; other soil parameters are neglected as their effect is assumed to be negligible; this assumption is reasonable because the neglected parameters vary slightly for the type of soils that represent belled piers in expansive soils and fully embedded in hard clay soils, (5) it is assumed that the belled piers must not be entirely located inside the swelling zone; at least the bell portion must be in the non-swelling zone; therefore, the belled piers considered in the trend lines will have a minimum allowable length based on the bell (enlarged base) dimension proportioning, (6) it is assumed that it is possible to linearly interpolate between the depths of the swelling zone, swelling pressures and applied load pressures, (7) bell dimension proportioning must be conducted as per recommendations of [4], and (8) minimum shaft diameter of the belled piers is taken to be 0.6 *m* and minimum base to shaft diameter ratio is taken to be 2 as per the recommendations of [4].

## 9. Comparison of trend lines to previous methods

Considering Fig. 19, it is observed that the proposed trend lines give smaller values of length, i.e. are more cost-effective, as compared to [14]. This is because [14] considers pier heave to be zero, neglects bell friction, and considers the interface shear stress incorrectly. [10] concluded that [14] was also uneconomical for the design of straight shaft piers in expansive soils.

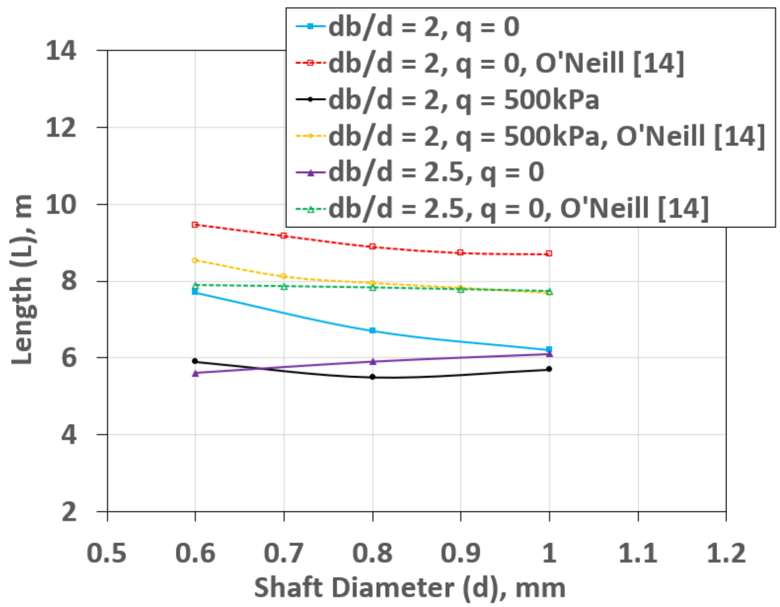


**Fig. 19.** Comparison of the Trend Lines to the equation proposed by [14].

## 10. Conclusions

Belled piers in expansive soils were modeled using the finite element software Abaqus. The elastoplastic and swelling natures of the soil were considered in the modeling. Sampling and laboratory testing were conducted to determine some of these properties of the soil. Special attention was given to the contact between the belled piers and the soil. Soil-pier slip was allowed. The model was validated using different mechanisms. The effects of various parameters that can affect belled pier behaviors in expansive soils were investigated. A cost comparison of piers in expansive soils was conducted. Trend lines that can be used to design belled piers in expansive soils were proposed.

Based on the parametric investigations, cost comparisons, and developed trend lines; the conclusions of the work can be summarized as follows: (1) increasing the shaft diameter decreases the pier heave. Furthermore, doing so also decreases the tensile stresses developed in the piers. Therefore, it is recommended to increase the shaft diameter instead of the length or the bell size to obtain safe designs when designing belled piers in expansive soils as increasing the length or the bell size increases the tensile stresses developed, (2) the limiting diameter for belled piers which is 0.3 is much higher (ten times) than the limiting diameter for straight shaft piers (0.03 or 0.04). Therefore, increasing the shaft diameter to obtain safe designs is more significant in belled piers than in straight shaft piers. (3) considering the usual case in Ethiopia where the swelling pressure is less than 500 kPa and the depth of the swelling zone is less than 4.5 m, most belled piers in expansive soils in Ethiopia do not need tensile reinforcement, though reinforcement for shrinkage and temperature may still be necessary, (4) both pier heave and tensile stresses attain their maximum values within 7 months of continuous saturation for 3 m depth of the swelling zone, (5) the applied load pressure needed to fully eliminate tensile stresses in belled piers is 1.2 times the maximum tensile stress in the corresponding free belled pier. This value is less than that observed for straight shaft piers where this value is 2.5 times the maximum tensile stress in the corresponding free straight shaft pier, (6) for smaller values of the swelling pressure and the depth of the swelling zone, straight shaft piers are more cost-effective; while for medium to large values of the swelling pressure and the depth of the swelling zone, large bell size belled piers are more cost-effective, and (7) Considering the usual case in Ethiopia where the swelling pressure is less than 500 kPa and the depth of the swelling zone is about 3 m, belled piers with the minimum possible values of the shaft diameter, base to shaft diameter ratio and length can be used considering an allowable pier heave of 50 mm.

## Acknowledgments

Salsawi Ferede, Fatema Safaa Noori, Ashenafi Yilikal, Belay Zeleke, Tenaw Workie, Admassu Tirualem, Alemayehu Bekele, Anteneh Mitiku, Askale Gebreyes, Samuel Tadesse, Messele Haile, Ameyou Temesgen, Alpha Seifu, Elias Yilma, Kidus Ayalneh, Besrat Eshetu, Kaleab Woldeyohannes, and Addis Ababa University for assisting, facilitating and funding this work.

## Funding

Addis Ababa University.

## Conflicts of interest

The authors declare no conflict of interest.

## Authors contribution statement

Gideon Amha Gebremedhin, Henok Fikre Gebregziabher: Conceptualization; Gideon Amha Gebremedhin: Data curation; Gideon Amha Gebremedhin: Formal analysis; Gideon Amha Gebremedhin: Investigation; Gideon Amha Gebremedhin, Henok Fikre Gebregziabher: Methodology; Gideon Amha Gebremedhin, Henok Fikre Gebregziabher: Project administration; Gideon Amha Gebremedhin: Resources; Gideon Amha Gebremedhin: Software; Henok Fikre Gebregziabher: Supervision; Gideon Amha Gebremedhin: Validation; Gideon Amha Gebremedhin, Henok Fikre Gebregziabher: Visualization; Gideon Amha Gebremedhin:

Roles/Writing – original draft; Gideon Amha Gebremedhin, Henok Fikre Gebregziabher: Writing – review & editing.

## References

[1] Al-Rawas AA, Goosen MFA. Expansive Soils: Recent advances in characterization and treatment. vol. 53. Taylor \& Francis; 2006.

[2] Mada T. Application of Marble Dust to Improve the Engineering Properties of Expansive Soils to be used as Road Bedding Material. 2016.

[3] Poulos HG, Davis EH. Pile foundation analysis and design. Wiley; 1980.

[4] Chen FH (Fu H. Foundations on expansive soils. Amsterdam ; New York New York NY U.S.A.: Elsevier ; Distributors for the U.S. and Canada Elsevier Science Pub. Co.; 1988.

[5] Nasir A, Fatema S, Noori. Effect of Swelling Soil on Load Carrying Capacity of a Single Pile. J Eng 2013;7:896–905.

[6] Challa P, Poulos HG. Behaviour of single pile in expansive clay. Geotech Eng 1991;22:189–216.

[7] Nelson JD, Miller DJ. Expansive soils : problems and practice in foundation and pavement engineering. J. Wiley; 1992.

[8] Mohamedzein YEA, Mohamed MG, El Sharief AM. Finite element analysis of short piles in expansive soils. Comput Geotech 1999;24:231–43. https://doi.org/10.1016/S0266-352X(99)00008-7.

[9] Fan Z, Wang Y, Xiao H, Zhang C. Analytical method of load-transfer of single pile under expansive soil swelling. J Cent South Univ Technol 2007;14:575–9. https://doi.org/10.1007/s11771-007-0110-4.

[10] Nelson JD, Chao KC, Overton DD. Design of Pier Foundations on Expansive Soils. Proc, 3rd Asian Conf Unsaturated Soils 2007:97–108.

[11] Kaufmann KL, Nielsen BN, Augustesen AH. Finite Element Investigations on the Interaction between a Pile and Swelling Clay. 2010.

[12] Xiao H, Zhang C, Wang Y, Fan Z. Pile-Soil Interaction in Expansive Soil Foundation: Analytical Solution and Numerical Simulation. Int J Geomech 2011;11:159–66. https://doi.org/10.1061/(asce)gm.1943-5622.0000046.

[13] Nelson J, Thompson E, Schaut R, Chao KC, Overton D, Dunham-Friel J. Design Procedure and Considerations for Piers in Expansive Soils. J Geotech Geoenvironmental Eng 2012;138:945–56. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000647.

[14] O'neill MW. Adaptive Model for Drilled Shafts in Expansive Clay. Geotech. Eng. Div. Natl. Conv., 1988, p. 1–22.

[15] Albusoda B. Performance Assessment Of Pile Embedded In Expansive Soil. Al-Khwarizmi Eng J 2016;12:1–9.

[16] Zhan YG, Wang H, Liu FC. Modeling vertical bearing capacity of pile foundation by using ABAQUS. Electron J Geotech Eng 2012;17 M:1855–65.

[17] Helwany S. Applied Soil Mechanics: With ABAQUS Applications. 2007. https://doi.org/10.1002/9780470168097.