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The Efficiency of Belled Piles in Multi-Layers Soils Subjected to Axial Compression and Pullout Loads: Review

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ABSTRACT

Multi-belled piles are piles with enlarged ends; these piles have one or further bells at the lower third part of the pile. These piles are suitable for many soils with problems such as softening clay, the variation of groundwater table, expansive soils, black cotton soil, and loose sand. The current study reviewed the behavior of belled piles in multi-layer soils subjected to axial compression and pullout loading. The review covered the experimental and theoretical works on belled piles in multi-layered soils. These piles were subjected to static and dynamic loadings in compression and pullout cases. Most theoretical results focused on software such as PLAXIS 3D. The axial load applied on the piles comes from the upper structure built above these piles, and negative skin friction comes from groundwater. The results obtained from previous studies showed the validity of using such piles in different types of soil and multilayer soils. According to previous studies, this study aims to find all the things about the belled piles, including the best shape of the belled pile being the half cone and the worst state being when the bell is fully cone. The best number of belled piles is two bells because the bearing capacity increases when the number of bells increases but does not exceed two due to hard work and high cost. The best location of a bell is at the base of the pile. The current study showed that the bearing capacity increased from 40% to 73.75% compared with ordinary piles.

Keywords: Belled-piles, Axial load, Pullout loads, Multi-Layers soils.

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كفاءة الركائز ذات الاجراس في تربة متعددة الطبقات معرضة لتأثير احمال الصغط والسحب المحورية

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الخلاصة

الركائز متعددة الأجراس هي ركائز ذات نهايات متضخمة تحتوي على واحد أو أكثر من الأجراس على الأكثر في الثلث السفلي من الركيزة. هذه الركائز مناسبة للعديد من أنواع التربة التي تعاني من مشاكل مثل الطين الضعيف، تغير منسوب المياه الجوفية، والتربة الأنتفاخية، والتربة القطنية السوداء، والرمل الرخو. استعرضت الدراسة الحالية سلوك الركائز ذات الأجراس في التربة متعددة الطبقات المعرضة للضغط المحوري وتحميل الانسحاب. تضمنت المراجعة الأعمال التجريبية والنظرية على الركائز ذات الأجراس في تربة متعددة الطبقات. تعرضت هذه الركائز لأحمال ساكنة وديناميكية في حالات الضغط والسحب. ركزت معظم النتائج النظرية على برامج مثل PLAXIS 3D. يأتي الحمل المحوري المسلط على الركائز من الهيكل العلوي للمنشأ المشيد فوق هذه الركائز، ويأتي الاحتكاك السلبي على سطح الركيزة من وجود المياه الجوفية. أظهرت النتائج التي تم الحصول عليها من الدراسات السابقة صحة استخدام هذه الركائز في أنواع مختلفة من التربة والتربة متعددة الطبقات. الهدف من هذه الدراسة ايجاد كل شي عن الركائز ذات الاجراس اعتمادا على الدراسات السابقة، فأن افضل شكل للجرس للركائز ذات الاجراس هو نصف مخروط ، واسوء حالة عندما يكون الجرس بشكل مخروط كامل. افضل عدد للاجراس هو جرسان لأن قابلية التحمل تزداد بزيادة عدد الاجراس ولكنها لاتتجاوز الاثنين لصعوبة التنفيذ والكلفة العالية. افضل موقع للجرس هو عند قاعدة الركيزة. اضهرت الدراسة الحالية ان قابلية التحمل زادت من40%الى 73.75% مقارنة بالركائز العادية.

الكلمات المفتاحية: الركائز ذات الاجراس , الاحمال المحورية , احمال السحب , تربة متعددة الطبقات.

1. INTRODUCTION

The pile's foundations are required when the bearing capacity of the soil is not enough to support the superstructure loads or to reduce the settlement under such structures. The projects that may be constructed on this soil are significant and voluminous, such as (bridges, hospitals, hotels, highway roads, andskyscrapers). The construction of piles in the ground using driven or cast-in-situ should reach a hard layer (rock layer), but in many cases, the hard layer is not found, and the pile may be raised. Many proposals have been adopted for such a problem, including the increase in pile length, pile diameter, and both length and diameter of pile, but at the same time, the cost will increase **(Moayedi and Mosallanezhad, 2017)**. Therefore, the belled piles are suggested in these cases as an economical and efficient solution. The soil investigation is the essential step that must be done before the design or construction. The appropriate type of foundation depends on the soil investigation report and the soil's properties. If the soil in the subsurface is insufficiently strong, Pile foundations are usually employed to transport the load of the superstructure to deep strata **(Bowels, 1996; Poorooshasb et al., 1996).** The shaft resistance is an essential source of pile capacity in cohesionless soils, especially when the pile is subjected to uplift loading. Uplift forces support piles of construction such as dry docks, basements, and pumping stations built below the water table. In sandy soil, uplift can also occur when the groundwater level is high. Also, the embedded and belled piles can be used in sandy soil with cavities **(Al-Mosawe et al., 2007).** The pile's tip in multi-layer soils should be placed on the hard or rocky layers. However, this layer is rarely found in many states. In these cases, the geotechnical designer depends on the increase in pile diameter or length or both; in these cases, piles are called (friction piles).

(Al-Mhaidib, 1998) developed a model for testing pile uplift resistance in the sand. The tension piles in the sand were studied by a method including degradation of shaft friction during pile driving (**Alawneh, 1999; Dhatrak et al., 2018).** The efficiency of employing belled piles on sandy soil was explained by (**Ilamparuthi et al., 2001**). The bells distribute the loads in soil and increase the piles bearing capacity under both pullout and compressive loadings **(Jebur et al., 2020)**. Belled piles are categorized as single, double, or multi-bell piles based on the number of bells **(Dickin and Leung, 1992).**

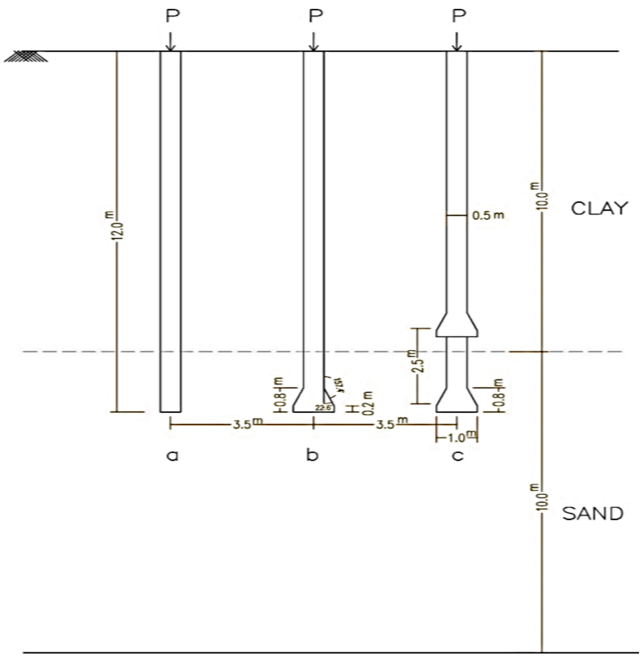


Figure 1. The multi-layer soil profile: a) pile without bell, b) Pile with a single bell, and c) Pile with double bells.

The bells provide sufficient anchorage by ignoring the effect of soil swelling or shrinking, according to the fundamental principle of the belled pile technique **(Abbas, 2021)**. As a result, the soil between the bells behaves as a pile part, increasing the pile's effective diameter **(Ilamparuthi and Dickin, 2001)**. The space between bells must be (1.5-2) times its diameter. Typically, the bell is found a few meters above the bottom of a single bell pile. Two or more bells are placed in the pile stem or at the end of double or multi-bell piles. The soil between the bells contributes as an element of the pile, increasing its diameter. In comparing the belled with the identical pile (equal section), the belled pile reduces the number of piles, decreasing the cost too.

The previous studies proved that using belled piles in clayey soil is more effective than using equal section piles for reducing settlement and increasing the bearing capacity. In multilayers, when the upper layer is weak, and the intermediate layer from sand (or the opposite), the supporting layer (hard layer or rock) is not found or is so far. Therefore, increasing the length or diameter (or both) is costly and not affected **(Guner and Chiluwal, 2019)**. A belled pile with a suitable length and diameter is better economically than a friction pile (increase in diameter and size) **(Honda et al., 2011).**
This study aims to review the previous work about the belled piles, including the best shape of the belled pile being the half cone and the worst state being when the bell is fully cone.

2. APPLICATIONS AND ADVANTAGES OF BELLED PILES

The belled piles have many applications in geotechnical engineering, such as:
1) The soil at the construction site is very loose or soft.
2) The plane area is insufficient due to excessive loading, and the foundation size is inadequate to support structure loads.
3) The foundation is subjected to high lateral stresses.
4) The foundation of belled piles is used for subterranean constructions and transmission towers under the groundwater that require the ability to withstand massive uplift loads, as shown in **Fig. 1 (Guner and Chiluwal, 2021)**
5) Belled piles are utilized in foundations that withstand inclined, eccentric, and moments.

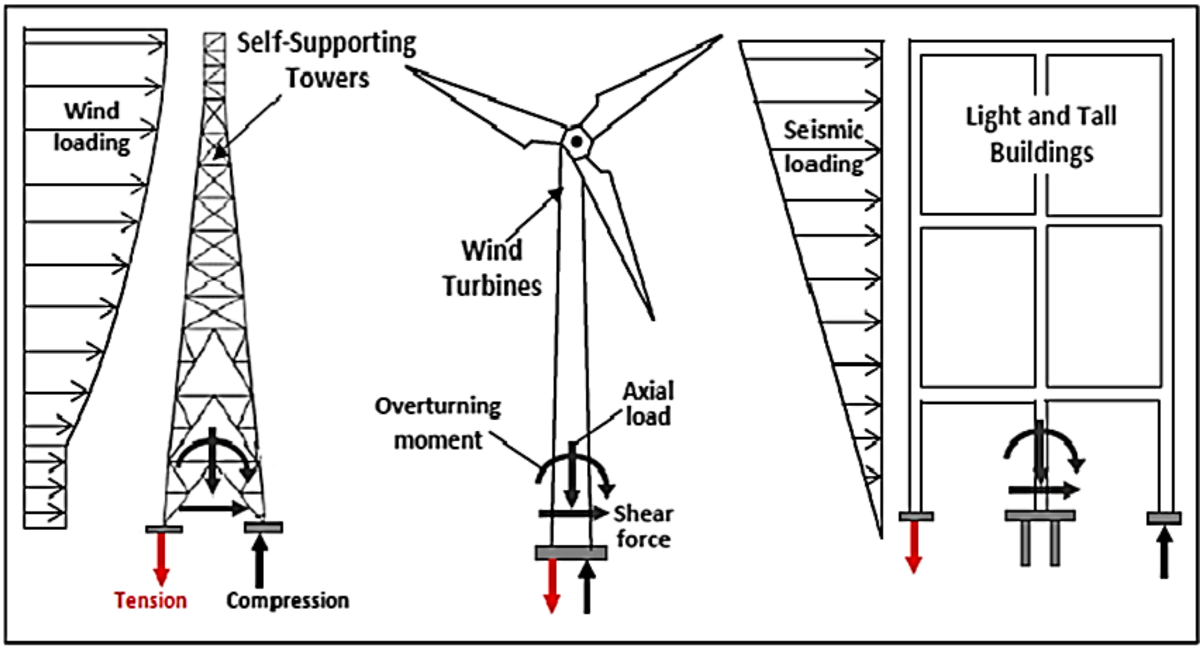


Figure 2. Uplift in (a) a transmission tower exposed to wind forces, (b) a wind turbine subjected to wind loads, and (c) earthquake loading on a residential building **(Chiluwal and Guner, 2019).**

Using the belled pile aims to increase the bearing capacity in weak soils. The bells decrease the settlement in the clay and expansive clay soil and resist the uplift force in sandy soil **(Moayedi and Mosallanezhad, 2017).**

Belled and multi-belled piles can increase the pile shaft's end (bottom) resistance and decrease negative skin friction **(Honda et al., 2011).**
The belled and multi-belled pile foundation is commonly used for heavy and massive highways, bridges, transmission line towers, skyscrapers, and offshore platforms.
The belled piles are most commonly powered manually by the hand-operated pump. When the number of bells increases by more than two, the workability is complex, and the cost increases. The disadvantages and the states when the belled piles are not used:

1) Installing the belled piles needs to be subject to stringent quality control and careful oversight.
2) Given that, all sorts of construction materials need storage space. Consequently, the engagement may be rather challenging**.**
3) Belled piles cannot be used for construction in situations with significant artesian pressure or groundwater movement.

3. BEARING CAPACITY OF BELLED PILES

The bearing capacity of belled piles is a function of many parameters such as length, the diameter of the stem, the diameter of the bell, L/D ratio, S/D ratio, the shape of bells, number of bells, location of bells, space between bells, number of belled piles, type of soil for each layer, the variation in porewater pressure, and location of it. The following sections will review the bearing capacity of belled piles under axial compression and pullout loading conditions.

3.1 Axial Compression Loading

The condition and type of loading are essential factors in choosing the suitable kind of foundation, especially for a long time when the projects are designed for many different objectives such as hospitals, hotels, multiple floors buildings, towers, skyscrapers, platforms offshore, factories with heavy types of Machinery, highways transportation, railways, subways, bridges, military shelters, basement, and other projects that are designed for the long term. These projects are essential and sensitive (location, function, and cost). Therefore, care must be taken to choose the appropriate type of foundation by analyzing the loads imposed on it. The static load represents the load transported from the buildings constructed on the foundation and depends on the structure's weight with the values of all the loads subjected to the foundation, such as the dead and live loads. The static load is the constant value applied to the compression load (as the Compression stress when the loads are divided on the area of the foundation) on the foundation, which uses the standard soil-mechanics method to calculate the load capacity from measured soil properties **(Poulos, 1994).** The pile shaft's bearing resistance (tip or end bearing) and side friction for a standard drilled cast in situ pile of equal shaft diameter supply the load-carrying capability in the compression axis, see **Fig. 2**. The ultimate bearing capacity of the pile is the summation of both the end bearing and friction resistances as shown in the following equations:

$$Q_u = Q_b + Q_s \tag{1}$$

$$Q_b = q_s\, A_{sh} \quad (2)$$

$$Q_s = f_s\, A_s \quad (3)$$

where:
Q_u is the maximum bearing capability of the pile.
Q_b is end-bearing resistance.
Q_s is side friction resistance.
f_s is the shaft-based unit skin friction or adhesion, provided by (α, c, and A_s)
α is reduction factor.
c_a is the coefficient of adhesion is (α.c).
A_s is the surface area of the pile.
A_{sh} is area of shaft pile.

The bearing of a bell or bells contributes to the extra-axial load-carrying capability of the belled bored cast in situ concrete pile. In addition, soil-pile adhesion, which is smaller than the pure cohesive force of soil, contributes to the side friction factor. The reduction factor is often estimated to be 1.0 for soft clays, 0.7 for medium clays, 0.4 for stiff clays, and 0.3 for extremely stiff clays (**Wagner, 2013)**. In this case above, the bearing capacity equation changes as the flowing**:**

$$Q_u = [q_s\, A_{sh} + q_b(A_b + A_{sh})] + f_s A_s + f_s' A_s' \quad (4)$$

where A_s' is the surface area of the bell and f_s' is e friction at the bell or bells.

Belled pile foundations are more effective than equal section piles in carrying vertical compression loads. When we talk about the type of soil and its properties, especially in multi-layer soil, the bearing capacity is a significant factor in choosing the suitable type of foundation. Many previous studies explained the efficiency of belled piles compared with equal-section piles. According to the soil properties and its condition, the type of suitable foundation was chosen. When the earth has a high bearing capacity, the traditional foundation style of the project is vast use piles, and in many situations (footing), it works. The problems of soils are too many, such (settlement, low bearing capacity, softening in clay, the volumetric changes in the expansive soil, negative skin friction, uplift, etc.) and to find suitable solutions related to studying the topography of the ground and the number of layers that the location the project consists from it.
Suppose the upper of the soil profile is sand. In that case, the intermediate is clay; the last layer is sand or hard soil (the weak ground is confined between two rigid layers). The Negative skin friction or Drag force withdraws the pile because the pile weight adds a load on the weak layer. Solve this problem by applying loading before construction to make the soil in the preloading state and allow the water to get out of the ground by improving the soil. Sometimes, the upper layer of the soil profile is soft clay, and the intermediate layer is sand. The last layer is rock; in this case, the thickness of every layer is essential to design the pile. If the rock layers (or complex layers) are so far or not found, the end bearing resistance is not effective, and the pile, in this case, is called a "Friction pile." (**Ashour and Helal, 2014).**

$$\mathbf{Q_u = q_{pu} . A_b + \bar{f}_s \overline{A_s} + f_s A_b}$$

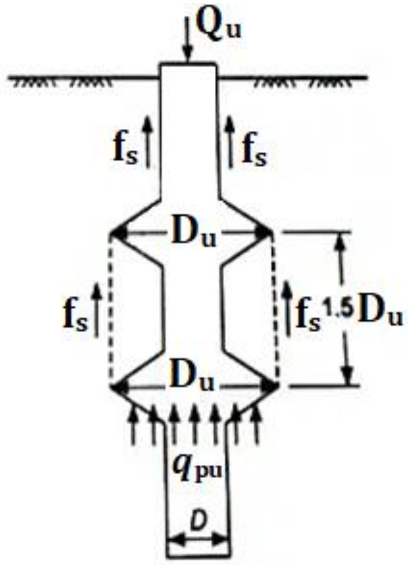


Figure 3. Resistant components of belled piles.

3.2 Axial Pullout Loading

Some structures, like massive transmission towers, soaring chimneys, jetting skyscrapers, and the ocean's surface or subsurface platform mooring systems, require foundations to withstand pressures other than compression. For beachfront structures to be stable and functional, the resistance to lateral and pullout loads must be considered throughout the foundation design phase. Due to the growing need for offshore and onshore construction and wind and earthquake-resistant systems, it is required to define the pullout behavior of pile foundations. The friction factor in both the pile shaft and the soil controls the lifting capacity of a straight shaft pile in the sand. The limit friction approach is commonly used, and (**Meyerhof, 1968)** proposed the net uplift capacity. Many laboratories' models testing piles with varying embedded depths have been reported. **(Das and Seeley, 1975; Chaudhuri and Symons, 1983; Meyerhof and Adams, 1968).** The latter first proved that the failure surface in the ground could be formed based on the embedded depth and that, in the belled piles, the soil above the bell interacts with the pile. Skin friction rises linearly to a constant value, according to (**Mohamed and Amr, 2014),** dependent on the L/D ratio of the pile and the sand's density. They also suggested that a crucial diameter-to-embedded depth ratio and relative density are related to net uplift capacity.

(Dickin and Leung, 1992) examined the effects of base diameter, embedment, and backfill density on the uplift behavior of belled piles in sand. Compared to the previously recommended analytical solutions, the vertical slide surface failure model was shown to be the most acceptable for the belled pile in sand.

However, based on field test results, little research has been done on the pull-out behavior of belled piles. The pullout resistance of belled piles is made up of two components: the pullout resistance of the drilled shaft (induced by frictional forces along the straight section of the pile) and the pullout resistance of the bell portion, which is formed by the sum of the earth's stress on top of the belled section and the skin friction of the soils around the bell section. The ultimate uplift capacity of an under-reamed pile is significantly greater than that of a conventional straight pile. The uplift action is critical for building port foundations, transmission tower foundations, and other facilities that must withstand uplift loading. The effect of foundation design on the pullout behavior of piles with larger bases was examined by (**Dickin and Leung, 1992)**. The uplift static loading test is a common and well-known method for testing pile uplift capacity. Before doing a field test, it is impossible to determine a pile's bearing capacity due to inherent soil heterogeneity, materials' non-linearity, and the disruption created by pile construction. The literature has several field test data on the optimum uplift capability of cast-in-place concrete piles subjected to a vertical rising force. **(Seo and Prezzi, 2007; Zhang and O'Kelly, 2014).**

(Shin et al., 1993) created a theoretical relationship for evaluating pile uplift capability based on results from earlier tests and research. Their research mainly focused on how friction piles respond to uplift. As a result of the interaction between the pile and the earth, belled pile uplift behavior is more challenging. **(Diana et al., 2017).**

(Zhang et al., 2020) showed that employing a suction cup rather than a flat base plate significantly increased the undrained ultimate tensile capacity and undrained maximum tensile capacity of shorter granular anchors. According to the findings of an experimental investigation, the applied pullout stress is absorbed in capacity of the shaft the for short granular anchors and causes localized bulging at the bottom for long granular anchors (**Sivakumar et al., 2012**).

(Kranthikumar et al., 2016 ; Karkush et al., 2019) used a three-dimensional finite element approach to investigate the influence of critical geometrical factors on the pullout capacity of granular anchor piles in a small-scale laboratory experiment on loose, dry sand. A full-scale field test is expensive, and field tests might be challenging owing to practical constraints. However, most tests cannot support such large diameters. As a result, various small-scale research and geotechnical centrifuge experiments have been carried out to understand better uplift behavior **(Madhusudan and Ayothiraman, 2015).** Using numerical and theoretical computations differs from field testing's practical restrictions **(Bouassida, 2006).**

(Ellis and Springman, 2001) used the finite element technique (FEM) to conduct research based on the centrifuge test results. The FEM numerical analysis may successfully analyze the uplift behavior of belled piles compared to the findings of centrifuge tests. **(Khatri et al., 2022)** conducted a detailed numerical study to determine the ideal pulling load for vertical and lateral plate anchors in frictional soils. To determine the maximum capacity of piles, **(Samui, 2012)** employed a multilayer modified regression model. (**Soomro et al., 2019)** examined how uplift piles behaved during a deep excavation using a nonlinear finite element method. They found that belled uplift piles may be subject to substantially more pressure during recess than straight uplift piles. The uplift failure types of belled piles in the sand are illustrated in **Fig. 4 (Ilamparuthi and Dickin, 2001)**. While **(A'amal and Al-Shakarchi., 2021)** found that the failure is shown to beat the first (1/3) pile length. **(Honda et al., 2011)** analyzed the pullout capacity of belled and multi-belled piles in dense sand. They showed that the bearing capacity of belled piles against pullout loading rises as the number of bells increases, see **Fig. 5.**

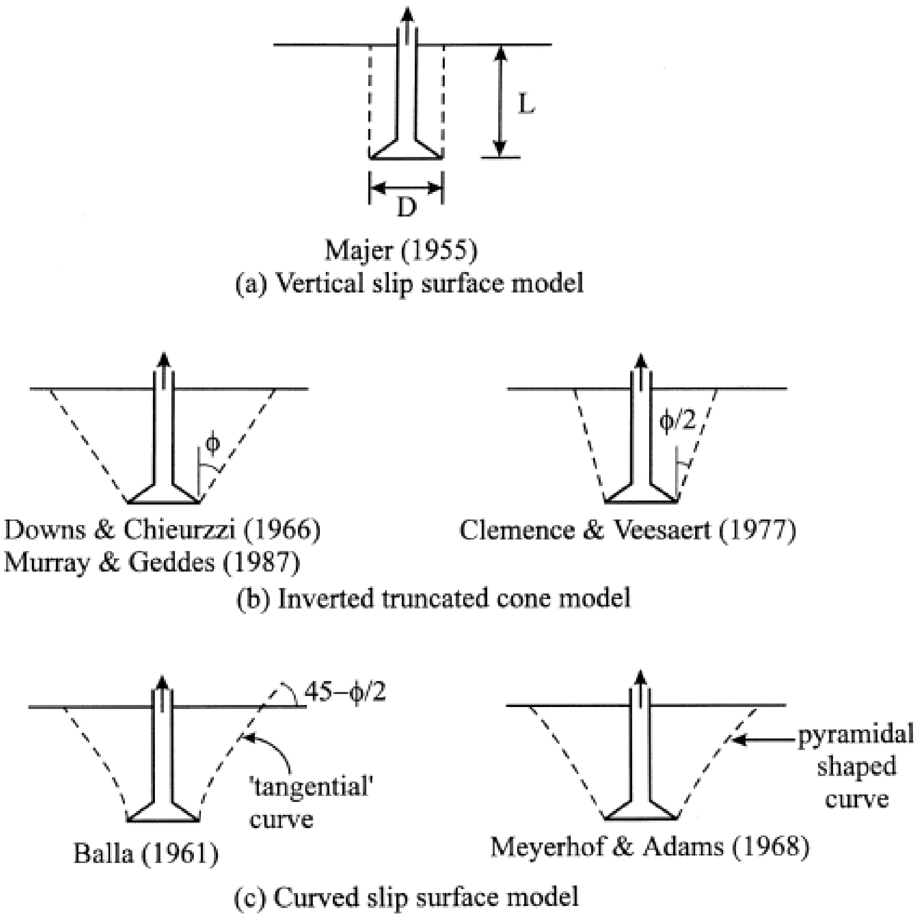


Figure 4. The assumed failure mechanisms for the belled piles are subject to uplift loads **(Ilamparuthi and Dickin, 2001).**

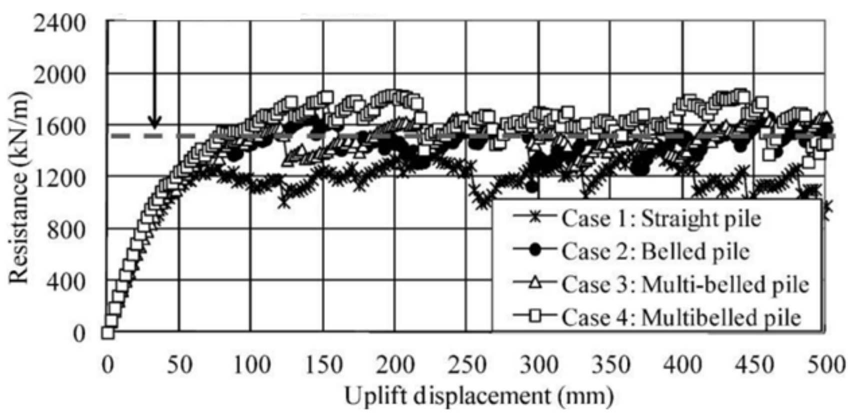


Figure 5. Relationship between several bells and bearing capacity **(Honda et al., 2011).**

The relationship between the embedment depth (L) and bell to shaft diameters ratio (b_b/b_s) and uplift capacities was previously investigated using computational uplift experiments. The findings demonstrate that increasing the bell-to-shaft diameter ratio (b_b/b_s) and embedment depth can improve the ability of belled piles to lift heavy loads **Fig. 6 (Qian et al., 2016).**

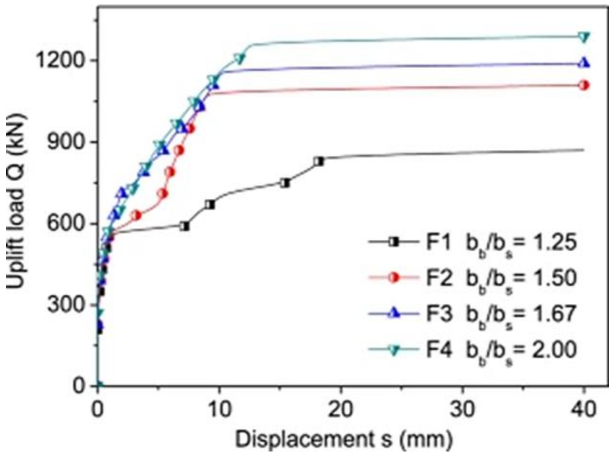


Figure 6. Relationship between (b_b/b_s) and uplift capacity **(Qian et al., 2016).**

(Gao et al., 2016) proved that the bearing capacity increases when the number of bells increases, and the percentage of this increase is 65% between the ordinary piles and single bell pile and about 5%between the single bell pile and double bell pile. Compared with ordinary piles, the ultimate bearing capacity can be increased by more than 50% **(Mingyuan et al., 2020; Al-Hassani, 2021). (Abbas, 2021)** investigated the compressive capacity of conventional and under-reamed piles in soft clay; he discovered that the ultimate capacity of reamed piles improves as the number of bells increases, where the percentage of increase between ordinary piles and single bulb piles is 73.75%, and the percentage between single blub and double blub is 5.25%, see **Fig. 7**.

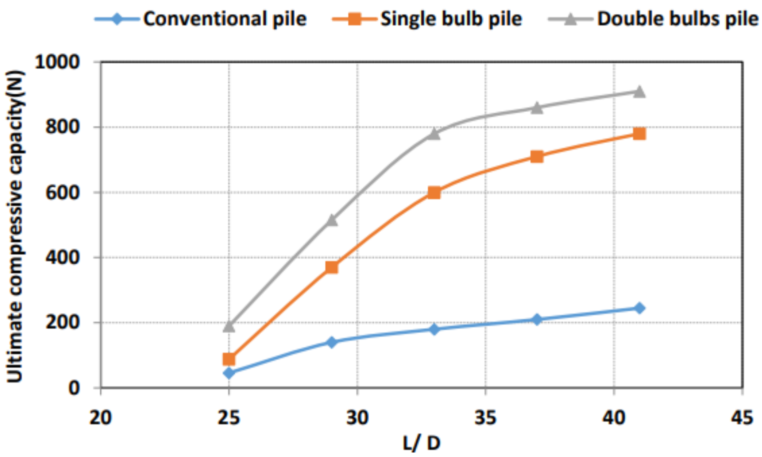
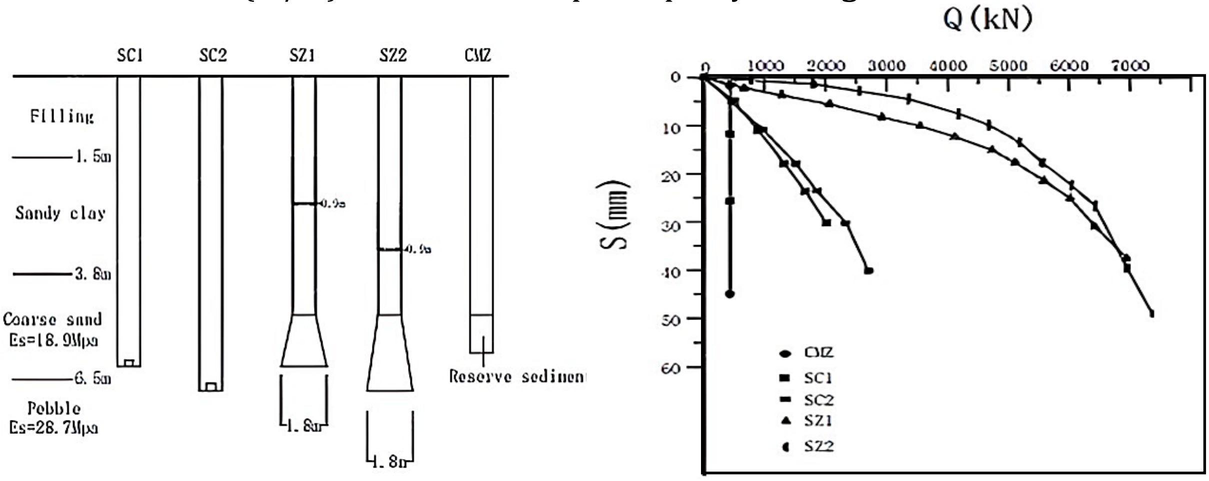


Figure 7. Variation of ultimate capacity of the conventional and under-reamed piles with L/D ratios **(Abbas, 2021).**

(Goudar and Kamatagi, 2022) found that the load-carrying capacity increased by 40% higher than ordinary piles. The belled pile is critical in creating compression and uplift-bearing capability **(Deb and Pal, 2019)**. Additionally, belled and multi-belled heaps can increase the pile shaft's tip (base) resistance friction and minimize negative skin friction **(Lei et al., 2022).** The belled pile is a suitable solution for many soil problems if the soil consists of many layers **(Nazir et al., 2015)**. In belled piles, the increase in diameter of the end effectively increases bearing capacity. (**Dickin and Leung, 1992; Sharma, 1978; Krishnan et al., 1983; Chow et al., 1997; Decourt, 1999)** proved that the bearing capacity increased with an increase in the diameter of piles. **(Wu et al., 2020)** explained that expanding the bell to shaft diameter (d_b/d_s) ratio increases uplift capacity, see **Fig. 8.**



(a) **(b)**

Figure 8. Field test general situation and Q-S curves (the increase of (d_b/d_s) ratio leads to increased uplift capacity **(Wu et al., 2020)** (a) Different types of piles. (b) Settelment.

Depending on how many bells there are, belled piles can be single, doubled, or multi-bell piles (**Tafreshi et al., 2014; Alkroosh and Nikraz, 2011)**. As bells rose, the load-bearing capability also increased **(Zhang et al., 2020; Yao and Chen, 2014; Sitharam, 2018).** The soil between bells also functions as a pile component, increasing the pile's apparent effective diameter **(Kang and Kang, 2022).**

(Ilamparuthi and Dickin, 2001; Sun et al., 2022) studied that the diameter of the bells can be (2-3) times the diameter of the stem pile. In the case of a single bell pile, the bell is typically located a few meters above the pile's base. The soil below the bell acts as the single unit of the pile, giving a wide base area for load transfer **(Kong et al., 2011).** In the double or multiple bells pile, two or more bells are in the pile stem or at the end of the pile **(Honda et al., 2011; Lee et al., 2010)**

The effect of the soil trapped between the bells acting as a part of the pile, increasing the adequate thickness; thus, the bearing capacity increases as the pile's surface area for friction increases, and the effective bottom area increases to transfer the load. In a group system of piles, piles are connected by a raft foundation or a cap to avoid the eccentricity of loads applied to piles in a group pile system **(Farokhi et al., 2014).**

(Chea et al., 2012; Liu et al., 2020; Kang and Kang, 2022) showed that the belled inclination angle has little influence on uplift bearing capacity and load-displacement curves of belled piles (see **Figs. 9 and 10).**

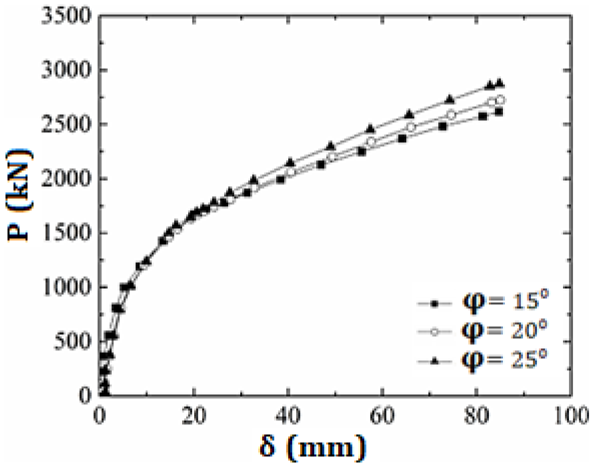


Figure 9. The belled inclination angle has little influence on uplift bearing capacity and load-displacement curves **(Chea et al., 2012).**

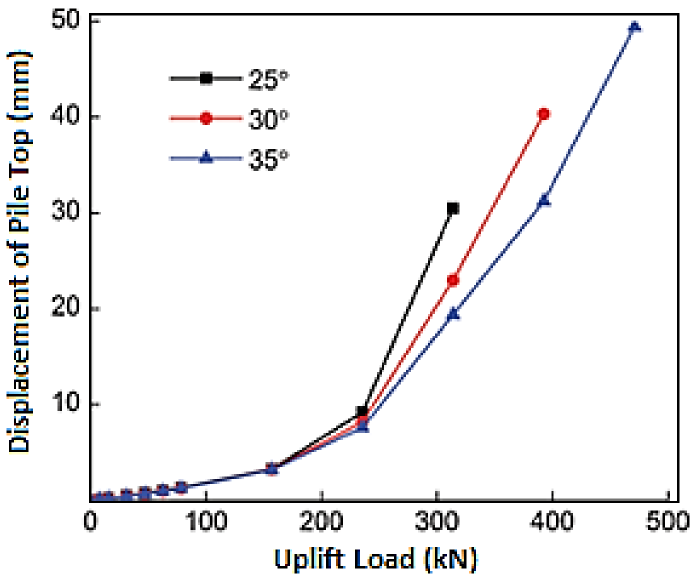


Figure 10. The belled inclination angle has little influence on uplift bearing capacity and load-displacement curves **(Liu et al., 2020).**

(Jebur et al., 2020) proved that the full sphere as the bell shape is the worst choice, as it has few effects on the distribution of vertical displacement. **(Farokhi et al., 2014)** showed that the half-cone bell of the belled pile had better performance than the other piles and had a higher ultimate tensile and compressive bearing capacity and lower displacement. **(Engin et al., 2008; Majumder and Chakraborty, 2021; AL-Shamaa et al., 2021)** proved that using belled piles in clayey soil is more effective than equal section piles by reducing settlement and increasing the bearing capacity. Many kinds of research are done in sandy soil to explain the efficiency of using a belled pile and compare it with the uniform section pile **(Emirler et al., 2020; Karkush et al., 2022).** The results of the studies show that the belled pile in sandy soil improves the uplift resistance (**Kang et al., 2019**; **Ruan, 2017).** Also, the belled pile is used in structures with a cyclic load, such as machinery in factories and airport runways, when the state of movement is not constant and stable in direction and magnitude **(Rao et al., 2011; Liang et al., 2021).**

4. CONCLUSIONS

According to previous studies of the belled pile, many researchers reach the perfect parameters through experiments and tests in the field or the laboratory.
In the following points, the previous studies and their result were summarized:

- The bearing capacity of the belled pile is higher than the ordinary pile range (40% to 73.75%).
- The best shape of the belled pile is the half cone, and the worst state is when the bell is fully cone.
- The best number of belled piles is two bells because the bearing capacity increases when the number of bells increases but does not exceed two to work hard and high cost.
- The best location of a bell is at the base of the pile.
- If the pile contains one bell only and when the pile has two bells, one of them is located at the bottom, and the other bell above it in a specified space from the center to the center of bells, and this space ranges from (2.5-3.5) of the diameter of the pile (2-4) m.
- The diameter of the belled pile should be more than the stem diameter 2.5 times.
- The bell's length depends on its angle because it joins two diameters of the pile stem and the diameter of the bell.
- The inclination angle ranges from (18°to 45°).
- In the previous studies, the bell's length has less effect than the angle of inclination, and the angle of inclination has more impact than the diameter and space of the bells.
- In a group system, the spacing between the piles is (2.5-3.5) times the diameter of bells from center to center.
- These typical dimension values significantly affect the belled pile's performance. They result from many studies a long time, so any change changes the calculation process, especially in bearing capacity values.

REFERENCES

Abbas, H.O., 2021, February. The compressive capacity of conventional and under-reamed piles in soft clay. IOP Conference Series: Materials Science and Engineering (Vol. 1076, No. 1, p. 012094). IOP Publishing. Doi:10.1088/1757-899X/1076/1/012094

Alawneh, A., 1999. Tension piles in the sand: a method including degradation of shaft friction during pile driving. *Transportation Research Record*, 1663(1), pp. 41-49.

Alhassani, A. M. J., 2021. Analysis of Under-reamed Piles Subjected to Different Types of Load in Clayey Soil. *International Journal of Engineering*, 34(8), pp. 1940-1948. Doi:10.5829/ije.2021.34.08b.15

Alkroosh, I., and Nikraz, H., 2011. Simulating pile load-settlement behavior from CPT data using intelligent computing. *Open Engineering*, 1(3), pp. 295-305. Doi:10.2478/s13531-011-0029-2
Al-Mhaidib, A.I., and Edil, T.B., 1998. Model tests for uplift resistance of piles in sand. *Geotechnical Testing Journal*, 21(3), pp. 213-221. Doi:10.1520/GTJ10895J

Al-Mosawe, M.J., Al-Shakarchi, Y.J., and Al-Taie, S.M., 2007. Embedded in sandy soils with cavities. *Journal of Engineering*, *13*(1), pp. 1168-1187.

Al-Saidi, A.A., Al-Mosawe, M., and Al-Shakarchi, Y.A.S., 2021. Behavior of Defective Cast in Place Piles. *Journal of Engineering*, *27*(4), pp. 96-117 Doi:10.31026/j.eng.2021.04.08

AL-Shamaa, M.F., Sheikha, A.A., Karkush, M.O., Jabbar, M.S., Al-Rumaithi, A.A., 2021. Numerical Modeling of Honeycombed Geocell Reinforced Soil. *Modern Applications of Geotechnical Engineering and Construction*, pp. 253-263. Springer, Singapore. Doi:10.1007/978-981-15-9399-4_22

Ashour, M., and Helal, A., 2014. Contribution of vertical skin friction to the lateral resistance of large-diameter shafts. *Journal of Bridge Engineering*, *19*(2), pp. 289-302. Doi: 10.1061/(ASCE)BE.1943-5592.0000505.

Ayothiraman, R., and Boominathan, A., 2013. Depth of fixity of piles in clay under dynamic lateral load. J. Geotech. Geol. Eng., 31(2), pp. 447–461. Doi:10.1007/s10706-012-9597-z

Bouassida, M., 2006. Modeling the behavior of soft clays and new contributions for soil improvement solutions. Proc. 2ndInt. Conf. on Problematic Soils. pp. 1-12.

Chae, D., Cho, W., and Na, H.Y., 2012. Uplift capacity of belled pile in weathered sandstones. *International Journal of Offshore and Polar Engineering*, 22(04). pp. 297-305. http://www.isope.org/publications

Chen, J.J., Wang, J.H., Liang, R., Fan, W., and Wang, W.D., 2010. Behavior of uplift pile foundation during large-scale deep excavation. In *GeoFlorida 2010: Advances in Analysis, Modeling & Design*. pp. 1727-1736. Doi:10.1061/41095(365)175

Chiluwal, S., and Guner, S., 2019. Design recommendations for helical pile anchorages subjected to cyclic load reversals. https://www.utoledo.edu/engineering/faculty/serhan-guner/docs/R2_DFI_Helical_Pile_Anchorages.pdf

Chow, F. C., Jardine, R. J., Nauroy, J. F., & Brucy, F., 1997. Time-related increases in the shaft capacities of driven piles in sand. *Geotechnique*, 47(2), pp. 353-361. Doi:10.1680/geot.1997.47.2.353

Das, B.M., Seeley G.R., 1975. Uplift capacity of buried model piles in sand. *Journal of the Geotechnical Engineering Division*, 101(10), pp. 1091-1094. Doi:10.1061/AJGEB6.0000208

Deb, T., and Pal, S. K., 2019. Comparison of Uplift Capacity and Nonlinear Failure Surfaces of Single-Belled Anchor in Homogeneous and Layered Sand Deposits. *Advances in Civil Engineering*. Doi:10.1155/2019/4672615

Decourt, L., 1999. Behavior of foundations under working load conditions. *11th Pan-American Conferenvce on Soil Mechanics and Geotechnical Engineering, Foz do Iguaçu*, *4*, pp. 453-488.

Dhatrak, P., Shirsat, U., Sumanth, S., and Deshmukh, V., 2018. Finite element analysis and experimental investigations on stress distribution of dental implants around implant-bone interface. *Materials Today: Proceedings*, *5*(2), pp. 5641-5648. Doi:10.1016/j.matpr.2017.12.157

Diana, W., Hardyatmo, H.C., and Suhendro, B., 2017. Effect of pile connections on the performance of the nailed slab system on the expansive soil. *GEOMATE Journal*, *12*(32), pp. 134-141. DOI: Doi:10.21660/2017.32.42773

Dickin, E.A., and Leung, C.F., 1992. The influence of foundation geometry on the uplift behavior of piles with enlarged bases. *Canadian Geotechnical Journal*, 29(3), pp. 498-505. Doi:10.1139/t92-054

Ellis, E.A., and Springman, S.M., 2001. Full-height piled bridge abutments constructed on soft clay. *Geotechnique*, *51*(1), pp. 3-14. Doi:10.1680/geot.2001.51.1.3

Emirler, B., Tolun, M., and Yildiz, A., 2020. Investigation on determining uplift capacity and failure mechanism of the pile groups in sand. *Ocean Engineering*, 218, P. 108145. Doi:10.1016/j.oceaneng.2020.108145

Engin, H. K., Septanika, E. G., and Brinkgreve, R. B. J., 2008. Estimation of pile group behavior using embedded piles. In Proceeding of the 12th International Conference of International Association for Computer Methods and Advances in Geomechanics, Goa, India. pp. 3231-3238.

Farokhi, A.S., Alielahi, H., and Mardani, Z., 2014. Optimizing the performance of under-reamed piles in clay using numerical method. *Electronic Journal of Geotechnical Engineering*, *19*(Bundle G), pp. 1507-1520.

Gao, G., Gao, M., Chen, Q and Yang, J, 2016. Field Load Testing Study of Vertical Bearing Behavior of a Large Diameter Belled Cast-in-Place Pile. *KSCE Journal of Civil Engineering*, 23, pp. 2009–2016. Doi:10.2514/3.56113

Goudar S., and Kamatagi A., 2022. An experimental evaluation of axial load bearing capacity of belled and straight piles embedded in sand. *International Journal of Engineering*. 35(8), pp. 1599-1607. Doi:10.5829/ije.2022.35.08b.16

Guner, S., and Chiluwal, S., 2021. Cyclic load behavior of helical pile-to-pile cap connections subjected to uplift loads. *Engineering Structures*, 243, P.112667. Doi:10.1016/j.engstruct.2021.112667

Hazzar, L., Hussien, M.N., and Karray, M., 2017. Influence of vertical loads on lateral response of pile foundations in sands and clays. *Journal of rock mechanics and geotechnical engineering*, 9(2), pp. 291-304. Doi:10.1016/j.jrmge.2016.09.002

Honda, T., Hirai, Y., and Sato, E., 2011. The uplift capacity of belled and multi-belled piles in dense sand. *Soils and Foundations*, 51(3), pp. 483-496. Doi:10.3208/sandf.51.483

Ilamparuthi, K., and Dickin, E.A., 2001. The influence of soil reinforcement on the uplift behavior of belled piles embedded in the sand. *Geotextiles and Geomembranes*, 19(1), pp. 1-22. Doi:10.1016/S0266-1144(00)00010-8

Jebur, M.M., Ahmed, M.D., and Karkush, M.O., 2020. Numerical analysis of under-reamed pile subjected to dynamic loading in sandy soil. IOP conference series: materials science and engineering (Vol. 671, No. 1, P. 012084). IOP Publishing. Doi:10.1088/1757-899X/671/1/012084

Kang, J.G., and Kang, G.O., 2022. Experimental and Semitheoretical Analyses of Uplift Capacity of Belled Pile in Sand. *International Journal of Geomechanics*, 22(12), P.04022217. Doi:10.1061/(ASCE)GM.1943-5622.0002511

Kang, J.G., Yasufuku, N., Ishikura, R., and Purnama, A.Y., 2019. Prediction of Uplift Capacity of Belled-type Pile with Shallow Foundation in Sandy Ground. Lowland Technology International, 21(2), pp. 71-79. https://cot.unhas.ac.id/journals/index.php/ialt_lti/article/view/683

Karkush, M.O., Ala, N.A., 2019. Numerical evaluation of foundation of digester tank of the sewage treatment plant. *Civil Engineering Journal*. 22(5), pp. 996-1006. Doi:10.28991/cej-2019-03091306

Karkush, M.O., Sabaa, M.R., Salman, A.D., Al-Rumaithi, A., 2022. Prediction of bearing capacity of driven piles for Basrah governatore using SPT and MATLAB. Journal of the Mechanical Behavior of Materials. 1;31(1), pp. 39-51. Doi:10.1515/jmbm-2022-0005

Khatri, V.N., Kumar, A., Gupta, S.K., Dutta, R.K., and Gnanandarao, T., 2022. Numerical study on the uplift capacity of under-reamed piles in clay with linearly increasing cohesion. *International journal of geotechnical engineering*, 16(4), pp. 438-449. Doi:10.1080/19386362.2019.1660527

Kong, G.Q., Yang, Q., Liu, H.L., and Liang, R.Y., 2013. Numerical study of a new belled wedge pile type under different loading modes. *European Journal of Environmental and Civil Engineering*, 17(sup1), pp.s65-s82. Doi:10.1080/19648189.2013.834586

Kranthikumar, A., Sawant, V.A., and Shukla, S.K., 2016. Numerical modeling of granular anchor pile system in loose sandy soil subjected to uplift loading. International Journal of Geosynthetics and Ground Engineering, 2(2), pp. 1-7. Doi:10.1007/s40891-016-0056-4

Krishnan, R., Gazetas, G., and Velez, A., 1983. Static and dynamic lateral deflexion of piles in non-homogeneous soil stratum. *Geotechnique*, 33(3), pp. 307-325. Doi:10.1680/geot.1983.33.3.307

Lee, W., Kim, D., Salgado, R., and Zaheer, M., 2010. Setup of driven piles in layered soil. *Soils and foundations*, 50(5), pp. 585-598. Doi:10.3208/sandf.50.585

Lei, J., Zhou, Z., Han, D., Zhu, S., Feng, H., Wang, K., and Tian, Y., 2022. Centrifuge model tests and settlement calculation of belled and multi-belled piles in loess area. Soil Dynamics and Earthquake Engineering, 161, P.107425. Doi:10.1016/j.soildyn.2022.107425

Liang, H., Zeng, H., Cao, K., Liu, C., and Cheng, X., 2021. Analysis of Cumulative Damage Characteristics of Long Spiral Belled Pile under Horizontal Cyclic Loading at Sea. Shock and Vibration, pp. 1-20. Doi:10.1155/2021/2667545

Liu, B., Li, H., and Liu, S., 2020. Influencing factors of load carrying capacity and cooperative work laws of metro uplift piles. Structural Durability & Health Monitoring, 14(3), p.249. Doi:10.32604/sdhm.2020.06482

Liu, G., Zhang, Z., Cui, Q., Peng, J., and Cai, M., 2021. Uplift behavior of belled piles subjected to static loading. *Arabian Journal for Science and Engineering, 46,* pp. 4369-4385. Doi:10.1007/s13369-020-04779-x

Madhusudan Reddy, K., and Ayothiraman, R., 2015. Experimental studies on behavior of single pile under combined uplift and lateral loading. *Journal of geotechnical and geoenvironmental engineering*, 141(7), P.04015030. Doi:10.1061/(ASCE)GT.1943-5606.0001314

Meyerhof, G.G., and Adams, J.I., 1968. The ultimate uplift capacity of foundations. Canadian geotechnical journal, 5(4), pp. 225-244. Doi:10.1139/t68-024

Moayedi, H., and Mosallanezhad, M., 2017. Uplift resistance of belled and multi-belled piles in loose sand. *Measurement*, 109, pp. 346-353. Doi:10.1016/j.measurement.2017.06.001

Mohamed, A., Amr, H., 2014. Contribution of Vertical Skin Friction to the Lateral Resistance of Large-Diameter Shafts. Journal of Bridge Engineering, 19(2), PP. 289-302. Doi:10.1061/(ASCE)BE.1943-5592.0000505

Mosallanezhad, M., and Moayedi, H., 2017. Developing hybrid artificial neural network model for predicting uplift resistance of screw piles. Arabian Journal of Geosciences, 10(22), P.479. Doi:10.1007/s12517-017-3285-5

Nazir, R., Moayedi, H., Pratikso, A., Mosallanezhad, M., 2015. The uplift load capacity of an enlarged base pier embedded in dry sand. Arab. J. Geosci., 8, pp. 7285–7296. Doi:10.1007/s12517-014-1721-3

Poorooshasb, H. B., Alamgir, M., and Miura, N., 1996. Negative skin friction on rigid and deformable piles. *Computers and Geotechnics*, *18*(2), pp. 109-126. Doi:10.1016/0266-352X(95)00026-7

Poulos, H.G., 1994. An approximate numerical analysis of pile–raft interaction. *International Journal for Numerical and Analytical Methods in Geomechanics*, *18*(2), pp. 73-92. Doi:10.1002/nag.1610180202

Rao, M. R., Sridevi, G., and Rao, A. S., 2011. Performance of cushions of waste materials in heave reduction of expansive soils. In Proceedings of Indian Geotechnical Conference December. pp. 15-17. https://gndec.ac.in/~igs/ldh/conf/2011/articles/T04_09.pdf

Ruan, X., 2017. Practical Algorithm for large diameter pile tip bearing capacity based on displacement control. In 2017 6th International Conference on Energy and Environmental Protection (ICEEP 2017), pp. 64-69. Doi:10.2991/iceep-17.2017.11

Seo, H.O.Y.O.U.N.G., and Prezzi, M.O.N.I.C.A., 2007. Analytical solutions for a vertically loaded pile in multilayered soil. Geomechanics and Geoengineering, 2(1), pp. 51-60. Doi:10.1080/17486020601099380

Sharma, D., Jain, M. P., and Prakash, C., 1978. *Handbook on underreamed and bored compaction pile foundations*. Jain.

Shin, E.C., Das, B.M., Puri, V.K., 1993. Ultimate uplift capacity of model rigid metal piles in clay. Geotech Geol Eng 11, pp. 203–215 . Doi:10.1007/BF00531251

Sitharam, T.G., 2018. Advanced foundation engineering. Taylor & Francis, a CRC title, part of the Taylor & Francis imprint, a member of the Taylor & Francis Group, the academic division of T & F Informa, plc.

Sivakumar, V., O'Kelly, B.C., Madhav, M.R., Moorhead, C., and Rankin, B., 2013. Granular anchors under vertical loading–axial pull. *Canadian Geotechnical Journal*, *50*(2), pp. 123-132. Doi:10.1139/cgj-2012-0203

Soomro, M.A., Mangnejo, D.A., Bhanbhro, R., Memon, N.A., and Memon, M.A., 2019. 3D finite element analysis of pile responses to adjacent excavation in soft clay: Effects of different excavation depths systems relative to a floating pile. *Tunnelling and Underground Space Technology*, *86*, pp. 138-155. Doi:10.1016/j.tust.2019.01.012

Sun, T., Cui, X.Z., Sun, Y.F., Han, R.N., Ma, R.J., Yang, J.J., Wang, Y.L., and Chang, Y.J., 2022. Model tests on uplift capacity of double-belled pile influenced by distance between bells. *Journal of Central South University*, *29*(5), pp. 1630-1640. Doi:10.1007/s11771-022-5018-5

Tafreshi, S.M., Khalaj, O., and Dawson, A.R., 2014. Repeated loading of soil containing granulated rubber and multiple geocell layers. Geotextiles and Geomembranes, 42(1), pp. 25-38. Doi:10.1016/j.geotexmem.2013.12.003

Wagner, J.F., 2013. Mechanical properties of clays and clay minerals. In *Developments in clay science* Vol. 5, pp. 347-381. Doi:10.1016/B978-0-08-098258-8.00011-0

Wu, P., Guo, Y., Zhu, D., Jin, W., Zhang, Z., and Liang, R., 2020. Flexural performances of prestressed high strength concrete piles reinforced with hybrid GFRP and steel bars. Marine Georesources & Geotechnology, 38(5), pp. 518-526. Doi:10.1080/1064119X.2019.1600081

Yao, W.J., Chen, S.P., 2014. Elastic-plastic analytical solutions of deformation of the uplift belled pile. Technical vjesnik/Technical Gazette. Nov 1;21(6). https://journals.riverpublishers.com/index.php/ACES/article/download/10379/8691

Yu, M., Liu, B., Wang, Q., and Song, Y., 2020. Study on bearing capacity of belled uplift piles in soft clay area. *Indian Geotechnical Journal*, *50*, pp. 848-858. Doi:10.1007/s40098-020-00420-8

Zhang, D.G., Shen, X.L., Gao, F., Ren, Y.N., Wang, L.H., and Ma, C., 2020, September. Application of double-enlarged excavation foundation in transmission line engineering. In *Journal of Physics: Conference Series* (Vol. 1634, No. 1, P. 012162). IOP Publishing. Doi:10.1088/1742-6596/1634/1/012162

Zhang, L., and O'Kelly, B.C., 2014. The principle of effective stress and triaxial compression testing of peat. Proceedings of the Institution of Civil Engineers-Geotechnical Engineering, 167(1), pp. 40-50. Doi:10.1680/geng.12.00038