MODERN BUILDING
MATERIALS, STRUCTURES
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May 19–21, 2010, Vilnius, Lithuania
The 10th International Conference

Faculty of Civil Engineering
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HELICAL PILE BEHAVIOUR AND LOAD TRANSFER MECHANISM IN DIFFERENT SOILS

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Abstract. This article explores the system of helical piles and its behavior in compression. Three calculation methods have been examined: Latvian building code LBN 214-03 “Geotechnics. Pile foundations and footings” (СНиП 2.02-03-85), the calculation method proposed by the company “A.B.CHANCE”, and the large load-bearing capacity screw piles calculation methods developed by Canadian building engineers, which are used for the determination of helical pile load-bearing capacity. The construction methods of screw pile foundations have been compared and the advantages and disadvantages have been described. The article analyzes helical screw piles in compression with a different number of capacitive plates in four different soils – fine sand, floating loam, sandy loam and hard loam. The capacity of screw pile was obtained using the method developed by the American company “A.B.CHANCE”. Factors causing incapability have been determined. As none of the methods mentioned above describes the deformation of screw piles and does not provide any calculation or evaluation principles, the finite element calculation model by computer software “Lira 9.2” was used for the simulation. The deformation of a screw pile with one or two capacitive plates was examined in four different soils. The model also showed the interaction between the screw pile and the soils. The stresses in the soil massif have been calculated. Further research should be directed towards the development of the calculation method for deformation, as well as towards the verification of the calculation model of finite elements, and the modification to take into account the soils plasticity.

Keywords: helical pile, screw pile, soils, compression load, capacity, displacement, finite element method.

Introduction

Pile foundations are widely used in construction. They are used in cases when the top layers of the soil foundations are weak and stronger soils are relatively deep (Laiviņš and Rosihins 1970). Reinforced concrete, timber and steel, hollow-shell concrete and reinforced concrete piles, replacement and drilled piles are used most often, and helical piles – more rarely. Since in many occasions weak soils are to be found and frequently an uneven settlement of building foundations occurs, which causes the deformation of the building, cracks in the structures and cladding, then helical screw piles are a good way to strengthen new and already existing foundations.

The earliest known use of a helical screw pile foundation was for the support of lighthouses in tidal basins around England. An English brick maker, Alexander Mitchell, is credited with design of a "screw pile" for this purpose in 1833 (CHANCE® 2009). Helical piles are ground anchors constructed of helical-shaped circular plates welded to circular or square steel shaft at a specified spacing. Fig 1 shows a typical configuration for a multi helix screw pile in compression (CHANCE® 2003).

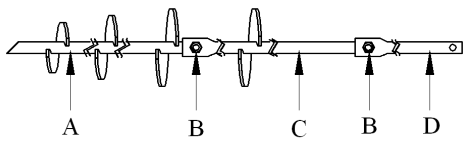

Fig 1. Typical configuration for a multi helix screw pile. A– lead section with several helices; B- joint; C– extension with one helice; D– extension without helices

During loading, the force applied to the pile is transferred to the surrounding soil. Thus, the ultimate capacity of the pile is dependant upon the strength of the soil. Soils derive their strength and ultimate load capacity from several characteristics like the internal friction angle φ, the adhesion factor α, the volume weight γ and the undrained shear strength of the soil (Narasimha *et al.* 1991). The depth of the screw pile construction is limited by soil density as well as by economical and practical obstacles. The piles are screwed into the ground using truck-mounted equipment with a special rotary head, and the soil structure is changed minimally (CHANCE® 2003).

Helical piles have several essential advantages in comparison to other piles: they can be screwed in with handy equipment, which is important in places, where heavy technology operation is limited, for example, in basements, under the bridges etc.; the installation of a screw pile foundation causes practically no vibration. These features make the screw pile foundation attractive on sites that are environmentally sensitive. Installations near existing foundations or footings generally cause no problems, and the piles can be used repeatedly. They also have some disadvantages, such as the load limitations due to the loading capacity of the handle, as well as corrosion which is possible in unfavorable soil conditions.

There are several calculation methods of screw piles load bearing capacity: the Latvian building code LBN 214-03 "Geotechnics. Pile foundations and footings" or СНиП 2.02.03-85 „Pile foundations", "A.B.CHANCE" company calculation method and the Canadian building engineers' large capacity screw piles calculation methods (Mitsch and Clemence 1985; Narasimha *et al.* 1991). If we look at all three helical piles calculation methods, conclusions are very different and hard to compare. The Latvian building code LBN 214-03 or СНиП 2.02.03-85 applies to screw piles with one capacitive plate; however, the "A.B.CHANCE" calculation method and the large capacity screw piles calculation methods developed by Canadian building engineers are used for the calculation of screw piles with one or several capacitive plates. Nevertheless, the behavior model of screw piles in each of the methods is different.

The ultimate compression capacity of the helical pile according to the Latvian building code

Theory suggests that the capacity of a foundation pile is equal to the capacity of helice and design strength of soil on the shaft end. The helice capacity is determined by calculating the unit bearing capacity of the soil and applying it to the helice area.

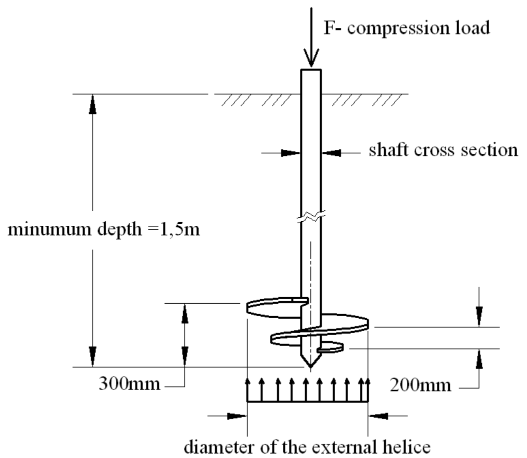

Fig 2. Design scheme of screw pile according to LBN 214-03

The ultimate compression capacity F_d of the helical pile (Fig 2), with helix diameter $d \leq 1.2$m and length $l \leq 10$m, see Equation (1).

$$F_d = \gamma_c[(\alpha_1 c_I + \alpha_2 \gamma_I h_1)A + uf_i(h-d)] \quad (1)$$

where F_d – pile compression capacity [kN]; γ_c – service factor; α_1; α_2 – dimensionless factors; c_I – cohesion of soils [kPa]; γ_1 – the volume weight [kN/m^3]; h_1 – depth to top helice [m]; A – area of the helice [m^2]; f_i – design strength of soil on the shaft end [kPa]; u – the perimeter of the helice screw pile shaft [m]; h – the embedment depth of pile [m]; d – diameter of the helice [m] (Latvian building code 2003).

The ultimate compression capacity of the helical screw pile according to the Canadian building engineer calculation method

Methods for estimating pile ultimate capacities were proposed by Narasimha Rao (Narasimha *et al.* 1991) for the design of screw piles in cohesive soils and (Mitsch and Clemence 1985) for the design of screw piles in cohesionless soils. In the case of compressive loading, see Fig 3.

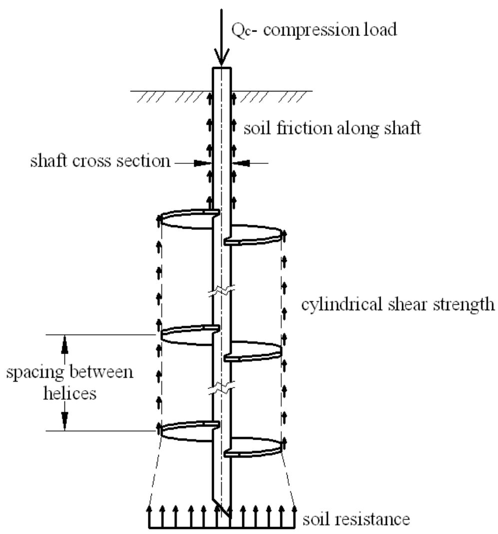

Fig 3. Design scheme of screw pile according to large capacity screw pile's method

The total failure resistance can be summarized as follows, see Equation (2):

$$Q_c = Q_{helix} + Q_{bearing} + Q_{shaft} \quad (2)$$

where Q_c – ultimate pile compression capacity [kN]; Q_{helix} – shearing resistance mobilized along the cylindrical failure surface [kN]; $Q_{bearing}$ – bearing capacity of pile in compression [kN]; Q_{shaft} – resistance developed along steel shaft [kN] (Mitsch and Clemence 1985; Narasimha *et al.* 1991).

For a cohesive soil the ultimate compression capacity of the helical screw pile using a cylindrical shearing method, see Equation (3), (4), (5), (6), as proposed by Mooney and Narasimha (Narasimha *et al.* 1991) is:

$$Q_{helix} = Sf \cdot (\pi \cdot D \cdot Lc) \cdot C_U \quad (3)$$

$$Q_{bearing} = A_H \cdot C_U \cdot N_C \quad (4)$$

$$Q_{shaft} = \pi \cdot d \cdot H_{eff} \cdot \alpha \cdot C_U \quad (5)$$

$$Q_c = Sf \cdot (\pi \cdot D \cdot L_C) \cdot C_U + A_H \cdot C_U \cdot N_C + \\ + \pi \cdot d \cdot H_{eff} \cdot \alpha \cdot C_U \quad (6)$$

For a cohesionless soil the ultimate compression capacity of the helical screw pile using a cylindrical shearing method (Where H/D ≥ 5) as proposed by (Mitsch and Clemence 1985) is, see Equations (7), (8), (9), (10):

$$Q_{helix} = \frac{1}{2} \cdot \pi \cdot D_a \cdot \gamma' \cdot (H_3^2 - H_1^2) \cdot K_s \cdot \tan\phi \quad (7)$$

$$Q_{bearing} = \gamma' \cdot H \cdot A_H \cdot N_q \quad (8)$$

$$Q_{shaft} = \frac{1}{2} \cdot P_S \cdot H_{eff}^2 \cdot \gamma' \cdot K_S \cdot \tan\phi \quad (9)$$

$$Q_c = \gamma' \cdot H \cdot A_H \cdot N_q + \frac{1}{2} \cdot \pi \cdot D_a \cdot \gamma' \cdot (H_3^2 - \\ - H_1^2) \cdot K_s \cdot \tan\phi + \frac{1}{2} \cdot P_S \cdot H_{eff}^2 \cdot \gamma' \cdot K_S \cdot \tan\phi \quad (10)$$

where Q_c – ultimate pile compression capacity [kN]; D – diameter of helix [m]; D_a – average helix diameter [m]; L_c – is the distance between top and bottom helical plates [m]; C_u – undrained shear strength of soil [kPa]; A_H – area of the bottom helix [m^2]; N_c; N_q – dimensionless bearing capacity factors; d – diameter of the shaft [m]; H_{eff} – effective length of pile [m]; α – adhesion factor; S_f – spacing ratio factor; γ' – the volume weight [kN/m^3]; K_s – coefficient of lateral earth pressure in compression loading; φ – soil angle of internal friction in degrees; H – the embedment depth of pile [m]; D_1 – diameter of top helix [m]; H_1 – depth to top helix [m]; H_3 – depth to bottom helix [m]; P_s – the perimeter of the screw pile shaft [m].

The ultimate compression capacity of the helical screw pile according to „A.B.CHANCE" (USA) method

This theory suggests that the capacity of a foundation anchor is equal to the sum of the capacities of individual helices, see Fig 4. The helix capacity is determined by calculating the unit bearing capacity of the soil and applying it to the individual helix areas. Friction along the central shaft is not used in determining ultimate capacity. A necessary condition for this method to work is that the helices be spaced far enough apart to avoid overlapping of their stress zones (CHANCE® 2003). The calculation uses different parameters of soil — the cohesive factor of soils, the volume weight, the pressure of soil, as well as the area of the helix and the depth to the helix.

The ultimate theoretical capacity of a multi-helix foundation equals the sum of all individual helix capacities, see Equation (11). To determine the theoretical bearing capacity of each individual helix, use Equation (12) (CHANCE® 2003).

$$Q_t = \sum Q_h \quad (11)$$

$$Q_h = A_h(9c + qN_q) \le Q_s \quad (12)$$

where Q_t – total multi-helix anchor capacity [kN]; Q_h – individual helix bearing capacity [kN]; A_h – projected helix area [m^2]; c – soil cohesion; q – effective overburden pressure [kN/m^2], use Equation (13); N_q – bearing capacity factor; Q_s – upper limit determined by helix strength [kN].

$$q = \gamma \cdot d \quad (13)$$

where q – effective overburden pressure [kN/m^2]; γ – effective unit weight of soil [kN/m^3]; d – depth to helix [m].

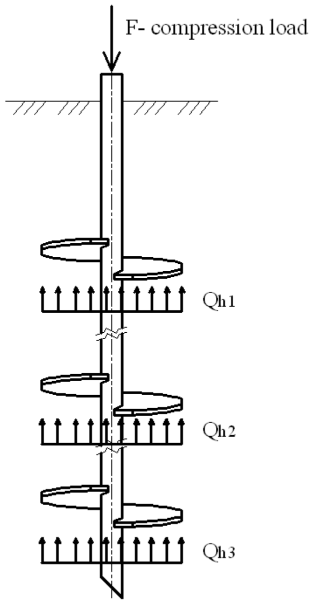

Fig 4. Design scheme of screw pile according to USA „A.B.CHANCE" company's method

The shear strength of a soil is most often characterized by cohesion (c) and the angle of internal friction (φ) in degrees. Soils are classified according to their cohesiveness or non-cohesiveness. Cohesive soils derive their shear strength from cohesion and are fine grained soils (clay or clayey silt), and non-cohesive soils derive their shear strength from the friction between particles (sands and gravels) (CHANCE® 2009).

Behavior analysis in different soils

The capacities of a screw pile are obtained using the method developed by "A.B.CHANCE" (USA). The screw pile is examined in four different soils with one to six capacitive plates. The geological properties of the soils are described in Table 1.

Table 1. Soil characteristics

Nr.	Void ratio e_n	Volume weight ρ_n, g/cm^3	Soil angle of internal friction, degree φ,	Cohesion *c*, kPa	Module of elastic. *E*, MPa,
1.	0.70-0.76	1.67	24	0-1	10
2.	0.90	1.75	15	15	7
3.	0.35	2.25	37	0	>21
4.	0.90	2.0	32	5	>10

Soil No 1 – fine, light grey with shivers of seashells, plants and wood, imbued with water, mealy, average compact sand. No 2 – flowing, plastic, muddy, peaty, brown grey, wet sand-clay. No 3 – hard, red brown, brown grey sandy loam (moren) with grit pebble. No 4 – hard loam, semi hard clay, grey green, dolomite macadam on top, with pieces of gypsum.

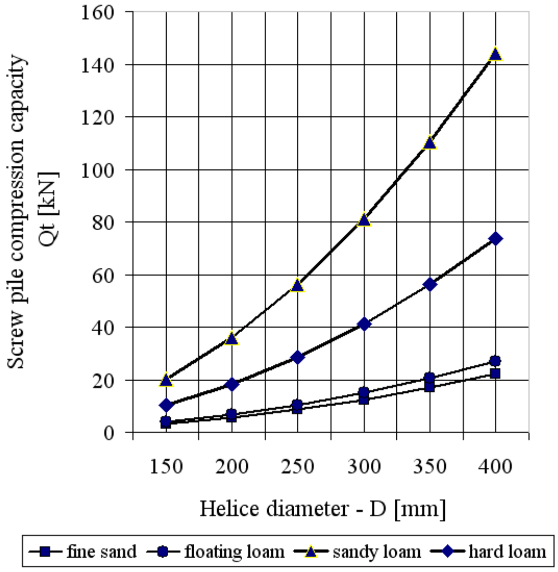

Fig 5. The compression capacity of screw pile in different soils depending on variety of plates diameter D, if all sizes of plates are into 150 cm depth from the top layer of soil.

It has been examined how the compression capacity of a helical screw pile changes in the same soil, while changing the diameter the helice. The examined screw pile is with one capacitive plate. All the plates are screwed within minimal allowable depth – according to the design guidelines provided by "A.B.CHANCE", it is the depth of five capacitive plates, or not less than 1.5 meters.

To sum up all the results, see Fig 5, we can see that the size of the plate diameter has an essential influence on the load-bearing capacity of the screw pile. It was established that the larger is the diameter, the higher is the load-bearing capacity, but not to the same extent in all soils. For example, let's compare a 400 mm diameter plate in all four soils. The highest load-bearing capacity is achieved in soil No 3, then soil No 4, and then the rest – in soil No 2 and No 1 the load-bearing capacity is very similar. The difference in results between the highest and the lowest load-bearing capacity in different soils is 6.5 times. Therefore it is impossible to determine the price of the screw pile capacity, because geometrically identical screw piles in different soils have different load bearing capacity (Sprince 2009).

It was also examined how the compression capacity of screw piles is influenced by the depth of screwing. The screw pile was screwed in starting with the minimal embedment depth till 2 meters depth. The minimal embedment depth is equal to five diameters of the plate, which is 5×0.15 m = 0.75 m. In all depths the smallest possible capacitive plate – 150mm – was examined.

As the result, see Fig 6, the linear correlation is observed in all the examined types of soil. By increasing the embedment depth, a higher load-bearing capacity of the screw pile will be obtained. The highest values of capacity in all depths were achieved in soil No 3, then soil No 4 and only then soil No 2 and No 1, where the load-bearing capacity is similar. For example, if we examine the capacity of the screw pile in soil No 3, when the plate is screwed 0.75 m deep, and also when this depth is two times bigger (1.5 m), we see that the difference in the load-bearing capacity is two times, the same as the difference of depths. In other soil types there is a similar correlation of results. Therefore, the load-bearing capacity of the plate enlarges in direct proportion and to the same extent as the depth of embedment, which means that when loading a screw pile with two plates of the same size, the bottom plate will carry more load than the top one (Sprince 2009).

The number of capacitive plates on a screw pile influences its capacity in compression. The load-bearing capacity of screw piles with one to six plates was determined in the soils mentioned above. The result, see Fig 7, shows that the highest capacity with different number of plates is in soil No 3. The maximum number of plates that was examined is six.

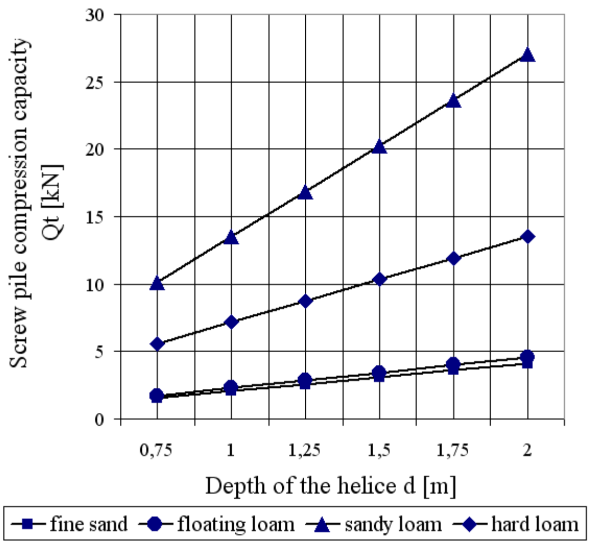

Fig 6. The compression capacity of a screw pile in relation to the helice depth

It has been established that the number of plates and the diameters of two screw piles can be very different, but give similar results. So it is vital to find the most feasible, suitable and rational type of the helical screw pile for each and every case individually, because the prime cost of a screw pile depends on the total length of the pile and the number of capacitive plates (Sprince 2009).

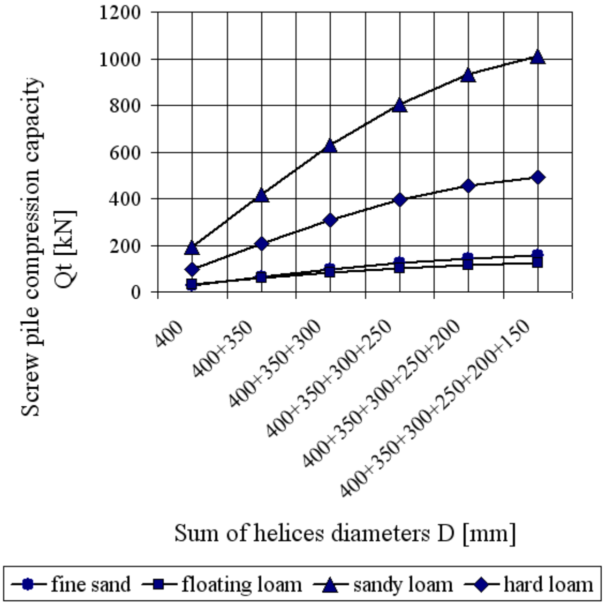

Fig 7. Compression capacity of screw piles with different number of helices.

The behavior of a screw pile modeled by finite element method

In Paragraph 33 of the Latvian building code LBN 214-03 "Geotechnics. Pile foundations and footings", it is provided that pile footings and foundations shall be calculated for two limit states: the load-bearing capacity test (the first limit state) and the possible deformation and moving inspection (the second limit state). In practice it has been observed that the second limit state often is the determinative.

As none of the methods mentioned above, including the Latvian building code LBN 214-03, describes deformation of a screw pile, and they don't provide any calculation or evaluation principles, the finite element calculation model by computer program "Lira 9.2" was used for simulation. With this program the deformations of screw pile plates in different loading conditions and in different soils were determined, as well as the character of the screw pile deformation with a specific pressure was examined (Sprince 2009).

This FE is meant for simulation of one-way behavior of the soil in compression taking account of shear. FE works on plane strain scheme according to Coulomb's law.

Coulomb's law is applied. Linear analysis is performed if principal stresses $\sigma1 <= Rt$, $\sigma2 <= Rt$, $\sigma1-\sigma2 <= -\sin(\varphi) * (\sigma1+\sigma2) + 2 * C * \cos(\varphi)$.

It is necessary to specify large number of iterations during the simulation of nonlinear loading. Other information is specified as usual ("Lira 9.2" user manual).

The plasticity of soil in these calculations was not taken into account. In this calculation model it is possible to model soils in the necessary depth and to specify soil layers according to the geological properties and depth. To facilitate the calculations, homogeneous soil was used in the whole length of the screw pile.

With "Lira 9.2" the screw pile was examined in four different soils – fine sand, floating loam, sandy loam, hard loam, and the behavior of the screw pile with one and two capacitive plates was determined. The type of the load is compression. Two examples with one and two capacitive plates on the screw piles shaft will be discussed.

The example of calculation of a helical screw pile with one capacitive plate

There is a helical screw pile model with one capacitive plate with the diameter of 800 mm and the thickness 10 mm. The depth of the plate embedment – 2 m from the soil surface. The soil in which the load-bearing capacity of the screw pile is calculated – floating loam ($\gamma = 17.5$ kN/m^3, $\varphi = 15°$), see Table 1. With the "A.B.CHANCE" method it was established that the capacity of a screw pile in such soil is 121 kN. A concentrated compression load of F=100kN is imposed on this screw pile, as well as the deadweight of the soil itself.

For the shear strain development of the soil massive during the analysis, see Fig 8.

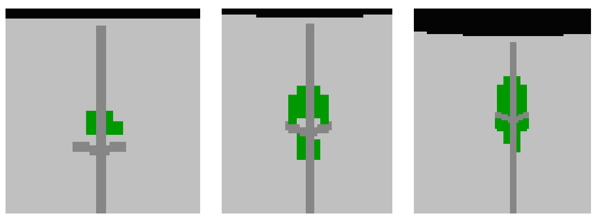

Fig 8. The shear strain development of the soil massive during the loading process

Fig 9 shows how soil is deforming along with the screw pile and how far the soil is influenced by such concentrated load imposed on the screw pile.

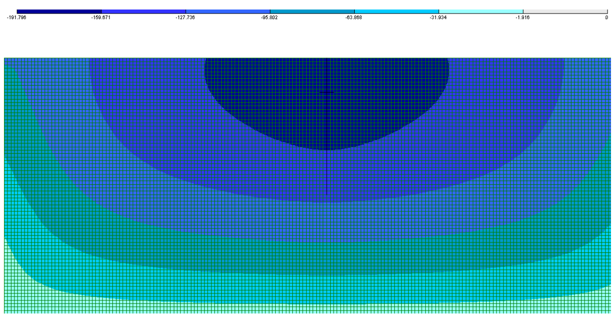

Fig 9. Deformations of the soil massive and the helical screw pile in a vertical direction

Figure 10 shows the soil stresses Nz. Under the capacitive plate the soil stresses are higher than above the plate.

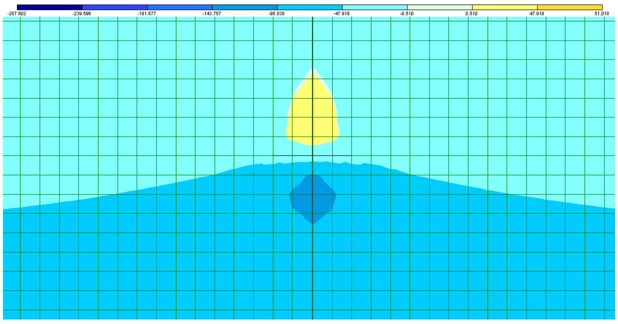

Fig 10. Soil stresses Nz around the helice

The example of calculation of a screw pile with two capacitive plates

A screw pile model with two capacitive plates was created. In order to facilitate the comparison, both capacitive plate diameters and the thicknesses are assumed to be 800 mm and 10 mm respectively. The embedment depth of the first plate – 2 m below the soil surface; the distance between the helices – three diameters of the bottom plate, i.e. 2.4 m. The soil in which the screw pile is calculated is floating loam (γ=17.5kN/m3, φ=15˚), see Table 1. With the “A.B.CHANCE” method the capacity of screw pile in such soil was established to be 304 kN. A concentrated compression load of F = 250 kN is imposed on this screw pile, as well as the deadweight of the soil itself.

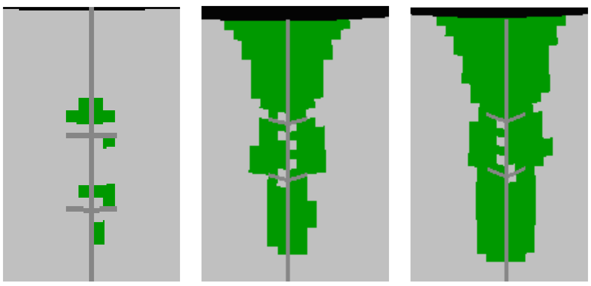

Fig 11. Shear strain development of the soil massive during the loading process

For the shear strain development of the soil massive during the analysis, see Fig 11.

Fig 12 shows soil stresses Nz. The stresses are larger underneath the capacitive plates. The largest stresses are under the lowest plate; and the smallest stresses are above the upper plate.

Having analyzed Fig 12 more carefully, we can see that the program “Lira 9.2” calculates every plate as a separate element, and that is in line with the screw pile behavior and calculation method developed by “A.B.CHANCE”.

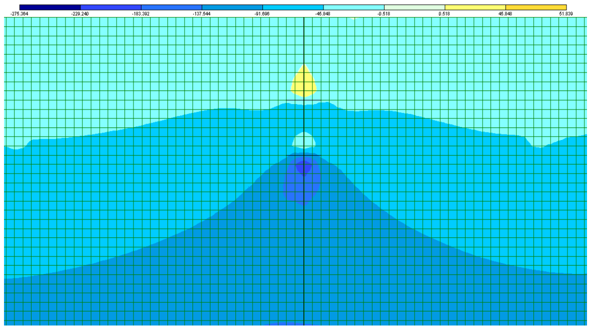

Fig 12. Soil stresses around helices

The obtained results are logical: in hard soils the screw pile deforms less and more uniformly, and the deformation of the screw pile’s plate is small in comparison to all other deformations of the screw pile; but in weaker soils this deformation enlarges (Sprince 2009). The permissible values of the screw pile deformations depend on the type of the building, which is established according to the project, the client or according to Appendix 4 of LBN 207-01 “Geotechnics. Pile foundations and footings”. This work which has been started on the finite element calculation models could be used as a basis for further research.

Conclusions

Three methods of helical pile load-bearing capacity have been examined. It was concluded that the LBN 214-03 method is incomplete: there is no information on how to proceed if calculations need to be performed for a screw pile with two or more plates, also there are no references to how the screw pile plates should be constructively placed on the handle.

The helical screw piles in compression in four different soils with different number of capacitive plates were analyzed.

As a result, the following relations were observed.

The load-bearing capacity of a helical screw pile is influenced by the size of the capacitive plate diameter, but not in all soils to the same extent. According to the results, the results between various soils can differ up to 6 times.

Geometrically identical screw piles will have a different capacity in different soils, therefore it is impossible to determine the price of screw pile capacity.

According to the results, it can be concluded that if the embedment depth of the screwed plate is enlarged, the capacity enlarges in a direct proportion.

The number and diameter of plates on two piles can differ, but give a similar capacity. Taking into consideration that the prime cost of a screw pile depends on its total length and the number of capacitive plates, it is important to find the best screw pile solution from the economical as well as the rational point of view.

The computer program “Lira 9.2” simulates the finite element model of the soil together with the screw pile, which helps to acquire information about the behavior of the screw pile and the soil in compression. In the same way it is possible to see the plate and soil deformations under load, as well as the stresses that appear in soils underneath the plates.

The calculation model developed in the computer program "LIRA 9.2" considers each plate as a separate capacitive element, and that is in line with the method of calculating screw pile capacity established by "A.B.CHANCE". From the results it is conducted that a plate which is lower takes more pressure than that which is higher, which matches the results of rationalization researches.

Further research should be directed towards the development of the calculation method for deformation, as well as towards the verification of the calculation model of finite elements, and the modification to take into account the soils plasticity.

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