Regulation of tubular pile bearing capacity by internal diaphragm

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ABSTRACT

One of the ways to reduce piling expenses is decreasing volume of piling works. It can be provided by shortening either the piles length or the number of pipes. These results may be achieved if each short-cut pile is improved and bears the same loading as a pile of normal length or if each pile of normal length is improved and bears larger axial force in comparison with its initially designed capacity. Presented study clarified possibilities to regulate the pipe pile's bearing capacity using an internal rigid diaphragm (closure) placed inside the pile's shaft. It increases the bearing capacity of the tubular pile due to additional soil reaction under the closure. Pressing the pipe pile's model into sand box was assumed as the most gentle and precise method to study considered driving process. Besides results of such approach may be good adapted to predict pipe behavior in case of Press-in method of the pile installation. Some conclusions were made clarifying the diaphragm's positive contribution to pile bearing capacity, the effect of the closure's location along the pipe shaft, and the influence of the diaphragm's design (flat, conical, and cylindrical closures). Numerical analysis of the gained experimental data gave the possibility to apply approximating functions with good correlation indexes.

Key words: *Pipe pile, Bearing capacity, Internal diaphragm, Model study, Press-in method*

Introduction

Modern marine transportation and offshore structures such as deep-water port berths, oil and gas platforms, raid and offshore fixed single point moorings, submerged stores, and others often include steel tubular piles of essential length (80-100 m and more) as main bearing elements. Such tubular piles should provide high bearing capacity in case of external axial loads application as shown by Tomlinson and Woodward (2008), Randolph et al. (1991), Doubrovsky et al. (2018).

Besides, piling works may provoke some environmental problems connected with the hammer's operation (noise, vibration, dynamic action, carbon footprint, etc.). One of the ways to reduce environmental hazards during pipe pile driving is decreasing piling work volume. It can be provided by shortening either of pile's length (i.e. depth of driving) or the number of pipes in the pile foundation (keeping another pile's dimensions and material properties without changes). Both such approaches should provide a required bearing capacity of the pile foundation despite the short-cut piles or fewer piles number (axial compressing loads are considered).

These results may be achieved if each short-cut pile is improved and bears the same loading as a pile of normal (initially designed) length or if each pile of normal length is improved and bears larger axial force in comparison with its initially designed capacity.

So, the study aimed to clarify some possibilities to improve the pipe pile's bearing capacity using an internal rigid diaphragm (closure) placed inside the pile's shaft. This innovation increases the bearing capacity of the tubular pile due to additional soil reaction inside the shaft as has been confirmed by known on-site measurements (Tomlinson and Woodward (2008) and our previous physical modeling (Doubrovsky et al. (2022)).

In many cases, large diameter tubular piles of shelf structures are installed without plugging effect or with partial plugging as considered by Randolph et al. (1991), White et al. (2010), Gudavalli et al. (2013), Lehane and Gavin (2004). So, the approach based on the use of the closure of the pile's shaft looks rather attractive for deep water port, marine, and offshore engineering. Thus, it needs detailed consideration and study aiming to determine the method's peculiarity, an appropriate sphere of application, details of diaphragm design, and its proper location along the pile's shaft.

Use of closure in pipe piles

Recommended technology to install the internal diaphragm was described (perhaps first) by Tomlinson and Woodward (2008). A hole is necessary for the diaphragm to release water pressure in the soil plug and to allow the expulsion of silt. Stresses on the underside of the diaphragm are high during driving and radial stiffeners are needed (**Fig. 1**).

According to Tomlinson and Woodward (2008), the minimum depth above the pile toe for locating the diaphragm is the penetration below the sea bed required for fixity against lateral loading. There are formulas in some norms allowing the determination of the fixity's depth depending on soil properties and the pile's bending rigidity; roughly this depth may be determined in the interval of (5-7) d, where d – pile diameter. However, sometimes further penetration is necessary to form the soil plug under the diaphragm by compacting the soil within the plug and developing the necessary base resistance. Thus, mentioned authors considered two locations for two soil plugs formation during the tubular pile driving: at the open end of the pile and under the internal diaphragm.

As an example of the diaphragm's practical application, we may refer to the piling works at the Hadera coal unloading terminal near Haifa (Tomlinson and Woodward (2008).

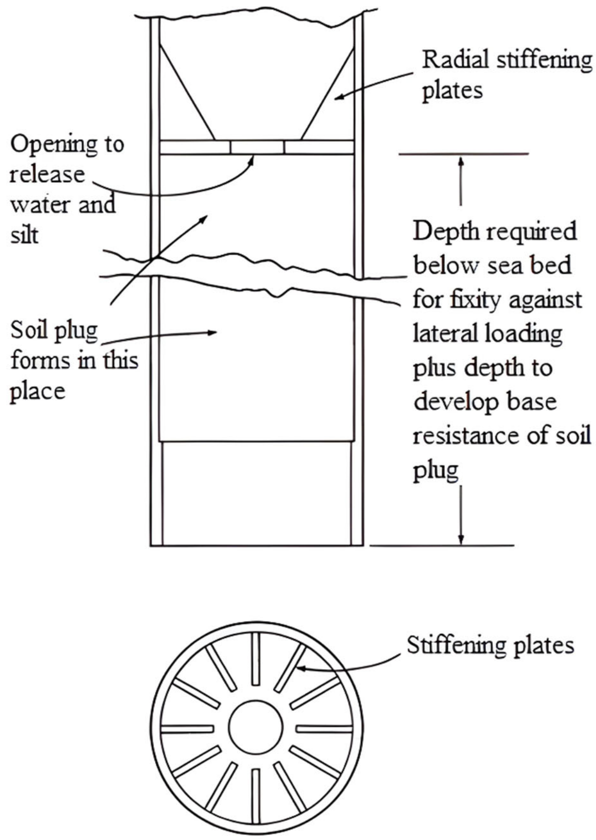

Fig. 1. Steel tubular pile with the diaphragm.

Open-end piles 1424- and 1524-mm OD were proposed but initial trial driving showed that very deep penetrations, as much as 70m below sea bed in calcareous sands, would be needed to develop the required axial resistance. The blow count diagram showed quite low resistance at 36m below the sea bed. Trials were then made of the diaphragm method. A diaphragm with a 600 mm hole giving 83% closure of the cross-section was inserted 20m above the toe. This increased the driving resistance at 39m below the sea bed and another trial with a 300 mm hole (95% closure) gave a higher resistance at 37m. It was supposed that such improvement of piles bearing capacity was stipulated by soil plug formation below the mentioned diaphragms.

Experimental modeling of pipe piles with diaphragm

Regarding that obvious effect (an increase of the pile's bearing capacity) has been achieved by the use of the rigid diaphragm, we intended to study the peculiarities of the considered approach by providing model static tests in laboratory conditions. We aimed to obtain parameters describing the considered pile driving process – both qualitative (related to the process in general) and quantitative (characteristic for the applied model pile-soil system) ones.

As to the method of pile installation, we suppose that traditional approaches (use of impact hammer or vibro hammer) are not reliable enough to provide safety of the rigid diaphragm fixed by welding inside the pile's shaft and interacting with soil under the diaphragm. In order to avoid dynamic actions upon the diaphragm during pile penetration we prefer to consider a safer but more effective method of pressing load application (jacking) (White, 2010).

To clarify the above-mentioned items related to the tubular pile with an internal diaphragm, we fulfilled a series of experimental studies in the Geotechnical Laboratory of the Department "Sea, River Ports and Waterways" at Odessa National Maritime University (Odessa, Ukraine).

For pile testing, we used a soil box of dimensions: width of 600 mm, length of 750 mm, and depth of 1100 mm (**Fig. 2**). For the model of the tubular open-end pile, we apply steel pipe d=50 mm external diameter, wall pipe thickness 1 mm, l=800 mm length. To drive the pipe into fine sand mechanical jack has been applied.

For experimental studies we used fine sand with the following characteristics: internal friction angle 33^0; density 14.5 kN/m^3; void ratio 0.71; moisture 0.07%; Young modulus 16 MPa, Poisson's ratio 0.3.

The first series of the experiment aimed to determine conditions of the soil plug formation at the tip of the open-end pile model. A detailed description of this study was presented in (Doubrovsky et al., 2022).

The second series of the experiment was devoted to clarification of the role and contribution of the internal diaphragm. For the model pile the diaphragm was produced as a circular steel plate (4 mm thickness), with its diameter corresponding to the inner diameter of the pile.

The internal diaphragm was fixed at several positions by changing the distance from the tip of the model pile: 0 (closed-end); 3d; 6d; 9d (total length of the pile was equal to 16d). As it is demonstrated by the diagrams presented in **Fig. 3**, the application of the internal diaphragm provides increasing open-end pile bearing capacity. The degree of such an increase depends on the diaphragm location. For the considered options of the diaphragm fixing point, the minimum increment of the open-end pile bearing capacity relates to the 3d distance between the diaphragm and the pile tip, and the maximal increment is measured at the 9d distance.

Perhaps mentioned circumstances may be commented by the following way. The upper plug under the diaphragm may be formed if there is a proper base reaction developed inside the shaft. Such a situation may occur if the upper plug (being in the process of formation) meets the already-formed lower plug. The last transfers additional pressure to the soil under the toe and provokes an additional base reaction.

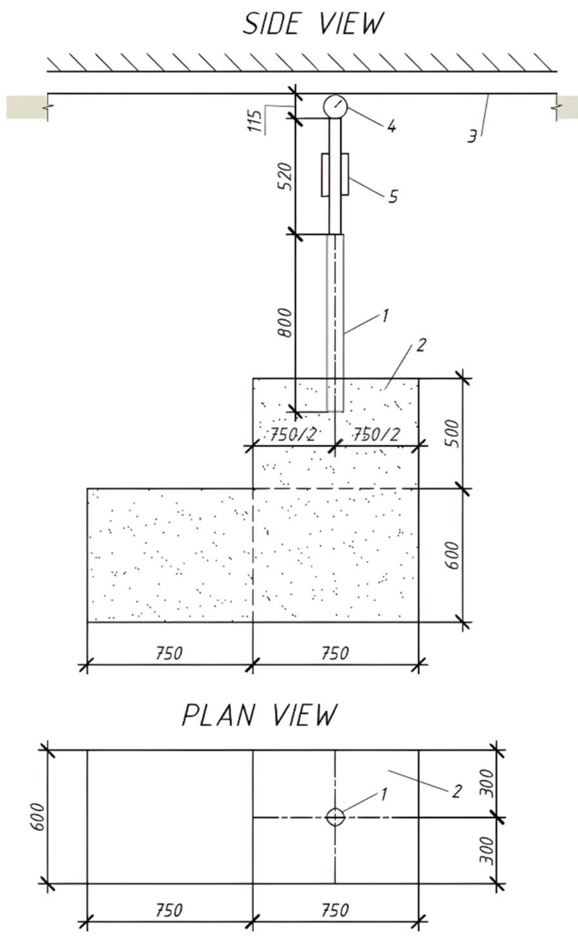

Fig. 2. Scheme of the experiment: 1 – pile model; 2 – sandbox; 3 – bearing beam; 4 – force gauge (dynamometer); 5 – jack loading system (telescopic) (all sizes in millimeters).

Thus, the additional external force acts on the plug and increases soil density in it. In fact, after that stage, two plugs are combined and work as one large plug between the diaphragm and the pile's toe. The creation of the mentioned large plug and its effective contribution to the pile bearing capacity may be provided only in case of the "right" location of the diaphragm (not too low and not too high). For our model tests the maximal bearing capacity of the open-ended pile was measured in the case of the 9d distance of the diaphragm from the pile tip.

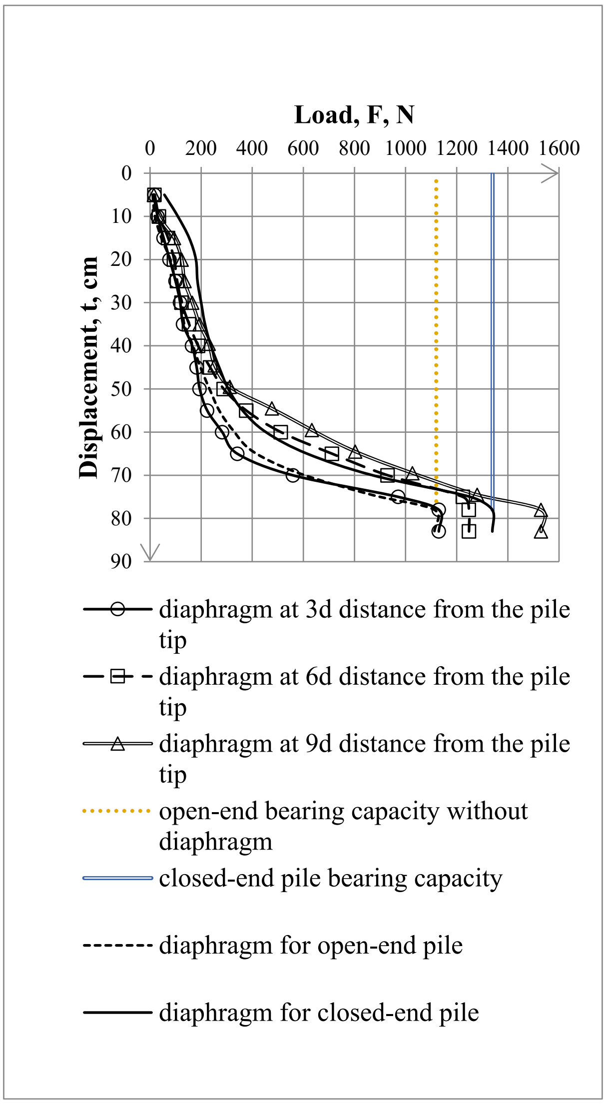

Fig. 3. Dependencies between vertical axial load upon the model open-end pile and its displacements.

It may be explained, particularly, by the fact that for the considered test conditions, approximate driving depth t= (4-5)d at the initial stage of pile installation is needed to dense soil due to the development of the friction forces inside the pile's shaft and to form a lower soil plug at the pile tip. If then to apply similar consideration for the follow-on stage of the driving process – compaction of the soil under the diaphragm due to the similar friction forces, required penetration depth for this stage to form the upper plug may be of similar value (4-5) d.

So, the total distance between the pile toe and the diaphragm may be considered as the sum of these two parts of the penetration depth, i.e., approx. (8-10) d. Such location of the diaphragm may be optimal to form two plugs consecutively and to combine them in one large plug.

Regarding quantitate parameters of open-end pile bearing capacity (Figure 3), we would like to note that due to the diaphragm's contribution, pile bearing capacity may be increased (in our tests up to 15-20%). Another effect consists in the possibility to decrease pile driving depth (10-15%). Mentioned figures should be considered concerning possible experimental errors stipulated by differences in the reproducibility of the model ground preparation as well as measurement inaccuracy (about 10% in total).

Also, it has been discovered that due to sand settlements inside the pile shaft during pile installation, there is an empty space under the diaphragm and, correspondingly, no contact between soil and diaphragm. In order to avoid clearance space under the diaphragm and to provide constant contact of the sand with under side of the diaphragm, we applied the diaphragm with several small holes allowing sand filling into the space under the diaphragm **(Fig. 5,f).** We tried to keep the density of sand in the pipe during the sand filling operation by controlling both required volume of additional sand to compensate discovered clearance and soil feed consistency through the holes in the diaphragm.

For the conditions of our laboratory model testing (skipping the details of intermediate conversions and calculations), it was determined that the related prototype is a tubular pile of diameter 1.0 m driven up to 10 m into similar sandy soil. Its bearing capacity (sum of the toe and shaft bearing capacities) is 1723 kN. For comparison: the calculated value of the prototype bearing capacity according to the recommendation of the related Ukrainian code occurred to be 2020 kN (some 15% difference). Also, for plugging effect assessment we have to consider scale effects stipulated by the influence of internal pile diameter. This aspect is subject to a study for further investigations.

Influence of closure design

To assess the effectiveness of various forms of the pile's closure, we considered 3 types of diaphragm: flat, conical (in 3 variants, differing in the angle of the cone), and cylindrical (**Fig. 4, 5**, dimensions in mm).

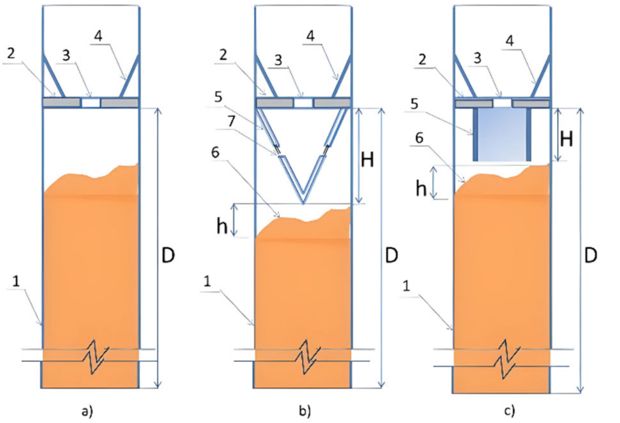

Fig.4. Variants of diaphragm:
a – flat; b – conic; c – cylindric; 1 – pile's shaft; 2 – diaphragm; 3 – drainage hole of the closure; 4 - stiffening rib; 5 – supporting element (conic or cylindric); 6 – soil surface in the pile; 7 – drainage hole of the conic diaphragm.

The driving of the model pile was carried out until the pile reached its bearing capacity, i.e. until the moment when the movements of the pile increased without an increase in the external load.

Of the three considered conical diaphragm options (with a cone angle of 30^0, 65^0, and 90^0), the best result was obtained for a pile's closure with an angle of 65^0.

A comparison of load-displacement dependencies for piles with different types of the diaphragm is shown in **Fig. 5**. The last shows that the cylindrical diaphragm occurred to be the most effective and the flat closure was least effective.

A comparison of the work of the model pile in two extreme cases (with an open and closed-end) and in the cases of the diaphragm of effective shape (cylindrical and conical with a cone angle of 65^0) is presented in **Fig. 6, 7.**

To analyze the influence of the location of the closure on the bearing capacity of the pile, the experimental dependence of the resistance of the soil to pile driving N (equivalent to the vertical load on the pile) on the depth D of the cylinder diaphragm location is of interest.

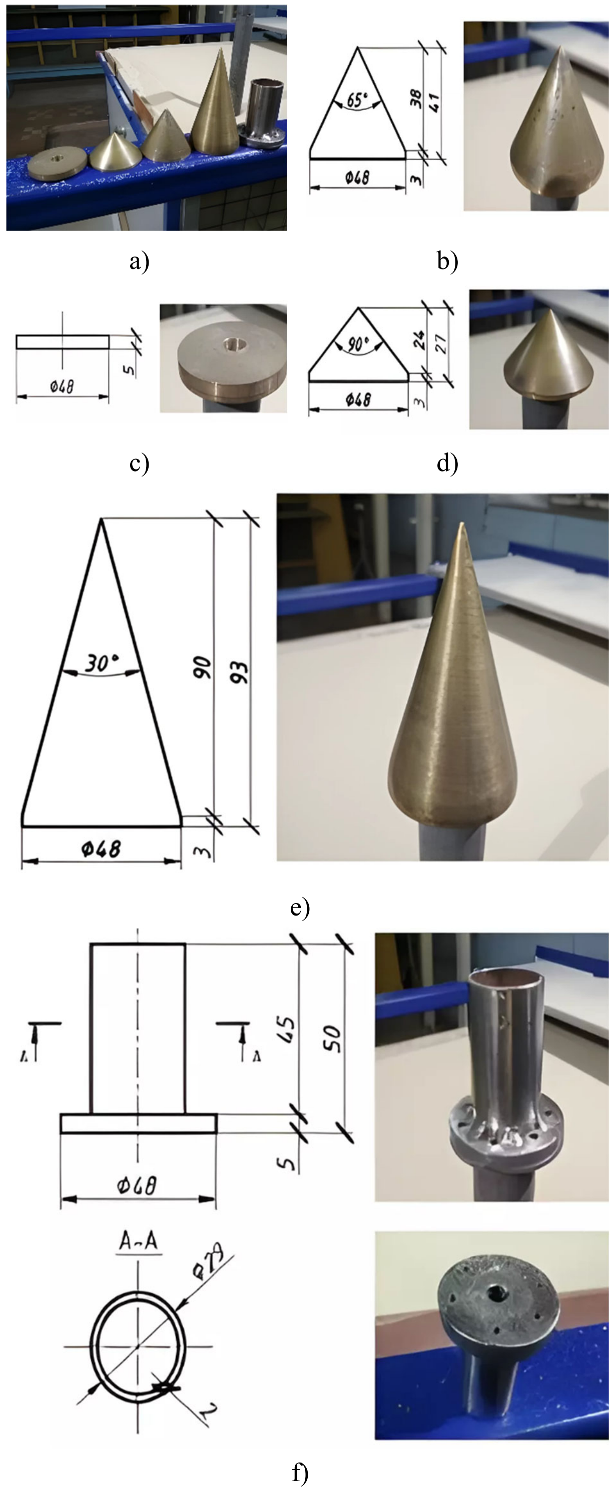

Fig. 5. Details of the experimental pile (sizes in mm): a – closures of different shapes applied in the experiment; b – conic closure 65^0; c - flat closure; d – conic closure 90^0; e - conic closure 30^0; f - cylindric closure.

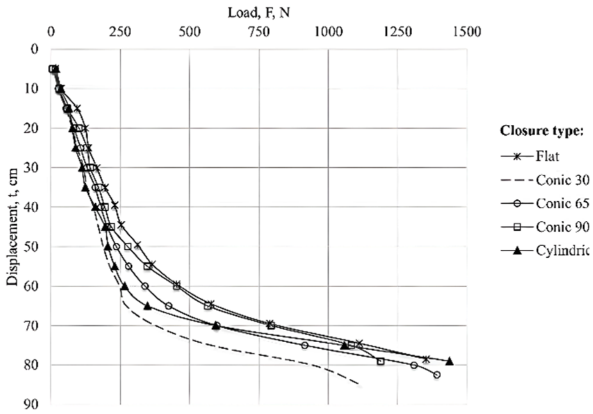

Fig. 6. Dependencies between vertical axial load upon the model pile and its displacements for closure of different shapes located at 9d distance from the tip.

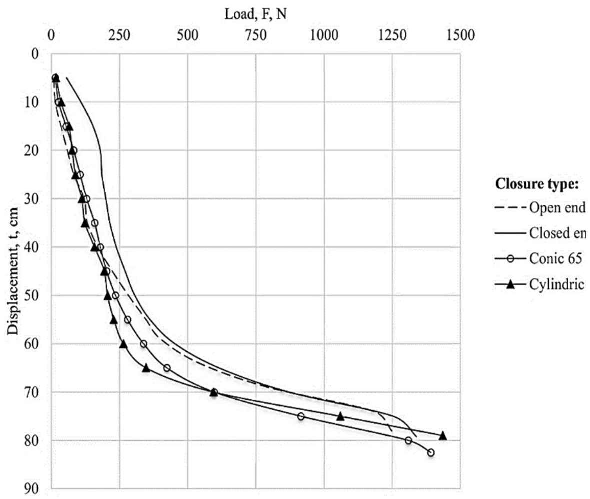

Fig. 7. Dependencies between vertical axial load upon the model pile and its displacements for the absence of the closure (open and closed ends) and for the presence of the closure (conic and cylindric) located at 9d distance from the tip.

Fig.8 shows an example of such a relationship, summarizing the data we obtained in the experiments. According to this diagram, by choosing in advance the location of the closure, it is possible at the initial stage to facilitate the pile driving compared to the pile with a closed-end, and at the final stage of pile installation, it is possible to approximate the value of the bearing capacity of the pile with closure to the parameters of the pile with a closed end. This ability to regulate the resistance to pile driving is important for the optimal and economical choice of technological equipment when installing the pile foundation of the structure.

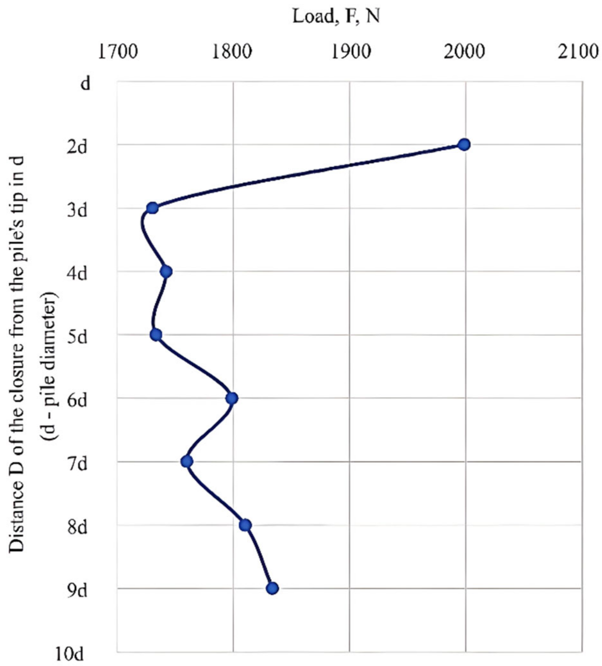

Fig. 8. Dependencies between vertical axial load upon the model pile and cylindrical closure's location (distance from the tip D).

In case of cylindrical closure (**Fig. 8**), the bearing capacity is maximal near the pile tip (within zone D=2d) because height of the cylinder H=d. Below this zone the bearing capacity is lowest at 3d, and increases slightly with increasing distance of the diaphragm from the pile tip.

Numerical approximation of experimental dependencies

Comparison of experimental values $F(t)$ using the Least Squares Method made it possible to conclude that the most plausible approximations turned out to be of the form

$$y(t) = \begin{cases} at^n \ln^m t & as \quad 5 \le t < t_1, \\ kt + b & as \quad t_1 \le t \le t_2, \end{cases}$$

where $t_1 \in [55;65]$, $t_2 \in [79,5;85]$.

Average approximation error

$$\bar{A} = \frac{1}{n} \sum_{i=1}^{n} \frac{|F_i - y(t_i)|}{F_i},$$

n is number of measurements;

for the considered cases $\bar{A}$ = 5,2% ÷ 7,7 %.

Correlation coefficient R:

$$R = \frac{\sum_{i=1}^{n}(F_i - \bar{F})(y(t_i) - \bar{y})}{\sqrt{\sum_{i=1}^{n}(F_i - \bar{F})^2 \sum_{i=1}^{n}(y(t_i) - \bar{y})^2}},$$

$$\bar{F} = \frac{1}{n}\sum_{i=1}^{n} F_i \quad , \qquad \bar{y} = \frac{1}{n}\sum_{i=1}^{n} y(t_i);$$

for the considered cases R = 0,990 ÷ 0,996.

Observe value t_{ob} of the Student ‘s distribution

$$t_{ob} = \sqrt{\frac{R^2(n-2)}{1-R^2}};$$

for the considered cases t_{ob} = 35,3 ÷ 56,2.

Related diagrams are presented on **Fig. 9 - 13**.

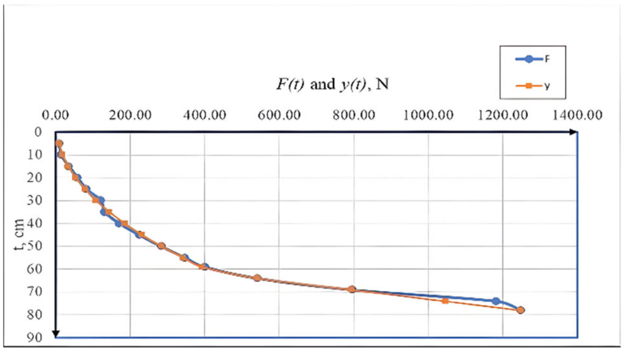

Fig. 9. Experimental F(t) and calculated y(t) load-displacement diagrams for open end pile

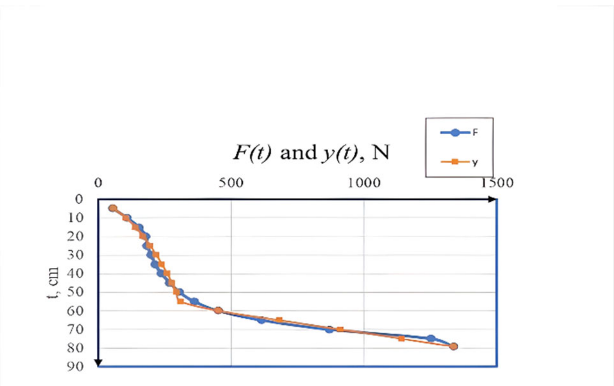

Fig. 10. Experimental F(t) and calculated y(t) load-displacement diagrams for closed end pile

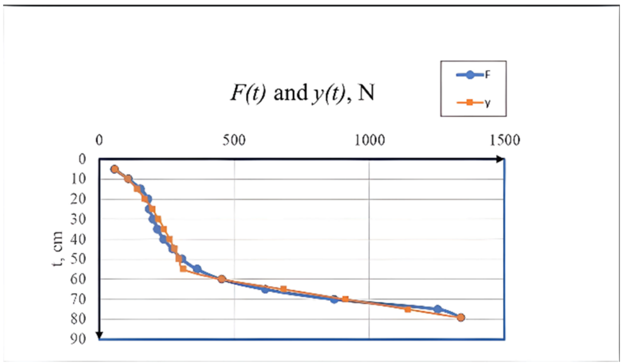

Fig. 11. Experimental F(t) and calculated y(t) load-displacement diagrams for pile with flat diaphragm

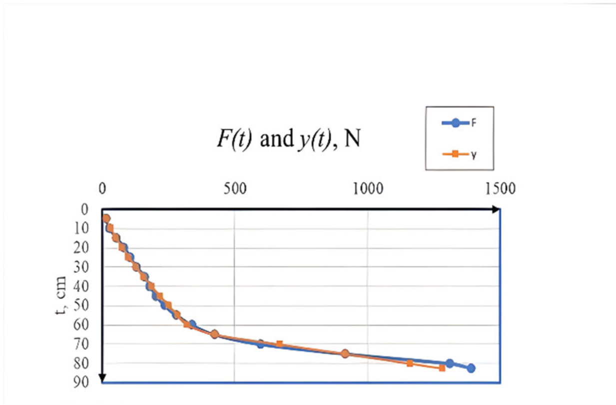

Fig. 12. Experimental F(t) and calculated y(t) load-displacement diagrams for pile with conical (65^0) diaphragm

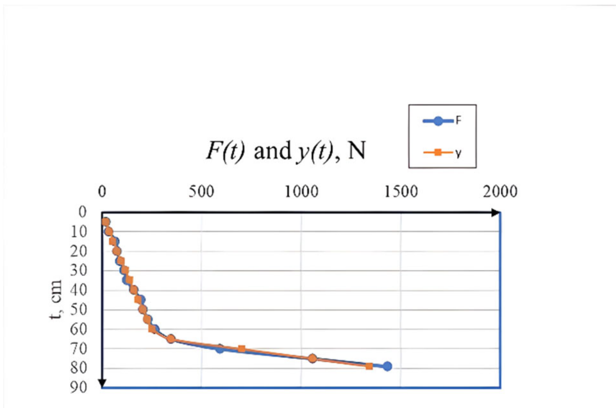

Fig. 13. Experimental F(t) and calculated y(t) load-displacement diagrams for pile with cylindrical diaphragm

In all considered cases, the correlation coefficient is quite high, which means that the relationship between the studied quantities is close.

Also, for all cases $t_{ob} > t_{cr}$, i.e. the observed value of the Student's test is greater than the critical value, with the number of degrees of freedom 15 or 16 (corresponding to the number of measurements 16 and 17) at the significance level 0,001 (t_{cr}=4,07 or t_{cr}=4,01).

Therefore, the obtained values of the correlation coefficients are considered significant (that is, the null hypothesis stating that the correlation coefficient is equal to zero is rejected). The average approximation error indicates that the model is quite good, since in almost all cases value of $\bar{A}$ turned out to be no more than 7%.

Since for the series presented in the **Fig. 8** eight tests were carried out, we can approximate the dependence F (t) by a polynomial of the seventh degree:

$$g(t) = -6{,}6501587 \cdot 10^{-6} t^7 + 1{,}2796 \cdot 10^{-3} t^6 - 0{,}1023611 t^5 + 4{,}4031833 t^4 - 109{,}7715778 t^3 + +1583{,}2107 t^2 - 27656{,}085 t + 40586$$

However, this curve can also be approximated by a polynomial of the second degree:

$$P(t) = \begin{cases} 5{,}58t^2 - 193{,}35t + 3373 & as \quad 10 \le t < 20 \\ 1{,}47t^2 - 67{,}85t + 2511 & as \quad 20 \le t < 30 \\ 1{,}77t^2 - 122{,}75t + 3888 & as \quad 30 \le t < 40 \\ 4{,}7t + 1622 & as \quad 40 \le t \le 45 \end{cases}$$

Comparison of related diagrams is presented in **Fig. 14.**

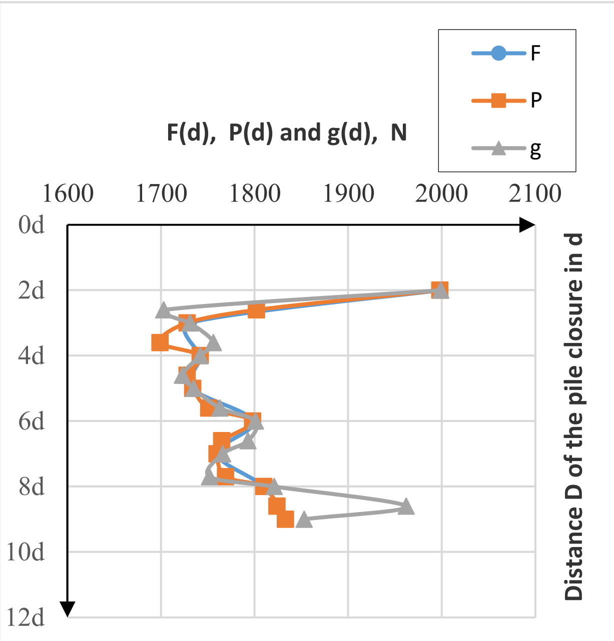

Fig. 14. Experimental F(t) and calculated P(t), g(t) diagrams for pile with cylindrical closure

For the considered case the number of measurements (eight) is not enough to construct perfect dependencies. In the future, by increasing the number of measurements, it will be possible to stop at a more accurate assumption. If to consider the coefficient of variation (calculated from 8 values), then CV(t)=0.0445, CV(F)=0.049=CV(P), CV(g)=0.062.

To clarify the differences between the graphs of the expected dependencies (since the values at eight nodal points are almost the same and Excel will build the same graph), intermediate points were added inside each interval. Then CV(t)=0.0013, CV(P)=0.00002, CV(g)=0.00003. Covariance was not considered, since there is no linear relationship between the studied quantities.

Conclusions

As obtained from the presented initial series of our experimental studies, a rigid diaphragm inside the tubular open-end pile may be a useful element for increasing the pile's bearing capacity.

Consecutive formation of two soil plugs (the lower one formed just at the pile tip and then the upper one formed under the diaphragm) leading to their partial or full integration is most effective when the optimal location of the diaphragm inside the pile shaft is provided.

Improvement of the pile effectiveness determined by our experimental modeling for the above-mentioned pile-soil conditions provides up to 15-20% increase of the bearing capacity or up to 10-15% reduction of the driving depth.

An interesting possibility of regulating the value of the bearing capacity of the pile by changing the position of the diaphragm along the pile's shaft is brought out. Such an approach can be effective if the open-ended tubular pile does not provide the required bearing capacity of the pile, and the closed-end pile results in excessive bearing capacity or causes the use of too-powerful and expensive pile-driving equipment. The use of a pile with a closure may lead to an intermediate option between piles with an open and closed-end.

Another possible effect of increasing the bearing capacity of a tubular pile through the use of an internal diaphragm is reducing the volume of piling and accordingly decreasing noise, vibration, dynamic action, carbon footprint, etc., providing the improvement of the environmental situation at the construction site.

Analysis of the gained experimental data gave the possibility to apply approximating function with good correlation indexes.

Due to rather "gentle" way of model piles installation (mechanical jacking) it was possible to drive pipes by comparatively small steps and obtain related values force-displacement at each step. So, similar approach may be good adapted to predict pipe behavior in case of Press-in method of the pile installation.

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