UDC 627.24
DOI 10.47049/2226-1893-2024-16-29

PIPE PILE WITH INTERNAL DIAPHRAGM AS EFFECTIVE BEARING ELEMENT OF DEEP-WATER STRUCTURES

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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.*

Keywords: *pipe pile, bearing capacity, internal diaphragm, model study, numerical approximation.*

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DOI 10.47049/2026-1893-2024-1-16-29

ТРУБЧАСТА ПАЛЯ З ВНУТРІШНЬОЮ ДІАФРАГМОЮ ЯК ЕФЕКТИВНИЙ НЕСУЧИЙ ЕЛЕМЕНТ ГЛИБОКОВОДНИХ СПОРУД

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Анотація. *Одним із шляхів зниження витрат на влаштування трубчастих паль є зменшення обсягів пальових робіт. Це може бути забезпечено за рахунок укорочення або довжини паль, або кількості труб.*

Ці результати можуть бути досягнуті, якщо кожна скорочена паля вдосконалена і несе таке ж навантаження, як і паля нормальної довжини, або якщо кожна паля нормальної довжини вдосконалена і несе на собі більше осьове навантаження в порівнянні з її початковою проектною спроможністю.

Представлене дослідження уточнило можливості регулювання несучої здатності трубчастої палі за допомогою внутрішньої жорсткої діафрагми (перегородки), розміщеної всередині стовбура палі.

Це збільшує несучу здатність трубчастої палі за рахунок додаткової реакції ґрунту під діафрагмою. Вдавлювання моделі трубчастої палі в пісочному лотку розглядалось найбільш щадним і точним методом вивчення розглянутого процесу занурення палі. Крім того, результати такого підходу можуть бути добре пристосовані для прогнозування поведінки труб при методі влаштування паль вдавлюванням.

Зроблено деякі висновки, що уточнюють позитивний внесок діафрагми в несучу здатність палі, вплив розташування перегородки уздовж стовбуру труби, а також вплив конструкції діафрагми (плоскі, конічні та циліндричні перегородки).

Чисельний аналіз отриманих експериментальних даних дав можливість застосувати апроксимаційні функції з хорошими кореляційними показниками.

Ключові слова: *трубчаста паля, несуча здатність, внутрішня діафрагма, дослідження на моделі, чисельна апроксимація.*

Introduction. Statement of a problem. As it has been considered in some previous studies, modern marine transportation and offshore structures often include steel tubular piles of essential length 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. (2020).

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). 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 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.

Last achievements and developments. Use of closure in pipe piles. Recommended technology to install the internal diaphragm was described (perhaps first) by Tomlinson and Woodward (2008). According to them, 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 a real 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).

The basic material of investigations. Experimental modeling of pipe piles **with diaphragm**

Regarding that 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.

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).

To clarify the above-mentioned items related to the pipe pile with an internal diaphragm, we fulfilled a series of experimental studies in the Geotechnical Laboratory at Odessa National Maritime University (the first series of the tests were described by Doubrovsky et al. (2020, 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. 1, 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.

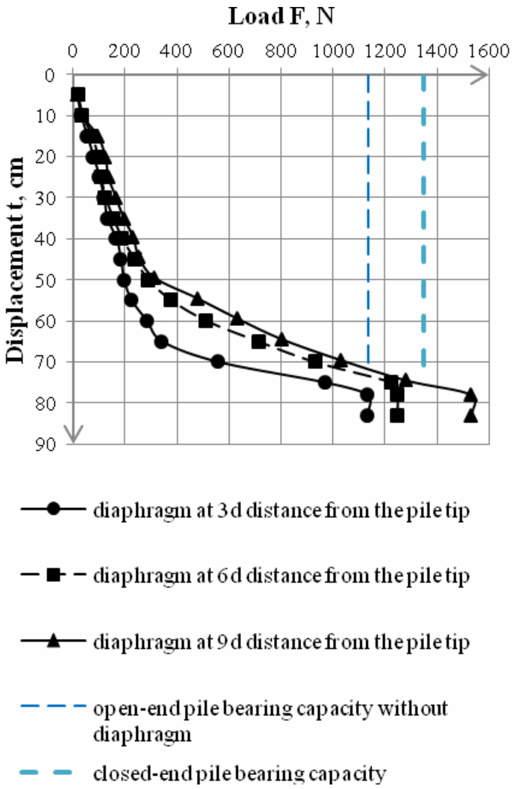


Fig. 1. Dependencies between vertical axial load upon the model open-end pile and its displacements

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.

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.

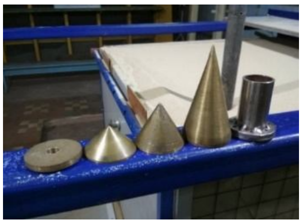
It may be explained, particularly, by the fact that for the considered test conditions, approximate driving depth $t = (4\text{-}5)$ d at the initial stage of pile installation is needed to dense soil due to the development of the friction forces inside the pile's shaft and to form a lower soil plug 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. $(8\text{-}10)\ d$. 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 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).

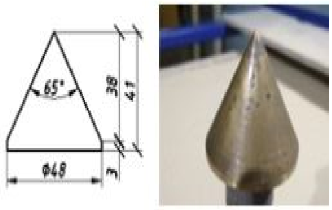
For the conditions of our laboratory model testing, it was determined that the related prototype is a tubular pile of diameter 1.0 m driven up to 10 m into similar sandy soil. Its bearing capacity (sum of the toe and shaft bearing capacities) is 1723 kN. For comparison: the calculated value of the prototype 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.

Assessment of the 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. 2, dimensions in mm). 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. 3. 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 pipe 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. 4.



a)



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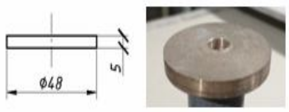

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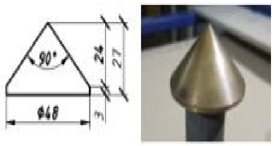

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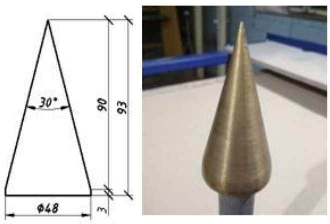

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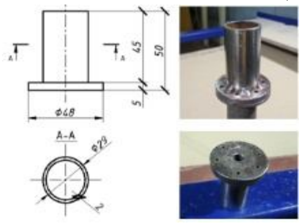


f)

Fig. 2. 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

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 on the depth D of the cylinder diaphragm location is of interest.

Fig. 5 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.

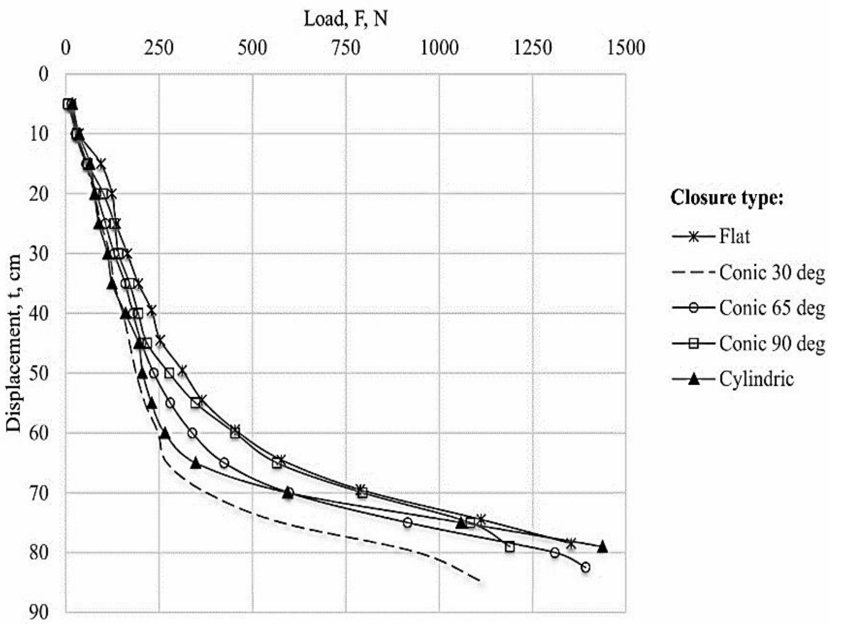


Fig. 3. Dependencies between vertical axial load upon the model pile and its displacements for closure of different shapes located at 9d distance from the tip

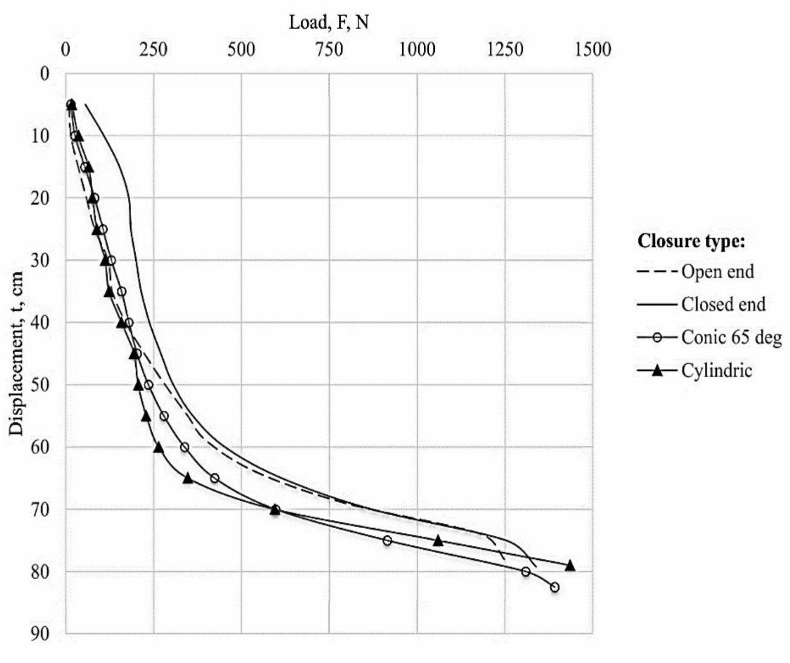


Fig. 4. Dependencies load – pile displacements for the absence of the closure and for the presence of the closure (conic and cylindric) located at 9d distance from the tip

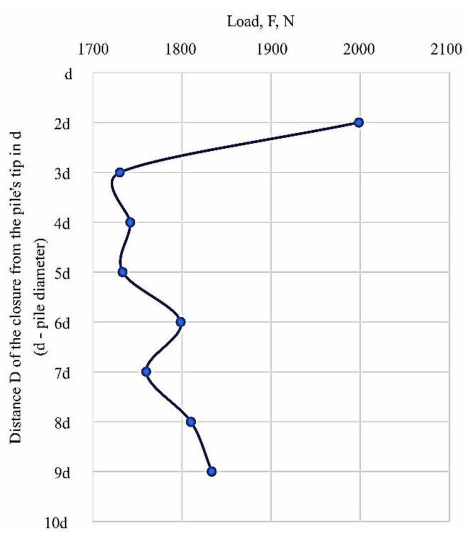


Fig. 5. Dependencies between vertical axial load upon the model pile and cylindrical closure's location (distance from the tip D)

Demonstrated 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.

Results of 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 $\overline{A} = \frac{1}{n}\sum_{i=1}^{n}\frac{|F_i - y(t_i)|}{F_i}$, where n is number of measurements; for the considered cases $\overline{A}$ = 5,2%-7,7%.

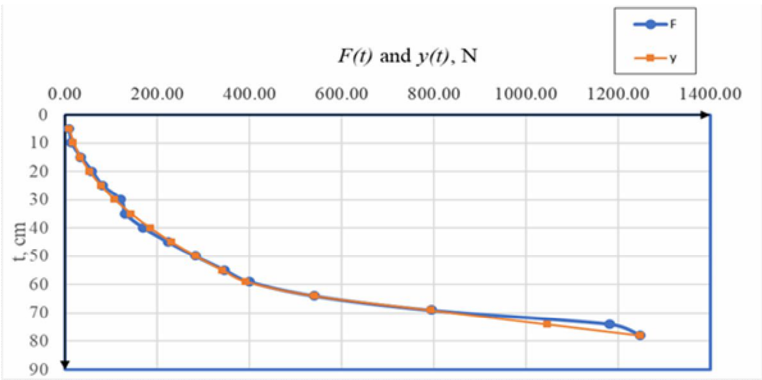
Correlation coefficient R

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

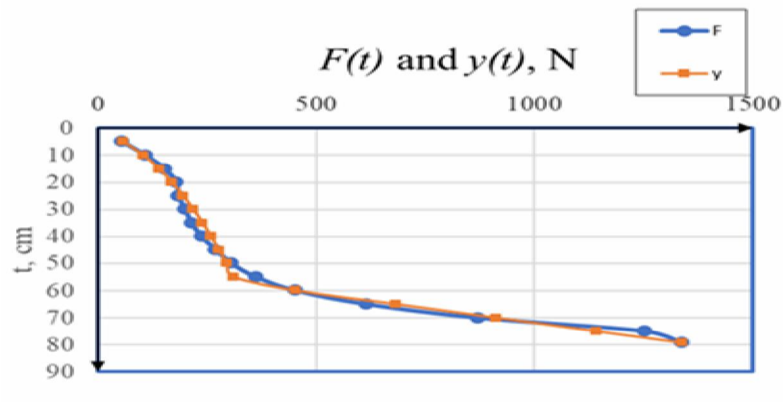
for the considered cases R = 0,990-0,996.

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 experimental $F(t)$ and calculated $y(t)$ load-displacement diagrams are presented on Fig. 6 and 7.

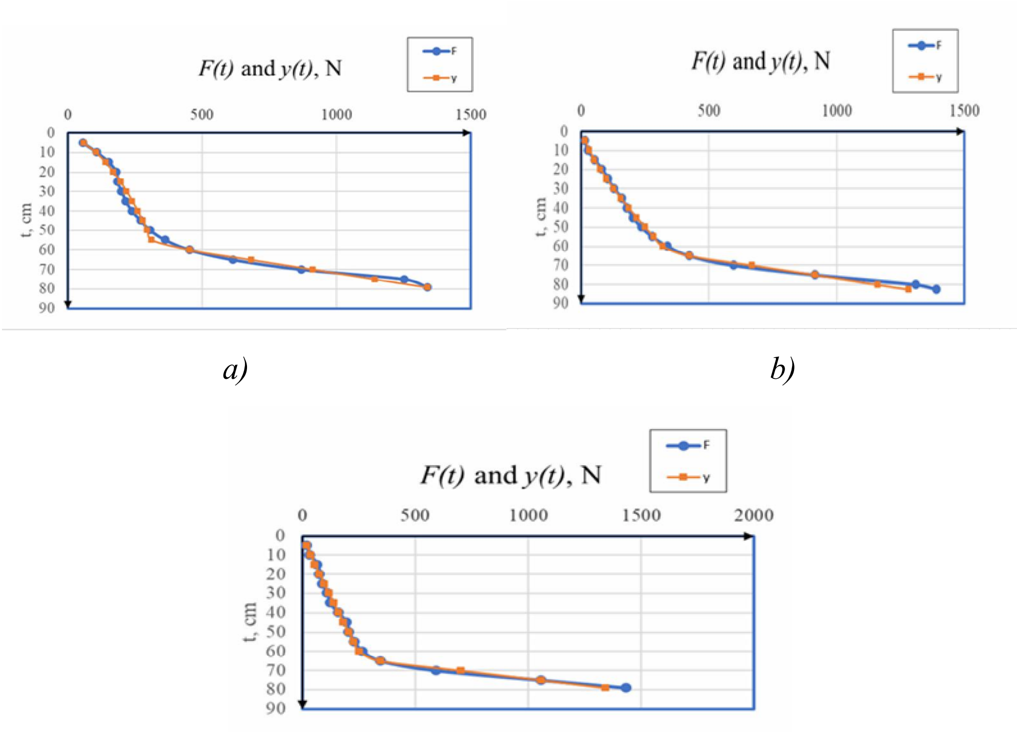


a)



b)

Fig. 6. Diagrams for open end (a) and closed end (b) pile



a) *b)*

c)

Fig. 7. Diagrams for pile with flat:
a – conical (65 ^{0});
b – cylindrical;
c – diaphragms

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 $t_\alpha = 4,01)$.

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 $\overline{A}$ turned out to be no more than 7 %.

Since for the series presented in the Fig. 5 eight tests were carried out, we can approximate the dependence $F(t)$ by a polynomial of the seventh degree:

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

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. 8.

In the future, by increasing the number of measurements, it will be possible to stop at a more accurate assumption.

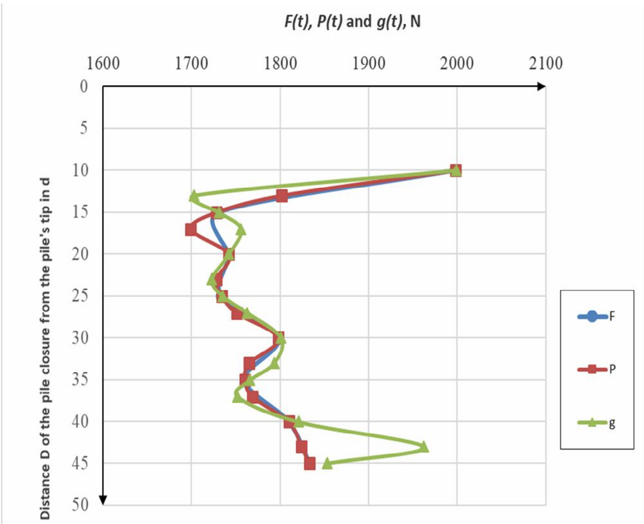


Fig. 8. Experimental $F(t)$ and calculated $P(t)$, $g(t)$ diagrams for pile with cylindrical closure

Conclusions. Consecutive formation of two soil plugs (at the pile tip and 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. From the point of view of pile bearing capacity under axial compressive load and for the considered experimental conditions, such proper distance between the pile tip and internal diaphragm occurred to be around $9d$ (d – pile diameter). Improvement of the pile effectiveness determined by experimental modeling for the above-mentioned pile-soil conditions provides 15-20 % increase of the bearing capacity or a 10-15 % reduction of the driving depth.

The use of a pile with a closure leads to an intermediate option between piles with an open and closed-end, which allows for optimization of the design of the pile foundation of the structure and reduces the cost of piling work.

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

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

Acknowledgements. The authors would like to express gratitude to colleagues from the Geotechnical Laboratory of the Department «Sea, River Ports and Waterways» at Odessa National Maritime University for their valuable support and assistance in model test arrangement and fulfillment. This study was supported at the Technion by a grant from the Lady Davis Foundation.

СПИСОК ЛІТЕРАТУРИ

1. *Doubrovsky M., Dubravina V. Physical modelling of steel tubular piles installation into sandy soil. Bases and Foundations. Issue 41, 2020. P. 14-21 (2020)*
2. *Doubrovsky M., Kusik L., Dubravina V. Bearing Capacity of Tubular Piles: Technological Improvements and Model Testing. Lecture Notes in Civil Engineering, vol 230. Springer, Singapore. . P. 137-154. (2022)*
3. *Randolph, M.F., Leong, E.C. and Houlsby, G.T. One-dimensional analysis of soil plugs in pipe piles, Geotechnique, Vol.41, No.4, P. 587-598 (1991)*
4. *Tomlinson M. and Woodward J. Pile design and Construction Practice, Fifth edition, Taylor & Francis, N.Y. (2008)*

REFERENCES

1. *Doubrovsky M., Dubravina V. Physical modelling of steel tubular piles installation into sandy soil. Bases and Foundations. Issue 41, 2020. P. 14-21 (2020)*
2. *Doubrovsky M., Kusik L., Dubravina V. Bearing Capacity of Tubular Piles: Technological Improvements and Model Testing. Lecture Notes in Civil Engineering, vol 230. Springer, Singapore. P. 137-154. (2022)*
3. *Randolph, M.F., Leong, E.C. and Houlsby, G.T. One-dimensional analysis of soil plugs in pipe piles, Geotechnique, Vol.41, No. 4. P. 587-598 (1991)*
4. *Tomlinson M. and Woodward J. Pile design and Construction Practice, Fifth edition, Taylor & Francis, N.Y. (2008)*

Стаття надійшла до редакції 12.01.2024

Посилання на статтю: Дубровський М.П., Кусік Л.І., Дубравіна В.О. Трубчаста паля з внутрішньою діафрагмою як ефективний несучий елемент глибоководних споруд: *Вісник Одеського національного морського університету:* Зб. наук. праць, 2024. № 1 (72). С. 16-29. DOI 10.47049/2226-1893-2024-1-16 -29.

Article received 12.01.2024

Reference a journalartic: Doubrovsky M., Kusik L., Dubravina V. Pipe pile with internal diaphragm as effective bearing element of deep-water structures: *Herald of the Odesa national maritime university:* Coll. scient. works, 2024. № 1 (72). 16-29 . DOI 10.47049/ 2226-1893-2024-1-16-29.