

# Study of bearing capacity of tubular piles with diaphragm under pressing loads

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**ABSTRACT:** Marine structures often include steel tubular piles of essential length (80-100 m and more) that should provide high bearing capacity in case of external axial loads application. One of the interesting peculiarities of long tubular piles' behavior is the formation of soil plug at the piles' tip. To increase piles bearing capacity under static pressing load, such an additional element as the internal diaphragm has been applied in some practical cases. Presented research aimed to study two connected processes during steel tubular pile driving: soil plug formation at the tip of the open-end pile and soil behavior under the internal diaphragm fixed inside the tubular pile's shaft. Obtained results of internal diaphragm application may be useful to provide an increase of pile's bearing capacity (in case of bearing capacity deficit) or to justify pile length reduction.

## 1 INTRODUCTION

Modern marine transportation and offshore structures such as deep-water port's 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. Some examples of these structures are presented on Figures 1-3 (Doubrovsky & Pereiras 2014).

Such tubular piles should provide high bearing capacity in case of external axial loads application (Doubrovsky & Pereiras 2014, Doubrovsky et al. 2017, Doubrovsky et al. 2018, Tomlinson & Woodward 2008).

One of the interesting peculiarities of long tubular open-end piles behavior is the formation of soil plug at the piles' tip (Randolph et al. 1991, White et al. 2010).

From this point of view, we support known opinion that it is important to study the influence of the soil plug not only on the pile's tip bearing capacity but also on soil behavior inside the tubular shaft (Tomlinson & Woodward 2008).

In case of necessity the bearing capacity of long tubular piles may be increased by different methods:

- by driving a pile with a closed end to develop increased end-bearing resistance (but it requires application of too powerful hammers)
- by installing the pile at larger depth in order to reach the bearing soil strata (but such penetrations are often much greater than those required for fixity against lateral loading)

- by grouting beneath the pile toe (but the operations of cleaning-out the pile and grouting are slow and relatively costly)
- by welding a steel plate diaphragm across the interior of the pile in order to increase bearing capacity by use of soil reaction under the diaphragm (such method demonstrated good results on some marine projects and got positive references (Tomlinson & Woodward 2008).

Regarding that in many cases large diameter tubular piles of shelf structures are installed without plugging effect (so called "fully coring mode" (Gudavalli et al. 2013) or with partial plugging, the last approach (closure of the pile's shaft) looks rather attractive for deep water port, marine and offshore engineering but needs detailed consideration and study aiming to determine method's peculiarity, appropriate sphere of application, details of diaphragm construction and proper location along the pile's shaft.

## 2 APPLICATION OF INTERNAL DIAPHRAGM IN STEEL TUBULAR PILES

Recommended technology to install the internal diaphragm was described by Tomlinson & Woodward 2008 (Figure 4).

A hole is necessary in the diaphragm for release of water pressure in the soil plug and to allow expulsion of silt. Stresses on the underside of the diaphragm are high during driving and radial stiffeners are needed.



Figure 1. Single point mooring fixed to the sea bottom by long steel tubular piles (LNG carrier service).

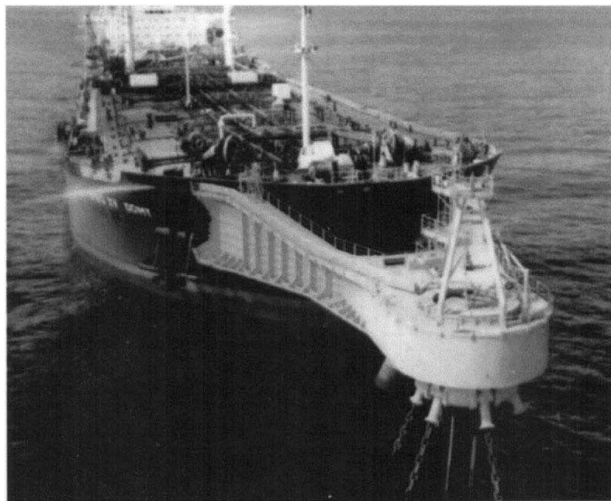


Figure 2. Piled cluster applied to fix mooring device of the tanker.



Figure 3. Use of large-diameter bearing monopile as fixed single point mooring for offshore industry.

According to Tomlinson & Woodward 2008, the minimum depth above the pile toe for locating the diaphragm is the penetration below sea bed required for fixity against lateral loading. There

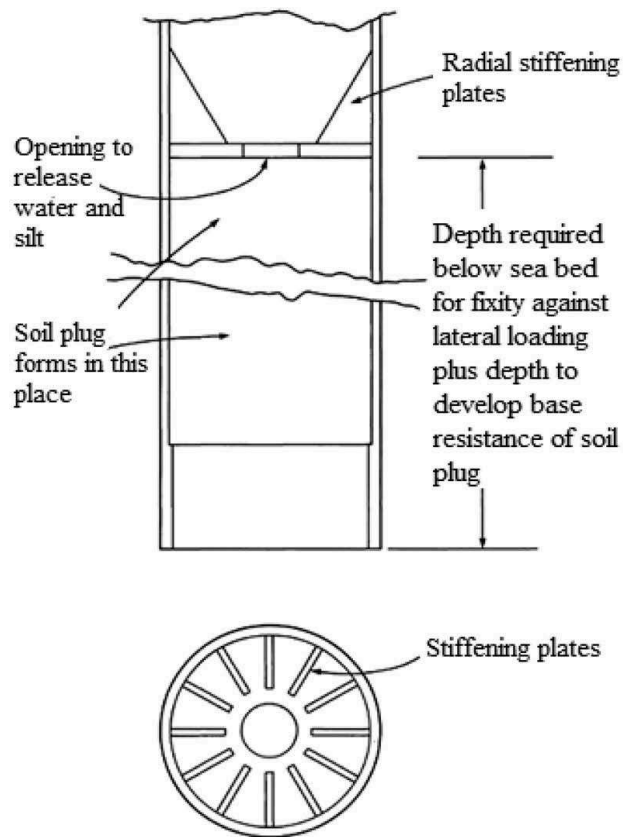


Figure 4. Steel tubular pile with diaphragm.

are formulas in some norms allowing determination of the fixity's depth depending on soil properties and pile's bending rigidity; roughly this depth may be determined in the interval of  $(5-7)d$ . However a further penetration is necessary to form the soil plug under the diaphragm by compacting the soil within the plug and to develop 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 diaphragm's practical application, we may refer to the piling works at the Hadera coal unloading terminal near Haifa (Tomlinson & Woodward 2008). 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 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 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.

### 3 LABORATORY MODEL TESTING

Regarding that obvious effect (increase of the pile's bearing capacity) has been achieved by use of the rigid diaphragm, our intention was to study peculiarities of the considered approach providing model static tests in the laboratory conditions. Our aim was to obtain parameters describing 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's 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 interacted 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 (White et al. 2010).

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

For pile testing we used soil box of dimensions: width 600 mm, length 750 mm, depth 1100 mm (Figures 5-8). For the model of 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  $33^\circ$ ; density  $14.5 \text{ kN/m}^3$ ; void ration 0.71; moisture 0.07%; Young modulus 16 MPa, Poisson's ratio 0.3.

The first series of the experiment was aimed to determine conditions of the soil plug formation at the tip of open-end pile model.

Measured parameters (at each stage of load application) were:

- applied vertical axial pressing force (named *Load, F* on the diagrams)
- pile's penetration depth (named *Displacement, t* on the diagrams)
- soil level inside the pile's model (the initial position was fixed when soil levels inside and outside the pile were equal).

In order to describe the process of the model tubular pile plugging we applied:

- earlier proposed IFR (Incremental Filling Ratio) and PLR (Plug Length Ratio) characteristics (for example, recommendations Gudavalli et al. 2013, Brucy et al. 1991, Paik & Salgado 2003, Lehane & Gavin 2004 and others) presented in Figures 9, 10
- assumption that as an evidence of completing of the process of soil plug formation we may

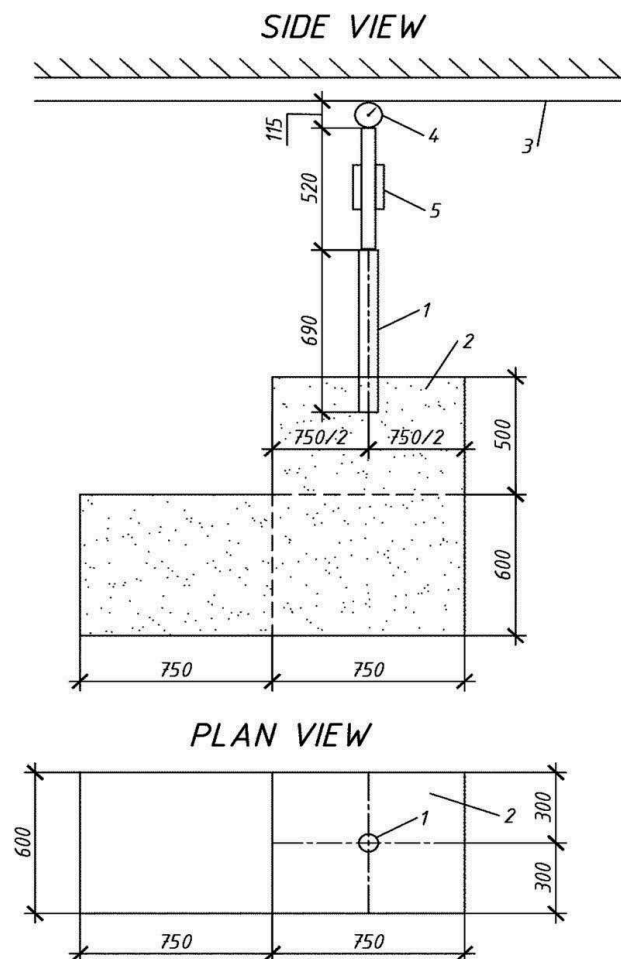


Figure 5. Scheme of the experiment.

1 – pile model; 2 – sand box; 3 – bearing beam; 4 – force gauge (dynamometer); 5 – jack loading system (telescopic) (all sizes in millimeters)

consider equal pile's vertical displacements and related settlements of the sand surface inside the shaft at each stage of further axial load application (related diagrams are presented in Figures 11, 12).

According to the PLR and IFR diagrams (Figures 9, 10) at the initial stage of pile installation [till  $t=(1.5-2)d$ ]  $PLR=IFR=100\%$ , i.e. pile is driven according to the “fully coring mode”. From the penetration depth of some  $(4-5)d$  soil plug length is almost unchanged; average IFR value is stable too. Some IFR fluctuations below the penetration depth=20 cm may be explained by technical reasons: resetting of the jack each 20 cm of the penetration process and corresponding installation of extension tubes.

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Figure 6. Experimental system: side view.

1 – soil box; 2 – model pile; 3 – mechanical jack;  
4 – dynamometer; 5 – displacement gauge.

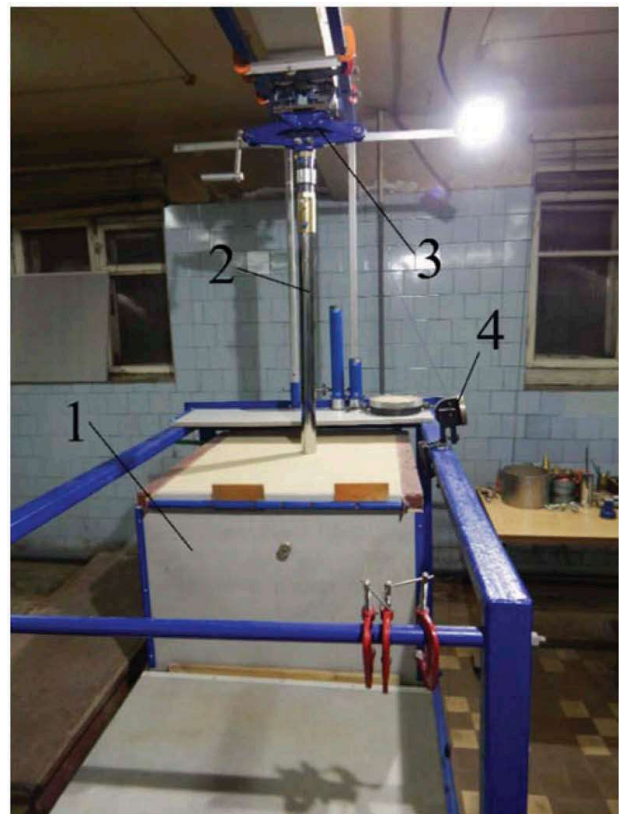


Figure 7. Experimental system: front view.

1 – soil box; 2 – model pile; 3 – mechanical jack;  
4 – displacement gauge.

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Similar conclusion may be done on the base of diagrams in Figures 11, 12. Soil level inside the pile's shaft become stable at the relative penetration depth (normalized pile displacement) approx.  $t/d=5-6$  (Figure 11). Dependencies for  $t/d$  and  $S/d$  describing pile and soil displacements also become parallel starting from the  $t/d=5-6$  and till reaching the pile bearing capacity  $=5-6$  (Figure 12).

Some important results of the first series of the laboratory experiments may be formulated in the following way:

- in fine sandy soil the plug is formed at the comparatively early stage of pile's driving (in the considered case – at the penetration depth of around 4-5 pile's diameters)
- if to locate the internal diaphragm at the recommended depth required for fixity against lateral loading as described above (approx. at the penetration depth of around 5-7 pile's diameters), we may meet the situation of no contact between the diaphragm and the soil inside the shaft (clearance space); i.e., the diaphragm does not catch up with soil.



Figure 8. Loading system.

1 – model pile; 2 – mechanical jack; 3 – dynamometer.

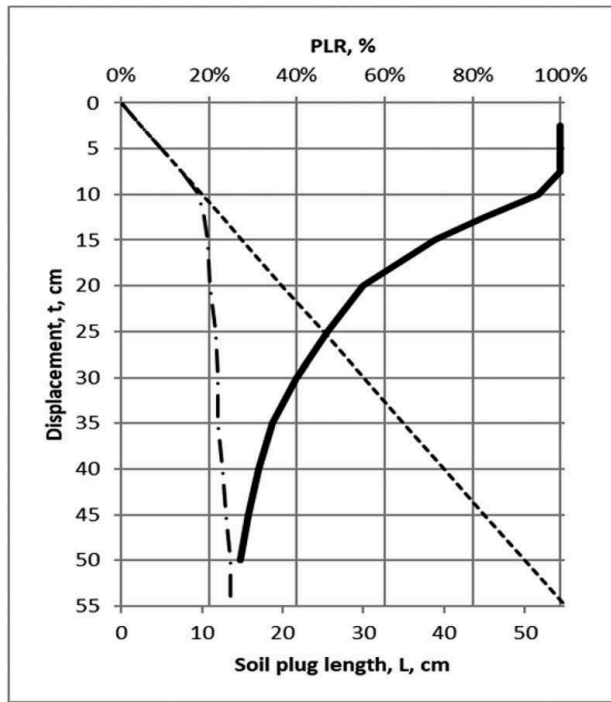


Figure 9. Typical dependencies for the tests of the first series.

----- 1; - · - - 2; ——— 3  
1- fully coring mode; 2 –  $L=L(d)$ ; 3 - PLR

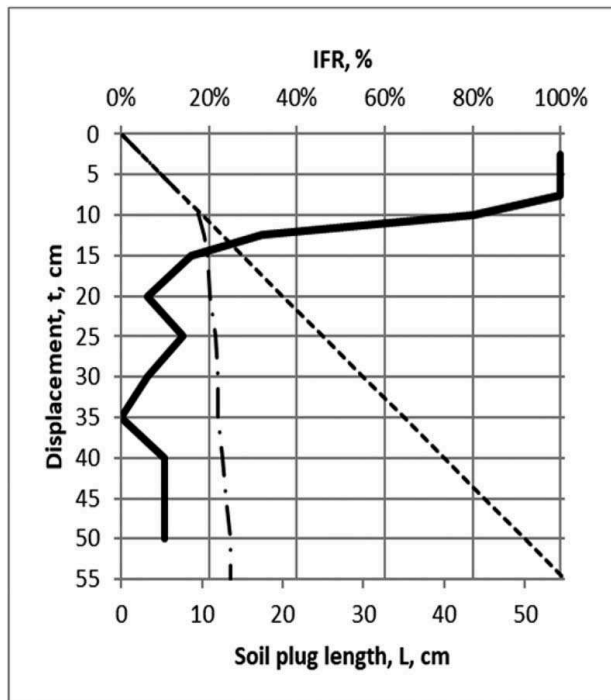


Figure 10. Typical dependencies for the tests of the first series.

----- 1; - · - - 2; ——— 3  
1- fully coring mode; 2 –  $L=L(d)$ ; 3 - IFR

The second series of the experiment was devoted to clarification of the role and contribution of the internal

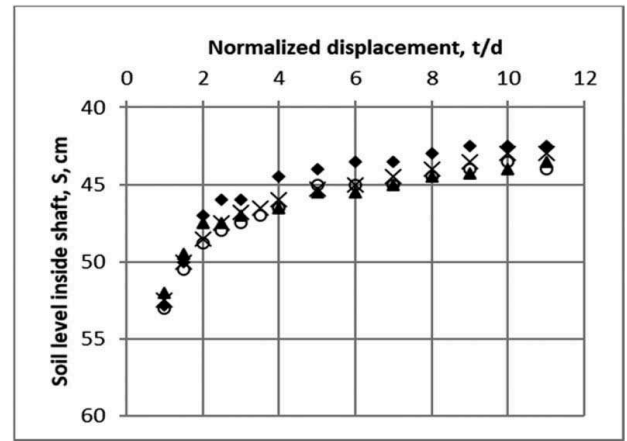


Figure 11. Results of open-ended model pile jacking (4 similar tests): S – distance between pile's top and soil in the shaft.

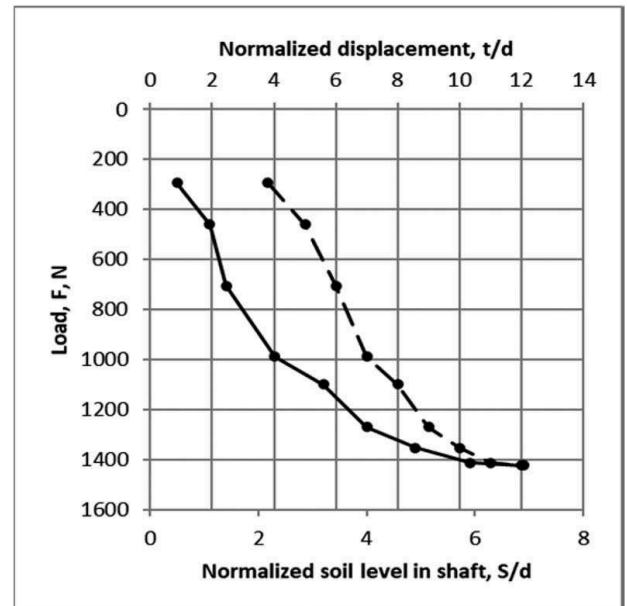


Figure 12. Results of open-ended model pile jacking (average points of 4 similar tests).

---●--- -  $t/d=t/d(F)$ ; —●— -  $S/d=S/d(F)$

diaphragm. For model pile the diaphragm was produced as a circular steel plate (4 mm thickness), with its diameter corresponded to the inner diameter of the pile.

By use of the rigid steel bar (located in the pile's shaft) the diaphragm was connected with the pile head. Varying the length of the mentioned rigid bar we had the possibility to locate the internal diaphragm at different places along the model pile's shaft.

At the second series of the experiment 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).

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 underside of the diaphragm, we applied the diaphragm with several small holes allowing sand filling into the space under the diaphragm (Figure 13). For above mentioned options of the diaphragm location the sand was filled after the pile driving on the depth  $3d$ ,  $6d$  and  $9d$  correspondingly (i.e., at the moment of the first potential contact of the soil surface with underside of the diaphragm).

The volume of the filled sand was calculated to provide required diaphragm-sand contact during the whole process of model pile jacking.

As it is demonstrated by diagrams presented on Figures 14-17, application of the internal diaphragm provides increasing open-end pile bearing capacity. The degree of such increase depends on the diaphragm location. For the considered options of the diaphragm fixing point, the minimal increment of the open-end pile bearing capacity relates to the  $3d$  distance between diaphragm and the pile tip (Figures 14, 17) and the maximal increment is measured at the  $9d$  distance (Figures 16, 17).

Perhaps mentioned circumstances may be commented by the following way. The upper plug under the diaphragm may be formed if there is the proper base reaction developed inside the shaft. Such situation may occur if the upper plug (being in the process of formation) meets already formed lower plug. The last transfers additional pressure to the soil under the toe and provokes additional base reaction. Thus, 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 pile's toe. Obviously that creation of the mentioned large plug and its effective contribution to



Figure 13. Underside of the internal diaphragm with peripheral holes for sand filling.

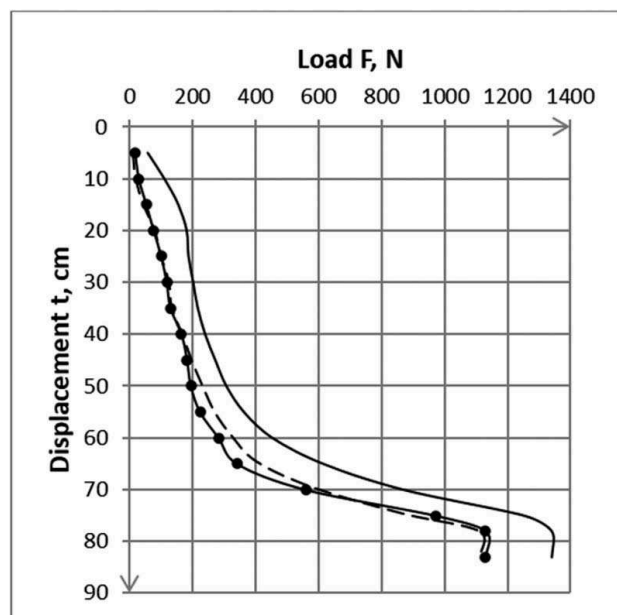


Figure 14. Dependencies between vertical axial load upon the model pile and its displacements.

--- - open-end pile; — - closed end;  
—●— - diaphragm at  $3d$  distance from the pile tip.

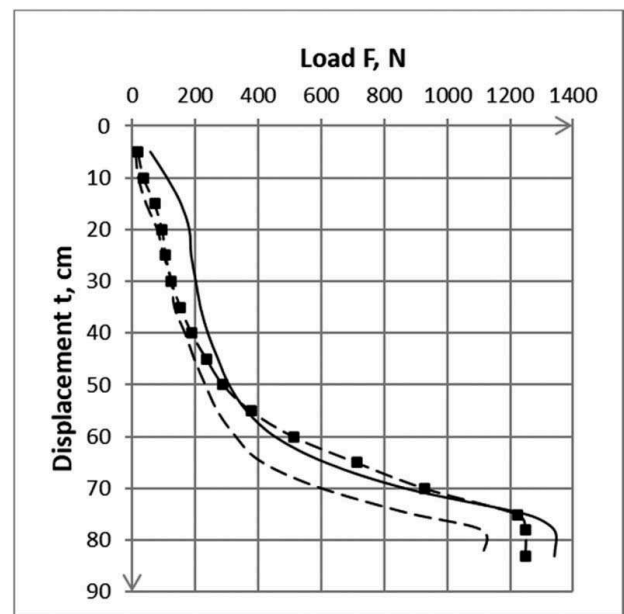


Figure 15. Dependencies between vertical axial load upon the model pile and its displacements.

--- - open-end pile; — - closed end;  
---■--- - diaphragm at  $6d$  distance from the pile tip.

the pile bearing capacity may be provided only in case of “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 case of  $9d$  distance of the diaphragm from the pile tip.

It may be explained, particularly, by the fact that for the considered test conditions, approximate

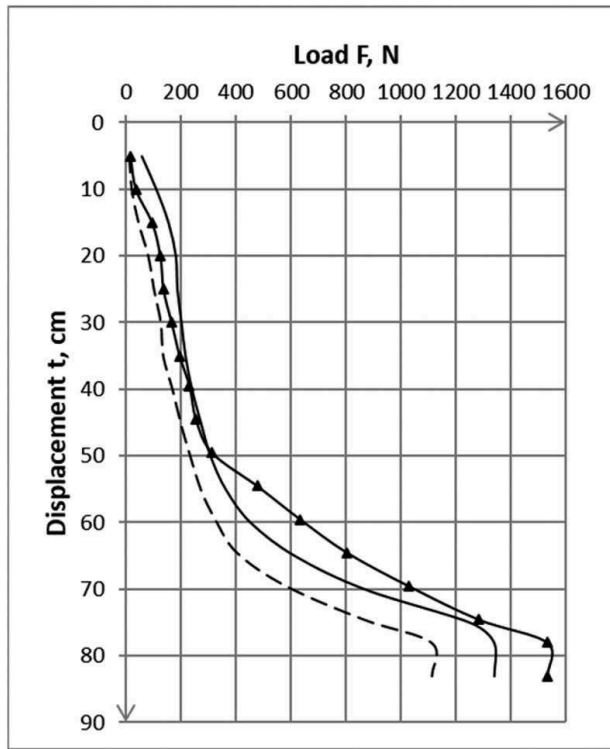


Figure 16. Dependencies between vertical axial load upon the model pile and its displacements.

--- - open-end pile; — - closed end;  
— · — - diaphragm at 9d distance from the pile tip.

driving depth  $t=(4-5)d$  at the initial stage of pile installation is needed to dense a 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 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 total distance between pile toe and the diaphragm may be considered as 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 quantitative parameters of open-end pile bearing capacity (Figure 17), 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 possibility to decrease pile driving depth (10-15%). Obviously mentioned figures should be considered with regard to possible experimental errors stipulated by differences in the reproducibility of the model ground preparation as well as to measurement inaccuracy (perhaps up to 10% in total).

Regarding scale-effects for the considered problem, it should be noted the following. From the point of view of so called "direct modelling" (Florin 1961, Ivanov 1985), dependencies between limit axial

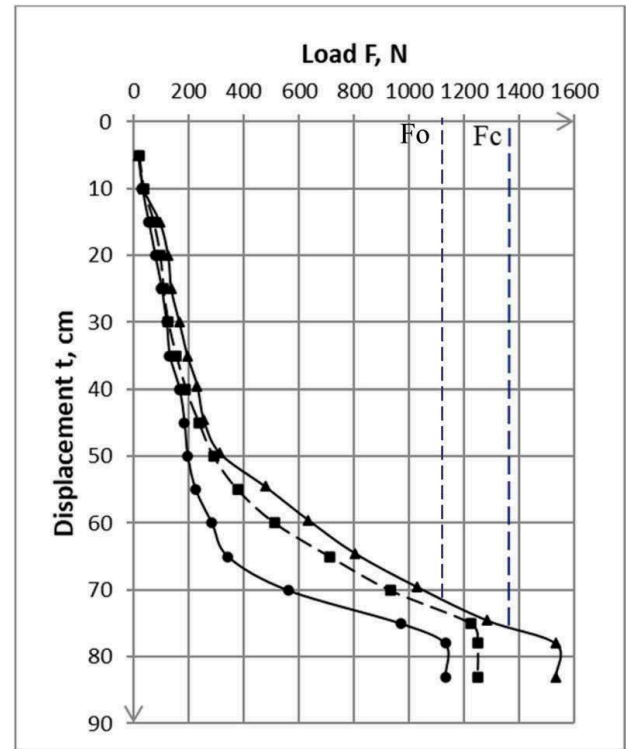


Figure 17. Dependencies between vertical axial load upon the model open-end pile and its displacements.

— ● — - diaphragm at 3d distance from the pile tip;  
--- ■ --- - diaphragm at 6d distance from the pile tip;  
— · — - diaphragm at 9d distance from the pile tip;  
 $F_o$  – open-end pile bearing capacity without diaphragm;  
 $F_c$  – closed-end pile bearing capacity.

force in the pile  $N_{lim,p}$  (as well as related displacements  $U_{lim,p}$ ) and similar parameters of the model may be presented as

$$\frac{N_{lim,p}}{N_{lim,m}} = C_L^n,$$

$$\frac{U_{lim,p}}{U_{lim,m}} = C_L^m,$$

where  $C_L$  – sizes (scales) correlation between prototype and the model;

$n, m$  – parameters depending on soil properties and pile dimensions.

For the conditions of our laboratory model testing (skipping the details of intermediate conversions and calculations) it was determined that 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: 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 influence of internal pile diameter. This aspect is subject to a study for the further investigations.

#### 4 CONCLUSION

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

Consecutive formation of two soil plugs (lower one formed just at the pile tip and then 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. 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).

As demonstrated by our tests, during pile jacking process there is a possibility of clearance space between the diaphragm and soil inside the pile's shaft (no contact situation). For real construction site conditions and inhomogeneous soil base it is complex task to check proper diaphragm-soil contact and their interaction or to determine clearance space formation under the diaphragm. That's why it is proposed (and checked by our tests) the technological improvement based on sand filling into space under the internal diaphragm to provide constant diaphragm-soil contact and related soil resistance. Such approach guarantees force interaction between the internal diaphragm and the soil inside the shaft via filled sand and may simplify calculation scheme of such interaction (the last is a task of future development of the considered problem).

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

Presented experimental studies should be continued and developed in order to study installation peculiarities of piles with diaphragm by pressing technologies. Also, it looks prospective to investigate influence of internal diaphragm's design (different from the considered flat plate option).

#### ACKNOWLEDGEMENT

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