Innovative Design and Technology Solutions for Development of Port and Offshore Pressed-in Piled Structures

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ABSTRACT

Deep water piled clusters and structures supported by large mono-piles are designed to take up significant lateral and pressing loads. In particular, it relates to offshore structures whose foundations need long piled supports of high bearing capacity. Correspondingly one meets high level of stresses and significant deformations in such constructions. It is especially important for port or offshore engineering to avoid environmental problems caused by traditional pile driving technologies. From this point of view, the Press-in Method is the most appropriate approach. Two improved structures and technologies have been worked out to optimize stress-strain state of such piled clusters and mooring/fender dolphins. (1) Developed is an effective and less resource-demanding design when connection of all pipe piles with large diameter steel casing provides their joint work and favorable distribution of stresses and deformations in pile clusters. It is foreseen that both casing and pipes are installed by pressing into bottom soil. (2) To increase energy-absorbing capacity of mooring/fender dolphins, a new design of combined tubular mono-pile structure was worked out and researched. It incorporates internal flexible pile and damping element (cushion) placed between external and internal piles' heads. For both innovative and patented solutions, laboratory tests and numerical modeling were fulfilled and compared.

Key words: *Pressed-in Piles, Piled Cluster, Fender/Mooring Dolphin, Model Tests*

1. Introduction

Deep water piled clusters and structures supported by large mono-piles are designed to take up significant lateral and pressing loads. In particular, it relates to offshore structures whose foundations need long piled supports of high bearing capacity [Doubrovsky & Poizner, 2016]. Correspondingly one meets high level of stresses and significant deformations in such constructions. It is especially important for port or offshore engineering to avoid environmental problems caused by traditional pile driving technologies. From this point of view, the Press-in Method is the most appropriate approach. Two improved structures and technologies have been worked out to optimize stress-strain state of piled clusters and mooring/fender dolphin. To study peculiarities of these innovative design solutions model testing in laboratory conditions have been produced in Odessa National Maritime University. Physical modeling was provided for two stages. The first one was simplified by testing of the model without soil media (instead of piles embedded into the soil piles with tips fixed by special clamps were considered (console scheme). The aim of this first (simplified) stage was to determine the most appropriate calculation model in order to reflect innovative structural peculiarities and to select proper software. The second stage was aimed to test the same models in the soil box without artificial fixing of piles' tips by clamps (piles were embedded into sandy soil). For model's installation of the both innovative solutions we applied pressing of the piled models into sandy soil by hydraulic jack.

2. Innovative piled cluster and its model testing

Developed is effective and less resource-demanding design when connection of all piles with large diameter casing provides their joint work and favorable distribution of stresses and deformations in pile cluster (**Fig. 1**) [Doubrovsky, Gerashchenko & Dobrov, 2018]. Mentioned large diameter casing (shell) is installed both above and below the sea bottom level relieving piles and decreasing stresses in them. Connection between casing and piles may be provided similar to sheet piles interlocks.

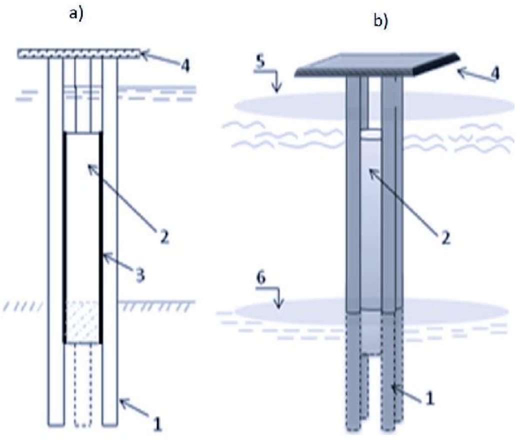

Fig. 1 Piled cluster of innovative design
a – cross-section; b – 3D view:
1 – bearing piles; 2 – steel cylindrical casing; 3 – interlock connections; 4 – superstructure; 5 – water level; 6 – bottom level

All bearing structural elements of this innovative piled cluster may be installed at the sea (in the sea port or at the offshore oil or gas field) by the Press-in Method driving both central shell and peripheral piles into the bottom soil. If designed shell diameter is larger than 2.5-3.0 m, the shell may be installed by driving of required number of straight web sheet piles along the shell's perimeter.

Such a structure has been tested on 3-D physical model (scale appr. 1:100). The layout of the structure and the location of the displacement indicators are presented on the **Fig. 2**. In the model central steel cylindrical casing (shell) was presented by steel tube of diameter D=50 mm (shell-wall thickness 1 mm); 4 piles equally spaced along the shell perimeter were modeled by steel bars of d=8 mm diameter. The total length of the model piles was preliminary determined according to the known recommendations of actual national design codes (770 mm).

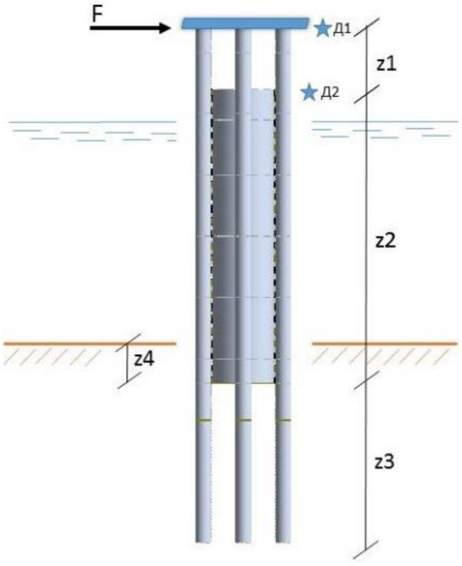

Fig. 2 Layout of the structural elements:
D1 and D2 – location of displacement indicators (marked by stars); F – applied lateral force; Z1 and Z3 – length of piles above and below the central shell; z2 – length of shell; z4 – embedment of the central shell..

At the first stage of experiments, pile supports were fixed by clamps to exclude their tips' displacements and central shell length was 350 mm (**Photo 1**).

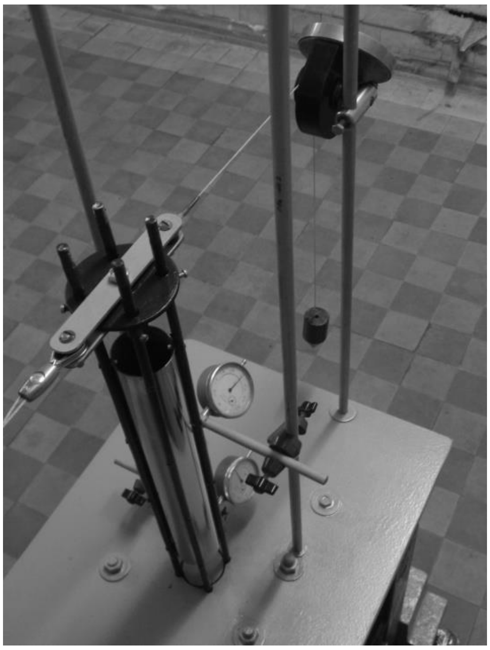

Photo 1. Piled cluster model at the first stage of testing

The same model was analyzed by a 3-D numerical simulation (FEM) using different programs in order to determine the most proper calculation model and software regarding peculiarities of the structure (i.e. interaction between the central shell and the peripheral piled elements). Three programs were applied to determine the stress-strain state of the model: AxisVM, Lira-SAPR and Midas-Gen. The closest data to the experimental results have been demonstrated by program Midas-Gen (**Fig. 3**).

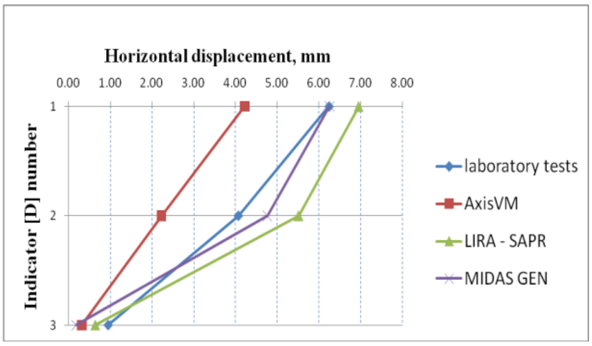

Fig. 3 Displacement diagrams from experiment and calculated data using different software (lateral force 350 N)

At the second stage of the experiment, the same structural model was tested in the sand box (internal friction angle 32 degrees; Young's modulus 18-28 MPa depending on pressure interval; unit weight 19,7 kN/m^3).

The model (**Photo 2**) has been loaded by the same horizontal forces as at the first stage. The main aims of this stage were to investigate influence of new structural element on the piled cluster, i.e. the central shell: its length along the peripheral piles (size Z2 on the **Fig. 2**) and its embedment into the soil (Z4 on the **Fig. 2**). Provided test series A corresponded to increase of the shell length Z2 due to enlargement of the embedment Z4. Test series B considered constant value of the shell length Z2 and increase of shell pressing depth Z4.

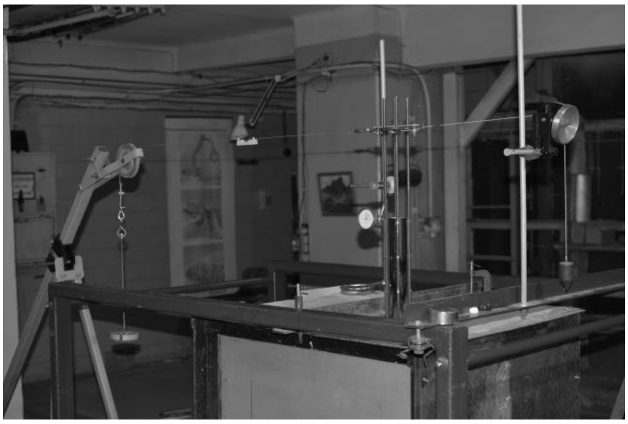

Photo 2. Piled cluster model at the second stage of testing

Displacements of the model were obtained by direct measurements during horizontal load application; stresses in the piles and shell as well as soil reactions were calculated by previously tested (at the stage 1) program Midas-Gen. Some measured and calculated results of this experiment are presented on the diagrams (**Fig. 4-11**).

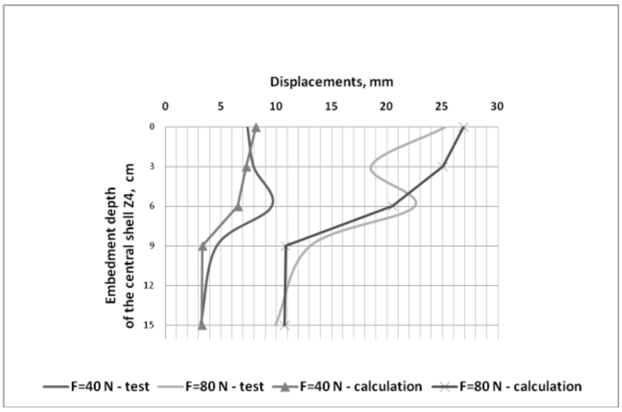

Fig.4 Displacements at the level of indicator D1 (test series A)

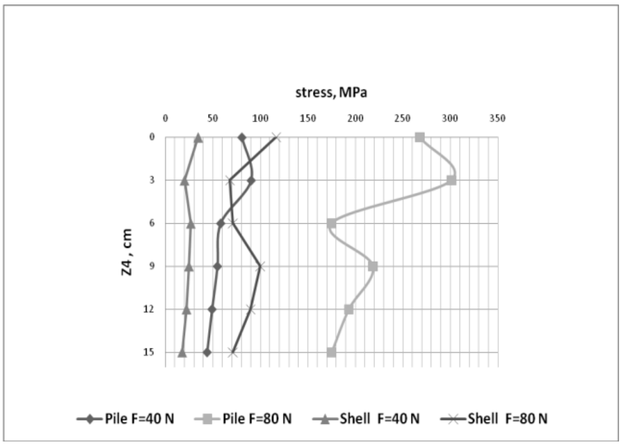

Fig. 5 Maximal stresses in the most stressed peripheral pile and central shell (series A, applied lateral force F= 40 N and F=80 N)

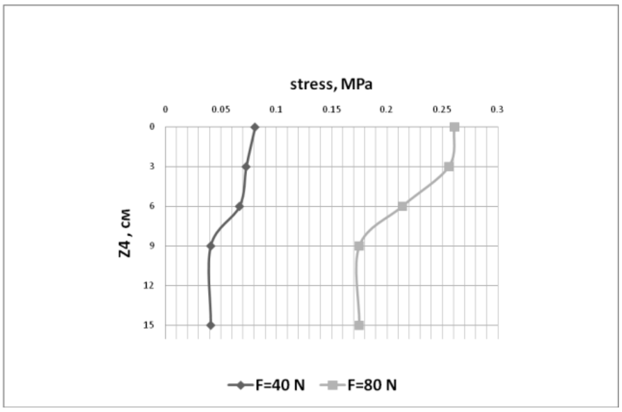

Fig. 6 Maximal soil reactions (test series A, applied lateral force F= 40 N and F= 80 N)

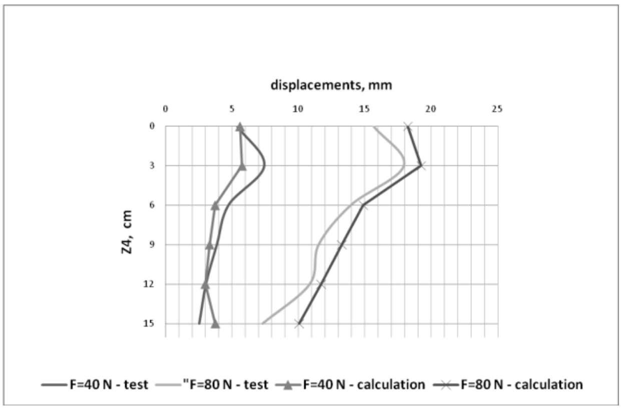

Fig. 7 Displacements at the level of indicator D1 (test series B)

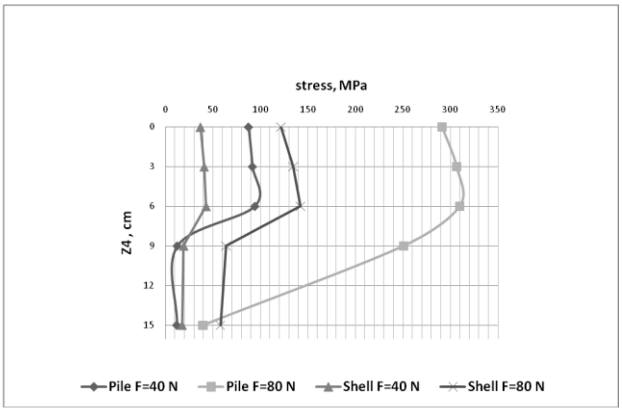

Fig. 8 Maximal stresses in the most stressed peripheral pile and central shell (series B, applied lateral force F= 40N and F= 80 N)

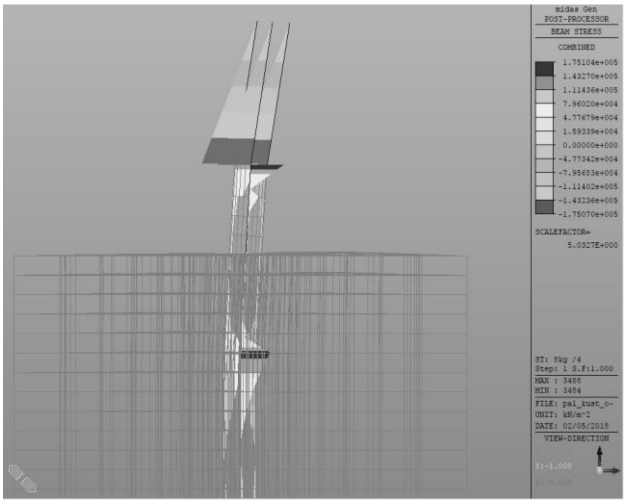

Fig. 9 Stresses distribution in the peripheral piles (test series B)

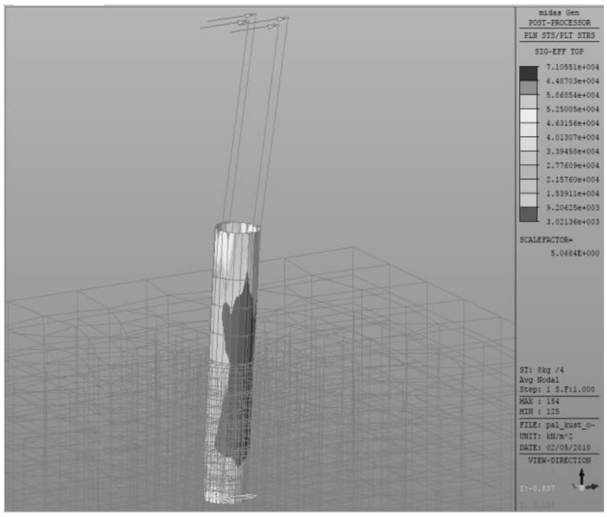

Fig. 10 Stresses distribution in the central shell (test series B)

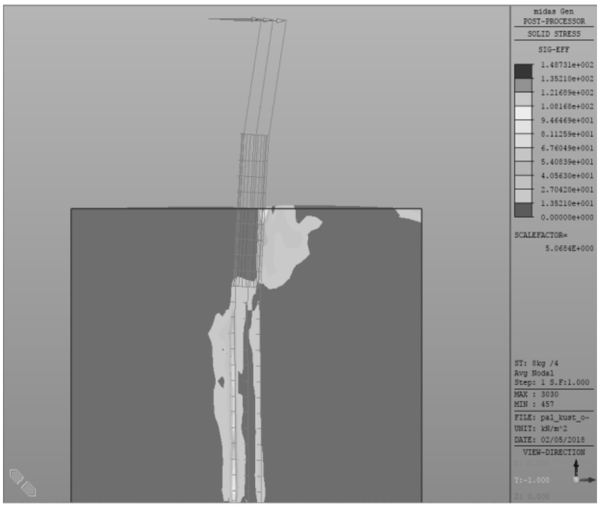

Fig. 11 Stresses distribution in the soil (test series B)

Obtained results and above mentioned diagrams give us possibility to make some important conclusions:

- measured and calculated values of model displacements demonstrate satisfactory precision (**Fig. 3, Fig. 4**); so applied calculation model works good
- considered system "structure-soil" shows sensitivity to the increase of the central shell pressing into the soil starting from the embedment depth exceeding approximately 1.5D. After reaching this driving depth we registered essential reduction of all stress-strain parameters: displacements, stresses in the piles and in the shell as well as soil reaction along the structure's supports (**Fig. 5 – Fig. 9**)
- the better distribution of the stresses in the system "structure-soil" corresponds to the increase of the embedment depth by pressing in the sand of the central shell of constant length (size Z2 on the **Fig. 2**). In such a case, the bearing capacity of piles, shell and soil is utilized in the optimal way (**Fig. 7** and **Fig. 8**). Another tested option (increase of the embedment depth by pressing in the sand of the central shell of increasing length Z2) shows excessive safety parameters and worse material utilization (**Fig. 4** and **Fig. 6**).

3. Innovative structure of combined mooring/fender dolphin and its model testing

To facilitate construction of deepwater mooring/fender dolphins and to increase their energy-absorbing capacity, a new design of combined tubular mono-pile structure was worked out and researched [Doubrovsky, Dobrov & Gerashchenko, 2018]. It incorporates internal flexible pile and damping element (cushion) placed at the zone of pile head (**Fig. 12**).

Sequences of installation operations foresees pressing of the internal pile into the bottom soil, mounting of the damping element, pressing of the external pipe into the bottom soil and assembling of fender/mooring equipment.

External force provoked by ship mooring (either via bollard of via fender) initially is taken by internal pile.

While bending the internal pile presses the damping element and through this cushion transfers the decreased force to the external tubular pile. Thus, due to joint work of three elements (internal and external piles and damping cushion between them) the dolphin may take essential ship load. It can be expected to make needless use of large diameter (3-4 m) heavy-walled (40-60 mm) tubular pile of ruggedness strength (and, correspondingly, of high cost).

In such a case combined dolphin made of two comparatively small diameter piles (of about 1 m for external pipe and 0.5 m for core one) may be profitably applied to withstand large operational force. Work of damping element is correlated with bending strain parameters of combined mono-pile elements.

At the first stage of the experiment (i.e. no soil in the system) pile supports of the physical model were fixed by special clamps to exclude their tips' displacements (**Photo 3**).

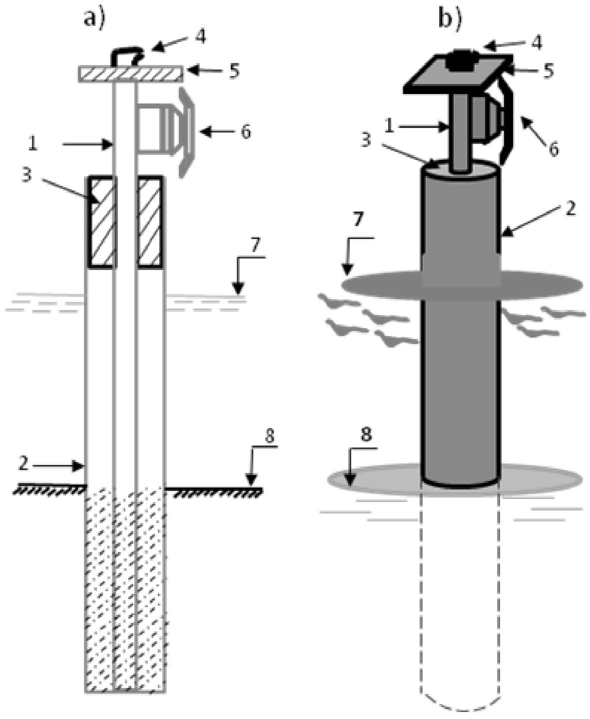

Fig. 12 Mooring/fender dolphin
a – cross-section; b – 3D view
1 – internal pile; 2 – external tubular pile; 3 – damping element (cushion); 4 – bollard; 5 - superstructure; 6 – fender; 7 - water level; 8 – bottom level.

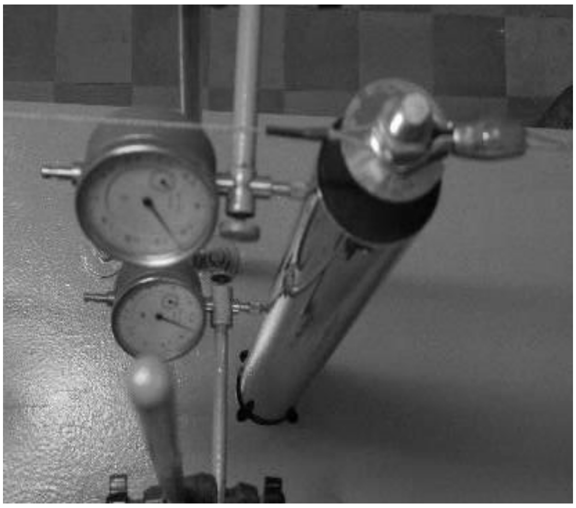

Photo 3. Dolphin model (1^{st} stage of the test)

Total length of the piles was preliminary determined according to the known recommendations of actual local design codes (**Fig. 13**). For initial calibration of the system it was convenient to place the dolphin's model in horizontal position.

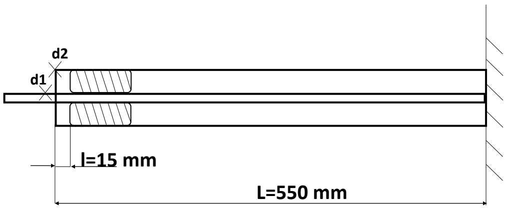

Fig. 13 Simplified scheme of the dolphin's model in horizontal position (d1 and d2 – location of displacement indicators)

External tubular pile was of 50 mm diameter (wall thickness 1 mm) and internal pile was made of steel bar of 12 mm diameter.

This model was also analyzed by a 3-D numerical simulation (as above) in order to determine the most proper calculation model and software regarding peculiarities of the structure and interaction between its elements. The most appropriate results were obtained by use of program Midas-Gen when, for description of damping element work, elastic-plastic model of Druker-Prager has been applied (discrepancy between test and calculations reaches up to 17 %).

At the second stage of the experiment, this structural model was tested in the sand box (**Photo 4**, soil parameters as above in Chapter **2)**.

To clarify advantages of the proposed combined mono-pile structure in comparison with usual (without internal pile) mono-pile, both models (of the same external diameter 50 mm) were tested by application of the same lateral forces. Main results of the displacement measurements are presented on the **Fig. 14, 15**.

Comparison of the experimental diagrams for external tubes shows that horizontal displacements of the combined mono-pile are up to 30% less than horizontal displacements of the usual mono-pile in the considered interval of applied lateral forces.

Photo 4. Mooring/fender dolphin model for the second stage of the experiment in the sandy box

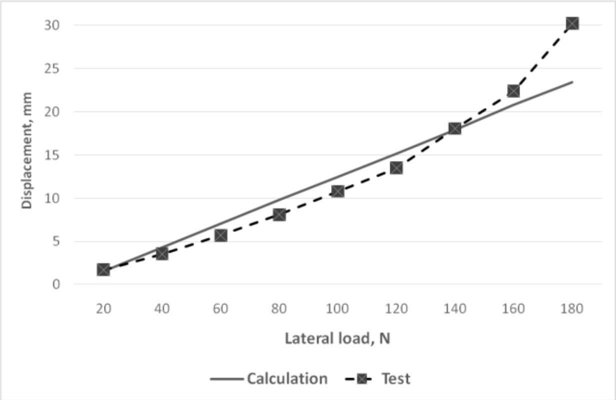

Fig. 14 Lateral load - horizontal displacement diagram for usual mono-pile model

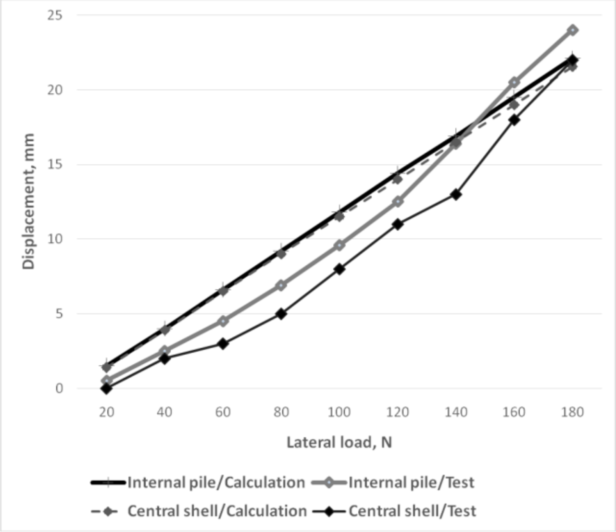

Fig. 15 Lateral load - horizontal displacement diagram for combined mono-pile model

Similar correlation of the studied parameters is demonstrated also by corresponding calculated curves on the **Fig. 14, 15**. This fact confirms effectiveness of use of the applied calculation model and software.

From the point of view of structure's operation reliability, it is important to compare horizontal displacements of external force application point for both models: at the upper end of the usual mono-pile model (similar to the point d2 on the **Fig. 13**) and at the level of point d1 of external pile of the combined model). Measured horizontal displacements in the external force application point differ up to 20% (reduction corresponds to the case of combined model). It confirms better energy absorbing ability of the proposed combined mono-pile.

Illustrations to the numerical modeling (FEM) of the considered models are presented on the **Fig. 16-20**.

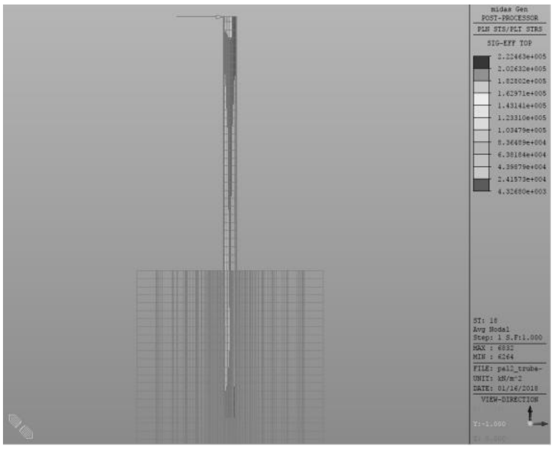

Fig. 16 Stresses distribution in the usual mono-pile structure.

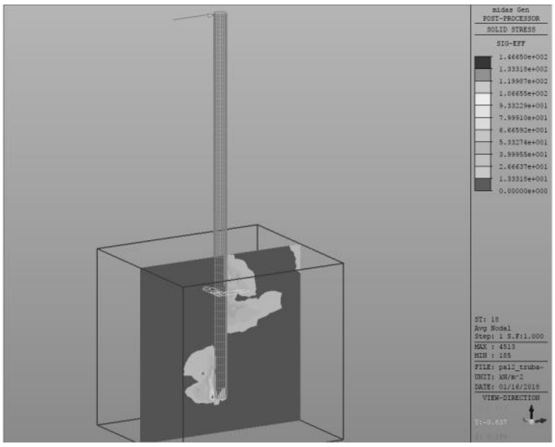

Fig. 17 Stresses distribution in the soil for usual mono-pile structure.

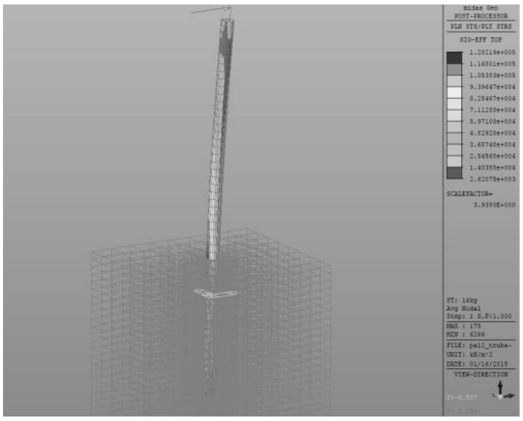

Fig. 18 Stresses distribution in the external tube of combined mono-pile structure.

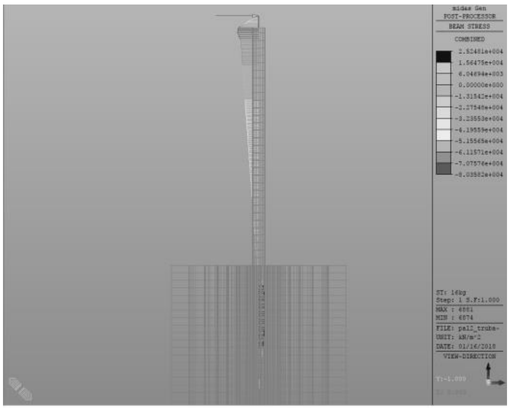

Fig. 19 Stresses distribution in the internal pile of combined mono-pile structure.

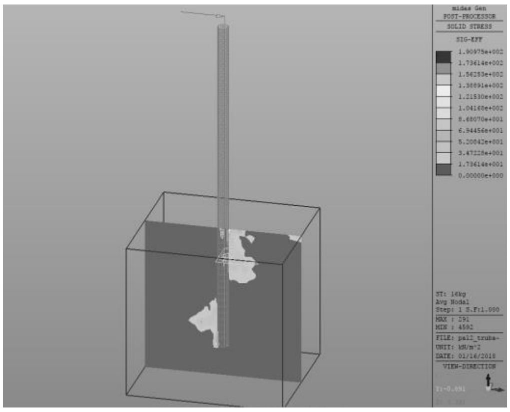

Fig. 20 Stresses distribution in the soil for combined mono-pile structure.

Comparison of the stresses maximal calculated values (corresponding to maximal applied lateral force F=180 N) in the external tube for usual mono-pile (222 MPa) and for combined structure (145 MPa) demonstrates 19% of stresses reduction. Correspondingly the external pile may be produced of smaller diameter or of smaller wall thickness, or made of weaker steel.

In the considered situation of maximal loading, the bending stress in the internal pile (steel bar) of the combined model does not exceed 91 MPa (about 30% of the yield stress), so internal pile also may be done light-weight (i.e. more flexible, at least in the interval of investigated displacement disparity in comparison with usual mono-pile as above).

Soil reactions are less in the case of combined mono-pile due to more favorable stress-strain state of pressed into soil external and internal piles.

4. Conclusions

Study of peculiarities of two innovative structural and technological solutions of piled cluster and mooring/fender dolphin on combined mono-pile was fulfilled by testing on physical models in laboratory conditions and by numerical modeling (FEM). Fulfilled tests occurred to be useful for study of structural behavior of both new designs as well as for determination of the appropriate calculation program (by comparison of measured and calculated data). Experiments in the sand box gave interesting results demonstrated advantages of proposed solutions.

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