Development and study of innovative deep water piled structures of high bearing capacity

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DOI: 10.32347/0475-1132.39.2019.19-26

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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 which foundations need long piled supports of high bearing capacity. Two innovative structures and technologies have been worked out to optimize stress-strain state of piled clusters and mooring/fender dolphins. (1) Developed is 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 cluster. (2) To increase energy-absorbing capacity of mooring/fender dolphins it is worked out and researched a new design of combined tubular mono-pile structure. 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.

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).

The preliminary stage of tests (experiments without soil with fixed piles' tips) occurred to be useful for study of structural behavior of both new designs [3, 4].

The main stage of experiments in the sand box with models of both proposed improved structures and their corresponding numerical modeling gave interesting results due to consideration of structure-soil interaction. It also confirmed proper selection of the appropriate calculation program (by comparison of measured and calculated data). Obtained results demonstrated advantages of proposed solutions and explained peculiarities of their innovative structures.

Keywords. Piled cluster, fender/mooring dolphin, model tests, numerical modeling.

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 which foundations need long piled supports of high bearing capacity [1]. Correspondingly one meets high level of stresses and significant deformations in such constructions. Two improved structures and technologies have been worked out to optimize stress-strain state of piled clusters and mooring/fender dolphin [2]. To study peculiarities of these innovative design solutions model testing in laboratory conditions have been produced in Odessa National Maritime University (Department "Sea, River Ports and Waterways"). Physical modeling was provided for two stages. The first one (preliminary experimental research) 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). Results of this first (simplified) stage of the phesical modeling were presented in the recent international conferences and published [3, 4]. They confirmed operability of the considered inventions and gave the possibility 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).

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) [2].

Mentioned large diameter casing (shell) is installed both above and below sea bottom level relieving piles and decreasing stresses in them. Connection between casing and piles may be provided similar to sheet piles interlocks.

Such structure has been tested on 3-D physical model (scale appr. 1:100). Layout of the structure and location of the displacement indicators are presented on the (Fig. 2).

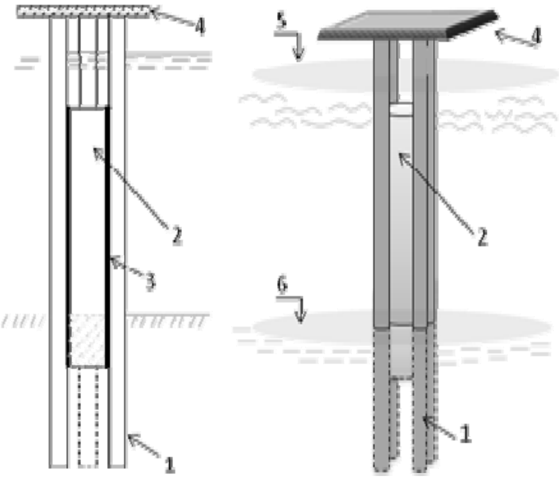


Рис.1. Пальовий кущ інноваційного дизайну: a - поперечний переріз; b - 3D-перегляд; 1 - несучі палі; 2 - сталевий циліндричний кожух; 3 - міжблокові з'єднання; 4 - надбудова; 5 - рівень води; 6 - нижній рівень.

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.

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 (Fig. 3). Total length of the model piles was preliminary determined according to the known recommendations of actual national design codes (770 mm).

Sand soil main parameters are:internal friction angle 32 degrees; Young modulus 18-28 MPa depending on pressure interval; unit weight 19,7 kN/m^3.

The main aims of this stage were to investigate influence of new structural element of 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.

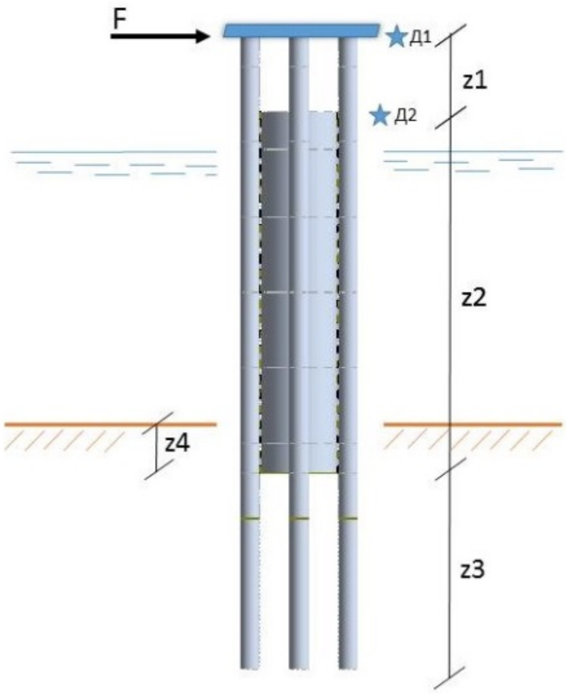


Рис.2. Схема структурних елементів та розташування індикаторів: D1, D2 і D3 - місця розташування індикаторів переміщення; F - прикладена бічна сила.

Fig.2. Layout of the structural elements and location of indicators: D1, D2 and D3 – locations of displacement indicators; F – applied lateral force.

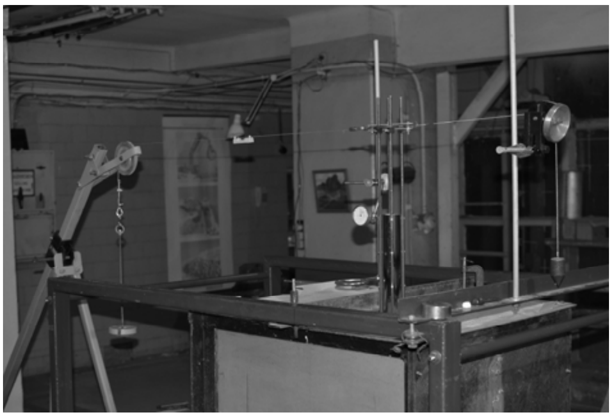
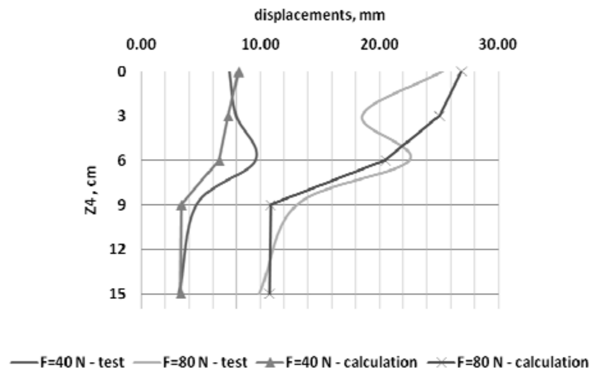


Рис.3. Пальовий кущ в моделі на другому етапі випробування.

Fig.3. 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. 4-7).

(a)



(b)

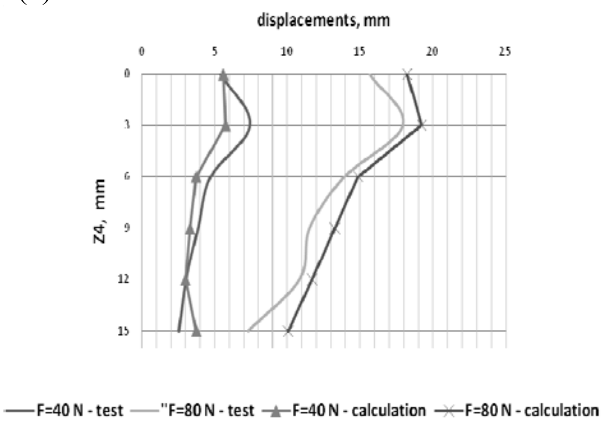
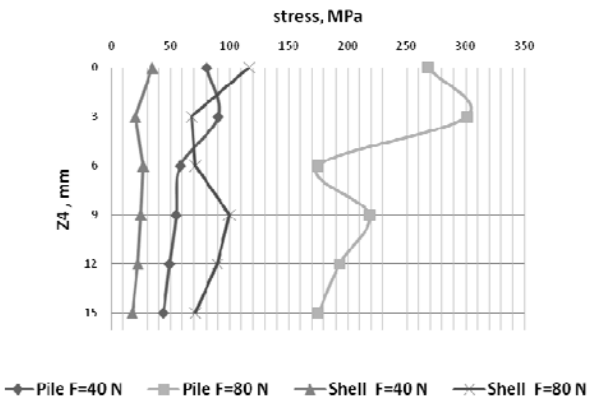


Рис.4. Зміщення на рівні індикатора D1: а - серії випробувань А; б - серії випробувань Б.

Fig.4. Displacements at the level of indicator D1: a - test series A; b - test series B.

(a)



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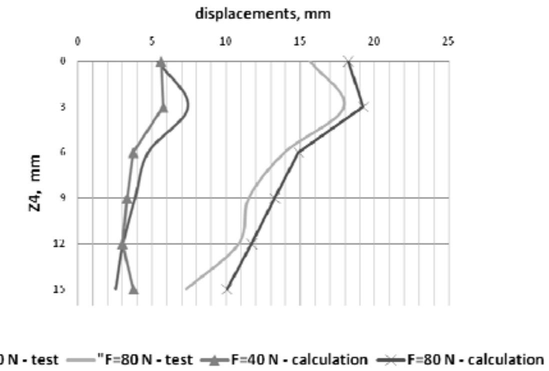
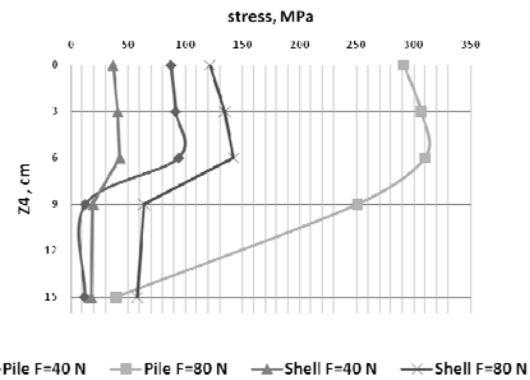


Рис.5. Максимальні напруження в периферійних палях і центральній оболонці: a - серії випробувань A; b - серії випробувань B (прикладена бічна сила F = 40 N і F = 80 N).

Fig.5. Maximal stresses in the peripheral piles and central shell: a - test series A; b - test series B (applied lateral force F= 40 N and F= 80 N).

(a)



(b)

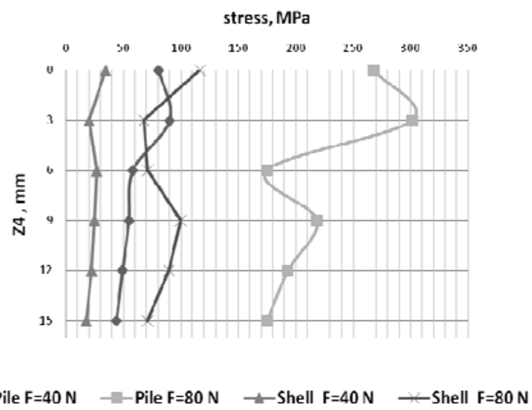
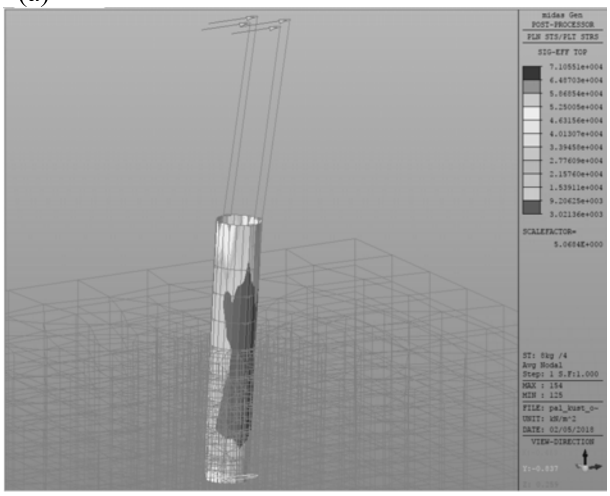


Рис.6. Максимальні реакції ґрунту: a - серії випробувань A; b - серії випробувань B (прикладена бічна сила F = 40 N і F = 80 N).

Fig.6. Maximal soil reactions: a - test series A; b - test series B (applied lateral force F= 40 N and F= 80 N).

(a)



(b)

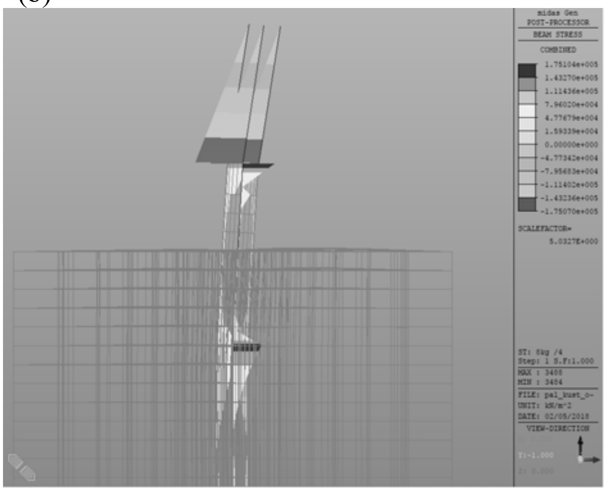


Рис.7. Приклади розрахованого перерозподілу напружень у центральній оболонці (a) та периферійних палях (b) для серії випробувань B.

Fig.7. Examples of the calculated stresses distribution in the central shell (a) and peripheral piles (b) for 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 (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;

- 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 case the bearing capacity of piles, shell and sandy soil is utilized in the optimal way. Another tested option (increase of the embedment depth by pressing in the sand of the central shell of correspondingly increasing length Z2) shows excessive safety parameters and worse materials utilization.

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 it is worked out and researched a new design of combined tubular mono-pile structure [3]. It incorporates internal flexible pile and damping element (cushion) placed at the zone of pile head (Fig. 8).

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

At the experiment the structure's model was tested in the san

d box (Fig. 9, soil parameters as above in Chapter 2).

At the preliminary stage of the experimental study [3] the most appropriate results of the numerical vodeling 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 main stage of the tests 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 and calculation data are presented on the Fig. 10.

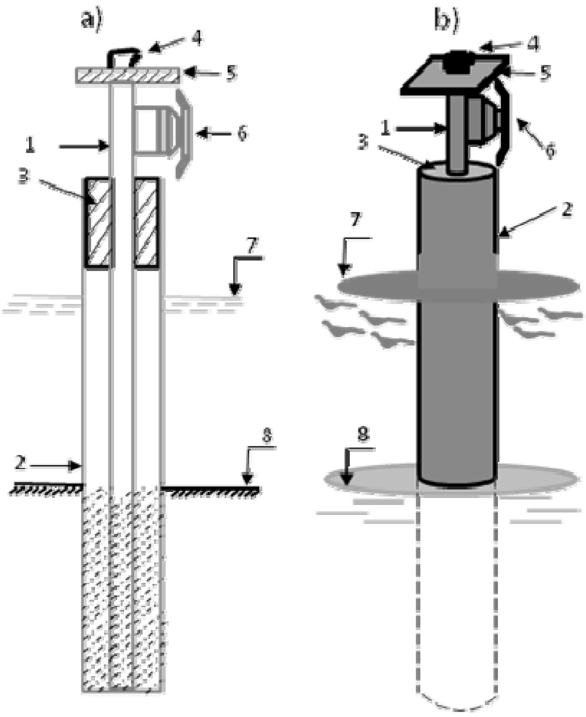


Рис.8. Швартовно-відбійні палі: a - поперечний переріз; b - 3D-перегляд 1 - внутрішня паля; 2 - зовнішня трубчаста паля; 3 - демпфуючий елемент (подушка); 4 - швартова тумба; 5 - надбудова; 6 - крило; 7 - рівень води; 8 - нижній рівень.

Fig.8. 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.

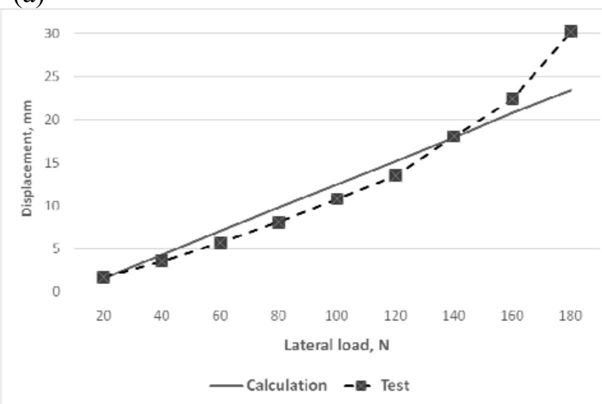
Comparison of both experimental and calculation diagrams for external tube shows that horizontal displacements of the combined mono-pile are up to 30% less than horizontal displacements of the usual mono-pile in the considered interval of applied lateral forces.

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 and at the same level on the enternal pile of the combined model).

Рис.9. Модель швартовно-відбійної палі для експерименту в лотку з піском.

Fig.9. Mooring/fender dolphin model for the experiment in the sand box.

(a)



(b)

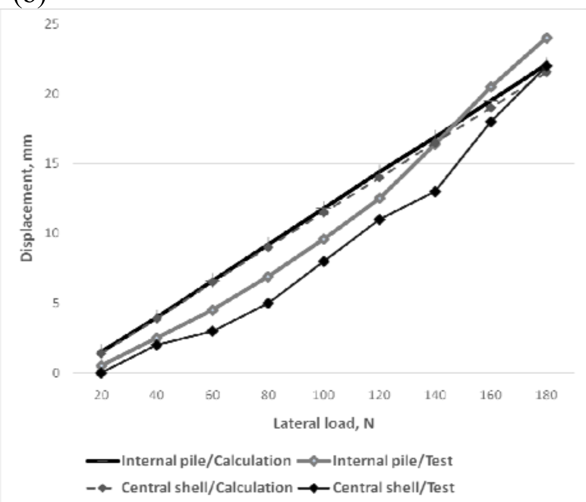


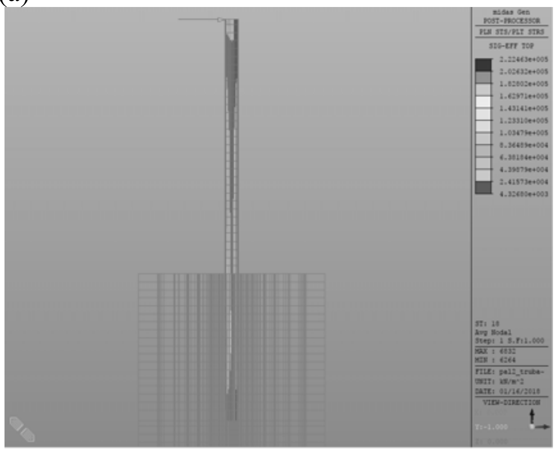
Рис.10. Діаграми навантаження-переміщення: (a) звичайна одно-пальова модель; (b) комбінована одно-пальова модель.

Fig.10. Load-displacement diagrams: (a) usual mono-pile model; (b) combined mono-pile 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. 11-13.

(a)



(b)

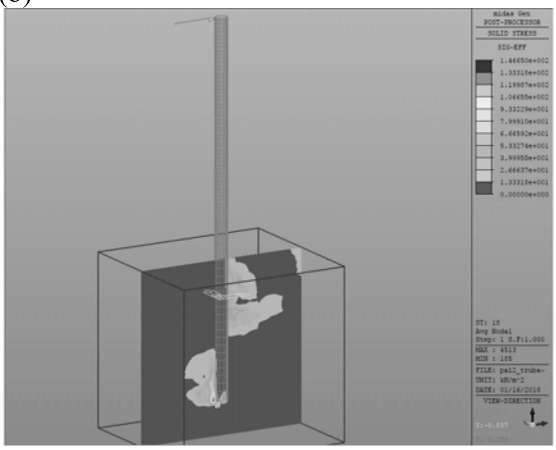
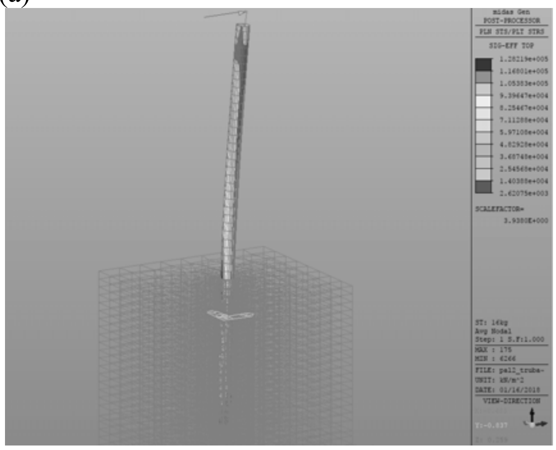


Рис.11. Перерозподіл напружень у випадку звичайної одно-пальової моделі: а - в трубчастій палі; б - у ґрунті.

Fig.11. Stresses distribution in the case of usual mono-pile structure: a – in the tubular pile; b – in the soil.

(a)



(b)

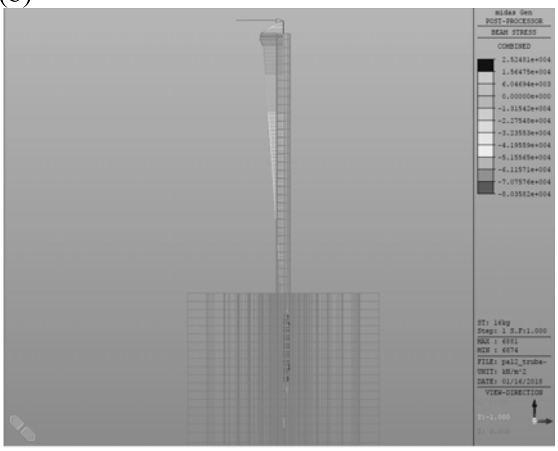


Рис.12. Перерозподіл напружень у випадку комбінованої одно-пальової моделі: а - в трубчастій палі; б - у ґрунті.

Fig.12. Stresses distribution in the case of combined mono-pile structure: a – in the tubular pile; b – in the enternal pile.

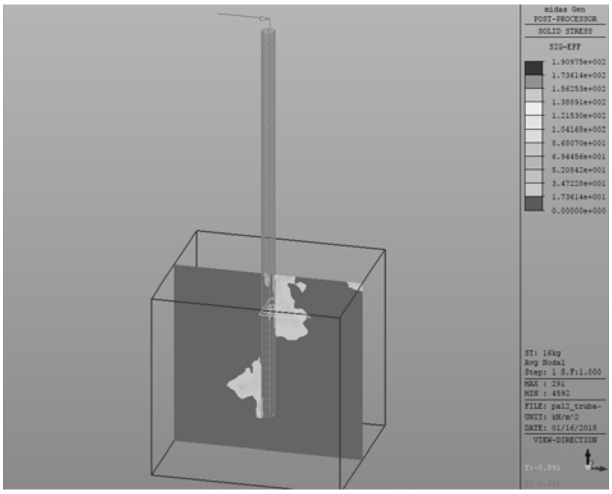


Рис.13. Перерозподіл напружень у ґрунті для комбінованої одно-пальової моделі.

Fig.13. 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 stress in the internal pile (steel bar) of the combined model does not exceed 91 MPa, so internal pile also may be done easer (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 case of combined mono-pile due to more favorable stress-strain state of pressed into soil external and internal piles.

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).

The preliminary stage of tests (experiments without soil with fixed piles' tips) occurred to be useful for study of structural behavior of both new designs [3, 4].

The main stage of experiments in the sand box with models of both proposed improved structures and their corresponding numerical modeling gave interesting results due to consideration of structure-soil interaction. It also confirmed proper selection of the appropriate calculation program (by comparison of measured and calculated data). Obtained results demonstrated advantages of proposed solutions and explained peculiarities of their innovative structures.

ACKNOWLEDGEMENTS

Authors are grateful to their colleagues from Odessa National Maritime University

(Faculty of Water Transport and Offshore Structures, Department "Sea, River Ports and Waterways") for valuable support and assistance on preparation of the presented research.

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Розробка та дослідження іноваційних глибоководних пальових споруд високої несучої здатності

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Андрій Геращенко,
Ігор Добров,
Ольга Дубровська

Аннотація. Глибоководні пальові кущі та споруди, що оперті на великі моно-палі, проектують на сприйняття значних бокових та стискних навантажень. Зокрема це відноситься до шельфових споруд, фундаменти яких потребують довгих паль високої несучої здатності. Дві інноваційних споруди та технології розроблені для оптимізації напружено-деформованого стану пальових кущів швартовно-відбійних палів. (1) Розроблена ефективна та економічна конструкція, в якій сполучення усіх трубчастих паль із металевою оболонкою великого діаметру забезпечує їх сумісну роботу та сприятливий розподіл напружень та деформацій в пальовому кущі. (2) Для збільшення енерго-абсорбційній здатності швартовно-відбійних паль розроблена та досліджена нова конструкція комбінованої трубчастої моно-палі, яка містить внутрішню гнучку палю та амортизатор, що розміщений між зовнішньою та внутрішньою палями у зоні їх голів.

Для обох інноваційних та запатентованих рішень були проведені лабораторні експерименти та чисельне моделювання. Отримані результати підтвердили їх ефективність та практичність.

Вивчення особливостей двох інноваційних структурних та технологічних рішень складених пальових кущів швартовно-відбійних палів на комбінованій трубчастій моно-палі було виконано тестуванням на фізичних моделях у лабораторних умовах та числовим моделюванням (FEM).

Попередній етап випробувань (експерименти без ґрунту з нерухомими наконечниками паль) виявився корисним для вивчення структурної поведінки обох нових конструкцій.

Основний етап експериментів в лотку з піском з моделями обох запропонованих удосконалених пальових конструкцій та їх відповідне числове моделювання дали цікаві результати завдяки врахуванню взаємодії надбудова-ґрунт. Він також підтвердив належний вибір відповідної програми розрахунків (шляхом порівняння вимірюваних та обчислених даних). Отримані результати продемонстрували переваги запропонованих рішень та пояснили особливості їх інноваційних конструкцій.

Ключові слова. Пальовий кущ, швартовно-відбійний пал, модельні випробування, чисельне моделювання.