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Modeling of infilled thin shell construction built on compressible soil

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Abstract. This paper presents review of author's researches of thin cylindrical shells of large diameter filled with soil and used in construction of berths, breakwalls, retaining walls, bridge piers, and etc. The theoretical model for soil stability of the researched structures based on soil boundary state of stress solution with allowance for bond slip is developed. Suggested correlation represents a theoretical model that functionally relates parameters of foundation soil and construction sizes with maximum horizontal force, which might be held by a structure without loss of soil bearing capacity. The numerical model of a thin cylindrical shell with infill under eccentric load is developed. Modeling and experimental determination of the interface strength of the contact surface between the infill and the inner surface of the shell is proposed. The details of testing of physical model used for the experiments are discussed. The effects of the interface friction on the shell behavior and on the foundation stresses are investigated. The influence of parameters affecting the interaction between the soil infill and the inner surface of the shell material is determined. It is based on a comparison of experimental results with calculations performed using the proposed mathematical model. The results of experiment are shown in comparison with calculation data's for proposed numerical model. Effect of ice load on shell structures with infill on compressible soil is also considered in this research. The numerical model is proposed, which takes into account the interaction between soil environment, effect of ice load and thin shell with infill, to predict the stability and durability of shell structures under ice load.

1 Introduction

Thin shells with infill can be used as alternative engineering solutions in the design of berths, docks, break walls, and in retaining walls supporting foundations of trestles and bridge piers.

These constructions consist of thin shell (made of steel or reinforced concrete) with infill of certain physical and strength properties. The shells have considerably large diameter of several meters with small wall thickness of few centimeters.

The structure's diameter (D) to its height (H) ratio, D/H, are within the range of 0.7 to 1.0 for these structures. Economically these structures are relatively cost-effective and have several advantages during the constructions.

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Conditionally, these shells can be divided into two main groups: first – shells installed on incompressible bed (Fig. 1, b) and second – partially undergrounded shells.

Currently, due to the necessity of offshore hydrocarbon field developments, there is a rise in the capacity expansion and/or construction of new port and coastal infrastructure facilities. Due to the relatively weak compressible foundation soils of Arctic offshore areas (Melnikov and Spesivtsev, 1995), the installation of specially prepared rubble bases seems rather difficult. In addition, the production and transportation of heavy reinforced structures are not possible due to remote locations of the construction sites. In these situations, these steel shells of large diameter partially grounded in the foundation soil have significant advantages over other types of supporting structures (Fig. 1, d).

2 Analytical solution for soil and structure stability

The theoretical model for the stability assessment of cylindrical shells installed in line (such as part of constructions at berths, docks, and retraining walls) bearing both its own weight and external loads is given below (Tsimbelman N. Ya et al. 2016).

These loads can be exposed on the shell structure by ice impact, docking and mooring impacts, lateral earth pressures, operational processes of various kinds, and other impacts. The fundamentals of the limit equilibrium theory and further use of plain-stain equilibrium equations help to determine the maximum lateral load (resultant) that the "shell–foundation" system can resist while still maintaining its stability.

The limit equilibrium theory principles applicable to the ground environment shall be used in assessment of the foundation load-bearing capacity under the influence of normal loads. The objective is to determine at what surcharge, q, on the given subsurface with a vertical foundation pressure, p, (Fig. 2, a), all points of ground mass reaches to boundary state of stress.

According to different sources (Christianovich, 1981) the figure reminds weight beam balance.

The resistance to the loads acting is provided by the soil's strength characterized by the friction angle Φ and cohesion pressure, σ_c, on the slip surface. For the absence of surcharge (q=0), then the function of «equilibrium» pressure is performed only by contact pressure, σ_c, and given as (Sokolovskiy, 1990):

$$p_0 = \sigma_c \cdot \frac{1+\sin\Phi}{1-\sin\Phi} \cdot e^{\pi \cdot tg\Phi} - \sigma_c. = c \cdot ctg\Phi \cdot \left(\frac{1+\sin\Phi}{1-\sin\Phi} \cdot e^{\pi \cdot tg\Phi} - 1 \right). \qquad (1)$$

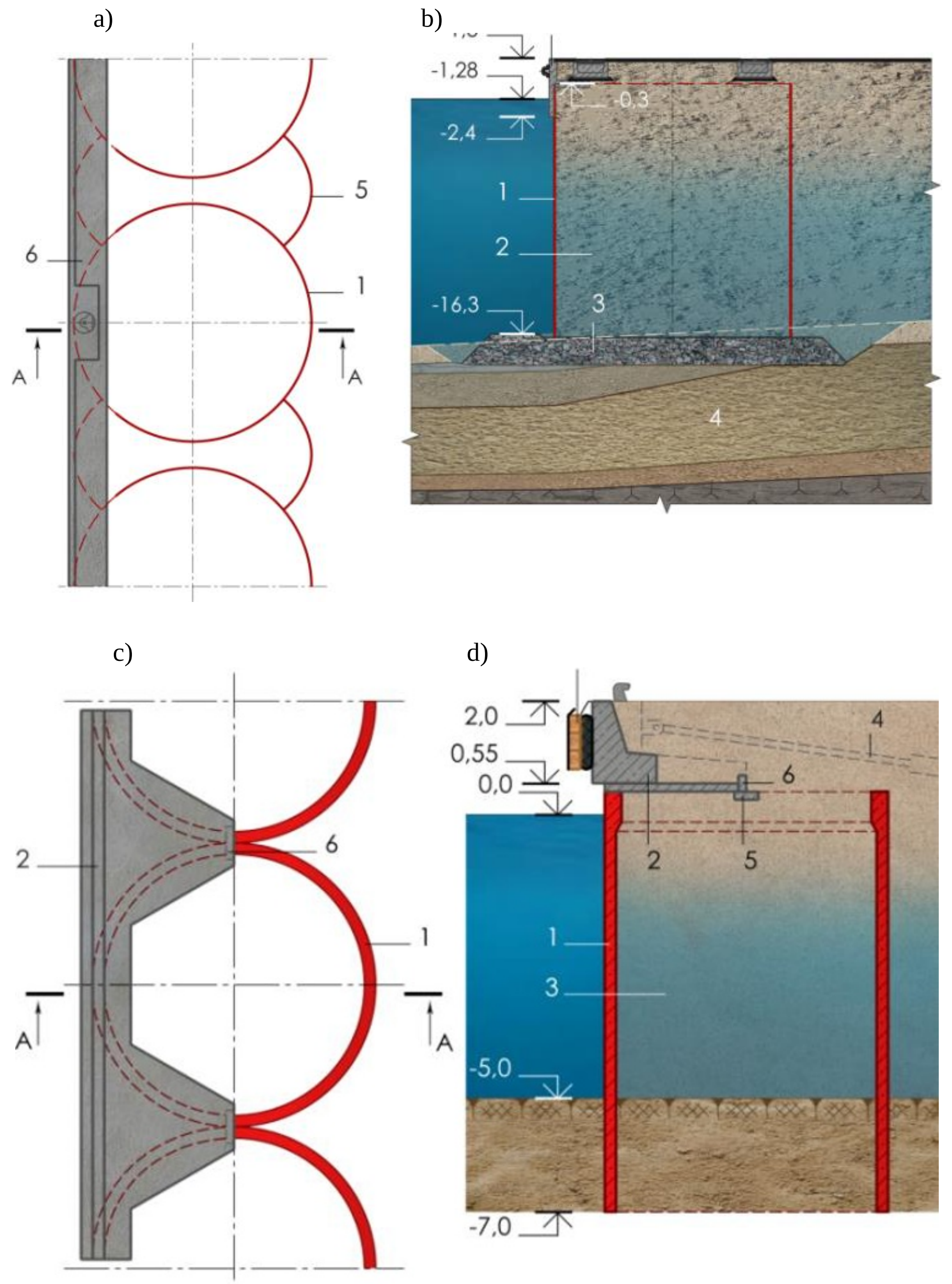


Fig. 1. Infilled gravitational shells: a, b – moorage wall at the Port of Vladivostok, Russia (1 – steel shell, 2 – ground infill, 3 – rubble base, 4 – foundation loamy soil); c, d - partially buried shell of Riga bund, Latvia (1 – shell, 2 – topside structure, 3 – sand soil infill, 4 – anchor bars, 5,6 – topside structure parts, 7 – fenders).

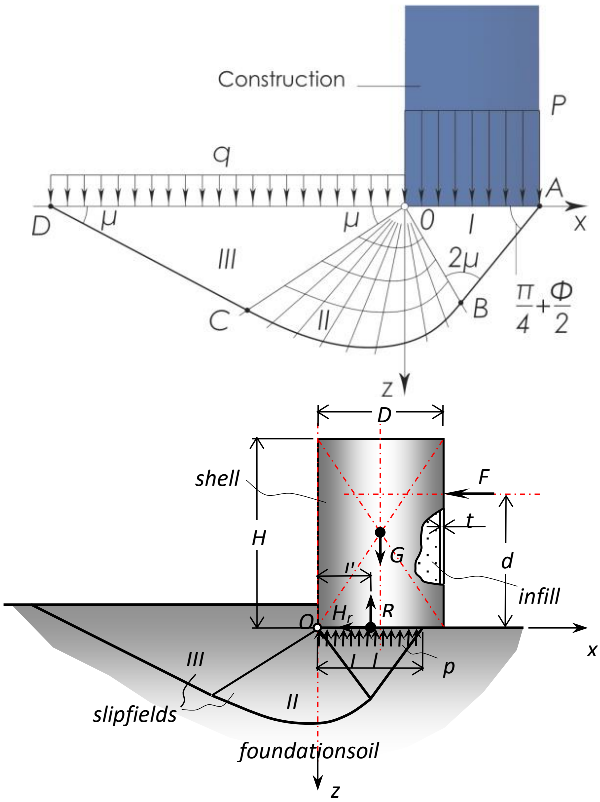


Fig. 2. Illustrations for theoretical model: a – sliding areas formation pattern; b – loads and pressures on the structure for stability calculation.

The maximum lateral force F_{max} (acting at a distance d from the bottom of structure) leading to overturning of the structure, is a function of several variables such as the size of the structure and the properties of the foundation soil. The stability calculation shall be made according to the method of integrate safety factor:$M_1 \geq k \cdot M_2$ (2), where M_2 is the driving moment determined by the lateral resultant force F and the moment arm d; k is a safety factor depending on a structure class and usually equal 1.2 (Dunkan and Wright, 2005); and M_1 is the restraining (stabilizing) moment caused by the structure's own weight.

Equilibrium criterion with the account of Eqns. (1), (2) can be used to calculate maximum (extreme) overturning force F_{max} as:

$$F_{max} = -n \cdot \frac{\gamma H \pi D^3}{8 \cdot d \cdot k} \left(\frac{\gamma H}{c \cdot ctg\Phi \left(\frac{1+\sin\Phi}{1-\sin\Phi} \cdot e^{\pi \cdot tg\Phi} - 1 \right)} - 1 \right). \tag{3}$$

The equation (3) is the proposed theoretical model functionally connecting physical and mechanical parameters of foundation soil and structure dimensions with maximum stabilizing moment, which can be maintained by a structure without violating the stability of the "shell – foundation" system.

3 Numerical model of construction

The theoretical model developed in the previous section based on the mathematically precise solution, provides opportunity of testing the previously suggested numerical model of the described structures with account of its parameters obtained from experiments (Bekker et al. 2015). The numerical model permits evaluation of the stress-strain behavior of infilled cylindrical shells placed on compressible foundation soils. Detailed description of the suggested numerical model is provided by Tsimbelman N. Ya et al. (2017). Some aspects of this model and an example of its use applicable to PLAXIS 3D software package is given below.

Main construction element of the researched structure is infill soil. Soil is modeled as solid element; the infill soil of cylindrical shape as an elastic-plastic material and foundation soil as an elastic-plastic semi-space. The infill and foundation soils shall be considered as compressible elastoplastic bodies.

The general components of the finite element model used in the analysis and the interface layer are shown in Fig. 3.

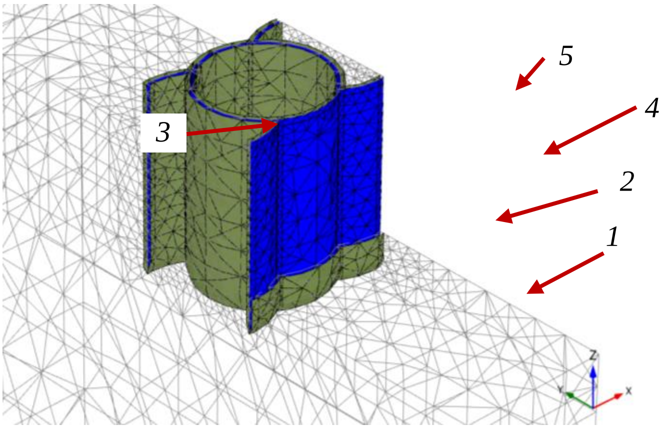


Fig. 3. Layout of conventional layers of the numerical model: 1-interface; 2-shell; 3 -soil outside the shell; 4 – connection arcs; 5-infill soil.

One of the most important factors of the model was identifying the conditions for the interaction of infill and shell's inner wall. The calculation model shall be added with conventional intermediate (transition) zone modeled with special "Interface" elements in software used for the numerical analyses (Brinkgreve, 2013). These elements have a number of strength and geometric characteristics, which modification in the areas of interaction is followed by certain processes, such as soil strengthening, creep of ground, and sliding of structure material. Strength properties of "Interface" are related to strength properties of the soil. Dataset of interface shell has its own coefficient of strength reduction R_{inter}. To find the needed parameter a physical experiment was performed on a small-scale infilled shell models. The study revealed recommended range of strength reduction coefficient R_{inter} to use for calculations of thin-walled cylindrical infilled shells of large diameter set on compressible soil foundations.

4 Experiment

The selection of the required parameter values for the computational model are made based on the experiment carried out on a physical laboratory model of a shell with soil infill. The simulation conditions for the shell material and structure, as well as for the infill material, should provide the complete similarity of the stressed state of the model to the real case. In order to accomplish this task, the scaling theory and dimensional analysis methods (Kirpichev, 1953) are applied. The detailed description of the laboratory setup, the basis for its sizes and material of the shell, simulation of the infill and loading conditions are given in the paper published by Bekker et al. (2014). The experimental setup was equipped by the loading gear, strain gauges, and tensiometers, in order to define stresses in the shell body. The loading gear setup allowed load to be applied horizontally to the shell top.

Additional series of calculations on the proposed mathematical model of facility was carried out in advance. As the calculation is implemented for the conditions precisely corresponding to the conditions of the experiment, it is possible to make a direct comparison of data obtained from calculation and the experiment. The curves labeled as 2, 3, and 4 in Fig. 4 show the displacements computed for the coefficient R_{inter} equal to 0.2, 0.3, and 0.4, respectively. The results show that the comprehensible range of values of the required parameter of the mathematical model (strength reduction coefficient, R_{inter}) on contact of a shell with infill is between 0.3 and 0.4.

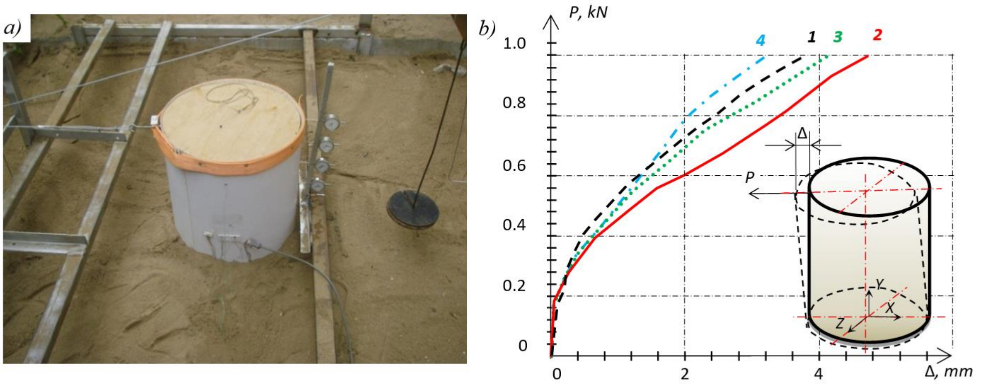


Fig. 4. Experiment: a – the experimental model setup; b – applied load versus the shell cap displacement; 1 – experiment, 2 – R_{inter} = 0.2, 3 – R_{inter} = 0.3, 4 – R_{inter} = 0.4.

5 Cyclic ice load

Also such structures may be exposed to severe climatic conditions, e.g., coastal infrastructure facilities of oil and gas exploration on the shelf of the Arctic and subarctic seas. Along with complicated soil conditions Arctic seas coast is also characterized by considerable ice loads. Seasonal nature of ice effect in many cases leads to the necessity of forming cyclic ice load application to the structure when making numerical models. Consequently, it is necessary to develop a numerical model for calculating shell structures with infill taking into account all loads in various combinations acting on these structures. One of the goals is to determine ice load on vertical shell structures, include it into the shell with infill model as cycles of loads and to find soil response under the load. The suggested technique of successive modeling of one and more cycles of ice loading will allow determining structure’s displacements and stresses in shell body and in foundation soil during operation period.

The loading described occurs, for instance, during the action of currents as well as during periodic effect of subglacial tides when fast ice exerts pressure on the barrier during high tide and then rushes away from it at low tide.

Impact of ice on cylindrical structures was defined according to the Russian Standards (SP 38.13330.2012 “Loads and impact on hydraulic structures (from wave, ice and vessels)”).

$F_{c,w}$, [kN] – is the global ice load, force from the impact of moving ice floes on section of the extended structures with a vertical front face (Fig. 5,a). Load from the frozen to the structure ice floe because of change of water level is formed of tangential component f_d [kN/m] and the moment $M_f = F_f \cdot d$[kNm/m] (Fig. 5, b).

Thus, the structure intermittently takes load from level ice floe $F_{c,w}$, and unloading from frozen up ice F_f and f_d. The number of stress cycles can be verified as a result of calculated evaluation of stress-strain behavior of «structure – foundation» system on cyclic load action.

In this part of study (Tsimbelman N. Ya et al. 2017), the infill is modeled as an elasto-plastic cylinder, and the backfill and foundation are considered as the elasto-plastic half space. The soil infill, backfill and the base are considered as plastically coercible elasto-plastic bodies. The Hardening-Soil model (HS-model) is selected for this study as the constitutive model for the soil. The HS-model gives a good agreement with experimental data during strain range. The present model allows taking into account plastic deformation (including load history) before soil reaches its limit, and looking at the stress-strain state of soil during unloading/reloading process (Brinkgreve, 2013).

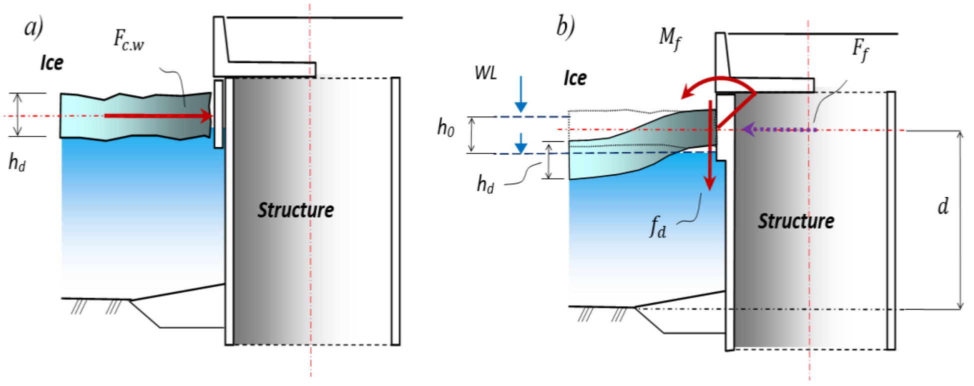
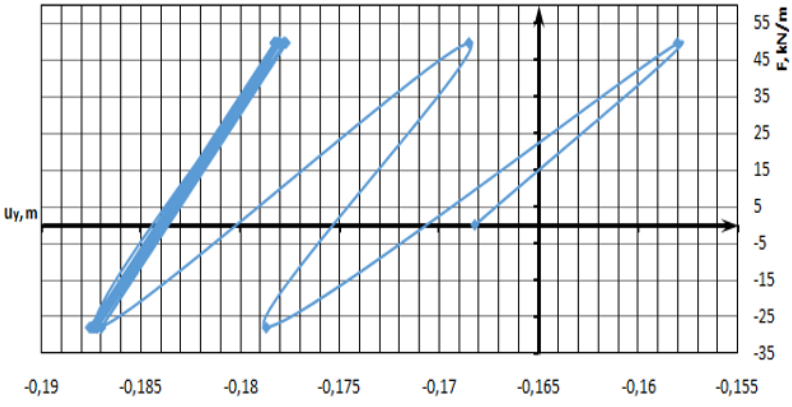


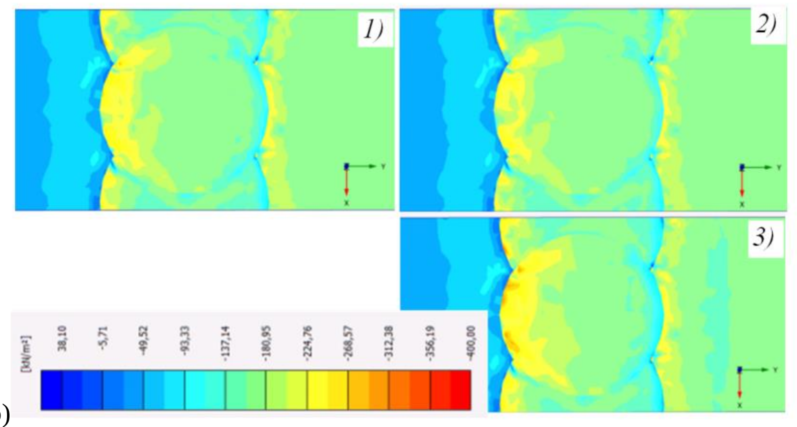
Fig. 5. Cyclical character of load application: a – scheme of application of the load from moving ice floe on a section of structure; b – schemetofrozen up ice load evaluation.

As the result of one ice effect cycle the structure received an additional displacement towards the water area. The structure's displacements dependence on the load applied is shown in Fig. 6,a. Then, according to the loading scheme considered above several cycles of load application were implemented until complete attenuation of deformations. The finite number of successive load applications makes up 5÷10 cycles, following which due to the use of hardening soil model the growth of finite strains stops.

The analysis of stresses distribution pattern in the foundation of the structure shows that at the third step of loading (un-loading) within a single cycle the soil experiences the maximum stresses which should be taken into account when assessing bearing capacity of the foundation (Fig. 6,b).



a)



b)

Fig. 6. Displacements and total stresses: a – load-displacement curves; b – total stresses (top view): a) σ_z= -341.7 kN/m^2 for step 1 (no additional load), b) σ_z= -325.5kN/m^2 for step 2 (horizontal loading); c) σ_z= -354.5 kN/m^2 for step 3 (horizontal un-loading).

6 Conclusions

This paper presents review of author's researches of special type of constructions: infilled thin shells built on compressible soil.

The first stage of research recommends an analytical model for the assessment of such structures. The model was developed based on the solution of foundation soil boundary state of stress with account of sliding fields. The model was also used for the verification of suggested numerical modeling of these structures.

The finite-element modeling and analysis of an eccentrically loaded shell with infill structures using PLAXIS was also presented in this study.The relevant factor influencing the results from mathematical model entered into the software is the parameter of strength properties reduction R_{inter} within the so-called interface, i.e. the element through which the environments (for example, a shell and an infill) interact. The interface parameters cannot be determined without physical experiment, and its properties will depend considerably on specificity of mutual functioning of elements in the considered facility.

In order to verify the offered model, the model tests of a thin-wall cylindrical shell with infill placed on a compressible foundation were performed. The recommended range of the strength reduction coefficient values proposed to be applied in calculations of thin-wall steel cylindrical shells of large diameter with soil infill on compressible foundation soils is revealed in the study. The range of interface reduction coefficient values is 0.3 to 0.4.

The paper also presents an example of modeling cyclic effect of ice on shell with infill gravity-type structure placed on the compressible soil foundation. The loading from level ice floe and unloading from frozen-up ice acting within one load cycle have been calculated, the sequence of cyclic action has been modeled. It has been determined that the structures of thin shells with infill carry ice loads well enough (in conditions of non-extreme, mean load intensity typical of water areas of operating ports), including alternating, «swinging» the structure. For the computational evaluation it is enough to consider 5÷10 cycles of successive loading of the structure with alternating load. This stage of research does not take into account cyclic degradation of soil properties due to short term cyclic loading. Only change of stiffness based on load history is taken into account. Cyclic degradation could be a subject for further research.

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