Definition of Limit Displacements for Structures Made from Infilled Shells used in a Coastal Engineering (Review)

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Abstract. A review is devoted to the question of designing offshore gravity structures made of cylindrical shells filled with ground. This article presents a review and investigation of the design criteria for cofferdam structures made from soil-filled shells. Based on a number of experiments on such structures, it is possible to make a statement about the allowable limit displacements, which governs the main principles of design criteria. The authors recommend, in addition to the general requirements for design criteria of the maximum displacements and the functional purpose of the structure (expressed in account of the features of the technological process of its operation), also determine the allowable displacements of the soil under the base of a structure with the subsequent allocation of the smallest (critical) values. To determine the limit displacements of the base for the initial stages of design, it is proposed to use the data of experimented stamp tests, which were conducted in the similar soil environment. As a criterion for determining the maximum settlement, it is proposed to consider the time of appearing the phase of plastic deformations in the ground soil.

1. Introduction
Infilled shells are often implemented for both offshore and onshore construction and operations worldwide. A shell is a thin-wall structure (steel or reinforced concrete) with an internal filler, which is usually a soil with specified physical and strength characteristics. Shells of large diameter can be used in any hydrological conditions and practically on any ground of the base (except for weak silts of high power and clays of flowing consistency). In these structures, the outer thin-wall shell acts as a retainer of the inner soil filling, which occupies most of the entire structure. Classification of these structures depends on the type of their functional purpose.

Examples of the use of these structures can be [8]: port hydraulic structures of large diameter shells (mooring, fencing, bank protection, etc.); load-bearing structures of transport culverts, crossings, foundations of bridges (figure 1), underground structures, etc.; retaining walls in industrial, civil transport construction from large and small pieces filled with soil shell elements (figure 2); the construction of foundations of buildings and structures in which the shell serves to ensure the strength and stability of the soil filling the ground, as well as pile foundations.
The most significant issue in the design of shell structures that work as gravity structures is the calculation of settlements and especially irregularities that cause a tilting of the structure.

The aim of research is to identify the most crucial criteria for determining the limit displacements and justify the need for their maximum permissible values for the offshore gravity structures.

Such criteria are determined by the following: firstly, the general requirements for structures based on their type in accordance with the standards and recommendations; secondly - requirements for limit displacements, because of the technological component of their design project; thirdly - the requirements, determined on the basis of the bearing capacity of the foundation soil.

To complete a proper design of an Infilled shell as a structure, the authors defined a sequence of tasks: analysis regulatory requirements and technical recommendations in terms of determining the maximum displacements of the structure; determination the necessary input data for the calculation based on the bearing capacity of the soil base; calculation of an example to evaluate the preliminary values of limit displacements using the experiment data (analogues) and compare them with the values determined by the standard requirements of the manufacture process on a structure; present an adequate illustration of the possibility of determining the maximum loads based on the obtained maximum allowable displacements. This sequence determines the step-by-step procedure for determination the maximum displacements, taking into account the criteria listed by the authors.

Based on the review, the authors propose the following design methods: the limit values are partially normalized, partly calculated, based on environmental conditions of the construction process. In that case, standard documents provide general requirements for such structures (preliminary assessment), on the other hand, project compliance with technological requirements (displacements that are inadmissible in accordance with the mode of operation of the superstructure equipment), and the calculation of maximum permissible displacements in accordance with specific soil base conditions. Typically, designers consider only first two stages, neglecting the third criteria, because of the necessity to perform the stamp experiment.

2. Principles of the determination of displacements for Infilled shells

The general displacement of a structure in the soil can be represented by three components: vertical displacement, horizontal displacement and tilt. Resistance forces and moments against tilting vary in magnitude depending on the specific gravity, the coefficient of friction of the soil, the Young's modulus of elasticity and the Poisson's ratio [9]. Depending on the types of structures and schemes for calculating displacements, different values of the Young's modulus for the soil are adopted. For the initial values, the modules are determined using compression tests or field experiments on stamps. A characteristic feature of structures from shells of large diameter, which distinguishes them from other gravitational structures, is the presence of local deformations (settlements and tilting of the shells), due to the compression of the internal backfill. The magnitude of these can be up to 30% of total deformations of the shell [3].
The study of the physical picture (figure 3) of the interaction of the shells with the soil of the base and the internal backfill has denoted that the general deformations of the shells $\Delta_0$, including settlement, horizontal displacements, and the slope angle, are determined from three main components under the action of real construction and operational loads [4]:

$$\Delta = \Delta_1 + \Delta_2 + \Delta_3$$  \hspace{1cm} (1)

where $\Delta_1$ – settlement of a shell as a stamp under the effect of all vertical loads from the action of the upper structure and the filling of the soil to the design mark and frictional forces from the lateral soil pressure and operational loads, m;

$\Delta_2$ – settlement of the shell from the rotation, caused by the action of the moment from the upper structure on the shell and with horizontal displacement of the shell from the horizontal operating loads and active soil pressure, m;

$\Delta_3$ - shell settlement from reverse rotation arising from the action of the operational load of the rear face of the shell, m.

![Figure 3. Components of the shell displacement: $\Delta$ - uniform settlement of the soil base and structure, $\Delta_h$ - horizontal displacement of the structure, $\omega$ - tilt of the structure.](image)

Calculation of the displacements of a structure could be done using the formulas given in codes and standards for design of offshore structures. Calculated displacements (figure 3) should not exceed limit values established by standard documents, which depend on the type and purpose of the infilled shell structure [3, 5, 8]. In order to limit displacements of the structure in terms of its proper operation, the following conditions must be satisfied:

$$\Delta \leq \Delta_{lim} \hspace{1cm} \Delta_h \leq \Delta_{h,lim} \hspace{1cm} \omega \leq \omega_{lim}$$

Where $\Delta_{lim}$, $\Delta_{h,lim}$, are the displacement limits and $\omega_{lim}$ is the limit of the tilt, set by the design of the facilities, under which normal operating conditions are not violated [3, 4].

3. Determination of the limit values of displacements for Infilled shell structures

3.1. General requirements

Limit values of joint deformations of the foundation soil and the structure are determined by the technical conditions for designing specific types of hydraulic structures, based on the need to comply with: technological requirements for deformation of the structure, including requirements for normal operation of equipment; requirements for strength, stability and crack resistance of structures, including the overall stability of the structure.
Particularly for mooring structures [1]:

$$\Delta_{lim} = 0.2 \text{ m;} \Delta_{h,lim} = 0.05 + 0.08 \text{ m;} \quad \omega_{lim} = 0.009.$$ 

For retaining structures:

$$\Delta_{lim} = 0.4 \text{ m;} \Delta_{h,lim} = 0.05 + 0.08 \text{ m;} \quad \omega_{lim} = 0.015.$$ 

The requirements for the movements of the cofferdam structures are given in table 1.

| Type                      | Unit | Limit value |
|---------------------------|------|-------------|
| Uniform vertical displacement | m    | 0.2         |
| Horizontal displacement   | m    | 0.8         |
| Tilt                      | -    | 0.008       |

For determination of the limit values of displacements, it is necessary to take into account: the allowable difference between the settlement and horizontal displacements of the structure, the seals of the joints between the shells; allowable difference of the settlements of adjacent shells according to the conditions of their normal operation; allowable deformations of the railways (in this case displacement, since calculation of the strength of the railways is not carried out) for reloading equipment installed on the structure.

The maximum permissible rotation can vary from 1/2000 to 1/300 to prevent the emergence of a second limit state in the construction. The maximum rotation of 1/500 is acceptable for many structures. The rotation that can cause the limiting state is about 1/150÷1/100 [11].

Repeats are replaced by synonyms. It is necessary to distinguish the deformations of the structure during the construction period and the deformation during the operational period. Comparison with limit values should be made only for deformations arising during the operational period. Deformations arising in the construction period should be determined to assess the possibility of neutralizing them in the construction of the superstructure.

3.2. Technological requirements

Based on the functional purpose of a cofferdam, its limit values of the displacements could be defined by scenario where displacements need to meet requirements of the superstructure normal operation and maintenance.

In case of the use of an infilled shell as a cofferdam structure with an operating crane over it, limit states of the shell are dictated by the requirements by the specific crane manufacturer. Therefore, governing limit values of the offshore structure displacements would be established by a particular design for the operating superstructure. For cranes the most crucial parameter is tilting, therefore the angle of the slope of a shell needs to meet the requirements for this crane in normal operation. Tilting of a crane may be caused by settlement in the soil supporting the structure and bearing the dead and live weights of the equipment. Settlements can cause structural damage to the equipment such as cracks, fractures, and complete failure. Furthermore, tilting caused by settlement in the soil can cause overturning of the equipment that may result in damage to the crane and surrounding equipment. Even though the allowable settlement, expressed as displacement, tilting degrees or tilting moments, are particular to each crane, a guideline for allowable settlement of soils for the use of crane rails is given in [12] as $0.003l$, which is a conservative figure, where $l$ is defined as the distance between adjacent columns of the railway track that settle at different amounts, or between any two points that settle differently. The maximum allowable value of the vertical displacement along the path are taken by 12 to 24 mm depending on the soil base type [7].
As an example, the authors cited the case of using a portal crane LPS 120 with a lifting capacity of 42 tons and a boom of 30 meters. The distance between the rails of the crane track is 9 meters. It could be concluded, that the limit value of settlement for a shell structure, taking into account the allowable tilt and uniform settlement of the soil base along the web, from 39 to 51 mm.

3.3. Calculation of the limit displacements

In case there are no requirements for the superstructure, the design displacements should be based on code limits. In the Russian code [6], the maximum horizontal displacements of the structure should not be more than \(0.75u_{\text{lim}}\), where \(u_{\text{lim}}\) is the horizontal displacement of the structure, which corresponds to the attainment of the ultimate equilibrium of the "structure-soil base" system along the planar shear and determined by the formula:

\[
u_{\text{limA}} = \frac{\nu_{\text{limst}}}{2} = \left(\frac{A}{A_{\text{st}}}\right)^{1-n_i}
\]

(2)

where \(u_{\text{limst}}\) – displacement of the stamp; \(A_{\text{st}}\) – area of a stamp; \(A\) –foundation area; \(n_i\) – the parameter determined from the results of tests of the \(i\)-th layer of soil by two punches of different areas \(A_1\) and \(A_2\) under the same load by the formula:

\[
n_i = 1 - \frac{2\log(\Delta s_{1,i})}{\log(A_1/A_2)}
\]

(3)

where \(\Delta s_{1,i}, \Delta s_{2,i}\) – increments of dumping of stamps with areas \(A_1\) and \(A_2\) from additional pressure from the test results of the \(i\)-th layer. In the absence of these stamp tests, the following values of the parameter \(n_i\) for soils are allowed:

| Type of soil               | \(n_i\)   |
|----------------------------|-----------|
| Dusty-clayey glacial       | 0.1 – 0.2 |
| Other silty-clays          | 0.15 – 0.3|
| Sand                      | 0.25 – 0.5|

For more substantiated determination of the limit values of the structure displacements made from Infilled shells, it is advisable to carry out stamp tests aimed at determining the working conditions of the soil. In the absence of such tests and at the initial stages of design, it is possible to use data from studies with similar ground-soil conditions with a certain degree of approximation (figure 4).

Onwards is an example of calculation of the limit displacements based on stamp experiment, that have been taken from [2]. Using the formula (2) it is possible to make an evaluation of the case mentioned in [13] (figure 5), where numerical model of infilled shells was calculated with the use of software PLAXIS 3D with the properties of the structure (table 3):

| Specification            | Unit   | Value  |
|--------------------------|--------|--------|
| Specific weight, \(\gamma\) | kN/m\(^3\) | 78.5   |
| Elastic modulus, \(E\)    | kN/m\(^2\) | 2.1x10\(^8\) |
| Poisson’s ratio, \(\nu\)  | -      | 0.28   |
| Diameter, \(D\)           | m      | 10     |
The soil parameters of the model correspond to sand soil, so it is possible to calculate assumed limits of displacements for this situation. Parameters of the stamp are taken from [2], where the diameter of the stamp is 3 m and maximum displacement is 14 mm (figure 4), which corresponds to the start of the appearing of zones of plastic deformations in the soil. In result:

\[ u_{\text{lim}} = 14 \cdot \frac{\pi \cdot (5000)^2}{\pi \cdot (1500)^2}^{1-0.25} = 34.54 \text{ mm} \approx 35 \text{ mm}. \]

![Figure 4. Applied load versus the shell settlement [2].](image)

![Figure 5. Diagram of shell top behavior under pressure [13].](image)

4. Results
In the paper, based on a review of the number of sources, presented the criteria for determining the maximum allowable displacements for hydraulic structures of gravitational type, made from Infilled shells. As an example, in this work was analyzed and calculated the maximum allowable settlement for a mooring structure installed on a compliant soil base, which ensures the normal operation of the gantry crane mounted on it. For proper definition of the limit values of deformations (displacements) (see table 4) for structures made from Infilled shells were considered: general requirements from the code design, technological requirements for normal operation of the crane above and allowable settlement, determined by calculation based on the bearing capacity of the soil-base. The results of the calculation are summarized in table 4.

**Table 4. Calculation results.**

| Design criteria                                      | Sources of definition   | The maximum allowable settlement of the structure $u_{\text{lim}}$, mm |
|------------------------------------------------------|-------------------------|-----------------------------------------------------------------------|
| General requirements                                 | [1, 3, 4, 5, 6]         | 200 ± 280                                                            |
| Technological requirements (superstructure operations) | Crane passport and [7]  | 39 ± 51                                                              |
| Limit deformation (displacement) of the soil-base    | [8]                     | 35                                                                   |

From the example above, it could be seen that in certain situations, in addition to the requirements for ensuring the normal operation of above equipment, the governing criteria for a limit value of shell displacement may be the bearing capacity of the soil-base. Since the indication of certain
displacements of the soil-base could tell about appearance of zones of plastic deformation under the structure.

For inverse problem, the value of limit allowable displacement could provide useful data for determination of the maximum permissible load on the considered structure. For example, based on the results of a study of the numerical model presented in figure 5, it is possible to determine the load corresponding to the maximum allowable displacement (settlement) of the shell. For the given case, when the resultant is conditionally applied concentrated to the top of the structure, the maximum permissible load is about 1600 kN.

5. Conclusion
The work presents a brief overview of the use of infilled shell structures and the basic failure mechanisms of the structure-soil system. The criteria for determining the values of maximum allowable displacements are viewed by three scenarios: on general requirements for structures in accordance of its type; technological requirements for ensuring the normal operation of the above equipment; based on a performance of the soil-base interactions. For the example, the limit value of displacement was determined for all scenarios. Calculation results showed the capacity of establishing critical values of limit displacements proceeding from the inadmissibility of plastic deformations of the foundation soil. The considered sequence of steps for determination of the limit displacements of structures was studied using the results of die tests, which showed that it could be efficiently applied at the preliminary design stage. Further research in this area can be aimed at the adaptation and development of test methods that regulate the shape and dimensions of the stamp, depending on the conditions of support of the structure under consideration on the base: from the shape of the foundation and the working conditions of the soil base of the structure.

6. References
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