Classification of Infilled Shells Structures Considering Soil-Construction Interaction

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Abstract. The paper examines retaining structures consisting of thin shells filled with soil or other material (in a varying degree providing structural integrity), keeping the soil from failure and sustaining the complex of technological loads. Filled shells structures serve as a constructive base for retaining structures and are used in various construction areas (industrial, transport, hydraulic engineering). The technique is proposed which allows to determine structural design model at an early design stage considering the key initial design parameters: overall dimensions of the structure, acting loads and the soil base properties. Based on the proposed ratios an example is given of the structure classification and the design model choice depending on its dimensions, depth of embedding and the magnitude of soil base design resistance. Extreme principal dimensions ratios of the structure are shown at which there is a need of fixing the structure in the soil, dependencies for determining setting depth are given.

1. Introduction

Depending on the purpose of the structure, the dimensions and shape of the filled shells may be different. The structure function, expected loads and desired site conditions besides the material and structure dimensions also determine the pattern of structure - base interaction. For example, the so-called major diameter shells with the scope of diameter/height ratio $D/H$ of 0.7 – 1.0 and more [3, 5, 6] are massive structures and transfer the load on the base mainly through the bottom, while there is either no fixing the structure in the soil or it does not produce significant confining forces ensuring the structure stability on the base. Sheet-pile walls, shell pile structures and other rod-shaped elements - on the contrary, maintain their design position mainly due to binding in the soil, and the fraction of load transferred through the base is insignificant. Between these extreme positions, depending on the design conditions, various design models can be accepted for calculation, differing by specified dimensions of the shell and the rate of its embedding into the base soil (figure 1).

The choice of calculation technique and the procedure of further design of the structure largely depend on the pre-accepted design model of structure – base interaction [4 ÷ 10]. Basic dimensions of the structure ($D; H$) can be assigned for checking calculation based on the functionality of the structure and the construction site conditions taking into account the desired construction technology.

Based on the stability conditions, in case of eccentric loading as the dimensions $D/H$ ratio decreases, there is a need to embed the structure into the base soil $d$. Further we propose the classification of eccentrically loaded filled shell structures based on the base soil involvement in
ensuring stability considering the given bearing capacity of the base. The classification will permit to clarify the pre-selected design model of the structure considering not only the specified dimensions of the structure and technological loads, but also the mechanical and physical properties of the soil base.

2. Classification of structures

To determine the classification characteristic, it is proposed to consider general design model of the structure (figure 2, a) of shells with soil infill (in) with diameter (section width) \( D \), supported by soil base (1), providing soil backing up (bf) of given height \( H \) and sustaining a complex of loads \( (q, F, G...) \), forming bending moment \( M \) at structure bottom level. Structure weight \( G \) is formed mainly by the soil held in the shell. The bottom end of the structure is embedded into soil on depth \( d \), equal to the cut through base soil layer thickness (2).

As a criterion for classification, it is proposed to introduce \( k_c \) parameter that reflects the fraction of stabilizing moment at structure bottom level provided by structure dead weight \( M_{y\theta(G)} \):

\[
k_c = \frac{M_{y\theta(G)}}{M_{y\theta(P_p+G)}}
\]  

(1)

where \( M_{y\theta(P_p+G)} \) is overall stabilizing moment at structure bottom level considering the action of passive reaction force \( P_p \):

\[
M_{y\theta(P_p+G)} = M_{y\theta(G)} + M_{y\theta(P_p)}
\]  

(2)

Figure 1. Changing the conditions of fixing the structure on the base depending on the dimensions of the structure

Figure 2. Structure design model
a – vertical cross-section; b – dead weight application arm.
Depending on \( k_e \) value the preliminary design model of filled shell can be accepted as for the massive (gravity) structure, in which dead weight contribution to providing stabilizing moment is between 80 and 100% \((1 \geq k_e > 0.8)\); in the range of \(0.8 \geq k_e > 0.2\) the shell can be referred to as semi-massive (semi-gravity) structure, and with value of \( k_e \leq 0.2\) the filled shell is subject to rules for calculating thin fixed walls, for which soil strength along the bottom is almost neglected.

At the same time, the value of dead weight stabilizing moment \( M_{\text{yol}(G)} \) is determined through the following reasoning. When the structure is inclined to the side opposite to the load, the turning point shifts deeper into the bottom. The arm \( l_G \) of structure dead weight \( G \) action is subject to the condition of exceeding the acting pressures along the structure bottom \( \sigma_{\text{max}} \) the value of ultimate pressure \( p_0 \) (figure 2, b):

\[
l_G = \frac{D}{2} - \frac{(\sigma_{\text{max}} - p_0)D}{\sigma_{\text{max}} - \sigma_{\text{min}}}, \text{ at that } l_G \leq \frac{D}{2}
\]

Here \( p_0 \) is determined based on V.V. Sokolovsky’s equation [1, 2]:

\[
p_0 = (\gamma_n d + c_n \cot \varphi_n) \left( \frac{1 + \sin \varphi_n}{1 - \sin \varphi_n} \right) - c_n \cot \varphi_n
\]

Here \( \gamma_n, \varphi_n, c_n \) are respectively specific weight, angle of internal friction and specific cohesion of the corresponding layer (figure 2, a). In this case the value of pressure along the structure bottom \( \sigma_{\text{max,min}} \) per 1 running meter of the structure length (from calculation plane) is determined taking into account the acting loads \( (q, F) \) in figure 2):

\[
\sigma_{\text{max,min}} = \frac{G}{D} + \frac{6M_{\text{onp}}}{D^2}
\]

Here \( M_{\text{onp}} \) is tilting moment at the bottom level of the structure per 1 running meter of the structure (equation (9)).

Next, \( M_{\text{yol}(G)} \) is determined through the equation:

\[
M_{\text{yol}(G)} = Gl_G
\]

Stabilizing moment from the action of soil passive reaction force is determined through the equation \((\text{kNm/run.m.})\):

\[
M_{\text{yol}(Fp)} = \gamma_n \frac{d^3}{6} t g^2 \left(45 + \frac{\varphi_n}{2}\right)
\]

As an illustration of the process of categorizing a particular structure to one of the three groups mentioned above conditioning further design procedure, the dependencies are given of classification parameter \( k_e \) on embedding value specified support height ratio \( d/H \) at equal specific weight values \( \gamma_n = 20 \text{ kN/m}^3 \), value \( p_0 = 400 \text{ kPa} \) (at the bottom level) and various ratios \( D/H \) (figure 3).

Thus, any structure of specified dimensions with known mechanical and physical characteristics of the filling, the base and specified loads can be pre-assigned to the design groups of massive (gravity), semi-massive (semi-gravity) structures or to the group of thin fixed walls.

3. Determining the design model

Preliminary dimensions of the filled shells (diameter \( D \), embedding depth \( d \)) structure (figure 1, figure 2), with the given support height \( H \) at the action of additional loads \( (q, F, \ldots) \) are proposed to determine from stability conditions on the base soil considering soil strength \( p_o \) along the structure bottom using unified safety factor \( k_e \) method:
Taking as preliminary the value of $k_r$ depending on the purpose of the structure $(1.0 \div 1.5)$.

$$k_r = \frac{M_{yp(P_r+G)}}{M_{op}}$$

Fig. 3. An example of determining classification parameter $k_c$.

Stabilizing moment is determined through the equations given in the previous section (equations 2, 6, 7), the tilting moment is determined: $(kNm/run.m.)$

$$M_{op} = q_{bf} \frac{H}{2} (\frac{H}{3} + d) + q_d H (\frac{H}{2} + d) + \frac{d^2}{6} (q_2 + 2q_{bf}) - FH_1$$

where $q_{bf}$, $q_2$ and $q_d$ are values of lateral soil pressure at the filling layer bottom level $bf$ (figure 3), the cut-through layer 2 and from tightening weight $q$ on the filling surface:

$$q_{bf} = \gamma_{bf} H \lambda_{u(bf)}; q_2 = q_{bf} + (\gamma_2 d \lambda_{u(bf)}); q = q \lambda_{u(bf)}$$

Here $\lambda_{u(bf)}$ is active soil pressure ratio of the corresponding layer approximately taken as $t g^2 (45 - \frac{\phi}{2})$ the corresponding value of soil internal friction angle of $\phi_{bf}$ and $\phi_2$.

These equations permit determining the necessity to embed the structure into the base $d$ and/or change to arranging anchoring system at specified values of base soil properties factors and the presence of additional loads ($q$, $F$, ...) provided that the structure is inspected by standard methods for displacement resistance [10]. An illustration of the example for determining the structure principal dimensions limit relation $D/H$ which ensures the stability of the structure on the base without embedding (at various ultimate pressure values $p_0$), for the specified support height $H$ is shown in figure 4.
Figure 4. An example of determining the $D/H$ limit relation for various base soils.

The required value of shell embedding $d$ into the soil at specified dimensions $D$, $H$ can be determined from stability condition (8) using expressions (2÷7, 9, 10) allowing to consider the base bearing capacity, properties of the cut-through soil and the acting loads.

4. Conclusion

The paper provides classification of filled shell structures made based on base soil involvement stabilization of the structure. The classification using the proposed criterion (reflecting the proportion of stabilizing moment at the structure bottom level provided by the dead weight of the structure) levels the structure as massive, semi-massive structures or thin walls which allows to clarify the preliminary choice of design model for the structure. At the same time, not only the specified dimensions of the structure and technological loads are taken into consideration, but also mechanical and physical properties of soil base. The equations are listed allowing or the structure of specified dimensions and taking the given loads to estimate the necessity of embedding into the base soil and determine the required value of embedding considering the interaction of embedded portion of the structure with the surrounding soil.

5. References

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