Classification of Shell Constructions with Infill

N Ya Tsimbelman¹, N M Malkov², T I Chernova³, M A Selivanova⁴

¹candidate of engineering sciences, associate professor, engineering school, Far Eastern Federal University (FEFU), Sukhanov St., 8, Vladivostok, 690091, Russia.
²candidate of engineering sciences, associate professor, engineering school, Far Eastern Federal University (FEFU), Sukhanov St., 8, Vladivostok, 690091, Russia.
³senior lecturer, engineering school, Far Eastern Federal University (FEFU), Sukhanov St., 8., Vladivostok, 690091, Russia.
⁴assistant, engineering school, Far Eastern Federal University (FEFU), Sukhanov St., 8., Vladivostok, 690091, Russia.

E-mail: selivanova.ma@dvfu.ru

Abstract. Filled shell structures are used for various engineering tasks in hydraulic engineering. Made of various materials, the shells retain the inner filler as a conserved medium or as a structural material that ensures the performance of the entire construction. The article provides a classification of constructions made of shell structures. A system of constructive solutions for filled shells is proposed, in which the material and method of forming the shell, the method of supporting the shell on the soil, the configuration of the transverse and longitudinal sections of the shell, as well as the presence of additional structural structures are adopted.

1. Introduction
Filled shell structures are used for various engineering tasks in hydraulic engineering. Made of various materials, the shells retain the inner filler as a conserved medium or as a structural material that ensures the performance of the entire construction.

The work considers only constructions in which the filler is not a conserved medium, but has the function of a structural material, although in most cases the operating conditions of shells with a filler used in various constructions make it possible to set and use general approaches to the calculation and modeling of a structure based on the provisions of the theory of plates and shells, dependences of the theory of limit equilibrium and limit stress state.

2. System of constructive solutions for filled shell
Existing and possible design solutions for shells with a filler used in projects of hydraulic structures can be systematized in order to make a reasonable choice based on several criteria. The main signs of systematization are the following:

- material and method of forming the shell;
- way of supporting the shell on the ground;
- configuration of the cross-section of the shell;
- configuration of the longitudinal section of the shell;
availability of additional constructive structures.

Shells with a filler are used to solve various engineering problems in hydraulic engineering, primarily in the construction of berthing structures (embankments, bollards, piers) and protective structures (breakwaters and cutwaters).

2.1. Shell material and forming method

The material from which the shell, planned for use for the needs of hydraulic engineering construction, can be made, must have high strength indicators, resistance to aggressive media, durability corresponding to the category of constructions importance laid down in the project. As a result, the shells are usually made of reinforced concrete and steel [1].

According to the method of formation, reinforced concrete shells are divided into prefabricated and monolithic ones (figure 1). The first of these groups includes structures formed by separate rings mounted on top of each other, as well as shells assembled from separate flat or curved vertical slabs (polygonal shells). Monolithic reinforced concrete shells are formed in two main ways: by spraying a cement-sand mixture onto the inner surface of the formwork ("gunite concrete" method), and by stage-by-stage laying of the matrix in the outer shield and inner sliding metal formwork.

Steel shells can be divided into two main groups according to the method of formation:

- solid steel shells;
- shells made of sheet pile walls forming closed contours of various shapes.

Solid steel shells are formed by the method of rolling according to the technology of tanks construction in accordance with Departmental building codes (DBC) 311-89 [2], as well as by the methods of sheet and sectional assembly (figure 2).

![Figure 1. Fragment of a monolithic shell [3, 4].](image1)

![Figure 2. Manufacturing process of a metal shell (sheet-by-sheet assembly) [5].](image2)

![Figure 3. The process of shell forming by immersing individual piles using a conductor [6].](image3)

Depending on the planning conditions and design requirements, the sheet pile shell (figure 3) is divided into three main groups:

- shells - diaphragms (figure 4) are arranged by connecting separate rectilinear segments or cylindrical arches;
- cylindrical shells (figure 5) (cylindrical or semicircular shells connected by curvilinear elements). This type of construction is used for structures with a height to diameter ratio equal to D/H = 0.7÷1.0;
- shells made of sheet pile, that have the shape of a clover leaf in plan, (figure 6) are made of four curved segments, fastened together and reinforced with a transverse diaphragm.
Figure 4. Scheme of a protective structure made of shells-diaphragms in plan.

Figure 5. Scheme of a protective structure made of cylindrical shells from groove in plan.

Figure 6. Scheme of a protective structure made of sheet pile shells having a clover leaf shape in plan.

The shells standing in a row are connected by arches. The difference in levels between adjacent sections of shells during filling with soil does not exceed 1.5 m. This type of shell is very difficult to design and is used for large width structures.

2.2. Constructive solution for supporting the shell on the ground

The adopted constructive solution for supporting the shell on the base soil is one of the main factors that determine the design parameters of the filled shell structure: its dimensions, dimensions of elements, material, layout of the shells in plan, etc. A classification of the filled shells according to the degree of depth of the shell in the base soil is following.

In accordance with this feature, the shells can be divided into freely supported (gravitational, without deepening into the base), partially recessed in the ground and completely recessed ones (table 1).

| Criterion | Constructive solution | Solution options | Scheme | Construction |
|-----------|-----------------------|------------------|--------|--------------|
| Without deepening into the base | directly on the soil | - | | protective structures; berthing facilities; fencing of artificial territories, islands; monoblocks; foundations of structures for navigation |
| | leveling preparation | - | | |
| | rubble base | unrecessed | | |
| | | partially recessed | | bucket foundations; suction caissons |
| Partially recessed in the base | | fully recessed | | |

Table 1. Classification of shell structures by the degree of penetration into the base.
2.3. Shell cross-section configuration

The shape of the cross-section of the shell is determined, first of all, by the magnitude of the expected loads and the characteristics of the effects on the structure, which, in their turn, are determined by the purpose of the construction and the conditions of its building and operation. Along with this, the technological capabilities of the contractor are taken into account, as well as the economic efficiency of the decision made. The main basic cross-sectional shapes are accepted for preliminary calculation, which can be changed or adopted in a more complex combination during subsequent verification justifying calculation.

The basic cross-sectional shapes of filled shells include four basic shapes (table 2), three of which (circular, oval and clover leaf) form cylindrical shells, and the fourth (regular polygon shape) forms a polygonal shell.

Table 2. Basic shapes of shells cross-sections.

| Name                             | Scheme | Sign                        | Material                  |
|----------------------------------|--------|-----------------------------|---------------------------|
| Circular (cylindrical shells)    |        | D - outer diameter, m       | steel, reinforced concrete|
|                                  |        | t - shell wall thickness, m |                           |
| Oval (segmental) (cylindrical shells) |        | D - outer diameter, m       | steel, reinforced concrete|
|                                  |        | t - shell wall thickness, m |                           |
| Regular polygon shape (polygonal shells) |        | D - outer diameter, m       | reinforced concrete        |
|                                  |        | t - panel thickness, m      |                           |
|                                  |        | n - number of panels, pcs.  |                           |
| Clover leaf shape (cylindrical shells) |        | D - outer diameter, m       | steel                     |
|                                  |        | t - shell wall thickness, m |                           |

Using the listed basic shapes, the shapes of horizontal sections of extended constructions can be compiled (figure 7,8,9) using the example of the layout of the basic shape of a circular outline. The layout can be performed in one row and in two or more rows, depending on the magnitude of the expected loads, engineering and geological conditions of the site, technological loads and other factors.

Figure 7. The combined forms of the cross-section of the shells in one row: a - close; b - with a seam; c - with connecting arches; d - with insert.

Figure 8. The combined forms of the cross-section of the shells in two rows: a, b - double shells; c - shielding shells.
2.4. **Configuration of the longitudinal section of the shell**

According to the shape of the longitudinal section, the filled shells can be divided into two main groups: constant in length (figure 10 a-c) and variable along the length of the section (figure 10 d-e).

Shells of constant cross-section can be solid or composed of separate elements (as a rule, rings - figure 10 a). A longitudinal section variable along the length of the shell is used in order to save material (reducing the size of the section to the top of the structure - figure 10 d, e), or based on the characteristics of the base: in case of discordant bedding of rocks (a significant drop in the roof of the bedrock within the dimensions of the structure), or when protecting weak surface layers from erosion (for coastal structures) - figure 10 f.

2.5. **Availability of additional structural structures**

The main additional devices (table 4) in the structures of filled shells, as a rule, are created in order to increase the safety factor and stability of the structure.

**Table 3.** Constructive techniques for increasing the stability margin.

| Structures location | Structures | Scheme, example | Effect | Sources |
|---------------------|------------|-----------------|--------|---------|
| Pier table          | Unloading platform | ![Unloading platform](image) | Reducing active soil pressure, creating a reverse moment | [7,8,4] |
In this case, structural elements providing additional rigidity and strength of the shell are introduced into the structure mainly temporarily, at the stage of mounting the shell to the stage of forming the inner filler. Additional structural structures providing an increase in the overall stability of the structure are oriented to (table 4):

- achievement of the effect of reducing the active soil pressure and creating a reverse moment by introducing unloading platforms in the pier table part of the construction;
- the introduction of additional supports in the design scheme of the construction by installing anchors in the pier table part of the construction;
- achievement of the effect of the inverse moment and stress distribution along the foot of the construction by introducing support plates of various shapes in the supporting part of the structure into the construction.

The first two of these directions (the pier table part) are quite well developed in the practice of calculating and designing gravity retaining constructions. Additional structures installed in the supporting part of the construction mainly provide additional holding moment and passively influence the distribution of stresses in the thickness of the construction foundation. At the same time, the tasks of ensuring a uniform distribution of stresses in the thickness of the base of the filled shell, as well as preventing the end from cutting through the base by the end of the thin shell under eccentric loading, remain relevant and cause the appearance of new types of additional structural structures.

3. Conclusions
A system of constructive solutions for filled shells is proposed, in which the material and method of forming the shell, the method of supporting the shell on the soil, the configuration of the transverse and longitudinal sections of the shell, as well as the presence of additional structural structures are conceived.

The review of the main design solutions for casing with filler was carried out in view of the urgency of the task of expanding the capacity of ports and the construction of new coastal infrastructure facilities, in connection with the need to develop shelf hydrocarbon fields. In the conditions of relatively weak compressible soils of the shelf zone base of the Arctic seas [11], the
construction of specially prepared rubble bases is difficult, and the production and transportation of massive reinforced concrete structures, as a rule, is impossible due to the remoteness of the object. Under these conditions, steel thin-walled shells of large diameter, partially recessed in the basement soil, have significant advantages over other types of load-bearing structures. Due to the relative ease of manufacture, cylindrical shells are the most common type of construction for both solid sheet and sheet pile shells (cells): their use can significantly reduce the time of work, ensure the durability and economy of the structure.

The choice of the shell design that is most suitable for solving a specific engineering problem of building a construction is based on the preliminary analysis of the significant number of factors and in most cases cannot be performed according to a step-by-step typical scheme. The system of recommendations for choosing the optimal design should be built on the basis of taking into account one main and, possibly, several accompanying construction conditions.

4. References

[1] 2019 SP 41.13330.2012 Concrete and reinforced concrete structures of hydraulic structures (Moscow: Standartinform) 82 p
[2] 1990 VSN 311-89 Erection of Upright Cylindrical Steel Tanks With Capacities of 100 to 50,000 Cubic Meters for Storage of Petroleum and Petroleum Product (USSR: TsBNTI Minmontazhpetsstroy) 40 p
[3] Seliverstov V I 1987 Method for calculating deformations of cylindrical steel cells of hydraulic structures (Vladivostok: DVPI)
[4] Levachev S N 1978 Shells in hydraulic engineering (Moscow: Stroyizdat) 168 p
[5] 2020 Information agency "Kaskad-Nakhodka" for LLC "Vostok-TV" 2008 (Access mode: http://kaskad.vtvn.ru/news/964/ )
[6] 2016 Bermingham Foundation Solutions (Access mode: http://www.berminghammer.com/Sir%20Adam%20Beck%20Cofferdam_web.aspx - Project Report: Sir Adam Beck Power Station Cofferdam)
[7] Gurevich V B 1969 River port hydraulic structures (Moscow: Transport) 416 p
[8] Darevsky V E, Romanov A M 2011 Design of structures that ensure the stability of soil massifs (embankments, bank protection, retaining walls, protection against landslides, etc) (Moscow: Master Publishing House) 596 p
[9] Almazov V O, Smirnov G N 1970 Transverse vibrations of a cylindrical shell loaded with a periodic force (Moscow) 86 p
[10] Bimbad G E 1984 Stability of large diameter shells with horizontal anchor (Moscow: MISI)
[11] Melnikov V P, Spesivtsev V I 1995 Engineering-geological and geocryological conditions of the shelf of the Barents and Kara seas (Novosibirsk: Nauka) 195 p