

Unsteady interaction simulation of a large RC shell with heterogeneous soil milieu for a gradually increasing caisson structure

N Perminov

Emperor Alexander I St. Petersburg State Transport University, 9, Moskovsky av.,
St. Petersburg, 190031 Russia

perminov-n@mail.ru

Abstract. Prediction and simulation of large shells construction parameters in heterogeneous soil milieu provided considerable expansion of the rational use area of megapolices underground areas for deep transport facilities and engineering infrastructure. Mega sizes of an RC shell allow creating open underground areas, unique in volumes and deepness. The analysis of massive gravitational fencing shell behavior at its gradual increasing and driving into heterogeneous soil milieu allowed identifying the nature of their non-linear and unsteady one. Unsteadiness of the massive structure interaction processes and soil milieu causes the necessity to create methods for strain-stress behavior control of the system “gravitational large body – heterogeneous host medium” for decreasing aggravating influence of the unsteadiness effect on the lowering process. Due to joint step-by-step implementation of geotechnical and structural calculations a history of the shell-soil milieu interaction processes is modeled and the adaptive control parameters of strain-stress behavior are predicted, thus providing conditions of controlled lowering. The paper demonstrates results of the given concept implementation during the unique underground structures of St. Petersburg sewage system design and construction.

1. General features of the problem under consideration and features of large shell interaction with heterogeneous soil milieu at the stage of its lowering

There is a need to ensure internal integrity of fencing structures with high degree of waterproofness at all stages of their life cycle in order to provide stable and safe operation of large caisson structures.

The existing standards [1] and regulations [2] envisage checking calculations of underground structures to be lowered for the stages of their construction and operation. However, based on this experience one can say, that in the case of large caisson structures it is not enough due to specific conditions of their interaction with a soil bulk and inclusion the effect (factor) of a large scale. Hyper sizes of a shell lateral surface area, which interacts with heterogeneous soil, and its super large weight, which creates a powerful kinetic impulse during instant, often sudden subsidence, cause a beyond-design situation for a caisson structure. Joint actions of these factors stipulate specific non-linear behavior of the structure at lowering as well as the host soil bulk. Due to the large massive structure strength and deformability, its geometric changeability is necessary to calculate not only the final stage of construction but also the whole history of lowering taking into account the history process of shell-soil bulk interaction during caisson lowering and, consequently, the gradual inheritance effect of



stress-strain behavior. These problems could be solved only by tackling non-linear problems, non-linear models and computer non-linear simulation [3-5].

The results' analysis in situ and calculation-experimental works and the comprehensive system data of geotechnical monitoring (Figure 1) of lowering large shells showed the features of their interaction with heterogeneous soil milieu [6]. The geotechnical profile for the monitored facilities is characterized as follows: the upper layer is represented by Quaternary strata down to the depth of 14.0–25.0 m (saturated silty sands of medium density, $E = 11$ MPa, $C = 0$ MPa, $\varphi = 30^\circ$; plastic silty clayey sands, $E = 4$ MPa, $C = 0.01$ MPa, $\varphi = 15^\circ$; liquid-plastic silty sandy clays, $E = 9$ MPa, $C = 0.025$ MPa, $\varphi = 16^\circ$; semi-solid silty sandy clays with gravel and pebbles, $E = 14$ MPa, $C = 0.028$ MPa, $\varphi = 28^\circ$), the lower level represents the bed of dislocated solid Proterozoic clays ($E = 19$ MPa, $C = 0.04 \dots 0.06$ MPa, $\varphi = 18 \dots 21^\circ$).

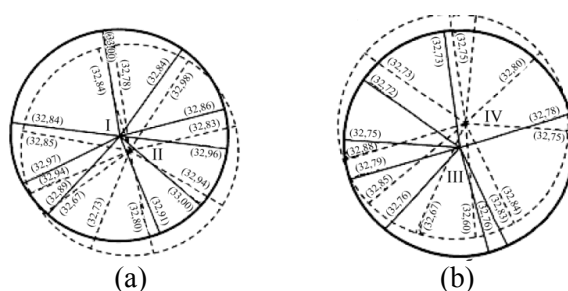


Figure 1. The measurement of a radius R and displacement of the center of circle O during its lowering to a depth H : (a), (b) – respectively I – for $H = 17$ m; II – for $H = 29$ m; III – for $H = 25$ m; IV – for $H = 29$ m; O (I–II) = 0.108 m; O (III–IV) = 0.234 m.

The monitoring identified a very important phenomenon: the peak values of horizontal stresses exceed the calculation values 2.3–2.5 times, and it is observed at deviation of the shell from the vertical axis and changes of its geometry (Figure 1, 2). It can be the reason of the process suspension of lowering the massive shell with a subsequent sudden, conditionally instant drop. Based on the analysis of the graph of lowering (Figure 2 (a)) it can be seen that a value of drop reaches 1.5 m and more. The shell structure takes impact beyond-design loads by creating a powerful kinetic impulse by its drop to the soil bulk of a pit bottom [7], that can cause occurrence of micro cracks in concrete of the structure and inevitably leads to violation of the structural hydro insulation. This phenomenon has been identified after 10–15-year-long operation of the gas and pumping station complex of the water treatment facilities of St. Petersburg [8].

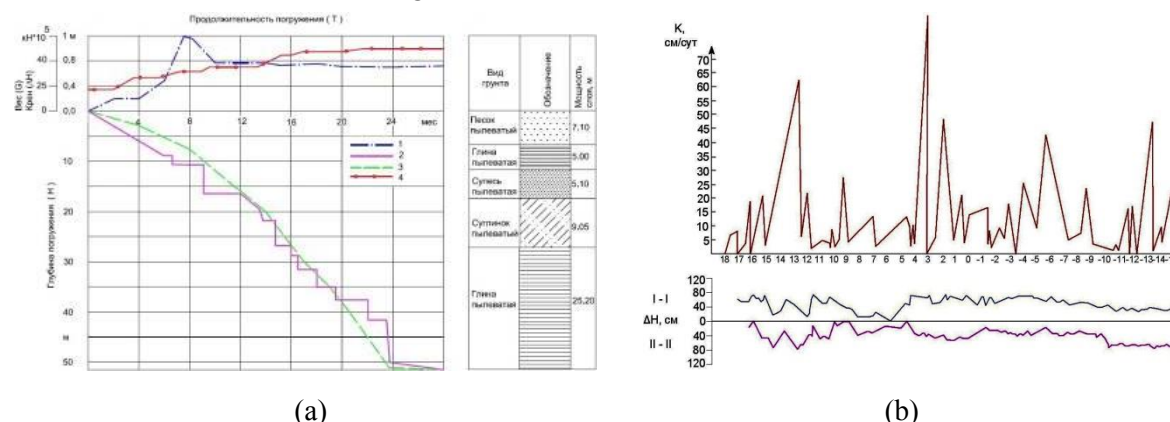


Figure 2. Graphs of shell lowering: $D=51$ m, $H= 53$ m (1 – tilt graph; 2 – an elevation of lower plane; 3 – soil elevation; 4 – increase of shell weight) (a); the diagram of deviation of the shell from the vertical axis (b).

Geo monitoring showed unsteadiness of the external contour of the massive structure interaction processes [9]. Complex, uncontrolled character of the processes during conditionally instant embedment of the shell into the host heterogeneous milieu as well as the environment, that has physical and genetic non-linearity [10], demonstrate the study of shell stain-stress behavior and soil bulk can be carried out only on the computer modeling basis of this process using geotechnical and structural software complexes.

2. The conditionally simulation instant drops of the massive shell during its lowering into heterogeneous soil milieu

The analysis of the caisson structure behavior during its sudden uncontrolled sliding (drop) to the bottom of an open soil cavern from the height 1.3 – 1.5 m with the angles of deviation from the vertical axis 0.5° – 5° was conducted with a help of the software complex Autodesk Robot Structural Analysis Professional [11].

While developing the calculation model (Figure 3) it was considered that the shell structure consists of two cylinders, one stands on the other: the upper cylinder: the external radius $R = 36$ m, the internal radius $R = 30.5$ m, the height $H_1 = 46$ m; the lower cylinder: the external radius $R = 36$ m, the internal radius $R = 30$ m, the height $H_2 = 25$ m. Therefore, the external diameter of the shell was $D = 72$ m, the height of the shell was $H = 71$ m. Concrete grade - B30.

In order to simulate a value of impact force at dropping the shell in the model the cylinder fell from the height $H = 150$ – 250 cm under the action of its own weight with the tilt angle 0.5° – 5° to a flexible soil (green-gray clay: $\varphi = 21^\circ$, $C = 0.04$ MPa, $E = 19$ MPa). A spatial calculation scheme of the shell was modelled: the weight $G = 210000$ tons; the amount of nodes 16944; the amount of volumetric finite elements 12496; the amount of static degrees of freedom 50828; the amount of loadings 27; the acceleration of gravity $g = 9.81$ m/kV.s; the time of drop $t = \sqrt{2 \cdot H / g}$; $\Delta t = 0.30$ – 0.54 s. Due to the tilt angle friction forces were applied in the upper part of the caisson from one side and in the lower part – from the opposite one.

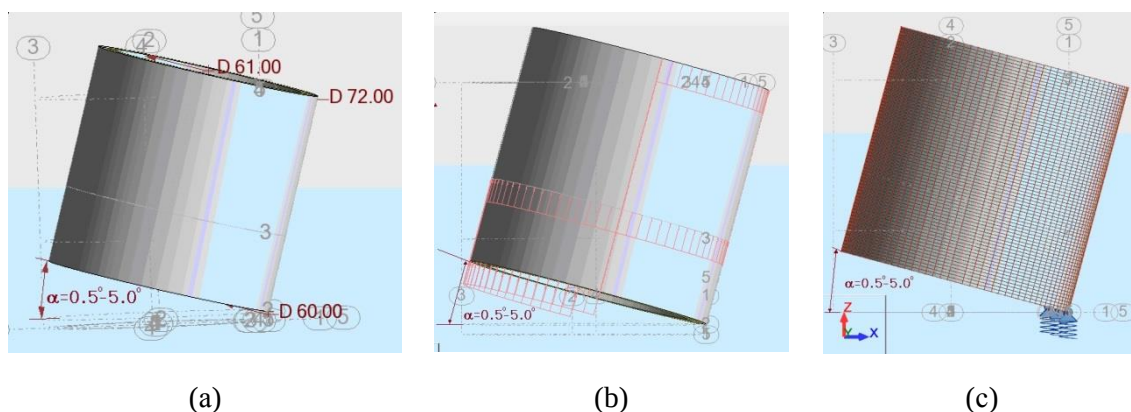
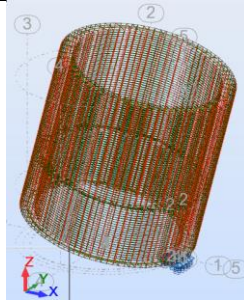
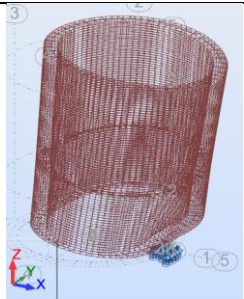
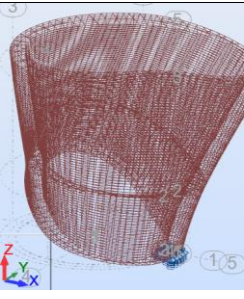
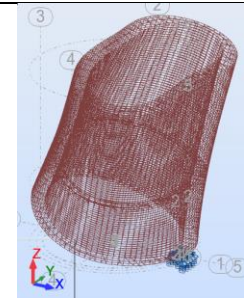


Figure 3. The calculation models schemes of the lowered shell at different angles of its deviation from the vertical axis: static support at tilt (a); drop and sliding at tilt (deviation from the vertical axis) (b), (c).

As the simulation of the drop processes at different angles of the shell deviation from the axis α and falling heights – ΔH was made in quite a large range, table 1 gives only the most typical results, which were taken for the analysis. The total results' calculation table of the motion equation integration for the shell during the drop (falling) at speeds V_Z , V_X , V_Y (cm/s), acceleration A_Z , A_X , A_Y (cm/s²) and displacements U_Z , U_X , U_Y (cm) included 186385 lines.

Based on the simulation results (Figure 4) there were set admissible parameters of the shell spatial location and the ranges of its conditionally instant drops, which provide pre-limit strain-stress behavior of the shell.

Table 1. The simulation results.

	$n^0=0.21$ $\Delta_{\max}^0=0.0\text{cm}$		$n^2=0.56$ $\Delta_{\max}^2=3.1\text{cm}$		$n^4=0.97$ $\Delta_{\max}^4=26.1\text{cm}$
The initial position $\alpha=0.5^\circ$; $\Delta H=0\text{ m}$		Shape 2 Pre-limit strain-stress behavior $\alpha=0.5^\circ$; $\Delta H=1.25\text{ m}$		Shape 4 Limit strain-stress behavior $\alpha=1^\circ$; $\Delta H=1.25\text{ m}$	
	$n^{11}=1.94$ $\Delta_{\max}^{11}=43.5\text{cm}$		$n^{17}=3.68$ $\Delta_{\max}^{17}=62.3\text{cm}$		$n^{22}=8.47$ $\Delta_{\max}^{22}=183.4\text{cm}$
Shape 11 Post-limit strain-stress behavior $\alpha=2.5^\circ$; $\Delta H=1.25\text{ m}$		Shape 17 Post-limit strain-stress behavior $\alpha=2.5^\circ$; $\Delta H=2.5\text{ m}$		Shape 22 Post-limit strain-stress behavior $\alpha=3.5^\circ$; $\Delta H=2.5\text{ m}$	

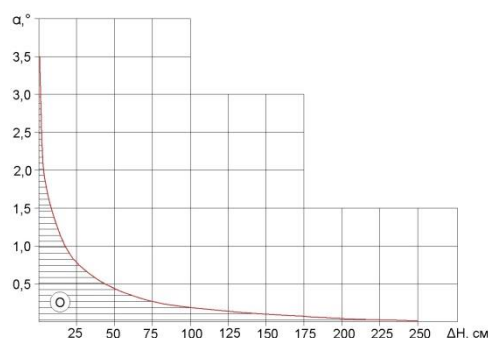


Figure 4. The area of limit admissible values of conditionally instant drops ΔH of the shell, $D=61\text{ m}$, height $H=71\text{ m}$, weight $G=210000\text{ tons}$, at different angles of deviation of the structure from the vertical axis α° (Concrete B30; $\varphi = 21^\circ$, $C = 0.04\text{ MPa}$, $E = 19\text{ MPa}$).

The simulation results show that for the large shell the recommendations of regulatory documents [12] have limited application and are needed to be confirmed via calculative modeling.

3. The controlled regimes simulation of lowering the massive shell into a soil of different strengths using the methods of geotechnology

Taking into account the previous steps' results of modeling, at this stage the geotechnical simulation problem of the process of lowering the shell into the soil bulk in a controlled mode was solved. The geotechnical methods served as external impacts on the "shell-soil bulk" system.

An incremental model of deformation type was used as the calculation soil model for solving the non-linear problem. A stress-strain connection in the model was taken separately for volumetric and shears components of a stress tensor

$$\begin{cases} dS_{ij} = 2G^T \cdot de_{ij} \\ d\delta_{cp} = 3K^T \cdot d\xi_{cp} \end{cases} \quad (1)$$

where dS_{ij} and de_{ij} are increments of stress deviator components and strain tensors, respectively; $d\delta_{cp}$ and $d\xi_{cp}$ are increments of average stress and strain; G^T and K^T - tangent module of shape deformation and volume.

Tangent module of deformation G^T and K^T were approximated according to linear polynomial of the second degree with one variable:

$$\begin{cases} G^T = G(S_{ij}; \delta_{cp}) = A_0 + A_1 \delta_{cp} + A_2 S_{ij} \\ K^T = K(\delta_{cp}) = B_0 + B_1 \delta_{cp} + B_2 \delta_{cp}^2 \end{cases} \quad (2)$$

Approximating dependencies (2) are experimentally substantiated on the example of stabilometer triaxial tests (STT) [1, 2]. The model considers the conditions of loading and unloading according to the following criteria:

$$\begin{cases} \text{loading : } dS_{ij} > 0; d\delta_{cp} > 0 \\ \text{unloading : } dS_{ij} < 0; d\delta_{cp} < 0 \end{cases} \quad (3)$$

In order to fulfill the condition of “loading” tangent module K_H^T and G_H^T were calculated according to formulae (2) in compliance with the current stress-strain behavior. In order to fulfill the condition of “unloading” K_p^T and G_p^T were defined according to other dependencies (4).

$$K_p^T = \text{const}; G_p^T = A_0 + A_1 \delta_{cp} \quad (4)$$

The calculation model parameters A_0 ; A_1 ; A_2 ; K_p ; B_0 ; B_1 ; B_2 were defined based on STT data. The medium-grained sandy soil of the density $P_d=1.65\text{g/cm}^3$ and water content $W=10\%$ was used as the tested soil. All calculations were made using the numerical method of finite elements with a help of geotechnical software “PCK”. The procedure of solving the non-linear problem was reduced to the well-known method of variable rigidity [12]. Due to it, the matrix of rigidity was transformed at each step of the solution in accordance with the current level of stress-strain behavior and orientation of additional loading vector.

Figure 5 (a) shows a characteristic graph of the shell contour displacement to the design position with inclusion of a geotechnical impact on strain-stress behavior of the surrounding soil bulk into the calculation. The results of simulation show (Figure 5 (b)) that rectification of the shell contour displacement almost to the design position (from 32.8 cm to 9.01 cm) allows decreasing an area of distribution and a value of the soil bulk settlement around the shell several times (the area of distribution reduces from 45 m to 9 m; the value of settlement, respectively, from 150 cm to 8 cm).

4. Conclusions

The analysis of behavior of the massive gravitational fencing shell during its gradual increasing and lowering into the heterogeneous soil milieu allowed identifying a number of factors, which characterizes its non-linear behavior in the conditions of joint interaction.

Physical non-linearity is caused by behavior in the elasto-plastic area of the soil bulk, which contacts with the lateral surface, during deviation of the structure from the vertical axis. Geometric non-linearity manifests itself when its geometry changes asymmetrically during instant-stepwise drops of the massive shell.

Unsteadiness of the massive structure interaction processes with the soil milieu as well as itself causes the creating control methods necessity of the stress-strain behavior of the system “gravitational large body – heterogeneous host milieu”.

Due to joint step-by-step making geotechnical and structural calculations a history of the shell-soil milieu interaction processes is simulated, the adaptive control parameters of the strain-stress behavior system, which are implemented with a help of external geotechnical impacts at the stage of construction of the structure, are predicted.

The results of the considered concept are applied at geotechnical support of the unique underground structures of the sewage system's lifecycle of St. Petersburg at construction stage of large caisson shells during simultaneous lowering and increasing of the structure.

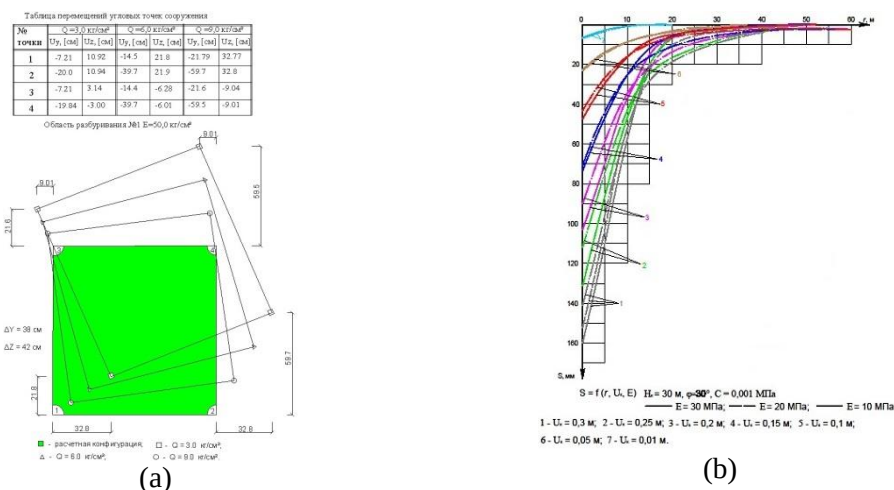


Figure 5. The displacement of the shell contour in continuous milieu: at correction of tilt under the conditions of action of a lateral additional load $Q = 0.3 - 0.9 \text{ MPa}$ (a); the influence of a value of the shell contour displacement U_x on settlements of the soil surface at correction of tilt (b).

References

- [1] Ilichev V A and Mangushev R 2016 *The Reference Book of a Geotechnical Engineer. Soils, Foundations and Underground Structures* (Moscow: ASV Press) p 1034
- [2] *Structures of Industrial Enterprises* RF Set of Regulations 2012 SR 43.13330.2012 p 101
- [3] Perminov N A, Zencov V N and Perminov A N 2013 *Proc. 13th World Conf. of ACUUS: Advances in Underground Space Development* pp 276–86
- [4] Barabash M 2012 *Int. J. Comp. Civil Struct. Eng* **12** (3) 15–25
- [5] Ilichev V A 2008 *Soils, Foundations and Soil Mechanics* **3** 12–6
- [6] Perelmuter A V and Kazantsev O V 2015 *The Analysis of Structures With a Changing Calculation Scheme* (Moscow: ASV Press) p 148
- [7] Perminov N A 1997 Comprehensive geotechnical support for the construction of large edifices as a part of st. petersburg *Proc. Int. Symp. Geotechnical Engineering for the Preservation of Monuments and Historic Sites* Naples, 3-4 October, 1996 ed. Viggiani (Rotterdam: Balkema) pp 1074–81
- [8] Perminov N A and Perminov A N 2014 *Journal of Perm Research University* **4** 111–28
- [9] Perelmuter A V and Slivker V I 2011 *Calculation Models of Structures and a Possibility of their Analysis* (Moscow: SCAD Soft Press) p 710
- [10] *Construction Code* RF Set of Regulations 2016 2.02.01-83 p 172
- [11] Carmody Y and Sterling R L 1993 *A Guide to Subsurface Utilization and Design for People in Underground Spaces* (New York: VNR) p 328
- [12] Ponomaryov A B, Kaloshina S V, Zakharov A V, Bezgodov M A, Shenkman R I and Zolotozubov D G 2015 *15th Asian Regional Conf. on Soil Mechanics and Geotechnical Engineering: Geotechnical Heritage* Part 2 vol 78 pp 2676–9