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STUDY OF THE STRESS-STRAIN STATE OF THE PONTOON ELEMENT OF THE SUPPORT BLOCK

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A B S T R A C T

Oil and gas production on the continental shelf is carried out from offshore structures, a significant part of which are fixed platforms. Many of them have a core spatial structure as a supporting block, consisting of pipes of various diameters. The article proposes a method for analyzing and improving geometric shapes, taking into account the physical properties of the pontoon material, which allows solving specific practical problems. The influence of various factors on the stress distribution of pontoons has been revealed. A general method for linearization of thin-walled structures with variable geometric parameters characterized by accelerated convergence is proposed. An effective calculation method based on the small parameter method has been developed. Based on the developed methods, a computational algorithm was found and a set of application programs was compiled. The problems of moment and the general theory of shells were considered accordingly. In designs that provide sufficient strength and manufacturability, all real properties of materials were taken into account and more accurate design methods were found. For a large-scale class of problems of nonlinear structural mechanics, taking into account the physical properties of materials makes it possible to identify additional reserves of their strength. The use of nonlinear theory makes it possible to clarify the calculation of stresses and select the optimal dimensions and cross-sectional shape of the pontoon element of the support block. Based on the calculation results, certain formulas and methods have been compiled that can be used in engineering practice.

Keywords: Pontoon; support block; offshore platform; shells of rotation; nonlinear model .

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1. Introduction

Currently, the problem of developing shelf fuel and energy resources, primarily oil and gas fields of the Caspian Sea, is given special attention. Solving this problem requires studying a large complex of scientific and technical issues. One of the most important problems is the transportation of the support block of offshore platforms as the main element of oil and gas field hydraulic structures designed to operate at great depths. Pontoons are used to transport and lower support blocks to the seabed.

To carry out the processes of lowering and transporting the support block, due to the insufficiency of its displacement, additional pontoons are installed on the support block. The head pontoons are installed on the side panels of the support block in the head part, the auxiliary pontoons on the bottom panel. The dimensions and placement of pontoons are determined by calculation. Anchoring of the support block of the Stationary Offshore Platform to the seabed by means of pile foundations was studied in the works of the authors [1-5].

Due to the fact that the support block's own displacement (total) is significantly less than its mass, 2 pontoons are installed on the block. , providing the required parameters of the launching process and the permissible settlement of the support block after launching. The diameter of the pontoon is 4.16 m, the weight is 4890 kN, the total displacement of the pontoon is 22690 kN. The pontoon is attached to the support block in the area between the diaphragms using welded elements made from 1750×25 mm pipes.

The pontoon refers to shells of rotation. Various research works related to shells of rotation have been carried out in domestic and foreign practice. The works [6-8] cover the increase in reservoir oil yield, traditional technologies of cementing oil and gas wells, new achievements in well cementing, and theoretical and practical information about nanocolloids. Dynamic characteristics [9], construction of two types of finite element models with natural curvature based on layer-by-layer analysis [10], static stability [11], dynamic response [12], free vibration with double curvature in large span roofs [13], free vibrations [14], damage from impact loads [15], and sandwich shells have been studied considering different shapes and applied loads.

Free vibration of cylindrical and spherical sandwich

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shells [16], a rotating shell in a curvilinear coordinate system [17], laminar composite curved shells under the action of a uniformly distributed load [18], thermoelastic buckling behavior of porous plates and shells [19], under the influence of pulsed dynamic loads, asymmetrically loaded three-layer hemispherical shell [20], spherical sandwich shells without axisymmetric internal pulse loading [21], nonlinear deflection of a multifunctional sandwich composite shell [22], double-curvature sandwich panel under the action of a moving constant force [23], filled ideal incompressible fluid, axisymmetric and asymmetric vibrations of a shell of rotation [24], a two-layer cylindrical shell with a cubic approximation of initial changes [25], were studied in their works by the finite element method.

Nonlinear deflection of a transversely loaded thin cylindrical shell made of a laminated composite [26], dynamic behavior of a laminated composite shell under dynamic load [27], nonlinear forced vibration of a composite cylindrical shell [28], influence on the stability of composite conical shells reinforced with carbon nanotubes [29], free vibration and dynamic response of laminated composite double cylindrical and conical shells [30], internal dynamic pressure generated in double-layer spherical metal composite containers [31], agglomeration patterns of solid shell composite structure [32], free vibration behavior of composite conical shell [33], nanocomposite , reinforced with a rotating sandwich cylindrical shell [34], as well as the nonlinear dynamic stability of a three-dimensional cylindrical polymer shell reinforced with foam plastic [35] were investigated.

Static and free vibration of spherical structures [36], vibration of inhomogeneous anisotropic load-bearing shell structures located on an elastic foundation [37], stability of a thin-walled cylindrical shell from vibration of a traveling wave [38], model of an orthotropic layered shell for geometric, static and dynamic analyzes [39] , buckling of a conical shell of circular cross-section under axial compression [40], low-speed response of cylindrical metal-plastic shells reinforced with graphene plates under axial motion with inappropriate geometry [41] were studied taking into account nonlinearity in their works.

The thin-walled design of dome shells with a light window [42], vibrations of layered shells of revolution made of piezoelectric viscoelastic materials [43], the yield condition and plane stress state when solving elastoplastic boundary problems of shells [44] were studied taking into account geometric nonlinearity.

Dynamic buckling of thin shells subjected to an external pressure pulse [45] , to different displacement components using the first-form shear deformation theory [46], to the stress-strain state of hydrotechnical devices consisting of thin shells filled with soil [47], to the effect of thermal shock on the effect of randomness on the shell structure of a functional gradient material [48], based on a numerical method and model over time non-uniform thermal loads taking into account changing environmental factors [49], virtual distribution of wind effects replacing actual irregular distribution [50] were considered.

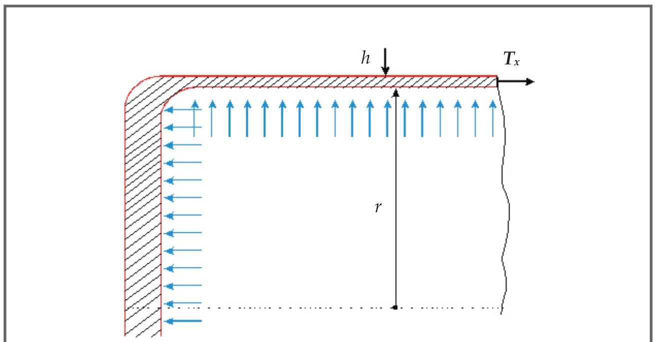

Fig. 1. Calculation diagram for a thin-walled pontoon

In studies of thin-walled spherical shells, isotropy beyond elasticity [51], nonlinear deformation and stability [52], thermomagnetic-elastic problem in a magnetic field [53], propagation and diffraction of unstable waves located in the elastic field of a half-space [54] were studied.

These works considered vertical and horizontal loads in the form of a bridge [55], to the construction of a cylindrical test section with dynamic internal pressure [56], to two-dimensional linear and nonlinear boundary value problems of statics for horizontal shells [57], to a wooden Voronoi shell with a mesh surface Voronoi mosaic [58] is an analytical solution for the nonlinear vibrations and dynamic response of cermet functionally graded double-curvature carbon nanotube-reinforced bearing housings under three different types of boundary conditions [59]. In the articles of T. V. Zinoviev [60, 61] when approximating the system equation, an implicit symmetric one-step difference scheme of the second order. However, none of them took into account the physical non-linearity of the material of the pontoon and the change of its geometrical parameters. In [62], an effective numerical technique was developed for studying the stress-strain state and bearing capacity of compressed pipe-concrete elements. When developing a calculation algorithm for compressed concrete, the relationship between stress and strain is a fractional-rational function proposed by the Eurocode, and for reinforcement a two-linear diagram is adopted. Taking the Eurocode diagram for compressed concrete and taking into account the elastic-plastic work of reinforcement, an effective universal numerical method was developed, suitable for any load level and for any flexibility of the compressed element. In [63], using a fractional-rational strain diagram for a rectangular section for compressed concrete, analytical dependencies for the normal force and bending moment were obtained. The presence of such analytical dependencies is important when improving the modern nonlinear deformation theory of calculation of reinforced concrete elements.

The results of technical diagnostics consisting of visual observation, instrumental measurements and inspection works are used in working out appropriate reports and estimation of reminder operation resources. The table consisting of actual measurements refecting the results of measurements, the composed real scheme of the components and the results of visual observations are performed for each object as a database, are preserved and used in current calculations. We can write the main equations of the momentess theory of equipments for restimation of operational and strength resources as follows [64].

Thin-walled bottoms are very hard pontoons under internal pressure (fig.1). The main equations of the moment theory of rotational shells symmetrically loaded with respect to the axis are written as follows [65]:

$$\begin{cases} T_x = \dfrac{Eh}{1-\mu^2}\left(\dfrac{du}{dx} + \mu\dfrac{\omega}{r}\right) \\ T_t = \dfrac{Eh}{1-\mu^2}\left(\dfrac{\omega}{r} + \mu\dfrac{du}{dx}\right) \\ M_x = D\dfrac{d^2\omega}{dx^2} \\ M_t = \mu D\dfrac{d^2\omega}{dx^2} \end{cases} \quad (1)$$

In equation (1), T_x, T_t – are normal forces in the shell's cross sections; r, h, z – is a current coordinate; P_1, P_2 – are the meridian, tangential projections of the given plane forces normal to the plane; u, w – are the displacement projections; E, β, μ – are elastic constants of material; ε_x, ε_y – are relative and anglular deformastions, $D = \dfrac{Eh^3}{12\left(1-\mu^2\right)}$ – flexural rigidity of the pontoon.

Taking the dependence between stress and strain as $\sigma = \varepsilon E - \beta\varepsilon^3$, we accept the physical equations as follows:

$$\begin{aligned} E\varepsilon_x - \beta\varepsilon_x^3 &= \sigma_x - \mu\sigma_y \\ E\varepsilon_y - \beta\varepsilon_y^3 &= \sigma_y - \mu\sigma_x \end{aligned} \quad (2)$$

If we find σ_x, σ_y from equations (2) and consider them in their nonlinear dependence between stress and strain

$$\begin{aligned} \sigma_x &= \frac{4}{3}\left\{E\left(\frac{\partial u}{\partial x} + \frac{\partial^2 w}{\partial x^2}z + \frac{1}{2}\frac{w}{r}\right) - \beta\left[\left(\frac{\partial u}{\partial x} + \frac{\partial^2 w}{\partial x^2}z\right)^3 + \frac{1}{2}\left(\frac{\omega}{r}\right)^3\right]\right\} \\ \sigma_y &= \frac{4}{3}\left\{E\left(\frac{w}{r} + \frac{1}{2}\left(\frac{\partial u}{\partial x} + \frac{\partial^2 w}{\partial x^2}z\right)\right) - \beta\left[\left(\frac{\omega}{r}\right)^3 + \frac{1}{2}\left(\frac{\partial u}{\partial x} + \frac{\partial^2 w}{\partial x^2}z\right)^3\right]\right\} \end{aligned} \quad (3)$$

Taking into account the physical nonlinearity of the material and loading, it is necessary to solve the system of nonlinear differential equations for studying the case of deformation under tension. To solve such a complex task, we use the method of small parameters. For this, we take a small parameter as follows: $\nu = \dfrac{\beta\varepsilon_0^2}{E}$, here: ε_0 is the relative linear deformation corresponding to the strength limit. The solution of the system of equations (1) is sought in the form of the following series with small parameters. Here: ε_0, γ_0 are relative and angular deformations corresponding to ultimate strength. It is seen from this expression that at the assumption of incompressibility of nonlinear materials $\left(\mu = \dfrac{1}{2}\right)$.

$$\begin{aligned} u &= \sum\nolimits_{j=0} u_j\nu^j \\ w &= \sum\nolimits_{j=0} w_j\nu^j \end{aligned} \quad (4)$$

there ($j = 0, 1, 2\ldots$)

We substitute the series (4) in (1) taking this into account, we get the following system of linear equations:

- for $j=0$,

$$\begin{cases} T_{x_0} = \dfrac{4}{3}Eh\left(\dfrac{\partial u_0}{\partial x} + \dfrac{\omega_0}{2r}\right) \\ T_{t_0} = \dfrac{4}{3}Eh\left(\dfrac{\omega_0}{r} + \dfrac{1}{2}\cdot\dfrac{\partial u_0}{\partial x}\right) \\ M_{x_0} = \dfrac{Eh^3}{9}\cdot\dfrac{d^2\omega_0}{dx^2} \\ M_{t_0} = \dfrac{Eh^3}{18}\cdot\dfrac{d^2\omega_0}{dx^2} \end{cases} \quad (5)$$

- for $j=1$,

$$\begin{cases} T_{x_1} = \dfrac{4}{3}Eh\left\{\dfrac{du_1}{dx} + \dfrac{1}{2}\cdot\dfrac{\omega}{r} - \dfrac{1}{\varepsilon_0^2}\left[\dfrac{1}{2}\left(\dfrac{\omega_0}{r}\right)^3 + \left(\dfrac{du_0}{dx}\right)^3 + \dfrac{h^2}{4}\cdot\dfrac{du_0}{dx}\left(\dfrac{d^2w_0}{dx^2}\right)^2\right]\right\} \\ T_{t_1} = \dfrac{4}{3}Eh\left\{\dfrac{\omega_1}{r} + \dfrac{1}{2}\cdot\dfrac{du_1}{dx} - \dfrac{1}{\varepsilon_0^2}\left[\left(\dfrac{\omega_0}{r}\right)^3 + \dfrac{1}{2}\left(\dfrac{du_0}{dx}\right)^3 + \dfrac{h^2}{8}\cdot\dfrac{du_0}{dx}\left(\dfrac{d^2w_0}{dx^2}\right)\right]\right\} \\ M_{x_1} = \dfrac{Eh^3}{9}\left\{\dfrac{d^2w_1}{dx^2} - \dfrac{3}{\varepsilon_0^2}\left[\left(\dfrac{du_0}{dx}\right)^2\cdot\dfrac{d^2w_0}{dx^2} + \dfrac{h^2}{20}\cdot\left(\dfrac{d^2w_0}{dx^2}\right)\right]\right\} \\ M_{t1} = \dfrac{Eh^3}{9}\left\{\dfrac{1}{2}\dfrac{d^2w_1}{dx^2} - \dfrac{3}{2\varepsilon_0^2}\left[\left(\dfrac{du_0}{dx}\right)^2\cdot\dfrac{d^2w_0}{dx^2} + \dfrac{h^2}{20}\cdot\left(\dfrac{d^2w_0}{dx^2}\right)^3\right]\right\} \end{cases} \quad (6)$$

- for $j=2$,

$$\begin{cases} T_{x_2} = \dfrac{4}{3}Eh\left\{\dfrac{du_2}{dx} + \dfrac{1}{2}\cdot\dfrac{\omega}{r} - \dfrac{1}{\varepsilon_0^2}\left[\dfrac{3}{2r^3}\omega_0^2\omega_1 + 3\left(\dfrac{du_0}{dx}\right)^2\dfrac{du_1}{dx} + \dfrac{h^2}{4}\cdot\dfrac{du_1}{dx}\left(\dfrac{d^2w_0}{dx^2}\right)^2 + \dfrac{h^2}{2}\cdot\dfrac{du_0}{dx}\cdot\dfrac{d^2w_0}{dx^2}\cdot\dfrac{d^2w_1}{dx^2}\right]\right\} \\ T_{t_2} = \dfrac{4}{3}Eh\left\{\dfrac{w_2}{r} + \dfrac{1}{2}\dfrac{du_2}{dx} - \dfrac{1}{\varepsilon_0^2}\left[\dfrac{3}{r^3}\omega_0^2\omega_1 + \dfrac{3}{2}\left(\dfrac{du_0}{dx}\right)^2\dfrac{du_1}{dx} + \dfrac{h^2}{8}\cdot\dfrac{du_1}{dx}\left(\dfrac{d^2w_0}{dx^2}\right)^2 + \dfrac{h^2}{4}\cdot\dfrac{du_0}{dx}\cdot\dfrac{d^2w_0}{dx^2}\cdot\dfrac{d^2w_1}{dx^2}\right]\right\} \\ M_{x_2} = \dfrac{Eh^3}{9}\left\{\dfrac{d^2w_2}{dx^2} - \dfrac{3}{\varepsilon_0^2}\left[2\cdot\dfrac{du_0}{dx}\cdot\dfrac{du_1}{dx}\cdot\dfrac{d^2w_0}{dx^2} + \left(\dfrac{du_0}{dx}\right)^2\dfrac{d^2w_1}{dx^2} + \dfrac{3h^2}{20}\cdot\left(\dfrac{d^2w_0}{dx^2}\right)^2\cdot\dfrac{d^2w_1}{dx^2}\right]\right\} \\ M_{t_2} = \dfrac{Eh^3}{9}\left\{\dfrac{1}{2}\cdot\dfrac{d^2w_2}{dx^2} - \dfrac{3}{\varepsilon_0^2}\left[\dfrac{du_0}{dx}\cdot\dfrac{du_1}{dx}\cdot\dfrac{d^2w_0}{dx^2} + \left(\dfrac{du_0}{dx}\right)^2\dfrac{d^2w_1}{dx^2} + \dfrac{3h^2}{20}\cdot\left(\dfrac{d^2w_0}{dx^2}\right)^2\cdot\dfrac{d^2w_1}{dx^2}\right]\right\} \end{cases} \quad (7)$$

If we consider the system of equations (5-7) in equilibrium equations $dQ/dx + T_t/r = P_1$; $\dfrac{dT_x}{dx} = P_2$; $\dfrac{dM_x}{dx} = Q$, we get the following system of linear differential equations:

$$\begin{aligned} &\frac{d^4\omega_0}{dx^4} + 4\beta^4\omega_0 = -\frac{1}{2}\cdot\frac{T_{x_0}}{rD} + \frac{P_1}{D} \\ &\frac{d^4\omega_1}{dx^4} + 4\beta^4\omega_1 = \frac{3}{\varepsilon_0^2}\cdot\frac{d^2}{dx^2}\left[\left(\frac{3}{4}\cdot\frac{T_{x_0}}{Eh}\cdot\frac{1}{2}\cdot\frac{\omega_0}{r}\right)^2\cdot\frac{d^2w_0}{dx^2} + \frac{h^2}{20}\cdot\left(\frac{d^2w_0}{dx^2}\right)^3 + \frac{9}{r^4h^2\varepsilon_0^2}\omega_0^3\right] \\ &\frac{d^4\omega_2}{dx^4} + 4\beta^4\omega_2 = \frac{27}{\varepsilon_0^2r^4h^2}\omega_0^2\omega_1 + \frac{3}{\varepsilon_0^2}\cdot\frac{d^2}{dx^2}\left[2\frac{du_0}{dx}\cdot\frac{du_1}{dx}\cdot\frac{d^2w_0}{dx^2} + \left(\frac{du_0}{dx}\right)^2\frac{d^2w_1}{dx^2} + \frac{3h^2}{20}\cdot\left(\frac{d^2w_0}{dx^2}\right)^2\cdot\frac{d^2w_1}{dx^2}\right] \end{aligned} \quad (8)$$

2. Materials and Methods

The purpose of the work is to determine the stress-strain state of oil field structures, taking into account various effects, on the basis of which to develop new methods for calculating structures and apply them to solving practical problems. The objectives of the study are to develop new versions of the formulas for specifying the middle surfaces of arbitrary shells, which allow calculating shells without imposing any significant restrictions on their dimensions. Calculation of the strength of shell structures in a physically nonlinear formulation under step loading. In the study of the stress-strain state, a model of a physical nonlinear elastic body (shell of revolution) was used, the reliability of the results obtained was obtained by mathematical methods. For the study of the stress-strain state, a nonlinear body model is used. To check the accuracy of the calculation results, the system of the obtained equations, which was considered on a large number of numerical examples, was solved by known methods. At the same time, some of the results obtained were compared with the works of other authors, and it was determined that the results coincide.

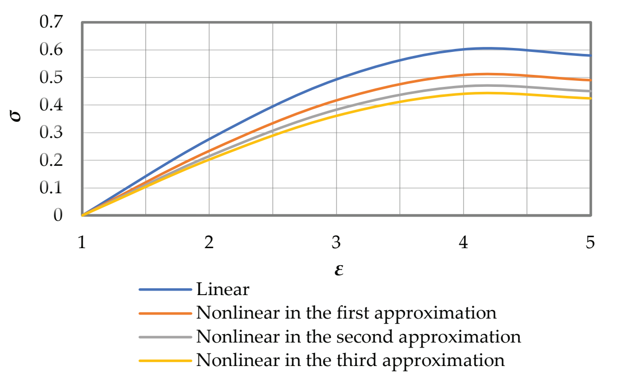

Fig. 2. Graph of stress changes in the meridional direction

3. Results and Discussion

The stress-strain state of oil field structures was determined, taking into account various influences, new methods for calculating structures based on it were developed and applied to solve practical problems. On the basis of an axially loaded nonlinear model, the cylindrical shell is calculated taking into account the change in the geometric parameter. The symmetrically loaded structure of the coating is calculated taking into account the physical properties of the material, changes in geometric parameters. Oilfield facilities are calculated taking into account internal pressure and a calculation method based on the method of small parameters is obtained. The calculation of the coating was carried out taking into account external and internal influences, symmetric and asymmetric loads, stiffeners, the optimal geometric dimensions for a wide range of materials were determined. In the first approach, the stress decreased by 11.4% compared to the linear one, in the second approach by 8.2%, in the third approach by 5.6% and by 7.9% due to a change in the geometric parameter.

On test examples, the accuracy and convergence of the constructed numerical scheme are investigated. The comparison is carried out, obtained in the linear and nonlinear formulations. Based on the calculations performed using the specified nonlinear model, when compared with the linear model, the stress decreases by 15.1%. (fig.2).

Conclusion

The results of the study make it possible to apply new calculation methods based on nonlinearity in the construction, design and repair of hydraulic structures.The research methodology used in the study of the stress-strain state of enclosing structures can be widely used in the practice of designing enclosing structures, and can also be a methodological tool in assessing the strength of existing enclosing structures. The proposed calculation methods make it possible to accurately calculate the effect of static loads on oilfield facilities, improve existing calculation methods and, most importantly, achieve technical efficiency. Application of nonlinear theory allows specifying of stress calculation, selection of optimum sizes and sectional shape of construction members. In accordance with calculation findings certain formula and practice were composed, which can be utilized in engineering practice. There was obtained problem solving for round cross-section coats, permanent and tapered thickness under the effect of external loading, as well as internal pressure with regard to effect of non-symmetrical and symmetrical loads, based on small parameters methods. Taking into account the change in the geometric parameter, an analytical solution was obtained for calculating the pontoon element of the support block in the third approximation according to the theory of moments. A method has been developed for calculating a pontoon element made of a nonlinear material of variable cross-section based on the theory of moments. The case was studied when the geometric parameter of the pontoon changes linearly in the meridional direction. With a constant volume, a pontoon of variable cross-section is compared with a pontoon of constant cross-section.

A method has been developed for calculating the strength of shells of revolution of variable thickness from a nonlinear elastic material, taking into account the surface load, as well as studying their supercritical deformation. The area of application of the developed methods of calculating the strength of shells made of nonlinear elastic material with different methods of setting the boundary conditions has been established. Accuracy and convergence of the constructed numerical scheme are investigated on test examples. Comparison of the results obtained in linear and nonlinear formulations is carried out.

References

1. Aslanov, L. F., Aslanli, U. L. (2024). Determination of load-bearing capacity of piles used in stationary offshore platforms. *SOCAR Proceedings*, 1, 116-123.

2. Aslanov, L. F. (2022). Optimization of the calculation of the piles of fixed offshore platforms /in book: El-Askary, H., Erguler, Z. A., Karakus, M., Chaminé, H. I. (eds). «Research developments in geotechnics, geo-informatics and remote sensing». CAJG 2019. *Springer, Cham.*

3. Aslanov, L. F., Aslanov, F. L. (2024). Choosing an effective design solution for fixing offshore hydro-technical structures to shelf ground /in book: Çiner, A., Ergüler, Z. A., Bezzeghoud, M., et al. «Recent research on geotechnical engineering, remote sensing, geophysics and earthquake seismology». MedGU 2021. *Springer, Cham.*

4. Aslanov, L. F., Aslanov, F. L. (2024). Some tasks of increasing and identifying the reserves of the bearing capacity of anchor fastenings of offshore fixed platforms /in book: Bezzeghoud, M., Ergüler, Z. A., Rodrigo-Comino, J., et al. «Recent research on geotechnical engineering, remote sensing, geophysics and earthquake seismology». MedGU 2022. *Springer, Cham.*

5. Aslanov, L. F. (2015). Interaction between large cross-sections bored piles with 'hard core' under dynamic loads and shelf soils. *Science Bulletin National Mining University*, 5, 21-25.

6. Vishnyakov, V. V., Suleimanov, B. A., Salmanov, A. V., Zeynalov, E. B. (2019). Primer on enhanced oil recovery. *Gulf Professional Publishing*.

7. Suleimanov, B. A., Veliyev, E. F., Vishnyakov, V. V. (2022). Nanocolloids for petroleum engineering: Fundamentals and practices. *John Wiley & Sons.*

8. Suleimanov, B. A., Veliyev, E. F., Aliyev, A. A. (2023). Oil and gas well cementing for engineers. *John Wiley & Sons.*

9. Adab, N., Arefi, M. (2023). Vibrational behavior of truncated conical porous GPL-reinforced sandwich micro/nano-shells. *Engineering with Computers*, 39, 419–443.

10. Bakulin, V. N. (2019). A model for refined calculation of the stress-strain state of sandwich conical irregular shells. *Mechanics of Solids*, 54, 786–796 .

11. Duc, N. D., Manh, D. T., Khoa, N. D., et al. (2022). Mechanical stability of eccentrically stiffened auxetic truncated conical sandwich shells surrounded by elastic foundations. *Mechanics of Composite Materials*, 58, 365–382.

12. Liu, Y., Qin, Z., Chu, F. (2021). Nonlinear dynamic responses of sandwich functionally graded porous cylindrical shells embedded in elastic media under 1:1 internal resonance. *Applied Mathematics and Mechanics (English Edition),* 42, 805–818.

13. Singha, T. D., Bandyopadhyay, T. (2024). Free vibration characteristics of FG-GRC sandwich shallow shells with porous core in thermal environments. *Journal of Vibration Engineering & Technologies*, 12, 6741-6762.

14. Song, L., Wang, T., Yin, Z., et al. (2024). Free vibrational characteristics of sandwich cylindrical shells containing a zero Poisson's ratio cellular core. *Journal of Vibration Engineering & Technologies*, 12, 1603–1620.

15. Yan, C., Wang, Y., Zhai, X. (2023). Numerical and theoretical study on failure characteristics and damage assessment model of curved steel-concrete-steel sandwich shells subjected to impact load. *KSCE Journal of Civil Engineering*, 27, 4274–4287.

16. Attia, A., Berrabah, A.T., Bourada, F. et al. (2024). Free vibration analysis of thick laminated composite shells using analytical and finite element method. *Journal of Vibration Engineering & Technologies*, https://doi.org/10.1007/s42417-024-01322-2.

17. Dzhabrailov, A. S., Nikolaev, A. P., Klochkov, Y. V., et al. (2023). Accounting for displacement of the shells of revolution as a solid in FEM algorithm. *Mechanics of Solids*, 58, 1946–1959.

18. Ghosh, A., Chakravorty, D. (2020). Fem analysis of progressive failure for composite hypar shells. *Strength of Materials*, 52, 507–520.

19. Joueid, N., Zghal, S., Chrigui, M., et al. (2023). Thermoelastic buckling analysis of plates and shells of temperature and porosity dependent functionally graded materials. *Mechanics of Time-Dependent Materials*, https://doi.org/10.1007/s11043-023-09644-6.

20. Lugovyi, P. Z., Gaidaichuk, V. V., Orlenko, S. P., et al. (2023). Dynamics of asymmetric three-layer hemispherical shells with a discrete-inhomogeneous filler under pulsed loads. *Strength of Materials*, 55, 265–276.

21. Lugovyi, P. Z., Orlenko, S. P. (2022). Dynamics of spherical sandwich shells with discrete-symmetrical light core reinforced with ribs under nonstationary loads. *International Applied Mechanics*, 58, 559–568.

22. Mahesh, V. (2021). Nonlinear pyrocoupled deflection of viscoelastic sandwich shell with CNT reinforced magneto-electro-elastic facing subjected to electromagnetic loads in thermal environment. *European Physical Journal – Plus*, 136, 796.

23. Sadripour, S., Jafari-Talookolaei, R. A., Malekjafarian, A. (2024). Dynamic response of open doubly curved sandwich shells with soft core subjected to a moving force. *Acta Mechanica*, 235, 2231-2257.

24. Shklyarchuk, F. N. (2015). Calculation of the oscillations of shells of revolution with a liquid using the finite element method. *Journal of Machinery Manufacture and Reliability*, 44, 14–24.

25. Yakupov, N. M., Kiyamov, H. G., Mukhamedova, I. Z. (2023). Calculation of two-layer cylindrical shells based on the spline variant of the finite element method. *Lobachevskii Journal of Mathematics*, 44, 1813–1819.

26.Bakshi, K. (2023). Nonlinear bending study of composite singly curved stiffened shells with complicated boundary conditions. *Mechanics of Composite Materials*, 59, 659–676.

27. Dogan, A. (2021). Dynamic response of laminated composite shells under various impact loads. *Mechanics of Time-Dependent Materials*, 25, 175–193.

28. Dong, B., Li, H., Wang, X., et al. (2022). Nonlinear forced vibration of hybrid fiber/graphene nanoplatelets/polymer

composite sandwich cylindrical shells with hexagon honeycomb core. *Nonlinear Dynamics*, 110, 3303–3331.

29. Eskandary, K., Shishesaz, M., Moradi, S. (2022). Buckling analysis of composite conical shells reinforced by agglomerated functionally graded carbon nanotube. *Archives of Civil and Mechanical Engineering*, 22, 132.

30. Kim, J., Om, C., Kang, D., et al. (2023). Dynamic analysis of laminated composite double cylindrical and conical shells with bulkheads using meshfree method. *Acta Mechanica*, 234, 4775–4800.

31. Lepikhin, P. P., Romashchenko, V. A., Tarasovs'ka, S. O. (2021). Peculiarities of strengthening of spherical composite pressure vessels with thin metal shells under static and dynamic loads. Part 2. Dynamic loading. *Strength of Materials*, 53, 717–726.

32. Mellouli, H., Mallek, H., Louhichi, R., et al. (2023). Dynamic analysis of piezolaminated shell structures reinforced with agglomerated carbon nanotubes using an enhanced solid-shell element. *Engineering with Computers*. https://doi.org/10.1007/s00366-023-01923-7.

33. Naderi, A. A., Pachdaman, H., Zandieh, A. (2024). A smeared stiffener model for vibration analysis of anisogrid-stiffened composite conical shells using differential quadrature method. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 46, 38.

34. Rostami, R., Mohammadimehr, M. (2022). Vibration control of rotating sandwich cylindrical shell-reinforced nanocomposite face sheet and porous core integrated with functionally graded magneto-electro-elastic layers. *Engineering with Computers*, 38, 87–100.

35. Zhang, F., Bai, C. Y., Wang, J. Z. (2023). Nonlinear dynamic stability analysis of three-dimensional graphene foam-reinforced polymeric composite cylindrical shells subjected to periodic axial loading. *Archive of Applied Mechanics*, 93, 503–524.

36. Shamloofard, M., Hosseinzadeh, A., Movahhedy, M. R. (2021). Development of a shell superelement for large deformation and free vibration analysis of composite spherical shells. *Engineering with Computers*, 37, 3551–3567.

37. Sofiyev, A. H., Turan, F., Kadıoglu, F., et al. (2022). Influences of two-parameter elastic foundations on nonlinear free vibration of anisotropic shallow shell structures with variable parameters. *Meccanica*, 57, 401–414.

38. Sun, S., Liu, L. (2021). Parametric study and stability analysis on nonlinear traveling wave vibrations of rotating thin cylindrical shells. *Archive of Applied Mechanics*, 91, 2833–2851.

39. Xue, B., Zhang, A. M., Peng, Y. X.. et al. (2023). A meshfree orthotropic laminated shell model for geometrically nonlinear static and dynamic analysis. *Computational Mechanics*, 73, 1033-1051.

40.Yılmaz, H., Kocabaş, I. (2023). Load capacity of concave conical shells with randomly positioned circular cutouts. *Experimental Mechanics*, 63, 1223–1238.

41. Zhang, Y. W., She, G. L. (2023). Nonlinear low-velocity impact response of graphene platelet-reinforced metal foam cylindrical shells under axial motion with geometrical imperfection. *Nonlinear Dynamics*, 111, 6317–6334.

42. Kolesnykov, A., Tsurik, T., Kurakina, S., Litvinova, K. (2024). Design and calculation of multifunctional canopies in the form of shallow shells /in book: Vatin, N., Pakhomova, E. G., Kukaras, D. (eds). «Modern problems in construction». MPC 2022. *Springer, Cham.*

43. Kozlov, V. I., Zinchuk, L. P., Karnaukhova, T. V. (2021). Nonlinear vibrations and dissipative heating of laminated shells of piezoelectric viscoelastic materials with shear strains. *International Applied Mechanics*, 57, 669–686.

44. Yamamoto, T., Yamada, T., Matsui, K. (2023). Elastoplastic analysis of shells without any local iterative calculations by block Newton method. *Computational Mechanics*, 72, 967–989.

45. Thierry, V., Tang, B., Joffrin, P., et al. (2022). Characterization of blast waves using solid and gaseous explosives: application to dynamic buckling of cylindrical shells. *Shock Waves*, 32, 703–713.

46.Thongchom, C., Saffari, P. R., Refahati, N., et al. (2022). An analytical study of sound transmission loss of functionally graded sandwich cylindrical nanoshell integrated with piezoelectric layers. *Scientific Reports*, 12, 3048.

47.Tsimbelman, N. Y., Bekker, A. T. (2023). Study of the stress-strain state of the system «thin-walled steel shell – ınfill – soil base». *Power Technology and Engineering*, 57, 346–350.

48.Verma, K. P., Swain, P. K., Maiti, D. K., et al. (2023). Uncertainty analysis of thermal stresses in shell structure subjected to thermal loads. *International Journal of Mechanics and Materials in Design*, 19, 621–643.

49. Xu, W., Zheng, X., Zhang, X., et al. (2024). Non-uniform thermal behavior of single-layer spherical reticulated shell structures considering time-variant environmental factors: analysis and design. *Journal of Zhejiang University - Science A*, 25, 223–237.

50. Zhang, J. F., Pei, H., Li, J., et al. (2022). A simplified procedure for the structural reinforcement design of hyperbolic cooling tower shells. *Arabian Journal for Science and Engineering*, 47, 4155–4169.

51. Astakhova, A. (2022). On the calculation of thin shells beyond the elastic limit /in book: Akimov, P., Vatin, N. (eds). XXX Russian-Polish-Slovak Seminar Theoretical Foundation of Civil Engineering (RSP 2021). *Springer, Cham*.

52. Bazhenov, V. A., Luk'yanchenko, O. O., Vorona, Y. V., et al. (2021). The ınfluence of shape ımperfections on the stability of thin spherical shells. *Strength of Materials*, 53, 842–851

53. Bian, Y. H., Tian, Z. G. (2023). Nonlinear Theory of thermomagnetoelasticity of spherical segment shells with joule's heat taken into account. *International Applied Mechanics*, 59, 370–380.

54. Fedotenkov, G. V., Orekhov, A. A., Rabinskiy, L. N. (2023). Wave diffraction in an elastic medium with a spherical cavity supported by a thin shell. *Lobachevskii Journal of Mathematics*, 44, 2279–2291.

55. Fenu, L., Hosseini, A., Punzo, S., et al. (2024). Form-finding with restraint topology optimization of a curved shell-supported footbridge under vertical and horizontal loads /in book: Gabriele, S., Manuello Bertetto, A., Marmo, F., Micheletti, A. (eds). Shell and spatial structures. IWSS 2023. *Springer, Cham.*

56. Garnier, C., Faucher, V., Lamagnère, P. (2022). Estimation of dynamic load factors for elastic cylinders under dynamic internal pressure. *Meccanica*, 57, 415–439.

57. Grigorenko, Y. M., Bespalova, O. I. (2023). Generalized method of finite integral transformations in linear and nonlinear static problems for shallow shells. *Journal of Mathematical Sciences*, 274, 618–640.

58. Hua, H., Hovestadt, L., Tang, P. (2020). Optimization and prefabrication of timber Voronoi shells. *Structural and Multidisciplinary Optimization*, 61, 1897–1911.

59. Nguyen, P. D., Duc, N. D. (2024). A semi-analytical sinusoidal shear deformation theory for nonlinear dynamic response and vibration of CNT–FGM doubly curved shallow shells. *Acta Mechanica*, 235, 2077-2112.

60. Zinovieva, T. V. (2017) Calculation of shells of revolution with arbitrary meridian oscillations /in book: Evgrafov A (eds). «Advances in mechanical engineering. lecture notes in mechanical engineering». *Springer, Cham.*

61. Zinovieva, T. V. (2012)/ Computational mechanics of elastic shells of revolution in mechanical engineering calculations /in book: Zinovieva, T. V. (ed). Modern engineering: Science and education. *Saint Petersburg: State Polytechnic University.*

62. Hajiyev, M., Damirov, M. (2023). Stress-strain state and bearing capacity of compressed reinforced concrete elements of anular section. *Architectural Studies*, 9(22), 35-46.

63. Hajiyev, M. A., Guliyev, F. M., Ovsii, D. (2023). Calculation of the normal force and bending moment from compression stresses in concrete. *Lecture Notes in Civil Engineereig*, 299, 167-174.

64. Aslanov, L. F. (2016). Reflected wafes from bored or CFA piles of large section in the offshore soils. *Oil Industry*, 7, 112-116.

65. Aslanov, L. F. (2015). Wave interaction of offshore structure and shelf soil through large section piles with a 'hard core' on the half-space model. *Oil Industry*, 2, 78-81.