Estimation of seismic stability of gravity base substructure for fixed offshore platform

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SUMMARY:
Seismic stability of several gravity base platforms was studied within the frame of oil-gas field development on Sakhalin offshore zone. The region of platforms location is characterized by severe climate and high level of seismicity. In accordance with the requirements of the Russian standards for substantiation of the design for support reinforced concrete substructure of the offshore platform under seismic loads the computation of bearing capacity, stability, displacements and tilts, stresses and deformations, structural strength have to be carried out. Seismic impacts of two levels – strength level earthquake (SLE) with the return period of 200 years and ductility level earthquake (DLE) **-** 3000 years – were defined by three-component accelerograms. The substructure should withstand SLE without threat for people and with retaining its repair ability and should take DLE without collapse. Substructures were computed by the finite element method that made it possible to substantiate the strength and stability of platforms.

Keywords: Seismic stability, offshore platform, finite element method

1. DESIGN CONSIDERATIONS FOR PLATFORM SUBSTRUCTURES

Vedeneev VNIIG is taking active part in feasibility studies and technical design of projects for fixed-site constructions in the Russian Sea Shelves. Institute research studies were used in the platform design for the Piltun-Astokh, Lunskoye (see Fig. 1), Arkutun-Dagi and Chaivo offshore facilities in the Sakhalin Island shelf and other (Bellendir et al, 2000, Glagovsky&Finagenov, 2011 b).

Figure 1. Platform on Sakhalin shelf

The following research and development work has been carried out on feasibility studies for gravity-based platforms (Bellendir, Finagenov&Glagovsky, 2004):

- Analysis of the geological engineering conditions of the construction sites; schematization of the foundation and composition of necessary characteristics and their design values;
- Determination of the design values of seismic, ice and wave loading of platforms;
- Assessment of the strength and stability of the platforms under the impact of static and dynamic loading.

Besides this, to provide reliability of structures at all stages of their installation and exploitation, it was necessary to carry out following calculations and assessments in the project:

- Calculations of the bearing capacity and stability of the "platform - soil foundation" system under various combinations of loading with consideration of actual features of the foundation;
- Calculations of consolidation of the foundation soils including evaluation of the excess pore pressure;
- Calculations of vertical and horizontal displacements and tilts of the platform;
- Calculations of stresses transferred from the foundation soils to the skirt and the bottom of the bearing slab; elaboration of the measures eliminating occurrences of tension stresses at the substructure - soil contact;
- Calculations of the possible scour and liquefaction of the soil adjacent to the construction foot and development of the necessary constructive measures;
- Calculations for determination of the conditions necessary for platform installation with pressing skirts into the foundation soil;
- Evaluation of the conditions for platform elevation.

The executed researches and the analysis of results of calculations make it possible to estimate reliability and safety of platforms (Finagenov&Glagovsky, 2005, Bellendir, Finagenov&Glagovsky, 2006, 2007).

One of the major issues for substantiation of the platform construction is provision of the platform seismic resistance, because the area of platforms location is characterized with 8-9 seismic intensity on the MSK-64 scale.

2. SPECIAL TECHNICAL SPECIFICATIONS

While designing fixed-site oil and gas production platforms on continental shelves, there emerge a big number of questions stipulated by the unique character of the project, complexity of climatic and natural conditions in the areas of perspective construction, availability of various methodical approaches and even specific distinctions between design fundamentals of various design standards. Fixed-site structures on the continental shelf are particularly complex projects for design and building both by their construction and installation means and by the natural conditions at the sites of their placement. However, until present time, there are no special regulating documents in Russia for engineering design of constructions of this type.

There are only general requirements to the initial data and calculation methods referring to types of hydraulic engineering structures in the actual Russian regulating documents; they do not consider sufficiently specific aspects of the fixed-site oil and gas production platforms on the continental shelf (Bellendir et al, 1999). This is why, as usual, each major project on the Russian continental shelf requires development and approval of Special Technical Specifications (STS). The purpose of STS is development of additional and specified positions in the actual regulating documents and original norms in case of their missing. STS shall contain obligatory regulating requirements for a construction, referring to its safety and reliability. Such requirements are formulated with consideration of approbated recommendations of internationally recognized standards. While developing STS, research and development results and design studies on solving major problems in the field of shelf constructions carried out by the executing organization and other leading national and foreign companies are used, as well as generalization of design, installation, and exploitation practices for similar constructions accumulated in the process of shelf facilities establishment in the last years (Bellendir, Finagenov&Glagovsky, 2010).

3. STATEMENT OF PROBLEM

Some outcomes of the work on seismic resistance substantiation for a gravity platform in the Sakhalin Island shelf are presented hereafter. The object of studies is a reinforced concrete substructure of the platform and its interaction with the soil foundation.

The purpose of this work was to identify the bearing capacity of the foundation, stability of the platform, the stress-strain state (SSS) of the gravity base substructure (GBS) and to evaluate the structure strength under seismic impacts (Glagovsky&Finagenov, 2011 a).

4. LOADING AND IMPACTS

Combination of loads, reliability factors by loads, and coefficients of their combinations were assumed in accordance with Russian regulating documents and STS (Glagovsky&Finagenov, 2004).

Normative seismic intensity of the platform site was identified as 8-9 on the MSK-64 scale. Assessment of the seismic intensity was carried out with consideration of a two-level approach. The lower level referred to “strength level earthquake” (SLE). At the engineering design of seismic resistant constructions, the lower-level events are regarded as design earthquakes. The platform substructure should withstand SLE without threat for people and with retaining its repair ability. The upper level event is stronger and less frequent; it is “ductility level earthquake” (DLE) so-called maximal calculated earthquake. Calculations for it are carried out with consideration possible non-elastic deformations of the construction. The foundation substructure should take DLE without collapse. The return period for SLE was set as 200 years, while for DLE it amounts to 3000 years.

Analysis of the regional seismic data in the area of the platform deployment has been carried out; outcomes of the probability seismic hazard analysis (PSHA) received in accordance with requirements of international standards were compared with the ranges of seismic accelerations calculated by Russian methods. The expert assessment showed that materials which were used for the dynamic analysis of the construction interaction with the soil foundation do not contradict with requirements of the Russian standards. For the site under consideration, the following horizontal soil accelerations were accepted: A_{max} = 0.163g for SLE; A_{max} = 0.493g for DLE. Accelerograms and corresponding scale coefficients were accepted in accordance with STS. In order to calculate the impact referred to the lower border of the computational domain re-calculation of accelerations was carried out down to 50 m depth with consideration of the soil structure and its dynamic and dissipative characteristics. The calculation was carried out in accordance with the wave propagation theory.

5. ASSESSMENT OF THE BEARING CAPACITY OF THE FOUNDATION AND PLATFORM STABILITY

5.1. Soil conditions

The soil foundation was schematized as a packet of 11 layers, see Fig. 2. In the calculations, the soil layers were considered as sub-horizontal. Dimensions of a part of the soil foundation included in the calculation scheme amounted to 408 x 50.5 m.

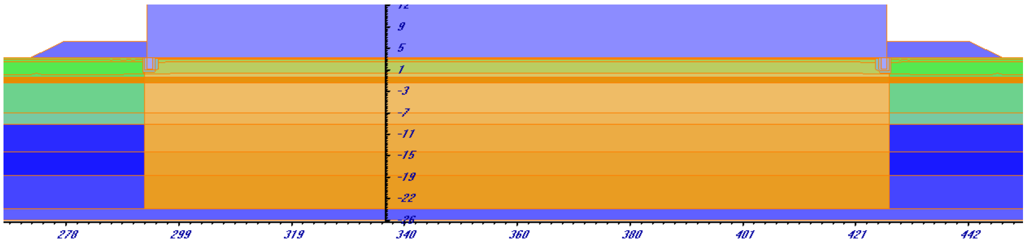


Figure 2. Design soil layers

Calculations for evaluation of the degree of influence of the soil strength and deformability on the magnitudes of possible foundation displacements were carried out on the basis of two sets of physical and mechanical characteristics. The first set of strength and deformation properties of the soils corresponded to the conservative design model; its parameters were identified at the initial stage of design works on the basis of field studies of soil properties. The second one – the major one on soil conditions – contained soil parameters specified on the basis of laboratory sample testing results. Design characteristics were assigned with consideration of soil reliability factors regulated by Russian standards.

Under cyclic loading, including seismic, strength of the soils under shifting goes down due to increase of the pore pressure. Reduction ratios of the strength parameters, recommended with consideration of the drainage conditions and character of loading, for calculation studies have been defined on the basis of dynamic laboratory tests of soils.

5.2. Calculation method

To assess the character of interaction between the gravity substructure and the soil foundation for various loading combinations including seismic impact, the following steps were carried out:

- Elaboration of a mathematical model of the “GBS – foundation” system with accounting of the engineering geological framework of the soil foundation;
- Assessment of SSS and the interaction between the bottom part of the platform and the soil foundation in accordance with the methodical instructions of the Russian standards (under seismic loading in common with accompanying ice loading);
- Calculated estimation of the deformation of the soil foundation, horizontal displacements, settlements, and tilts of the substructure.

All calculations were carried out in accordance with methods of the Russian regulating documents.

The DISK-Geomechanika program, developed at the Vedeneev VNIIG, was used to calculate SSS for the system with the finite element method (FEM). The computational domain was divided by the FEM mesh with 21 764 nods and 42 708 triangle elements. The finite element mesh had concentrations within the zone of contact between the caisson and the foundation and along the perimeter of the metal skirts (see Fig. 3).

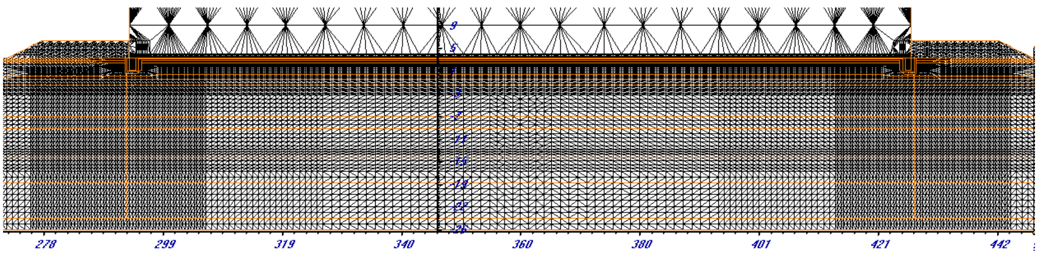


Figure 3. Fragment of finite element mesh

Analysis of the seismic resistance of the system was carried out for both calculations of SSS with use of inertia forces applied quasi statically, and for aggregate static and dynamic stress fields. Components of the dynamic stresses were determined using the linear-spectral theory (LST). The basic seismic impact was predetermined as an acceleration spectrum. Fifteen natural modes were accounted while calculating displacements, accelerations, deformations and stresses caused by dynamic loading. With that, depending on the natural period of vibrations, dynamic parameters of the system were predetermined by generalized standard spectral distribution curve.

Such setting of the problem with use of the standard dynamic response factors leads to overestimation of reactive loading on the system as compared to the reaction level in accordance with PSHA and give estimates with additional safety margins for stability and bearing capacity. Besides this, an assumption was made on the steel skirt present only along the GBS perimeter without intermediate rows; this also added to the stability reserve. Additional loading with rock banquet was also considered at the zone around GBS for protection of the surface from scour. The bearing part of GBS was modeled as a hard block.

5.3. Bearing capacity of the foundation and platform stability

Given that magnitudes of inertial loading of GBS, as well as intensity of pressure on the bottom of the sea, directly depend upon the construction weight parameters, calculations were carried out with variations of the construction mass. It is obvious that these loads for each particular calculating variant are stipulated by the ballast mass. Assessment results for displacement and stability are shown for the worst conditions of the construction operation. In other cases the system shall be characterized by higher bearing capacity.

Provision of the conditions regulated by Russian norms for a special load combination with seismic loads was the stability criterion. Calculated stability factor shall be no lower than the standard level for the 1st class constructions: for the SLE level of impact - 1.1875, for the DLE level of impact - 1.0625.

Stability factor was calculated with the use of the “Stability” program developed at the Vedeneev VNIIG. Verification of the system stability was carried out under assumption of a three-link polygonal shift surface. The shape of the middle link had been varied from a flat sliding surface to a convex curvilinear going up.

Stability calculations by accumulated SSS and the static field under application of the stress dynamic components calculated by LST showed that under the horizontal impact minimal value of the stability factor 1.21 is stipulated by the sliding surface which deepens into the foundation and goes through the V-layer in the most part. In case of such shift form implementation, the soil massive with depth of 9 – 11 m is included in the movement under the GBS bottom. The stability factor calculated under the inclined impact on the sliding surface going in the layer III A-B has the value 1.22.

Consequently, the construction stability meets the standard requirements.

Assessment of the bearing capacity of the foundation was numerically modeled by gradual intensity loading increase up to failure point and GBS stability loss. Initial calculation was carried out with gradual load increase up to the parameters of the design level; further on, taking the calculated SSS as the initial state, additional increases of horizontal loading and momentum up until the critical level was applied. In such calculations, sharp increase of calculated construction displacements or no convergence of the iteration process are manifestations of failure (Belkova et al, 2004). Appearance of a closed zone of plastic deformations and sharp increase growth of the foundation deformability show the practical exhaustion of the foundation bearing capacity. The calculations define both the mechanism of stability loss and numerical assessment of the reliability factor. The value of the overloading ratio achieved by the moment of failure was assumed as the stability factor.

SSS calculations showed that with growth of the loading, soils of the layers II and III are the first to go into the limit state. Under the horizontal seismic impact with 135% overloading plastic zones will emerge in the V clay layer. Under over than 131% loading increase, there will appear preconditions for formation of surfaces of possible sliding deepening into the foundation. Zones of plastic deformations in the III and V layers will merge under the 145% overloading making closed zones under the base with outcomes beyond GBS bottom. Merging of the plastic zones proves exhaustion of the foundation bearing capacity and increase of probability of a shift with foundation uplift along the deep form. Fig. 4 shows zones of plastic deformations developing in foundation soils under the special load combination with account for seismic impact for two variants of load on the system: 100% and 145% of the design impact.

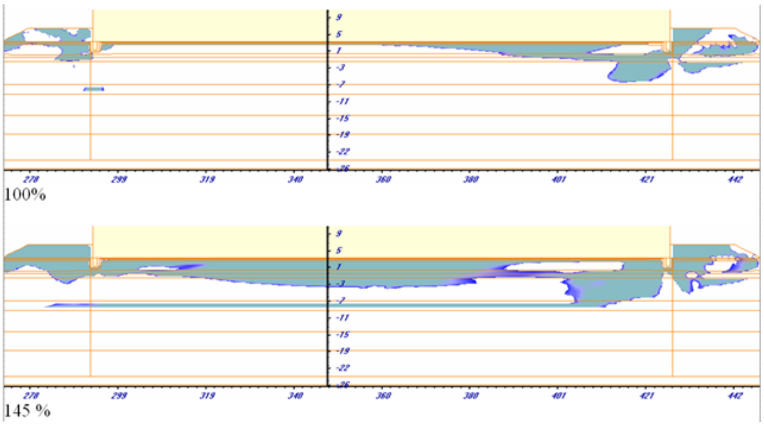


Figure 4. Plastic deformation zones under horizontal seismic loading

Sharp growth of horizontal displacements of the foundation is registered after the overloading level of 131% as compared to the level of calculated SLE impact. In this case, a surface shift along the base is formatted in the layer I. However, it should be mentioned that such scenario is quite hypothetical, as the model did not take into account the intermediate rows of skirts. Construction of the GBS bottom provides a higher reserve of stability in the contact zone as compared to the one calculated for assessment of the deformations.

Stresses transferred from the foundation soil to the skirt and bottom of the foundation slab under the impact of extreme loading were received from calculations of the system SSS.

5.4. Evaluation of the displacements and tilts

In case of the conceptual variant of the GBS weight, calculations were carried out under the horizontal and incline impact of seismic forces (two directions of the vertical component: up and down). Assessment of the scale of possible displacements of the support block was carried out with consideration of inertial loading from the upper construction under different damping options.

For the calculated combination corresponding to SLE, the following scales of GBS displacements were received depending on the direction of seismic forces: amplitude of the horizontal displacements 1.7÷3 cm; vertical displacements (settlements) of the center 2.9÷3.1 cm; tilt (difference between settlements of the slab edges) no more than 0.4 cm. At 145% overloading as compared to the design value of seismic impact, horizontal GBS displacements amounted to 20 cm, while the difference between displacements of the edges amounted to 2.5 cm.

A method giving conservative assessment of the situation was used for calculations of the GBS displacements. Assessment of the scale of construction displacements under the seismic impact was carried out through a non-linear dynamic analysis of a simple three-mass model with elastic-plastic connections. The calculated settlement was set as a sum of two components: of the immediate reaction of the foundation in the process of seismic impact and a settlement at the account of soil consolidation in the result of dissipation of excess pore pressure after an earthquake.

Estimation of the settlements showed that in time of an earthquake vertical displacements up to 65 mm could be expected; the residual vertical displacements under consolidation will not exceed 45 mm.

Estimation of residual displacements of GBS was carried out with use of accelerograms of seven strength level earthquakes for two values of the foundation stiffness. The calculated displacements are within the scale from 1 to 13 cm. Maximal displacements in the horizontal direction were registered in case of modeling for two of the seven impacts. They amounted to 11 and 13 cm correspondingly. The probability of the fact that residual displacements will not exceed 7 cm is estimated at the 82% level.

6. EVALUATION OF DEFORMATIONS AND CONSTRUCTION STRENGTH

6.1. Calculation procedure

Studies were carried out on three-dimensional mathematical models with the use of finite element method on the basis of the ANSYS and LS-DYNA calculation complexes (Glagovsky et al, 2011). The model, its components and the types of finite elements used are shown on Fig. 5, 6, 7. The soil foundation was modeled by an array with dimensions 260×200×51.5 m. Its side borders were predetermined on the consideration of optimal placement of non-reflecting borders. The bottom border of the model was set on the condition of no impact of the construction on the vibration process.

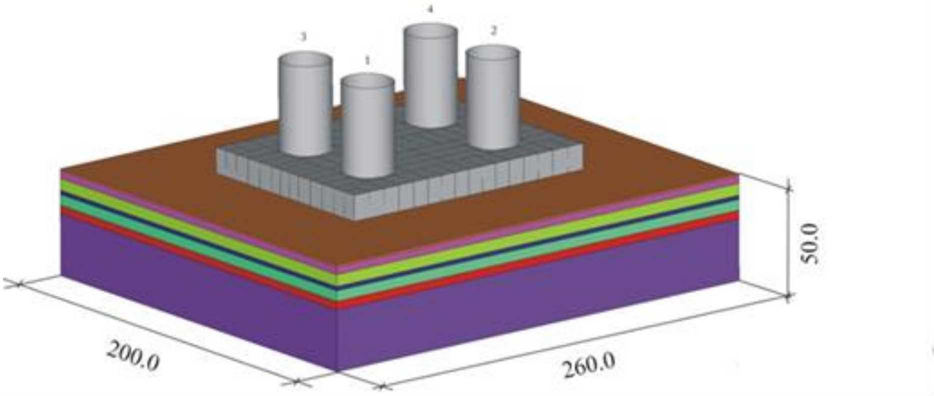


Figure 5. Model of the structure – foundation system

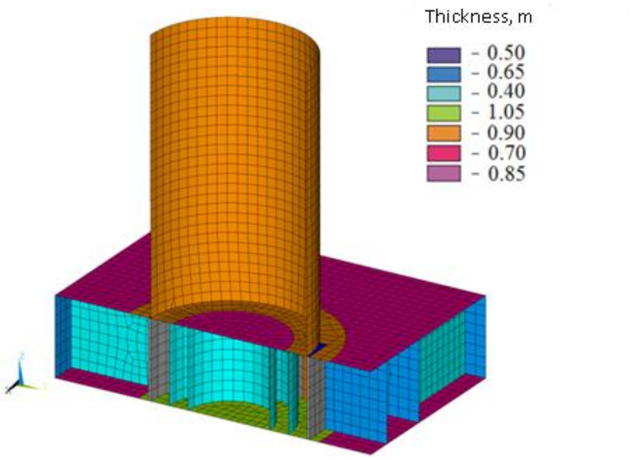


Figure 6. 3D fragment of the shaft model

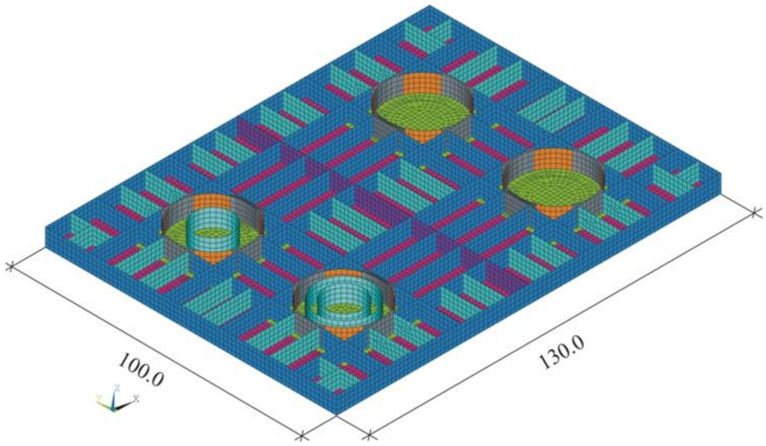


Figure 7. Caisson model section by a horizontal plane

According to the project, all contacting reinforced-concrete elements of the substructure (columns, the upper caisson slab, the bottom caisson slab, and diaphragms) are cast together in a monolith. Conditions of the bottom and soil displacements compatibility at the points of designed placing of the skirt were imposed; a non-linear contact of the caisson bottom and the soil was predetermined.

The stress-strain state of the construction under GBS own weight, the weight of the topside and hydrostatic water pressure was evaluated at the first stage of calculations and was considered as the initial state of the construction preceding its seismic loading.

The mass of water filling the caisson and columns and participating in the development of the inertia forces was distributed among the nods of the finite element mesh along the internal surfaces of the constructions. Hydrodynamic pressure of the water from the outside of the GBS construction in case of a seismic impact was considered as an added inertial mass distributed by the nods of the finite element mesh on the external surface.

Two models were considered: the case of a rigid connection of the upper construction with GBS and the case of seismic isolation in the form of frictional pendulous bearings. The full mass of the topside was considered for calculations of the construction without frictional pendulous bearings, while in case of accounting of the pendulous supports participation of the mass in the development of horizontal inertial forces was 40% reduced. This is a conservative value for constructions with curvilinear contact surfaces.

A dynamic problem with use of step by step integration of differential equations of movement was to be solved for consideration of seismic impact. Prestressing had not been introduced to the calculation combinations. The design prestressing was considered at the stage of verification estimating of the calculated reinforcing with the assessment of crack opening in the concrete. Reinforced concrete and soil massive were considered as elastic materials in these studies.

6.2. Major results

Seismic resistance studies showed that without seismic isolation in case of SLE the required strength level of the reinforced concrete foundation construction is provided in accordance with requirements of the Russian regulations, while in case of a DLE the strength conditions will not be met.

In case of DLE, considerable compressing stresses were registered, mostly in the contact zone of the support columns and the caisson. Reliability of GBS construction depends of the strength of the column-caisson fixing units; this is even more so in case of their alternating-sign stressed state under a seismic impact. Emergence of these vulnerable zones might lead to destruction of the concrete.

On Fig. 8 a), b) development in time of main stresses at the joint of shaft with the top slab of the caisson for two ductility level earthquakes is shown.

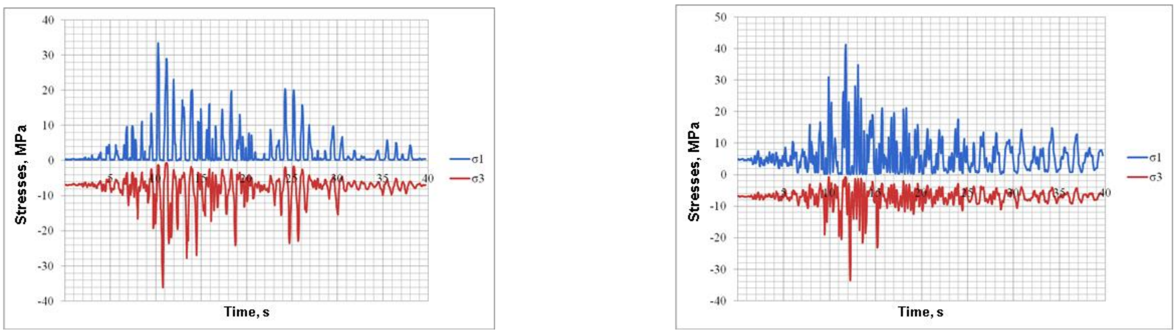
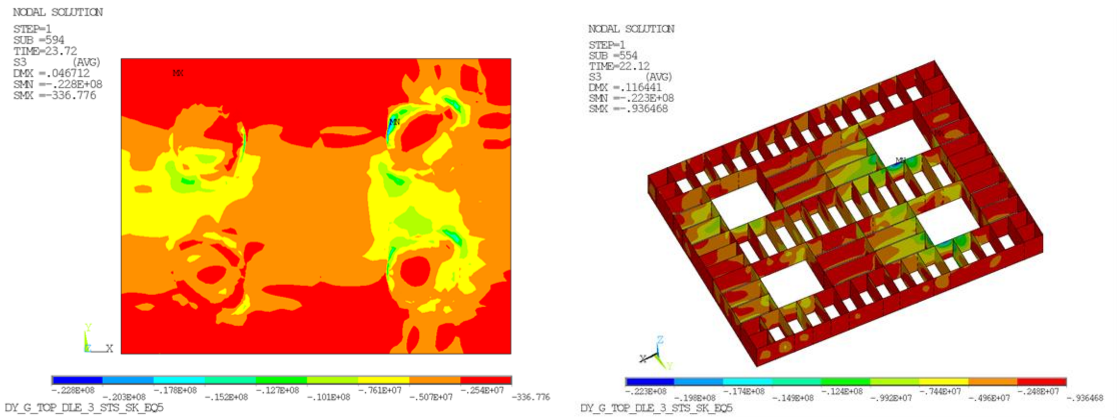


Figure 8. Maximum tension in the shaft (σ_1) and accompanying compression (σ_3)

Fig. 9 shows as the illustrations the fields of the main stresses σ_3 in structural elements of GBS at DLE. Fig. 10 shows the fields of main stresses in fragments of shafts in their mating zones with the top slab of the caisson at the moment of their maximum stresses at DLE. The high level of stresses is obvious. The analysis showed that the strength condition is not satisfied here.



slab at 23.72 sec

bulkheads at 22.12 sec

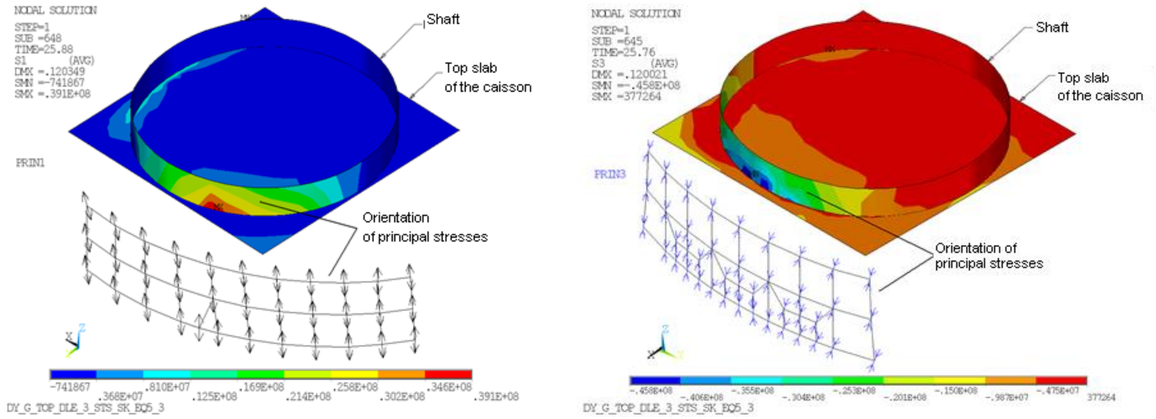
Figure 9. Minimum main stresses σ_3 under seismic impact of DLE level (Pa)

In case of presence of frictional pendulous bearings, noticeable reduction of the magnitudes of stresses under the seismic impact as compared to the option of rigid anchorage of the upper construction to the GBS support columns was registered. Zones of increased compressing stresses at the tie-in points of columns and caissons were localized and caused not danger to the general strength of the contact. In this case, maximal compression at the tie-in points of columns and caisson was caused by ice loading.

All complex of the executed researches has allowed us to substantiate seismic stability of the platform. According to Russian regulations, strength of the reinforced concrete construction of a gravity type platform is provided.

7. CONCLUSION

The paper describes the application of the developed technique of a design substantiation of seismic stability of a structure in the conditions of severe climate and high level of seismicity. The project of gravity platform on Sakhalin offshore zone is taken as an example.



σ_1 at 25.88 sec σ_3 at 25.76 sec

Figure 10. Zones with main stresses under seismic impact of DLE level at the shaft joint with the top slab of the caisson (Pa)

REFERENCES

Belkova, I.N., Bellendir, E.N., Glagovsky, V.B., Prokopovich, V.S. and Vekshina, T.Yu. (2004). On evaluation of bearing capacity of foundations of gravity platforms on shelf (in Russian). *Izvestiya Vedeneev VNIIG* **243**, 45-55.

Bellendir, E.N., Finagenov, O.M. and Glagovsky, V.B. (2004). Basic Issues of the Design of Support Elements of Gravity Platforms on Sakhalin Shelf. *Sixth ISOPE Pacific/Asia Offshore Mechanics Symposium, Vladivostok, Russia*, 12-19.

Bellendir, E.N., Finagenov, O.M. and Glagovsky, V.B. (2006). Conceptual Risk Assessment of Offshore Structures. *Sixteenth International Offshore and Polar Engineering Conference, San Francisco, USA*. **Vol IV:** 411-417.

Bellendir, E.N., Finagenov, O.M. and Glagovsky, V.B. (2007). Hazard Analysis of Failures on the Substructure of Stationary Offshore Platform. *Seventeenth International Offshore and Polar Engineering Conference, Lisbon, Portugal*, 3713-3717.

Bellendir, E.N., Finagenov, O.M. and Glagovsky, V.B. (2010). Selection of the optimal structural solutions of reinforced concrete gravity base substructures for platforms on Sakhalin shelf. *The 20th International Offshore and Polar Engineering Conference, Beijing, China.*

Bellendir, E.N., Glagovsky, V.B., Kotov, A.V. and Malyutin, A.A. (2000). Experience of a substantiation of design of gravity type platforms for soil conditions of Sakhalin island shelf (in Russian). *Izvestiya Vedeneev VNIIG* **238,** 96-100.

Bellendir, E.N., Glagovsky, V.B., Lipovetskaya, T.F., Mischenko, S.M. and Sapegin, D.D. (1999). Standard base for designing of the bases of hydraulic engineering constructions on a shelf. The analysis and offers on perfection (in Russian). *The 10th International Conference RAO / CIS Offshore 1999, St.Petersburg, Russia*. **Vol 2:** 239-246.

Finagenov, O.M. and Glagovsky, V.B. (2005). Assessment of Reliability of Offshore Marine Hydraulic Structures under Seismic Impacts. *Fifteenth International Offshore and Polar Engineering Conference, Seoul, Korea*. **Vol IV:** 407-412.

Glagovsky, V.B. and Finagenov, O.M. (2004). The analysis of seismic impacts on shelf hydraulic engineering constructions (in Russian). *International Geotechnical Conference, Almaty, Kazakhstan*, 631-635.

Glagovsky, V.B. and Finagenov, O.M. (2011 a). Approaches to substantiation of project solutions for fixed oil and gas production platforms at Sakhalin shelf (in Russian). *The 10th International Conference RAO / CIS Offshore 2011, St.Petersburg, Russia*, 250-254.

Glagovsky, V.B. and Finagenov, O.M. (2011 b). Constructions on a continental shelf (in Russian). *Hydrotechnical Construction* **9,** 95-102.

Glagovsky, V.B., Kassirova, N.A., Turchina, O.A., Finagenov, O.M. and Tsiruchin, N.A. (2011). Computation researches of seismic stability of the support substructure of an oil and gas platform (in Russian). *Hydrotechnical Construction* 7**,** 29-35.