Analysis of seismic stability of large-sized tank VST-20000 with software package ANSYS

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Abstract. The work is devoted to the study of seismic stability of vertical steel tank VST-20000 with due consideration of the system response "foundation–tank–liquid", conducted on the basis of the finite element method, modal analysis and linear spectral theory. The calculations are performed for the tank model with a high degree of detailing of metallic structures: shells, a fixed roof, a bottom, a reinforcing ring.

1. Introduction

The problem of seismic stability of vertical steel tanks for oil storage has been relevant for a long time, as there is a need to provide conditions for safe operation of existing and planned structures in zones with high seismic activity.

Tanks carry a large mass of fluid, ten times the weight of the structure itself. The correct account of convective and impulsive components of the fluid, the structure of the tank, loads and parameters of the soil in the calculation while calculating seismic resistance of VST are a very complicated scientific problem.

The most earthquake-prone areas of Russia are mostly the Caucasus and the Far East with major oil storages. However, the activities of national oil companies have recently been registered around the world: in the Asia-Pacific region, South America, Europe, all marked with devastating earthquakes. Therefore, researches aimed to improve calculation methods of seismic stability of large-sized vertical steel tanks are especially in demand.

The present paper suggests implementing a basic framework of the linear-spectral method of seismic stability calculation, which uses the principle of converting the system to the normal coordinates. It allows bringing a linear dynamic system with N degrees of clamping to N independent systems with one degree of clamping (oscillators). Each oscillator has its own frequency and energy parameters corresponding to one of the self frequencies and vibration modes of the original system. This type of converting allows defining the magnitude response of the given systems with one degree of clamping with the help of a response spectrum and further obtaining the response acceleration due to back-transformations, the inertial forces and displacements in the source system.

The main advantage of this method is that the underlying spectrum of response can be obtained by synthesizing a variety of accelerograms of real earthquakes. Furthermore, the more they were considered when building a spectrum of influence, the less likely the load on the tank will exceed the expected one during a new earthquake. The novelty of this work is that the authors have obtained...
values of stresses that occur during earthquakes with magnitude of 7, 8, 9 points, depending on the degree of fullness of the tank. The design scheme without significant simplifications of the structure, the properties of the stored product and actual loads were proposed for the first time.

2. Methods

To analyze the seismic stability of tank VST-20000, constructed due to standard design 704-1-60 (D = 45.6 m, \(H_{sh} = 12\) m), the authors performed a modal analysis so as to determine self frequencies and vibration modes of the structure. Applying software ANSYS [1], the authors developed and verified a geometric tank model in [2], which also confirmed the accuracy of the calculations for static problems. Next, the authors conducted the optimization and export to modules "Modal" and "Response Spectrum". Due to the fact that in the process of modal analysis, the self frequencies of the VST structures are determined, it is important to consider all the available metal structures, receiving the load. Many works are marked by assumptions; in the part that simplifies the top node of the tank – the roof is not modeled, though restrictions are imposed on the movement of the top edge of the shell. However, the authors in [3] have proved that this is not acceptable as it distorts the real stiffness of the structure and the results are not consistent with real observations. Therefore, this work considers the system "tank-liquid-foundation" as a single system taking into account all of the constructive elements.

Let us consider the basic steps of the modal analysis of VST-20000.

A geometric model of VST-20000 is developed that includes metal shells, a fixed roof, edges, the central part of the bottom, a support ring; a reinforced concrete foundation ring; the stored oil. The model defines the properties of the materials: tank steel 09G2S with cold flow \(\sigma_{v.d.} = 325\) MPa, oil (density - 865 kg/m\(^3\), sound speed in the medium - 1348 m/s, dynamic viscosity - 8.9 \times 10^{-4}\) cPs); metal structures are modeled by finite elements SHELL181, BEAM188, SOLID186; oil stored in the reservoir is modeled by tetrahedral elements FLUID80.

The calculation is performed for five cases of VST being empty, filled by 1/3 \((H_f = 3.63\) m); 1/2 \((H_f = 5.44\) m); 2/3 \((H_f = 7.25\) m), and filled to the top-level \((H_f = 10.88\) m).

Boundary conditions take into account an elastic fixation (on the model of Winkler) of a reinforced concrete foundation ring and sheets of the central part of the bottom on the lower plane, the properties of which are set by elastic coefficient \(k = 200\) mN/m\(^3\) (for argillo-arenaceous artificially consolidated soil).

Contact of shells and the bottom with the liquid is set within the parameters of the frictional slip – "no separation" that allows simulating the slip of the liquid along the shell and the bottom in case of vibrations during an earthquake.

According to [4-5] and the obtained results of the modal analysis of the VST-20000, the most devastating effects are observed at a frequency of 0 up to 50 Hz. At this frequency, the greatest contribution is introduced with the impulsive (inertial) and convective (kinematic) components of the hydrodynamic pressure, so the most unfavorable case is a design scheme with a tank filled with oil to the top.

The next step includes the compilation of responses, calculated from the obtained values of natural modes and vibration frequencies of the structure (and the stored fluid). It is necessary for the linear-spectral analysis of the seismic impact. The method of modes combinations SRSS is used (Square Root of Sum of Squares), which takes into account the contribution of every vibration mode in the overall system. This method gives a reliable estimate if the natural resonance frequencies differ greatly from each other (in this case the frequencies vary from 0.66 to 50 Hz).

To specify the external seismic forces, generalized broadband seismic response spectra recommended in [6], are applied. Dependence of the horizontal and vertical accelerations of the soil on the wave frequency in the range from 0 to 50 Hz for earthquake intensity of 7, 8, 9 points due to the MSK-64 scale is described in the previous work of the authors [3]. For areas with a 6-mark and below seismicity, it is not required to take into account the seismic loads [7]. The logarithmic decrement of the vibrations is assumed to be \(\delta_{v.d.} = 0.31\) for a welded steel construction according to [8]. The value
of the vertical components of acceleration decreases by a factor of 0.67 from the values of horizontal component X, Y in accordance with [9].

The design scheme of fully-filled tank VST-20000, which is located on the elastic Winkler foundation, is shown in Figure 1.

Figure 1. The design scheme for the analysis of seismic resistance of VST-20000: $A_x$, $A_y$, $A_z$ – components of horizontal and vertical accelerations under seismic loads.

### 3. Results and Discussion

Figure 2 shows the calculation results of the most indicative self-resonant frequencies of VST-20000, completely filled to the design level. On the whole, 400 modes were considered in calculations, the figure shows distribution diagrams of total deformations with the first, second, sixth and thirteenth wave forms with self-resonant frequencies that equal 0.66; 1.14; 1.87; 2.43 Hz respectively.

![Figure 2](image)

Figure 2. Distribution diagrams of deformations VST-20000 (in section), filled to the full up to $H_f = 10.88$ m: a, b, c, d – first, second, sixth and thirteenth wave forms with self-resonant frequency respectively that equal 0.66; 1.14; 1.87; 2.43 Hz respectively.
Table 1 shows the calculation results of self-resonant frequencies in three cases of VST filling for the first 10 vibration modes.

**Table 1. The calculation results of self-resonant frequencies of VST-20000**

| VST filling             | Natural resonant frequency, Hz (№ vibration modes) |
|-------------------------|----------------------------------------------------|
|                         | I | II | III | IV | V | VI | VII | VIII | IX | X |
| Empty tank              | 0.16 | 0.19 | 0.23 | 0.28 | 0.31 | 0.38 | 0.41 | 0.51 | 0.64 | 0.7 |
| Tank filled by 2/3 Hf=7.25 m | 0.62 | 1.31 | 1.34 | 1.61 | 1.64 | 1.79 | 2.15 | 2.3 | 2.5 | 2.6 |
| Fully-filled tank Hf=10.88 m | 0.66 | 1.14 | 1.2 | 1.42 | 1.45 | 1.87 | 1.96 | 2.13 | 2.29 | 2.35 |

The results of a numerical calculation conducted in software module ANSYS "Response Spectrum", allowed one to determine that the case of complete filling of VST-20000 up to the level of 10.88 m is the most dangerous. So, unacceptable stress in 6-8 horizontal belts of the shells appear due to the 9-mark seismic impact according to the MSK-64 scale that reaches the value of 420 MPa (Figure 3). The cold flow of tank steel 09G2S is \( \sigma_{cf} = 325\text{MPa} \).

![Figure 3](image.png)

*Figure 3. The distribution of equivalent stresses in the structures of completely filled VST-20000 at the 9-mark earthquake according to the MSK-64 scale.*

When reducing the intensity of seismic impacts, as well as reducing the amount of stored oil, the values of stresses within the metal tank are reduced. Current equivalent stress in structural elements does not exceed the value of 38 MPa even with the 9-mark earthquake in the empty RVS-20000 tank.

The authors obtained dependences of maximum stresses in steel structures on the amount of oil loading during earthquakes with a magnitude of 7, 8, 9 points (Figure 4).

### 4. Conclusion

The application of a linear spectral analysis to estimate the seismic forces on large vertical steel tanks is the most optimal method in solving practical problems, as it takes into account the parameters of natural vibrations of the fluid and the VST structure itself, the maximum number of spectra effects is involved due to really happening earthquakes. This allows simulating the most unfavourable cases of earthquakes in accordance with regulations in [4, 7-10].
Figure 4. Dependence of maximum stress in the neutral layer of the shell in VST-20000 at the height of the oil loading under seismic impacts with magnitude of 7, 8, 9 points.

The maximum stress in the metal structures of VST-20000 in all the studied cases are deployed in zones of 5-8 belts of the tank shells. In contrast to the earlier studied Vertical Steel Tank with floating roof-50000 that is marked by the maximum stress level at height of 1-2 belts under seismic excitation in the present work, a tank with a fixed roof has other rigidity parameters. This confirms the assertion of the authors [3], according to which, when calculating the stress-strain state in a non-axisymmetric setting, the simplification of the geometry (the introduction of restrictions on the degrees of freedom for the elements of the upper edge of the shell) in the top node of the tank is unacceptable.

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References
[1] Korobkov G E, Zaripov R M and Shammazov I A 2009 Numerical modeling of the stress-strain state and stability of pipelines and tanks in complicated operating conditions (St. Petersburg: Nedra) p 410
[2] Tarasenko A, Chepur P and Gruchenkova A 2018 Advances in Intelligent Systems and Computing 692 936-943
[3] Chirkov S, Tarasenko A and Chepur P 2017 IOP Conference Series: Earth and Environmental Science 90 012102
[4] GOST 53166 2009 Earthquake. The influence of natural external conditions for technical products (Moscow: Standartinform) p 24
[5] Belostotskiy A M, Akimov P A, Kaitukov T B, Afanasiev I N, Vershinin V V, Dmitriev D S, Usmanov A R, Chugunov A S and Shcherbina S V 2014 Structural mechanics and calculation of structures 5(256) 21-28
[6] Sinelschikov A V, Panasenko N N and Sinelschikova L S 2012 Herald of Astrakhan state technical University 1 66–74
[7] STO SA 03-002-2009 2009 Rules for the design, manufacture and installation of vertical cylindrical steel tanks for petroleum and petroleum products (Moscow: Rostekhekspertiza) p 331
[8] NP 031-01 2001 *Norms of designing earthquake-resistant nuclear power plants* (Moscow: Gosatomnadzor of Russia) p 25

[9] SP 14.13330.2014 2014 *Construction in seismic areas. The updated edition of SNiP II-7-81* (Moscow: The Department of construction and housing utilities of the Russian Federation) p 13

[10] RTM 108.020.37-81 1981 *Equipment of nuclear power installations. Strength calculation under seismic excitation* (Saint Petersburg: The Department of power engineering) p 37