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## **DESIGN PECULIARITIES OF OIL STORAGE TANKS IN COMPLEX GEOTECHNICAL CONDITIONS AT SEISMIC EFFECTS**

*Problematic issues of construction and operation of oil storage vertical steel tanks in complex geotechnical conditions, including the seismically unstable territories are systematized. The technique of seismic danger decreasing (increasing the seismic stability of the ground) for ensuring the accident-free operation of tanks during earthquakes of various intensities is proved.*

*The practical experience of design solutions of the highly effective systems «man-made grounds – foundation – tank» in complex geotechnical conditions for static and dynamic effects (earthquakes, emergency technogenic loadings, etc.) is given.*

**Keywords:** *seismic effects, seismic resistance, oil storage tank, complex geotechnical conditions, man-made grounds, soil-cement elements.*

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## **ОСОБЛИВОСТІ ПРОЕКТУВАННЯ НАФТОВИХ РЕЗЕРВУАРІВ У СКЛАДНИХ ІНЖЕНЕРНО-ГЕОЛОГІЧНИХ УМОВАХ ПРИ СЕЙСМІЧНИХ ВПЛИВАХ**

*Систематизовано проблемні питання будівництва та експлуатації нафтових вертикальних сталевих резервуарів у складних інженерно-геологічних умовах, у т. ч. на сейсмічно небезпечних територіях. Обґрунтовано методику зниження сейсмічної небезпеки (підвищення сейсмічної стійкості ґрунтової основи) з метою забезпечення безаварійної експлуатації резервуарів у разі землетрусів різної інтенсивності.*

*Наведено практичний досвід проектних рішень вискоєфективних систем «штучна основа – фундаменти – резервуар» у складних геотехнічних умовах для статичних і динамічних впливів (землетрусів, аварійних техногенних навантажень тощо).*

**Ключові слова:** *сейсмічні впливи, сейсмостійкість, нафтовий резервуар, складні інженерно-геологічні умови, штучна основа, ґрунтоцементні елементи.*

**Introduction.** The development of the oil and petrochemical industry is connected with the necessity of building a significant number of storage tanks for raw materials and completed products. Vertical steel tanks (VST) are the constructions that provide not only the storage of oil and oil products in raw material bases, refineries but the safety and continuity of supply of products in main trunk pipeline system also. At the same time tanks are constructions of an increased danger. The accidents with tanks are followed by a flood of huge mass of liquid that can lead to catastrophic consequences with losses of human lives, due to violation of normal modes of operation the objects of transportation and storage of oil and oil products, and to significant environmental pollution and serious economic consequences also.

Construction areas for VST are often characterized by complex geotechnical conditions. For example, on soft soils which are widespread in the territory of Ukraine. The increasing of volumes of VST construction has been observed. At the same time pressure which is transferred to the ground also considerably increased. Therefore, the cost of modern VST has considerably increased in complex geotechnical conditions. The possibility of maintaining the design production requirements also becomes more complicated as its operation due to ground differential settlements. That's why it is necessary to create new geotechnical technologies that would minimize risks and provide accident-free operation of modern VST, especially in complex geotechnical conditions.

In the territory of Ukraine, including its platform part, there are danger local strong earthquakes reaching more than 5 points (more than 6 points on MSK-64 scale) according to the modern seismological researches [1]. It creates additional danger of operation of the existing and new oil storage tanks.

During the design of oil storage tanks which are objects of the increased responsibility according to Ukrainian codes [2] it is necessary to consider 1% probability of excess the calculated seismic intensity within 50 years. This factor increases the possibility of accident-free operation and respectively a cost and complexity of construction of these engineering constructions. It is necessary to carry out additional calculations and to develop the relevant constructive decisions on minimization of risks during accidents in case of an earthquake.

**Analysis of recent sources of research and publications.** The analysis of world and domestic experience of usage the various methods of decreasing the dynamic and vibration effects on soft soil [2 – 8] has shown that the most effective option for its transformation is cementation by the means of jet or mixing technologies. The primary feature of these technologies is that they allow strengthening practically all soil types. At the same time there is destruction and simultaneous soil mixing with cement in the «mix-in-place» mode. During soil reinforcing there are strong connections between firms particles are being established. These connections increase the soil strength and reduce the soil compressibility.

The effect of such soil reinforcing is that a certain volume of soft soil is replaced by low compressibility material (soil-cement with big module of deformation,  $E=70-200$  MPa). The natural soil is clamped between vertical soil-cement elements also raises its mechanical characteristics due to impossibility of lateral expansion. The module of deformation of the man-made grounds is considered to be average value between soil-cement and nature soil [5, 7, 11, 12]. Its value can be regulated due to change of distance between such elements.

**Identification of general problem parts unsolved before.** Nowadays there is almost no experience of oil storage tanks operating in the complex geotechnical conditions on man-made grounds, especially under the action of dangerous geological phenomena like earthquakes.

Building the responsible structures in complex geotechnical conditions taking into account seismic effects is one of the most difficult tasks of geotechnics. Therefore, **the aim of work** is the analysis of geotechnical solutions of construction of RVS on collapsible and soft soil in seismic areas and development of an effective type of the seismic resistance man-made grounds.

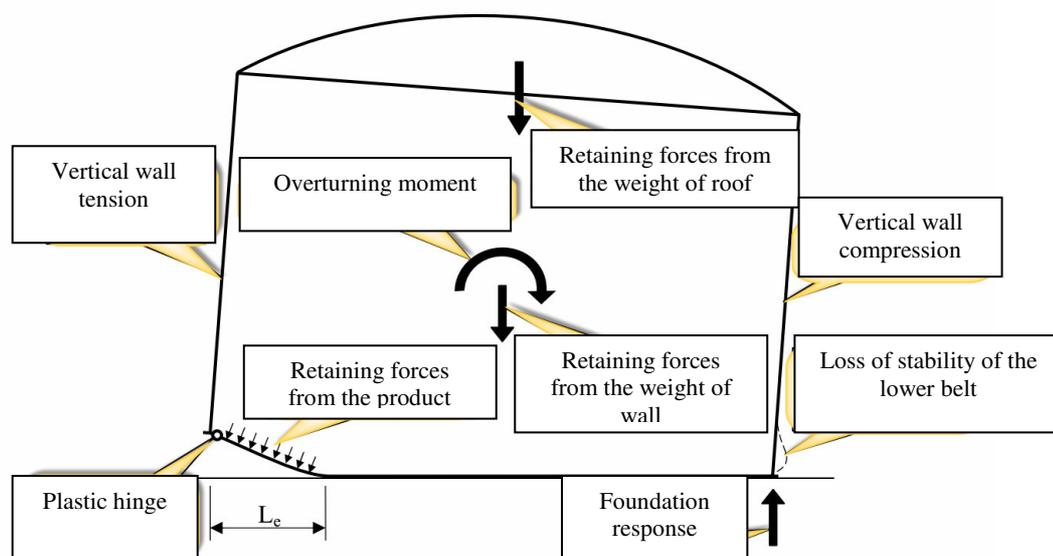
**Basic material and results.** VST in the normal mode of operation are in complex stress-strain state (SSS). The SSS of the VST elements arises at the stage of construction and installation works. Further stress increasing in tank elements is a consequence of the operational loadings (hydrostatic, overpressure, vacuum, snow, wind and temperature load). Consequence of stress increasing is the ground differential settlements on area and perimeter of tank foundation. Therefore, for providing production operational requirements for oil storage tanks on soft soil it is necessary to use the pile foundation or different types of man-made grounds.

During the design of tanks in seismic areas with intensity higher than 6 points it is necessary to consider the additional requirements: 1) use of tanks with lower height; 2) in tanks with a floating roof or a pontoon to apply locks of soft type; 3) in case of usage the tanks with a stationary roof it is necessary to carry out calculation of the maximum height of filling of the tank with liquid to avoid hydrodynamic blow in a roof the wave arising in the tank from a horizontal push, and others. For tanks with a floating roof or a pontoon one should consider horizontal inertial forces from a floating roof or a pontoon.

Tanks need to be calculated on a resistance to overturning and displacement from wind loads, on differential settlements of ground and on seismic effects. Tanks foundation calculated for two groups of limit states: 1) ultimate limit state – on the bearing capacity for check of stability of tanks on overturning; 2) serviceability limit state – on deformations (absolute vertical settlements of the center and a contour circle of the foundation, differential settlements of ground taking into account local moistening of collapsible thickness, tilt). Calculation of ground bearing capacity, the vertical settlements, tank tilt is similar to other buildings and structures according to requirements of norms [9]. Medium settlements of the contour circle of the foundation for tanks up to 30000 m<sup>3</sup> should be no more than 20 cm, for tanks with volume 30000 m<sup>3</sup> and above – no more than 30 cm [10].

The total design scheme for determination seismic resistance of the tank is shown in Fig. 1.

In earthquakes conditions there is an addition to external vibrations further load of the product on the wall and bottom of the tank, namely: 1) hydrostatic loads and loads of overpressure; 2) impulsive (inertial) component of hydrodynamic pressure; 3) convection (kinematic) component of hydrodynamic. The impulsive component of pressure arises from a part of the product moving in an earthquake together with a tank wall. Fluctuations of liquid in the tank create convective pressure and leads to emergence of waves on a product surface. Vertical fluctuations of a tank ground also induce additional load of his wall.



**Figure 1 – Design scheme to determine seismic resistance of the tank**

Tank's seismic resistance is considered to be reached if: a) the tank doesn't overturn during an earthquake (overturning criterion is the limit state at which on the external radius of the lifted part of the bottom a full plastic hinge appears); b) stability of the lower belt of a wall at action of longitudinal and cross loading is provided; c) durability condition for all bearing elements of the tank is provided.

The main author's idea is development of the universal man-made grounds which will be able to provide standard and production requirements for oil storage tanks on soft soil as for static service conditions and in case of action of seismic influences of various intensity.

Reduction of dynamic load influence by a superstructure in case of earthquakes can be reached due to reduction of the ground acceleration and vibration amplitude. One of options of reduction the seismic intensity is an increasing the seismic rigidity  $V_{s\rho}$  of an active soil layer due to increase the speed of distribution in it seismic waves. Such effect can be reached due to increase the ground elastic deformation characteristics using soil mixing technology [4, 8]. At such approach it is possible to raise the ground module of elasticity to 500 – 2000 MPa, the speed of waves distribution to 600 – 1000 m/s at the constant density.

For example, there are given geotechnical solutions of the oil storage tank. Technological parameters of the tank are given in Table. 1. Geometrical tank parameters: 1) nominal volume 20000 m<sup>3</sup>; 2) gross space 20956 m<sup>3</sup>; 3) wall height 17,926 m; 4) inside diameter 39,9 m; 5) product-surface area 1250,4 m<sup>2</sup>.

The foundation diameter is about 40,5 m. The pressure under the foundation at hydro testing is 168,14 kPa, at operation – 180,86 kPa. Uniformly distributed load on a base contour at hydrotesting is 31,65 kN/r.m., at operation – 40,33 kN/r.m., at wind load – ±6 kN/r.m., at seismic influence – +353,73/ -268,67 kN/r.m. The value of the seismic horizontal forces that transmitted to the tank foundation is 65500 kN.

**Table 1 – Technological parameters of oil storage tank**

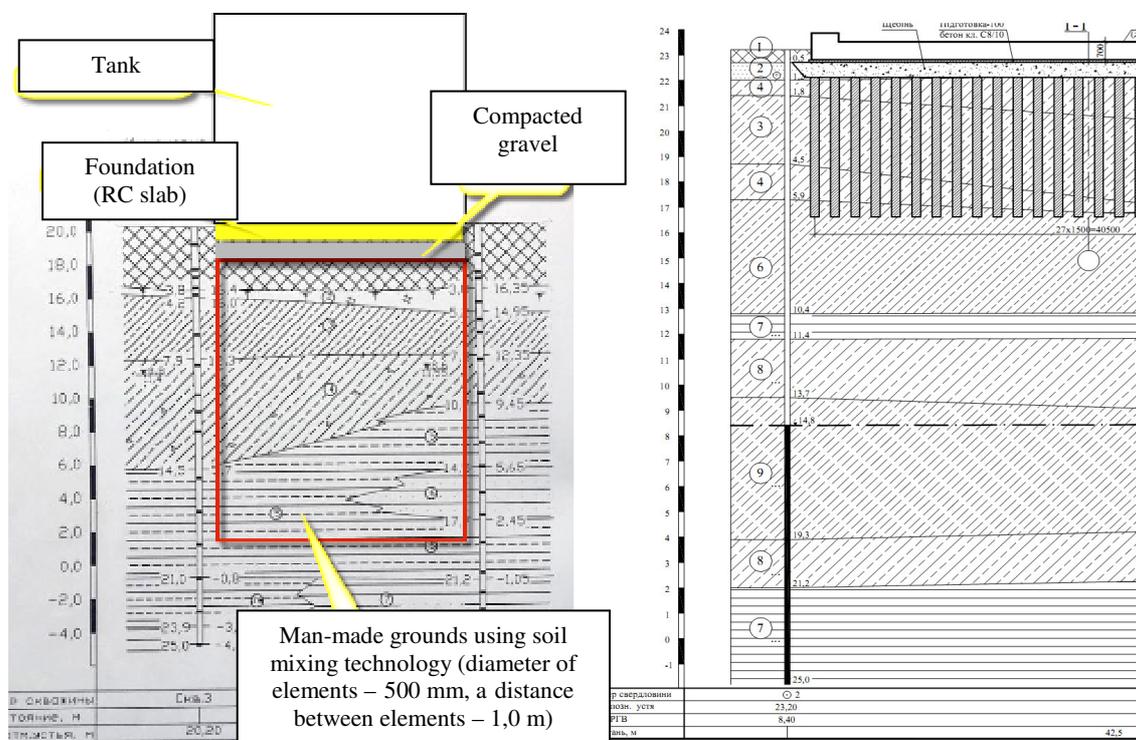
Parameters	Value
Product density (oil), t/m <sup>3</sup>	0,89
Expected level of product filling, m	16,2
Water level at hydrotest, m	16,75
Internal overpressure	missing
Standard internal vacuum	missing
Operation rate (cycles per year), min/max	20/100
Characteristic value of snow load, kg/m <sup>2</sup>	102
Characteristic value of wind load, kg/m <sup>2</sup>	51
Seismic intensity, points	8
The temperature of the coldest days with the use factor 0,98, °C	– 24
Maximum temperature of oil storage, °C	+ 25
Design service life, years	40
Design wave altitude of oil at seismic loadings, m	0,32
The size of an allowance for corrosion for sheets of a wall, mm	0

Two sites with complex geotechnical conditions are considered. Level of ground waters is at a depth of 8,6 – 8,8 m from Earth's surface level. Complexity of the first site is characterized by soft loams and sandy loams (the module of deformation is  $E = 3 – 5$  MPa) of 12 – 13 m thickness at 7,6 m depth. Below a depth of 21,7 – 23,9 m there are solid and semi-

solid clay (Fig. 2). Soft soil during seismic influences could be liquefied (thixotropic properties), to receive additional consolidation therefore, there will be additional deformations of the foundation tank. Complexity of the second site lies in the existence of collapsible thickness more than 5 m. Soil seismic properties category is III. Standard seismic intensity of construction sites is 8 points (according [2]), calculation – 9 points.

In such conditions such geotechnical options were considered: 1) penetration of soft and collapsible soil thickness using piling foundation (a section of 350×350 mm), dynamic deep soil compaction in space between piles (a diameter of elements is 300 mm), concreting pile cap of 0,7 m thick, piles connection with a cap is hinged; 2) the same, as in the first option, but over the piles is compacted gravel for the purpose of damping of the tank fluctuations and for avoidance of transfer of horizontal loads on piles; 3) reinforcing of soft and collapsible soil by vertical soil-cement elements with a diameter of 500 – 650 mm (man-made grounds using soil mixing technology), further the same, as in the second option.

Perception of horizontal seismic loading due to work of piles is provided only at their significant amount (~ 1000 pieces). It is economically inexpedient as vertical load of piles will make no more than 35% of admissible. Therefore this option wasn't compared further.

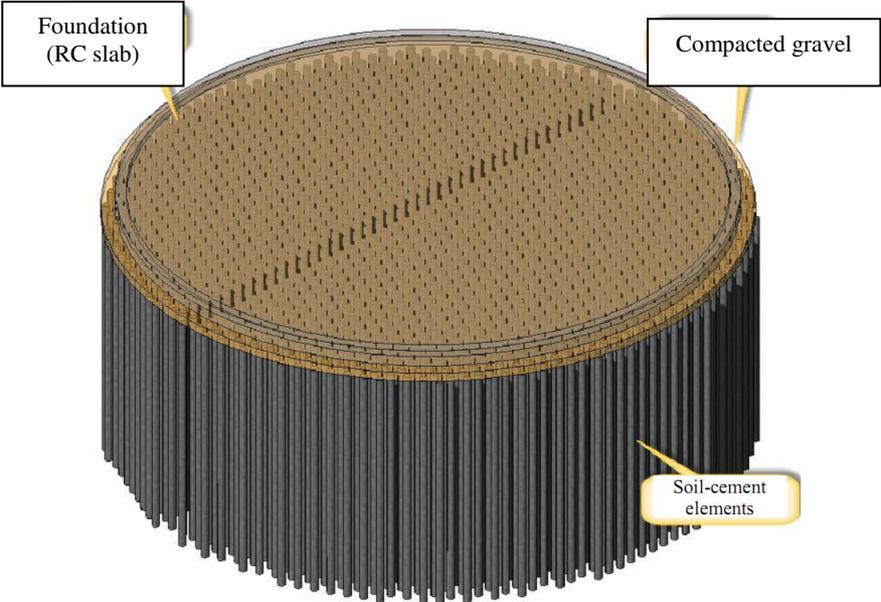


**Figure 2 – Soil profiles (left – soft loams and sandy loams of 12 – 13 m thickness; right – collapsible thickness more than 5 m)**

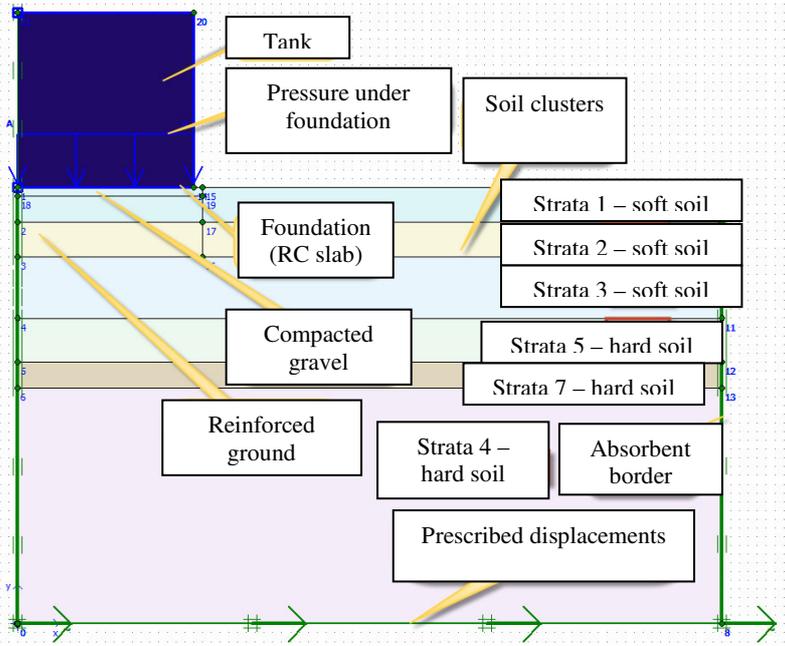
Option with vertical soil-cement elements was much cheaper and it was possible to implement it faster.

Length and diameter of soil-cement elements and distance between it were defined by an iterative method. Providing smaller critically admissible values of the settlement of center and extreme foundation points, tilt, and the ground bearing capacity at seismic influences was the main criterion of calculation. As a result of calculations it is established that optimal diameter of elements – 500 mm, a distance between elements – 1,0 m (2d). Informative geotechnical model of the tank is shown in Fig. 3.

The SSS modeling of the «soil – reinforced ground – compacted gravel for damping – foundation – tank» system is carried out. The problem was solved in 2D («axisymmetric») scheme using the finite elements method (FEM), taking into account seismic effects. The soil, the man-made grounds and crushed-stone pillow are clusters with the appropriate characteristics. The foundation is a beam element with the corresponding flexibilities EI and normal rigidness EA for a plate 0,7 m thick. The tank is beam elements; oil is a cluster with the appropriate characteristics. The design axially symmetric scheme is provided on Fig. 4.



**Figure 3 – 3D design scheme of the system «reinforced base – crushed stone pillow – foundations»**



**Figure 4 – Design axially symmetric scheme of the system «soil – reinforced ground – damping compacted gravel – foundation – tank»**

The sizes of a calculation zone around a construction were accepted from a condition of prevention of its influence on results. The depth of the calculation zone is 50 m (on this depth there is a rocky or semi-rocky deposits). The fluctuations at the bottom boundary in the form of an earthquake acceleration diagram are set (with the parameters corresponding to intensity of seismic influences in 9 points). At the far vertical boundaries, absorbent boundary conditions are applied to absorb outgoing waves. In this way the boundary conditions as described above are automatically generated. For soil was using linear model. Influence of hydrostatic water pressure using appropriate ground water level. Damping of the building and the ground is simulated by means of Rayleigh's coefficients. The horizontal prescribed displacements is set to  $u_x = 0,01$  m at the bottom boundary. The vertical component of the prescribed displacement is kept zero  $u_y = 0$ .

According to the analysis of results of calculations, modeling and comparison of options it is possible to make the following **conclusions**:

1. The foundation on the man-made grounds, using soil mixing technology which turns soft and collapsible ground into composite material, is a seismic resistance option. It cost less than pile foundation and at the same time it is more technological. All production and standard requirements imposed to tanks operation are satisfied.

2. Due to the reinforcement of soft and collapsible soil the tank's vibration amplitude decreases, the soil accelerations decrease in the bottom of foundation. Such result is provided with increase in speed of distribution of seismic waves in the man-made grounds using soil mixing technology, and also due to increase in strength characteristics and the module of deformation.

3. At seismic influences with intensity of 9 points the maximum horizontal displacement of the tank top didn't exceed 6 mm, a bottom – 10 mm. The difference of displacements of a bottom concerning top is 16 mm that less than 20 mm. The tank doesn't overturn; shear strength of foundation relatively of crushed-stone pillow achieved.

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