International Journal of Engineering & Technology, 7 (3.2) (2018) 486-493

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper

Experience of Weak Soil Reinforcement by Soil-Cement Elements Manufactured by Deep Soil Mixing Technology

Mykola Zotsenko[1], Yuriyvynnykov[2]*, Maksym Kharchenko[3]

[1]*Poltava National Technical Yuri Kondratyuk University, Ukraine*
[2]*Poltava National Technical Yuri Kondratyuk University, Ukraine*
[3]*Poltava National Technical Yuri Kondratyuk University, Ukraine*
**Corresponding Author E-Mail: Vynnykov@Ukr.Net*

Abstract

Problematic issues of construction and operation in complex geotechnical conditions are systematized (subsiding and peaty soil, silt, filled, man-made soil, saturated, land sliding and seismically hazardous territories, densely developed areas) by the means of reinforcing soil massif by vertical soil-cement elements (SCE) using deep soil mixing (DSM) technology. The practical solution experience of highly efficient "man-made soil-cement base – foundation – structure" systems is shown by the example of complex geotechnical conditions under static and dynamic influences (including earthquakes and critical failure man-made loads), and excavation using SCE. A decreasing in a settlement of soil-cement bases of buildings by 2 – 4 times compared to natural soil massif and increasing in soil-cement mechanical features by 2.5 times has been established. The options of decreasing the seismic hazard (increasing the seismic stability of soil) for securing the emergency-free operation of oil storage vertical steel tank in case of the varying intensity earthquakes utilizing the man-made soil-cement base has been justified.

Keywords: *complex geological conditions, soil-cement element, weak soil, settling, strength, seismic stability, vertical steel tank, calculation scheme.*

1. Introduction

The subsiding and peaty soil, silt, filled, man-made soil, wsaturated, land sliding and seismically hazardous territories, densely developed areas are characteristic features of Ukraine [1 – 8]. Without accounting for soil features and adjusting the structural design to them the development of uneven soil settling is inevitable.

Struggling against the latter is way more expensive and complicated than foreseeing it during the designing stage and develop the respective prevention mechanisms such as penetration through the weak soil by piles (foundations); strengthening the base; partial or complete replacement of weak soils with low geotechnical characteristics. Traditionally these measures are combined with increasing the rigidity or flexibility of buildings, and dewatering of construction sites. [9, 10].

Method of improving the construction properties of soils by erection of vertical SCE by DSM technology is one of the most effective ones for solving the mentioned above geotechnical tasks. It is technologically simple, sufficiently universal and economical due to the use a local soil as a material for elements, and also does not have a dynamic effect on the surrounding buildings and their foundations. [2 – 4, 6 – 17].

The main feature of SCE is that they allow to strengthen practically the entire range of soils from gravel deposits to fine-grained clays, silts, peat, loess loams. In this case, the destruction and simultaneous mixing of soil with cement mortar in the mode of "mix-in-place" (mixing on-site).

Between solid particles, there are strong, due to binders, bonds that significantly increase the strength of the soil and reduce its compression [10 – 16].

The effect of solidification (strengthening, reinforcing) of the bases is that in a certain volume of weak soil a part of it is replaced by a rigid artificial semi-rock material – soil-cement, with a relatively large deformation module (E = 70 – 200 MPa), specific cohesion (c = 80 – 200 kPa).

In this case, the angle of internal friction of the soil usually corresponds to its natural value, and the Poisson coefficient is – 0.25 – 0.33. Soil-cement strength amounts R = 2 – 6 MPa [2 – 4, 10 – 17]. The natural (including subsidence and weak) soil, clamped between the created vertical SCE, also increases its mechanical parameters due to the impossibility of lateral protrusion (Fig. 1).

The deformation module and the strength parameters of the created artificial base of various, including plate, foundations are generally considered to be weighted average [2, 7, 10 – 17].

Its value can be adjusted by changing the distance between the SCE and its length. Further calculations are performed taking into account the specified characteristics as for natural bases using standard methods or numerical methods, in particular, the finite element method (FEM) [2 – 4, 16, 17].

Depending on the loads and engineering-geological conditions, the required number and length (up to 40 m) of the SCE are determined. A number of structural schemes of reinforcement of an array with vertical SCE have been allocated (fig. 2).

The grid of SCE is created with a different step without mutual interaction or with their "intersection" [2 – 4, 10 – 17].

Copyright © 2018 Authors. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

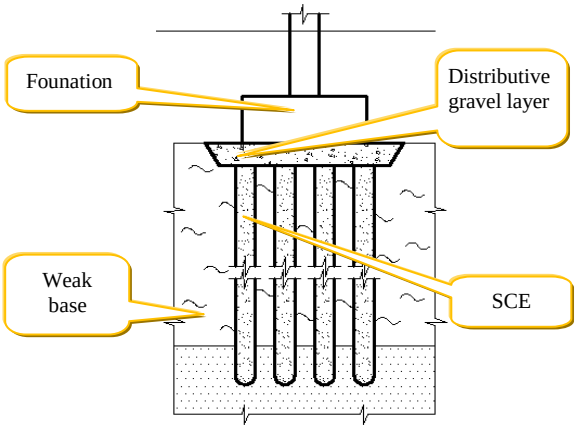


Fig. 1: Strengthening the weak and subsidence soils by vertical SCE

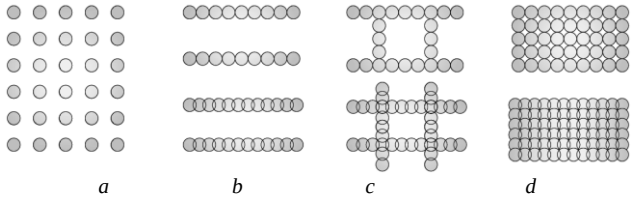


Fig. 2: Structural schemes of reinforcing the massif by vertical SCE: a – singular SCE; b – panel type; c – net type; d – block type

The degree of damage to an object during an earthquake depends not only on the level of seismic influences but also on the quality of seismic design and construction [5, 6, 18 – 22].

According to new seismological studies [5], it has been established that in the territory of Ukraine and other countries, including on its platform part, there is a danger of local and strong submarine earthquakes with magnitude greater than 5 (more than 6 points on the MSK-64 scale). This creates an additional risk of exploitation of existing and new oil storage vertical steel tanks. Therefore, according to the norms [5, 6], the probability of exceeding the estimated intensity of seismic influences over 50 years should be taken into account when designing vertical steel tanks (VST) for storing petroleum products that are objects of high responsibility.

This significant factor increases the risk of trouble-free operation and, accordingly, the cost and complexity of the construction of these engineering structures, as it is necessary to perform additional calculations and develop appropriate design solutions to minimize the risks of their earthquake accidents.

Studies performed the by experts from Japan, Canada and the United States have indicated that in the conditions of significant seismic loads, the deformation characteristics of the soil become non-linear [5, 18].

An analysis of the world and national experience in using different methods of reducing the dynamic and vibrational effects on weak, water-saturated, structurally unstable soils showed that the most effective means for their artificial transformation is cementation with the help of jet or mixing technologies [6, 21, 22].

When constructing deep foundation excavation for objects, there is a problem of ensuring the stability of their sides, especially in weak soils, since the excavation significantly affects the stress-strain state (SSS) of a soil massif, the hydrological situation in the territory, the condition of surrounding buildings, structures and communications [8, 10].

To reduce the cost of constructive solutions for the stabilization of foundation excavations, a positive experience has been accumulated in securing their sides by vertical SCEs. This method is also suitable for excavations in the conditions of dense urban development since it does not have a dynamic effect on surrounding buildings and structures.

But today the problem of building and exploitation of buildings and structures in complex geotechnical conditions with application of SCE manufactured by DSM technology is not systematized yet.

Therefore, the goal is to analyze author's decisions on the bases, reinforced by vertical SCEs, to provide the engineering methods for their calculation, and compare the results of analytical decisions with the data of long-term physical observations.

2. Main Body

A characteristic research object of a vertical reinforcement of the weak base of plate foundation by SCEs is a grain storage facility consisting of 2 silages the volume of each is 24121 м^3 (20000 tons of crops).

The silages are cylindrical tanks manufactured of the steel wavy profile sheets connected by bolt joints (Fig. 3, *a*, *b*).

The construction site is – Ivkivtsi village of Chernihiv region. The engineering and geologic conditions of the site (Fig. 3, *c*) to the depth of 13 m are characterized by compressible clay soils (table. 1).

According to analytical calculations, in order to reduce the absolute settlement of the building in these engineering-geological conditions, it was decided to arrange a foundation plate on the reinforced to the depth of 12 m by SCE. In order to provide the necessary characteristics of strength and deformability of the base, the percentage of its reinforcement was approximately 25%. At the same time, the SCE diameter was 0.5 m, and their step - 0.9 and 0.95 m.

Table 1: Physical and mechanical properties of the soils

Layer #	Soil's name	Specific gravity of soil γ (kN/m^3)	Humidity W	Plasticity I_P	Flow index I_L	Specific cohesion c_S (kPa)	Internal friction angle φ_{II} (deg)	Deformation module E (MPa)
1	Filled soil	15,0	-	-	-	-	-	-/-
2	Loam with the organic admixtures	17,0	0,2	0,10	0,10	20	18	6
3	Loam	18,8	0,22	0,10	0,30	14	21	9
4	Loam	18,5	0,28	0,15	0,40	13	20	8
5	Loam	19,0	0,22	0,10	0,30	15	22	10
6	Sandy loam	19,1	0,18	0,06	0,50	7	23	15
7	Clay	19,3	0,25	0,20	0,20	40	19	26
8	Loam	19,2	0,23	0,08	0,63	20	20	19

The value of the specific cohesion of the reinforced mass was taken as the weighted average between the characteristics of the soil and the soil cement, and the angle of internal friction - did not change. The value of the deformation module of the soil cement is accepted as E_{sc}=180 MPa, and specific cohesion is c_{sc}=100 kPa.

The calculated values of the mechanical characteristics of the reinforced soil mass are given in Table 2.

For uniform pressure transfer on the reinforced base between it and the plate the intermediate layer of crushed stone of a fraction of 20-40 mm and the thickness of 0,5 m was established. Stamping tests of the reinforced base were carried out, the results of which correspond to those calculated in Table. 2

Geometric leveling was carried out to control the settling of the foundation at the initial loading/unloading. The settling was determined using the marks, that were placed over the perimeter of the silage structure (4 marks per each), in the process of loading, and then - unloading.

As a result of leveling in the subsequent study, the parameters of the finite-element spatial model of the basis were selected.

a

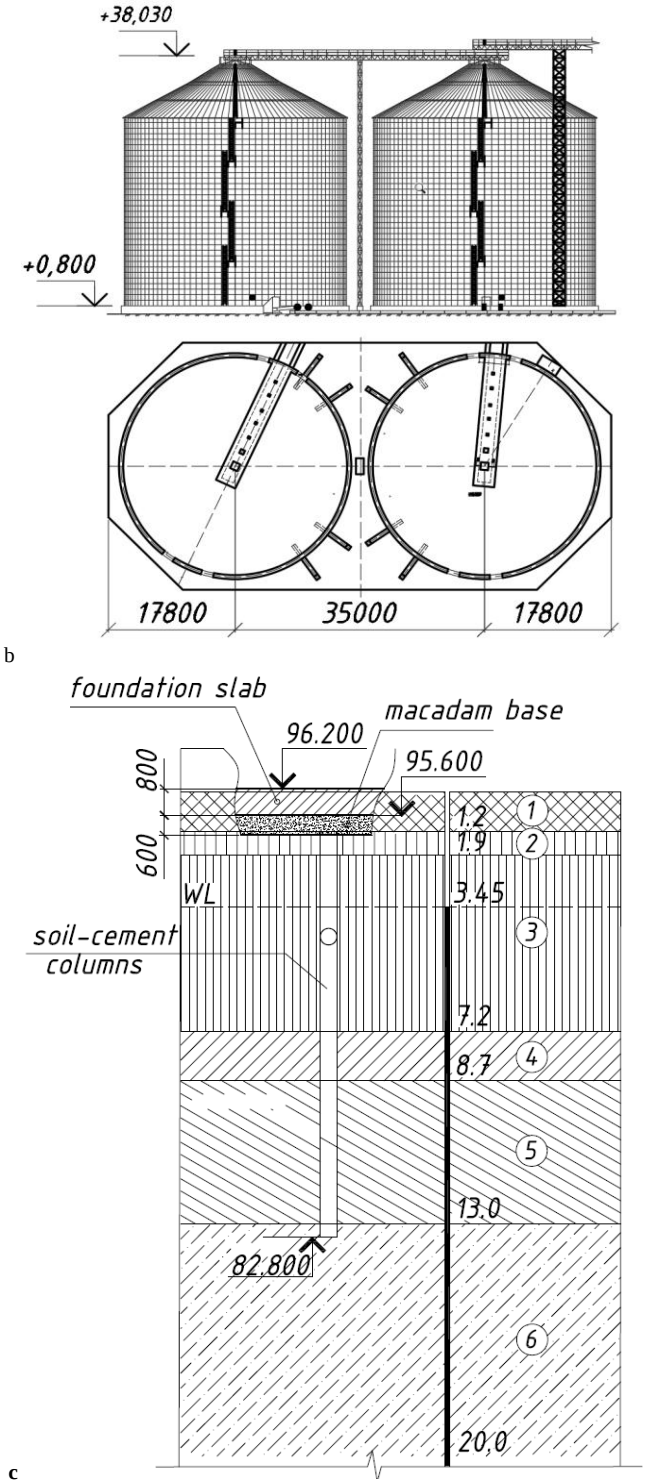


Fig. 3: The general view of silages by the volume of 24121 m^3 each (20000 tons of crops): *a* – facade; *b* – plan at +0.800 level and the plate cross section; *c* – engineering and geological profile

Table 2: Calculated values of mechanical properties of the reinforced soil massif

№	# of EGE	Specific gravity of soil γ (kN/m^3)	Specific cohesion c (kPa)	K internal friction angle φ (deg)	Deformation module E (MPa)
1	EGE-2	18,5	39,5	18	49,0
2	EGE-3	19,4	35,0	21	50,8
3	EGE-4	18,5	34,3	20	50,0
4	EGE-5	19,0	35,8	22	51,5

The simulation of the SSS of the reinforced by SCE base of the plate foundation of silages was performed in the PLAXIS 3D FOUNDATION software in the spatial formulation. The design scheme of the plate foundation and its base corresponds to the provisions of the building mechanics and soil mechanics [23]. At the same time as a model of soil, there was HSM accepted using the parameters, that were obtained from geodesic observations over the settling of a reinforced base of the foundation plate. This model adequately describes the basis of SSS at stages of loading and unloading.

To apply the HSM model you need to set seven basic output parameters: φ – internal friction angle; c – specific cohesion; ψ – dilatancy angle; E_{50}^{ref} – sectional deformation module at the stress equal to the half of a collapsing one; E_{oed}^{ref} – compression deformation module; E_{ur}^{ref} – deformation module over the trace of secondary loading (assumed to be $E_{ur}^{ref} = 3E_{oed}^{ref}$ according to geodesic data); m – rigidity indicator of hyperbolic function (soil strengthening intensity).

Fig. 4 shows a deformed finite-element spatial grid of the calculation model at one of the simulation stages. Fig. 5 shows graphs of the settlement of the base at the initial loading (by 50%) and unloading according to geodesic observations and numerical simulation.

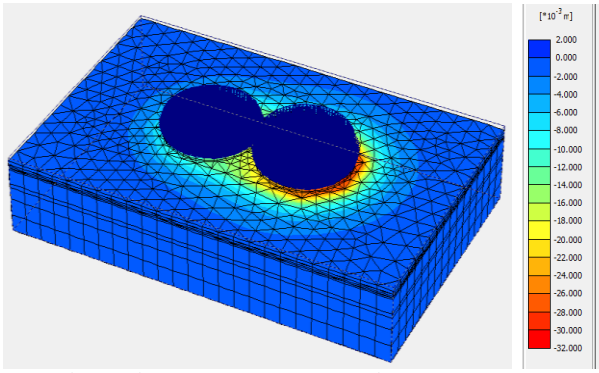


Fig. 4: deformed finite element spatial grid of calculation model at one of the modeling stages

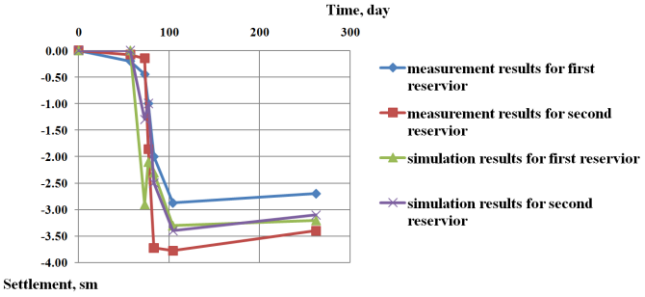


Fig. 5: Base settlement curves in time according to geodesic observation and numerical simulation

In the general case, the reservoirs are designed for the resistance against overturning and shifts from wind loads, non-uniform deformations of foundations or seismic influences. At the next stage, the calculation of the main and auxiliary structures of the reservoir is performed. The base of the reservoir foundation is calculated: 1) for the bearing capacity and checking the stability of the reservoirs and avoiding their capsizing; 2) for deformations (absolute vertical settling together with the subsidence of the center of the foundation and contour circle, unevenness of the subsidence, taking into account the local damping of the subsidence layer, the tilt). Calculation of bearing capacity of the base, determination of the settling, the settling and reservoir's capsizing is similar to other buildings and structures and is carried out in accordance with the standard requirements. The average settling of the contour circle for tanks of up to 30,000 m^3 should not be more than 20 cm, for reservoirs with a volume of 30,000 m^3 or more - no more than 30 cm. The calculation scheme for determining the seismic resistance of the reservoir is given in Fig. 6

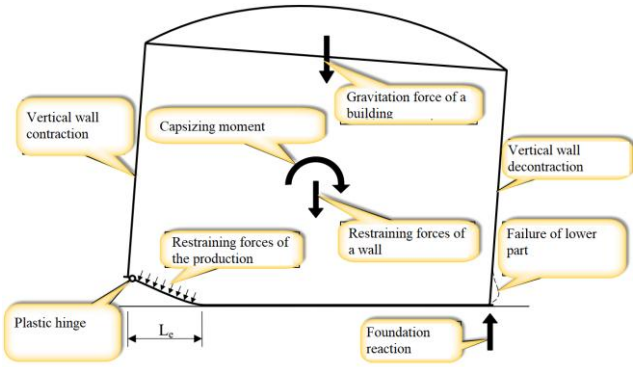


Fig. 6: Calculation scheme for seismic stability of a reservoir

In the conditions of an earthquake, in addition to external oscillations, the component of the seismic load from the vertical vibrations of the soil, there are additional loads from the side of the product on the wall and bottom of the reservoir - is: 1) hydrostatic load and pressure from the effect of excess pressure; 2) impulsive (inertial) component of the hydrodynamic pressure; 3) convective (kinematic) component of hydrodynamic pressure.

The impulsive component of the pressure arises from the part of the product moving in the conditions of the earthquake together with the wall of the reservoir. Fluctuations in the fluid inside the reservoir create convective pressure and lead to the appearance of waves on the surface of the product. Vertical fluctuations of the base of the reservoir also induce an additional load on its wall.

The seismic stability of the reservoir should be considered secured with the simultaneous fulfillment of the following conditions: a) the reservoir does not overlap during the earthquake (the criterion of overturning is the limiting state in which an entire plastic hinge appears on the outer radius of the raised part of the bottom); b) the stability of the lower belt of the wall is ensured by the action of longitudinal and transverse loading; c) ensuring the condition of strength for all supporting elements of the reservoir.

There may be several concepts for reducing the seismic hazard by improving the properties of soil bases by reinforcing them by vertical SCE.

Concept 1 – limiting damage from liquefaction "limiting soil seismic shock absorber" – a seismically isolating technology to mitigate impact during earthquakes which include the work of the soil mass of a continuous soil-cement wall. Such a structure can effectively limit the settling and lateral displacement of the soil, as well as the displacement of structures.

Concept 2 – method of limiting lateral displacement of soil due to its reinforcement by SCE. Lateral displacement of soil, which is caused by their liquefaction during the earthquake, and the horizontal displacement and sedimentation of tanks reduced by soil reinforcement using SCE placed in chess board manner in the existing dam. Such technology prevents the leakage of contaminated liquid from damaged pipelines.

Concept 3 – method of the solid cement sheath. The soil degradation during an earthquake is limited by the use of a "limiting soil seismic shock absorber", resulting in the soil being a closed solid cement wall. The leakage of contaminated liquid due to the displacement of the reservoir or damage to the pipeline is warned by reducing both the values of precipitation of the foundation of the foundations, and their unevenness.

Concept 4 – method of fencing by SCE. The sedimentation and loss of stability of the oil-protective soil dam caused by earthquakes, as well as the leakage of contaminated liquid outside the dam, may be limited or prevented by the arrangement of the soil cement wall along the contour of the dam. In addition, the soil leaching during an earthquake is limited by the use of a "limiting soil seismic shock absorber", through which the soil turns out to be a closed solid ground cement wall. This can prevent leakage of contaminated liquid due to displacement of the reservoir or damage to the pipeline.

Concept 5 – method of a continuous artificial ground cement base. Reducing the influence of dynamic load on the aboveground part of the structure during earthquakes due to the increase of elastic deformation parameters of the base.

Reducing the effect of the dynamic load on the aboveground part of the structure in earthquakes can be achieved by reducing the acceleration and the amplitude of fluctuations in the base of its foundations. One of the options for reducing seismic intensity is to increase the seismic hardness V_{sp} of the active layer of soil by increasing the rate of propagation of seismic waves in it. Such an effect can be achieved by increasing the elastic deformation characteristics of the base, using the mixing technology. With this approach it is possible to increase the modulus of elasticity of the base to 500-2000 MPa, the rate of propagation of waves up to 600 - 1000 m / s at constant density.

Improvement of the damping characteristics of an artificial base occurs due to the presence of a gravel or sand layer, as well as due to the friction and grip of clogged soil on the contact surface SCE.

Therefore, the vertical components of the seismic impulse (vertically directed pulses) are damped by the gravel layer and being transferred only in a weakened form to the plate base. In the zone of artificial foundation, vertical SCEs partially absorb and dissipate the energy of a seismic wave (dissipation) in a manner similar to a pile foundation.

The elimination of thixotropic and liquefaction properties of soils is due to local cementation within the SCE and to increasing in the soil shrinkage resistance, which is clamped between these elements. It also increases the filtration consolidation resistance of the weak base due to its reinforcement.

The main idea of the authors is the development of a universal artificial base, which will meet the regulatory and technological requirements for both the static conditions of RVS exploitation on subsiding and weak soils, as well as in the case of seismic influences of varying intensity. As an example, the geotechnical solutions for the oil tank of the RVSP-20000 oil-pumping station "Avgustivka" (Avgustovka, Odesa region) are given.

The technological parameters of RVS-20000 are shown in Table 3.

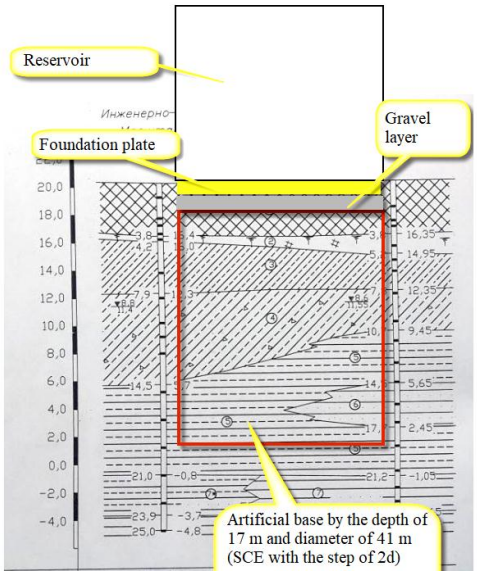
Table 3: Technological parameters of oil reservoir RVSP-20000

Parameters	Value
Density of the product (oil), t/m^3	0,89
Calculation level of filling by the product, m	16,2
Water table during the hydraulic testing, m	16,75
Internal excessive pressure	none
Standardized internal vacuum	none
Exploitation intensity (cycles during a year), min/max	20/100
Characteristic snow load, kg / m^2	102
Characteristic wind load, kg / m^2	51
Estimated seismic intensity, points	8
The coldest day temperature with a 0,98 provision ^{0}C	minus 24
Maximum storage temperature of oil, ^{0}C	plus 25
Estimated lifetime, years	40
Estimated height of the wave of oil under the influence of seismic load, m	0,32
The amount of corrosion on the walls of the sheet, mm	0
Minimum marking of the surface of the loop relative to the surface of the crust, mm	+0,5

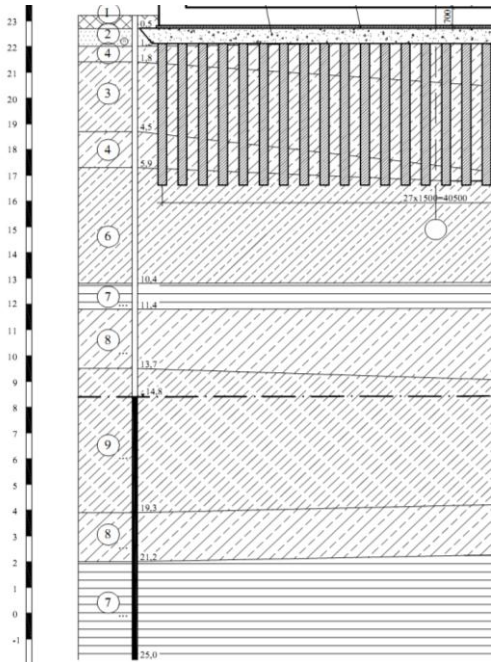
Geometrical parameters of RVS-20000: 1) nominal volume 20000 m^3; 2) geometrical volume 20956 m^3; 3) height of the wall 17,926 m; 4) inner diameter 39,9 ,; 5) surface area product 1250,4 m^2. The diameter of the base plate is approximately 40.5 m. The pressure under the plate footing during the hydraulic testing was 168,1 kPa, during the exploitation, it was 180,9 kPa. The evenly distributed load along the contour of the foundation during testing was 31.65 kN / m, during the exploitation, it was 40,33 kN/m, at wind loads – ±6 kN/m, at seismical impacts – +353,73/-268,67 kN/m. The magnitude of the surplus horizontal seismic forces, transmitted from the construction of the reservoir to the plate - 65,500 kN.

Geomorphologically, the site is located on a water slide between Kuialnytske and Khadgybeiske gulfs. The structure involves bulk soils, quaternary loams, which are submerged by sandy-clay deposits of the tunnel level of the Neogene, below the section are meiotic clays.

The level of groundwater - at a depth of 8.6 - 8.8 m from the earth's surface. The horizon is unpressurized, unloaded down the trench. Two sites with complex engineering-geological conditions are considered. The complexity of the first of them is characterized by the presence of mollusctic and fluid loams and sandy loams at the depth of 7.6 m from the surface of the land, the loams belong to weak and strongly compressed soils (the deformation module fluctuates within E = 3 - 5 MPa).
The total depth of these soils is approximately 12 - 13 m. The weak and strongly compressed soils are underlied by semi-solid clay at a depth of 21.7 - 23.9 m



a



b

Fig. 7: Engineering and geological profile of the construction site

The weak soil in a case of seismic influences may become liquefied, and get additionally densification, resulting in excessive deformation of the reservoir. The complexity of the second site is characterized by the presence of a subsidence soil of a more than 5 m thickness.
According to seismic properties, the category of soils is III. Normative seismic intensity of construction sites is 8 points (according to the map of the ZSR-2004-C [20]), the estimated – 9 points. For these conditions, several decisions were considered:
1) penetrating through the weak and subsidence soil by reinforced concrete piles of 350x350 mm section in order to reach the strong clay formation, as well as the elimination of the subsiding properties of the soil of the inter-pile space by deep densification (erection of ground piles with the diameter of 300 mm), the construction in the base of a foundation a plate with a thickness of 0.7 m, hinged joints of piles with a plate;
2) the same as in the first variant, but on top of the piles it is assumed that the gravel layer is placed in order to damper the vibrations of the reservoir and avoid the transfer of horizontal loads to the piles;
3) the erection of the artificial base by reinforcing the weak soil by vertical SCEs by the diameter of 500…650 mm, the rest is the same as before.
The perception of horizontal seismic loading due to the work of piles with the soil is provided only by a significant amount (~ 1000 piles), which is economically inexpedient since the vertical load on the piles will not be more than 35% of the permissible. Therefore, this option was not further compared.
The option with vertical SCE was much cheaper and could be realized over a shorter period of time. The length, diameter, and step of the SCE were determined by the iterative method.
The main criterion for calculating was the provision of less than the critical values of the settlement of the center and the extreme calculation points of the base plate, the reservoir tilt, as well as the load-bearing capacity of the foundation during the seismic influences. As a result of calculations, it was established that the optimal diameter SCE is 500 mm, step - 1,0 m (2d). Information geotechnical model of RVSP-20000 is shown in Fig. 8

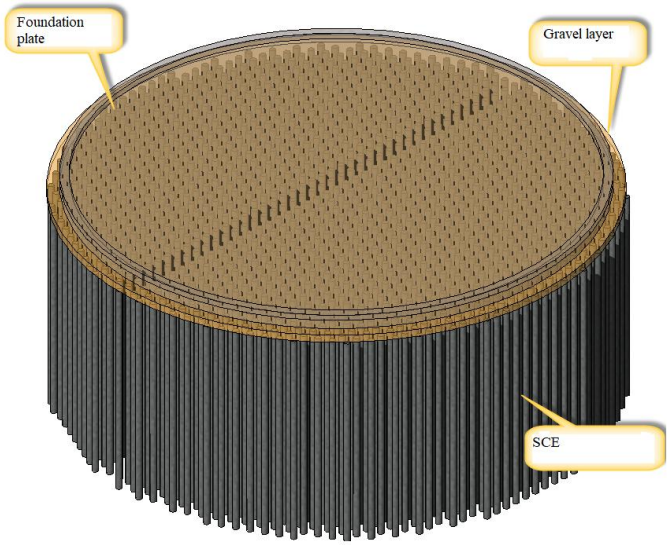


Fig. 8: Spatial calculation scheme of the «reinforced soil – gravel layer – foundation» system

Modeling is carried out to confirm the correctness of the solution of «soil mass - reinforced base - gravel damping layer - foundations - reservoir» system's SSS. The problem was solved in a two-dimensional ("axial") statement using FEM taking into account the estimated seismic impact [23].
Soil foundation, artificial foundation and gravel layer are given in the form of clusters with the corresponding characteristics. The base plate is given by a beam element with a corresponding bending EI and a normal EA rigidity, which corresponds to a thickness of a plate of 0.7 m.
To determine the parameters of the fluctuations of the tank, it was modeled by beam elements, and oil was modeled by a cluster with corresponding characteristics. The calculation scheme is shown in Fig. 9

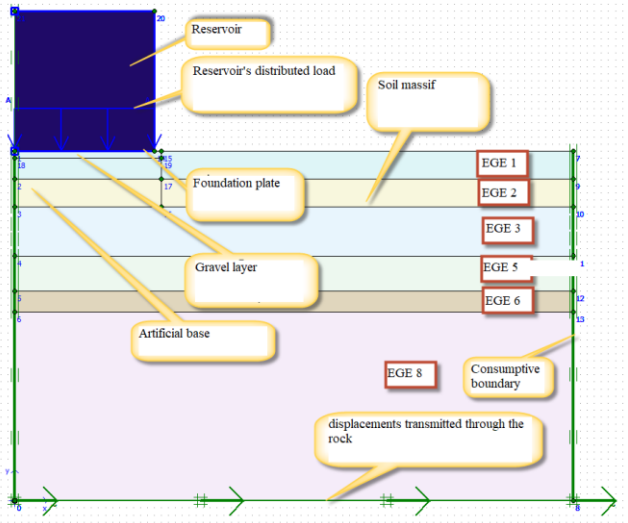


Fig. 9: Estimated axisymmetric scheme of the system «Soil massif - reinforced soil - gravel damping pillow - foundations - reservoir»

The dimensions of the calculation zone aside from the construction are taken from the condition of preventing their influence on the deformation of the foundation.

The depth of the boundary of the calculated area was chosen from the condition of the absence of additional stresses and taken 50 m (for the conditional achievement of rocky or semi-rocky soils); forced oscillations to the lower plane of the calculated model in the form of an accelerograph of the earthquake (with parameters corresponding to the intensity of seismic influences at 9 points) are given. On the right side of the model, absorbing boundaries are given, the task of which is to prevent the reflection of waves from the side faces of the grid; The soil is modeled by a linear model with corresponding coefficients of elasticity.

The influence of hydrostatic water pressure was taken into account when determining the appropriate level of groundwater. Damping the building and the base is modeled using Relay coefficients. Forced horizontal displacements of the lower boundary of the calculated area are given ux = 0.01 m, vertical - uy = 0.

An example of the general form of an artificial basis with vertical SCE is shown in fig. 10.



Fig. 10: A general view of the artificial basis from the vertical SCE

The construction of the protective structure of the ditch sides is a soil mass reinforced by a rigid vertical SCE in a checkerboard pattern. In this case, the natural soil is trapped between the frame, which is created by vertical SCE. This design works as a single massif [9].

Therefore, to determine its durability, it makes sense to use the design scheme of a massif retaining wall (Figure 11). Its calculation goes down to determining the ratio of shear and restraint forces to the retaining wall [8].

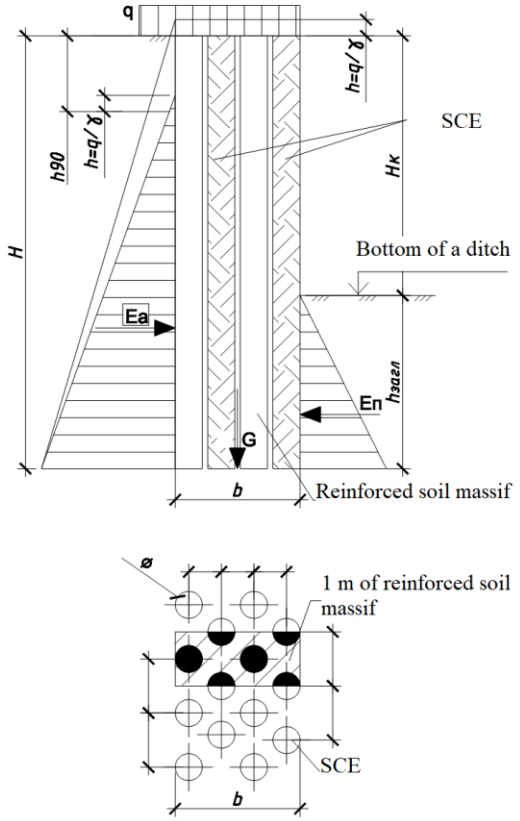


Fig. 11: The calculation scheme of the method for determining the stability of the ditch sides reinforced by vertical SCE: H – length of SCE; b – width of soil-cement wall; $h_{заел}$ – length of SCE below the bottom of a ditch; G – gravity of the wall; $E_п$ – reactive pressure of the soil ; E_a – a total active soil pressure ; q – load at the ditch edge; γ – specific gravity of the soil

The retaining forces are: the own weight of the retaining wall G (taking into account the weighing action of the water for the case that the bottom is lower than the groundwater level), the adhesion forces acting behind the lower edge of the wall, and the passive backing of the soil En, acting on the lower part of the excavation bottom walls.

The shifting forces are the total active pressure E_a on the wall (pressure σ on the wall from the natural soil) and the load q on the ditch (figure 11).

The active pressure of the soil on the wall with vertical GCE, taking into account the adhesion forces (in Fig. 11 the calculation scheme for a homogeneous base is given) is

$$E_a = \frac{\gamma H^2}{2} tg^2(45° - \varphi/2) - 2cHtg(45° - \varphi/2) + 2c^2/\gamma, \quad (1)$$

where φ and c – are the angle of internal friction and specific cohesion of the soil, which must be determined by unconsolidated-drained tests (soil samples are pre-saturated with water and compacted only to the values of vertical pressure, which takes place in the massif, provided it is completely saturated, γ is the specific gravity of the soil (below the groundwater level, the weighing action of water should be taken into account), and H is the length of the vertical GCE.

The sum of the projections of the restraint forces F_{sr} on the horizontal plane will be

$$F_{sr} = (G - h_w \cdot b) \cdot \mathrm{tg}\varphi_c + A \cdot c_c + E_п, \quad (2)$$

where G – the weight of soil-cement wall, $G = \gamma_c \cdot b \cdot H$; $h_w \cdot b$ – hydraustatic resistance (if water table exceeds h_w wall footing level); φ_c and c_c – the angle of internal friction and the specific cohesion of the reinforced massif, which are defined as the weighted average in terms of area (the strength parameters of the soil and ground cement are set by unconsolidated-drained tests); A – the area of 1 m of

soil-cement wall; $E_п$ – the active pressure of the soil on the soil-cement wall, which is determined by the formula (3); γ_c – specific weight of the reinforced massif (weighted average over the area); b – width of the soil-cement retaining wall.

$$E_n = \frac{\gamma}{2} \cdot h_{загл}^2 \cdot tg^2(45° + \varphi/2), \quad (3)$$

where $h_{загл}$ – length of vertical SCE below the ditch bottom; φ – internal friction angle, obtained via unconsolidated-drained tests (to determine the stability of the wall for the period of excavation), to determine the pressure on the underground part of the building during its operation, it is necessary to use the value of the internal friction angle obtained by the consolidated drainage tests ; γ – specific gravity of the soil.

Expression (4) derived from Coulomb-More strength criteria $\tau = \sigma \cdot \text{tg}\varphi + c$ provided that the tangential stresses in the reinforced massif are equal $\tau = (E_a - E_п)/A$, and normal stresses are $\sigma = (G - h_w \cdot b)/A$

$$E_a - E_п = (G - h_w \cdot b) \cdot \text{tg}\varphi_c + A \cdot c_c . \quad (4)$$

Using equation (4), it is possible to determine the stresses in all horizontal sections of the retaining wall, choose the dimensions of the section of the reinforced massif, diameter, quantity, step and length of the SCE.

Calculation of such a construction by a flat shear along its footing can be performed according to formula (4), in which the φ_c and c_c reinforced massif should be replaced by strength characteristics (φ and c) of soil in the base of retaining wall, which are determined by the scheme of consolidated drainage tests.

Checking the stability of the retaining wall against the capsizing must be carried out using the condition $p_{min}>0$ (where p_{min} – minimum pressure under the edge of the footing of the retaining wall from the ditch side).

Determining the minimum pressure on the soil under the edges of the footing of the soil-cement retaining wall is possible using formula (5)

$$P_{\min} = \frac{G + q \cdot b}{b} - \frac{\sum M}{W}, \quad (5)$$

where W – a moment of resistance of the footing of the retaining wall; ΣM – the sum of the moments with respect to the point at which the resultant of the vertical force (G – retaining wall's gravity) and a plane of the retaining wall footing intersect each other.

In this case, if the tangential stresses in the body of the "retaining soil-cement soil wall" do not exceed normal, then the "deformation-stress" relationship will be linear, respectively.

To evaluate the stability of the sides of the ditch, reinforced by vertical SCE, the graphoanalytical method of round cylindrical sliding surfaces is tested, which is based on the theory of limiting equilibrium of soils, and considers the limiting stress state of the massif (Fig. 12).

In this case, the weighted average values for the horizontal cross-sectional area of the slip surface between the values of the natural soil and the soil cement should be included as strength characteristics in the calculation.

The properties of the strength of the soil -cement should be determined by unconsolidated-drained tests, which is closer to the real conditions of their work.

The diameter, number, width, and length of the vertical SCE determined by the analytical method are checked by graphoanalytical calculation. In this case, it is necessary that at a value of the coefficient of stability kst = 1,2, there wouldn't be any landslide pressure.

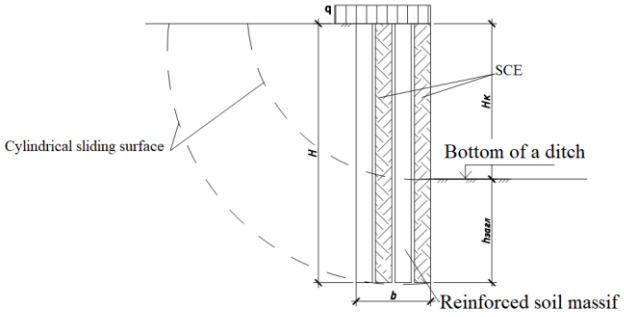


Fig. 12: The calculation scheme for determining the stability of the ditch edges fixed by vertical SCE according to the graphoanalytical technique

To achieve the goal, it is rational to apply numerical approaches that enable the FEM to estimate the SSS of the massif reinforced by vertical SCE.

The advantage of this approach is the ability to analyze SSS at each stage of construction, if necessary, develop additional engineering solutions and make appropriate design activities in the calculation area.

In this case, the Plaxis software complex is used, in which the problem is solved in a flat setting. At the same time, an elastic-plastic model of the Mohr-Coulomb soil was used.

Calculation of the stability of the sides of the excavation was carried out according to a scheme that takes into account the change in the strength characteristics of the soil until the massif passes into the state of limiting equilibrium.

The coefficient of stability of the pit wall is defined as the ratio of the initial strength characteristics to their limit values:

$$k_{st} = \frac{c + \sigma \cdot tan\,\varphi}{c_r + \sigma \cdot tan\,\varphi_r}; \quad (6)$$

$$\frac{c}{c_r} = \frac{\tan\varphi}{\tan\varphi_r} = \sum M_{sf}, \quad (7)$$

where c and φ – strength parameters; σ – component of the normal voltage ; c_r and φ_r – parameters of reduced strength, which are necessary to maintain equilibrium.

The strength parameters are controlled by a common factor ΣM_{sf}. This parameter changes with a phased calculation until destruction occurs.

Further, the safety factor is defined as ΣM_{sf} when destroyed, from the condition that we get it practically constant value for successive stages of loading.

3. Conclusions

The method of reinforcing the bases by SCE has confirmed its effectiveness for weak and subsidence soils. The high reliability of the FEM modeling of the "reinforced soil - foundation - structure" system with the use of the PLAXIS complex has been confirmed. For the SSS simulation of the plate foundations bases of silages and reservoirs, there should be HSM model used since it correctly describes both loading and unloading steps.

The variant of the base plate on an artificial cement-based basis, which transforms the weak and subsidence thickness into a composite material, is earth-resistant, costs less than a pile and is more technological.

Due to the reinforcement of a part of an massif of weak and subsidence bases, the amplitude of the vibrations of the reservoir decreases, the nature of the acceleration of the soil changes, and the values of soil acceleration in the level of the bottom of the foundation are reduced, which is ensured by an increase in the velocity of the spread of seismic waves in the soil cement base, as well as by increasing the strength and deformability characteristics.

In case of seismic influences with a calculated intensity of 9 points, the maximum calculated horizontal displacement of the top of the reservoir did not exceed 6 mm, the bottom – 10 mm. The difference in displacement of the bottom with respect to the top is 16 mm, which is less than 20 mm and therefore is permissible. The reservoir does not overturn, the condition for the shift of the base plate relative to the gravel pillow is observed.

The effectiveness of constructive solutions for securing the sides of trenches with vertical SCE is established. An analytical technique for assessing their stability has been developed.

Acknowledgement

The research is carried out within the framework of the research work of the Ministry of Education and Science of Ukraine "Effective structural and technological solutions for the objects of transportation and storage of oil and petroleum products in complex engineering and geological conditions" (state registration number 0117U003086).

References

[1] Interaction of the artificial bases with Collapsing Soils / V. Shokarev, V. Shapoval, A. Tregub, V. Grechko, A. Shokarev, A. Serdyuk, G. Rozenvasser, M. Kornienko, E. Petrenko, N. Zotsenko, Y. Vynnykov// *Geotechnical Engineering in Urban Environments. – Proc. of the 14th European Conf. on Soil Mechanics and Geotechnical Engineering* (Madrid, 24-27 September 2007). – Millpress Science Publishers Rotterdam, 2007. – P. 481 – 486.

[2] Zotsenko N.L. Comparative effectiveness of bed reinforcement based on plate tests and mathematical modeling / N.L. Zotsenko, N.I. Lapin, R.V. Petrash // *Soil Mechanics and Foundation Engineering.* – 2008. – Vol. 45 (4). – P. 138 – 143. http://link.springer.com/article/10.1007%2Fs11204-008-9014-z (DOI: 10.1007/s112040089014z, Scopus, SNIP (2014) – 0,151).

[3] Innovative projects in difficult soil conditions using artificial foundation and base, arranged without soil excavation / P. Kryvosheiev, G. Farenyuk, V. Tytarenko, I. Boyko, M. Kornienko, M. Zotsenko, Yu. Vynnykov, V. Siedin, V. Shokarev, V. Krysan // *Proc. of the 19th Intern. Conf. on Soil Mechanics and Geotechnical Engineering* (Sep. 17 – 22, 2017 / COEX, Seoul, Korea) – ed. by W. Lee, J.-S. Lee, H.-K. Kim, D.-S. Kim. – Seoul. – 2017. – P. 3007 – 3010.

[4] Long-term subsidence of a multistory building on the base reinforced with soil cement elements / Yu. Vynnykov, I. Miroshnychenko, O. Landar, V. Zotsenko, P. Omelchenko // *Academic Journal. Series: Industrial Machine Building, Civil Engineering.* – Poltava: Poltava National Technical Yuri Kondratyuk University. – 2017. – Issue 2 (49)′. – P. 234 – 251.

[5] Kendzera A.O. Modeliuvannia vplyvu gruntovoi tovshchi na parametry seismichnoii nebezpeky / A.O. Kendzera , A.Yu. Semenova // *Svit heotekhniky*. – 2017. – №3 (55). – S. 4 – 14.

[6] Design peculiarities of oil storage tanks in complex geotechnical conditions at seismic effects / M. Zotsenko, Yu. Vynnykov, M. Kharchenko, I. Lartseva // *Academic Journal. Series: Industrial Machine Building, Civil Engineering.* – Poltava: Poltava National Technical Yuri Kondratyuk University. – 2017. – Issue 1 (48)′. – P. 175 – 182.

[7] Vynnykov Yu. Rozrakhunok fundamentnoii plytyt sylosiv na ramovanii stokhastychnii plyti / Yu. Vynnykov , M. Kharchenko, V. Marchenko // *Mosty ta tuneli: teotiia, doslidzhennia, praktyka: zb. nauk. prats Dnipropetrovskoho natsionalnoho universytetu zaliznychnoho transportu im. akademika V. Lazariana*. – Vyp. 3. – Dn.: FOP Udovychenko O.M., 2012. – S. 26 – 32.

[8] Vinnikov Yu. Metodika i opyt rascheta ustoichivosti bortov glubokih kotlovanov, zakreplennyh vertikalnymi gruntotsementnymi elementami / Yu. Vinnikov, M. Harchenko // Fundamenty glubokogo zalozheniia i problemy osvoeniia podzemnoho prostranstva. – Materialy Mezhdun. konf. (Perm, 2011). – Perm: Izd-vo PNIPU, 2011. – S. 260 – 271.

[9] BS EN 1997-1:2004 Eurocode 7: Geotechnical Design, P. 1. General Rules, British Standards Institution, London, 1994. – P. 17–35.

[10] Spravochnik heotekhnika. Osnovaniia, fundamenty I podzemnyie sooruzheniia / Pod red. V.A. Ilicheva i R.A. Manhusheva. – M.: Izd-vo ASV, 2014. – 728 s.

[11] Brandl H. Excavation support using deep mixing technology / H. Brandl, C.J. Rutherford // *Proc. of the Intern.geotechnical conf. "Geotechnical challenges in megacities"*. – Vol. 1. – Published by GRF, 2010. – P. 29 – 54.

[12] Denies N. Summary of the short courses of the IS-GI 2012 latest advances in deep mixing / N. Denies, G.V. Lysebetten// *Proc. of the Intern. Symposium on Ground Improvement IS-GI*. – Brussels. – 2012. – P. 73 – 123.

[13] Soil mix: influence of soil inclusions on structural behaviour / P. Ganne, N. Denies, N. Huybrechts et al. // *Proc. of the 15th European Conf. on Soil Mechanics and Geotechnical Engineering* (Athens, 2011). – Amsterdam: IOS Press, 2011. – P. 977 – 982.

[14] Strength properties of densely compacted cement-mixed gravelly soil / A. Ezaoui, F. Tatsuoka, S. Furusawa, K. Yirao, T. Kataoka // *Proc. of the 18th Intern. Conf. on Soil Mechanics and Geotechnical Engineering*. – Paris. – 2013. – Vol. 1. – P. 329 – 332.

[15] Innovative solutions in the field of geotechnical construction and coastal geotechnical engineering under difficult engineering-geological conditions of Ukraine / M. Zotsenko, Yu. Vynnykov, M. Doubrovsky et al. // *Proc. of 18th Intern. Conf. on soil Mechanics and Geotechnical Engineering*, Paris, 2013, Vol. 1. – P. 2645–2648.

[16] Zotsenko N. Soil-cement piles by boring-mixing technology / N. Zotsenko, Yu. Vynnykov, V. Zotsenko // *Energy, energy saving and rational nature use*. – Oradea University Press, 2015. – P. 192 – 253.

[17] Probabilistic analysis of deformed mode of engineering constructions' soil-cement grounds / Yu. Vynnykov, O. Voskobiinyk, M. Kharchenko, V. Marchenko // *Materials Science, Engineering and Chemistry. – MATEC Web of Conf. Proc. of the 6th Intern. Scientific Conf. "Reliability and Durability of Railway Transport Engineering Structures and Buildings" (Transbud-2017)* (Kharkiv, Ukraine, April 19-21, 2017). – Vol. 116 (2017). – 02038 (2017). – ISBN: 978-2-7598-9022-4. Published online: 10 July 2017. DOI: https://doi.org/10.1051/matecconf/201711602038.

[18] Rayamajhi D. Dynamic Centrifuge Tests to Evaluate Reinforcing Mechanisms of Soil-Cement Columns in Liquefiable Sand / D. Rayamajhi, S. Tamura, M. Khosravi, R.W. Boulanger, D.W. Wilson, S.A. Ashford and C. Guney Olgun. – *Journal of Geotechnical and Geoenvironmental Engineering* · February 2015. – DOI: 10.1061/(ASCE)GT.1943-5606.0001298. – 04015015-1 – 04015015-12.

[19] Selvaraju S. Vibro replacement stone columns for large steel storage tanks in Vietnam / S. Selvaraju, Z. Wei He, K. Weng Leong // *Proc. of the 19th Intern. Conf. on Soil Mechanics and Geotechnical Engineering* (Sep. 17 – 22, 2017 / COEX, Seoul, Korea) – ed. by W. Lee, J.-S. Lee, H.-K. Kim, D.-S. Kim. – Seoul. – 2017. – P. 2651 – 2654.

[20] Anumod A.S. Finite Element Analysis of Steel Storage Tank Under Siesmic Load / A.S. Anumod, S. Harinarayanan, S. Usha *// Intern. J. of Engineering Research and Applications (IJERA)*. – January 2014. – P. 47 – 54. – ISSN: 2248-9622 Trends and Recent Advances in Civil Engineering (TRACE- 24th-25th January 2014).

[21] Seismic behavior of LNG storage tank considering soil-foundation-structure interaction with different foundation types / J. Gon Ha, H. Joon Park, M. Kyo Lee, H. Lee, D.-S. Kim, S. Kwon, H. Kim // *Proc. of the 19th Intern. Conf. on Soil Mechanics and Geotechnical Engineering* (Sep. 17 – 22, 2017 / COEX, Seoul, Korea) – ed. by W. Lee, J.-S. Lee, H.-K. Kim, D.-S. Kim. – Seoul. – 2017. – P. 931 – 934.

[22] Ground improvement using rigid inclusion for the foundation of LNG tanks / B. Hor, S. Hyun Jee, M. Jun Song, D. Young Kim // *Proc. of the 19th Intern. Conf. on Soil Mechanics and Geotechnical Engineering* (Sep. 17 – 22, 2017 / COEX, Seoul, Korea) – ed. by W. Lee, J.-S. Lee, H.-K. Kim, D.-S. Kim. – Seoul. – 2017. – P. 2907 – 2910.

[23] Plaxis 3D Foundation. Reference Manual. Version 1.5 / R. Brinkgreve at al. – Delft: Delft University of Technology. – 2006. – 152 p.