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GEOPHYSICAL CRITERIA FOR SEISMIC LIQUEFACTION OF TAILINGS ANTHROPOGENIC SOILS OF ORE-DRESSING AND PROCESSING ENTERPRISES OF UKRAINE

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ГЕОФІЗИЧНІ КРИТЕРІЇ СЕЙСМІЧНОГО РОЗРІДЖЕННЯ ТЕХНОГЕННИХ ГРУНТІВ ХВОСТОСХОВИЩ ГІРНИЧО-ЗБАГАЧУВАЛЬНИХ КОМБІНАТІВ УКРАЇНИ

Purpose. Approbation of approaches to the assessment of seismic liquefaction of technogenic soils by geophysical data in Ukraine's tailing dumps of ore mining and processing enterprises.

Methodology. Velocity models built on the data of the borehole and field seismology are used for the prediction of seismic liquefaction of technogenic soils at the base of bund walls in tailing dumps of Kryvyi Rig GOKs: Ingulets Iron Ore Enrichment Works (InGOK), Central Iron Ore Enrichment Works (CGOK), Northern Iron Ore Enrichment Works (Northern GOK). Empirical dependences of the liquefaction potential upon the speed properties of soils and predictive values of peak accelerations during earthquakes are taken as a basis of the methodology being used.

Findings. It has been found that the principal geophysical factors determining the possibility of liquefaction are the values of predictive peak horizontal accelerations of the soil surface as well as the law of changes in the shear wave velocity with depth. The depth of the point in the section has also made an essential contribution to the phenomenon. For the points willingly located below the groundwater level (GWL), variations of the DWL position as well as of the soil density above and below the water level (for physically real situations) have far less effect on the potential liquefaction than the factors enumerated above.

Originality. The perspectives of geophysical assessment of the dynamic stability of soils in technogenic objects have been substantiated. The given approach has been tested for the first time on the areas of tailing dumps of Ukraine's ore mining and processing enterprises.

Practical value. Under the progressive deposition of tailings, the low-velocity dewatered technogenic soils settle at the base of bund walls of subsequent tiers. When designing these facilities it is necessary to take into consideration the possibility of soil liquefaction at their base. The given approach is a promising alternative or a supplement to the approaches based on the penetration properties, and it will considerably increase the reliability of the prediction of the possibility of liquefaction of technogenic soils in case of seismic effects of different nature.

Keywords: *tailing dam, anthropogenic soils*, *earthquake, liquefaction, shear wave velocity*

Statement of the problem. Consequences of severe earthquakes in different regions of our planet convincingly testify that residual ground displacements often play a primary role in the destruction of buildings and structures. One of the most frequently occurring phenomena is seismic soil liquefaction during earthquakes [1].

Water-saturated fine and silty sands are attenuated more often than other soils. The greater the porosity of the soil, the less dynamic effect are needed to start the liquefaction. The phenomenon of liquefaction consists in the complete or partial loss of load bearing capacity by the soil and its transition into the flowable state as a result of destruction of structures and displacement of particles relative to each other. Necessary conditions of the liquefaction are: the destruction of structures (often under dynamic influences), the possibility of hardening of the soil and its full saturation with water. With the destruction of structures and wringing out pore water the contacts between soil grains are lost, and the soil completely or partially loses its carrying capacity for a certain period of time. In this case, settlement and destruction of the structure may oc-

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cur, since fine sands, unlike other coarse soils, may be in a liquefied state for several hours. The looser the soil and the weaker the structural links, the more compaction and settlement, following the dynamic effect, can be observed. In this connection, the areas of increased power of sands, having extremely loose composition, are especially dangerous.

Soil liquefaction can occur during earthquakes with different magnitudes. Soils lying within the first few meters below the level of groundwater are in greater danger [1]. With the passage of an elastic wave, the oscillations of soil grains with different speeds are excited and part of the contacts (the greater the wave energy, the larger it is) are broken. As a result, the strength of the soil significantly (sometimes several times) decreases and the construction, which stands on it, can sink, become distorted or overturn. Water-saturated soils (in particular, fine loose sands) can be attenuated under a sufficiently strong seismic impact: with the disappearance of a direct contact between the sand grains, at some point they appear to be as if suspended in the water contained by them. In this case, water tends to be wrung out, but this process needs some time since it is limited by the soil watertightness. The undercount of the factor of seismic liquefaction can lead to the severe damage of even antiseismic facilities: they have time to "sink", become distorted or even "break" on the surface of the liquefied depositions, etc (fig. 1).

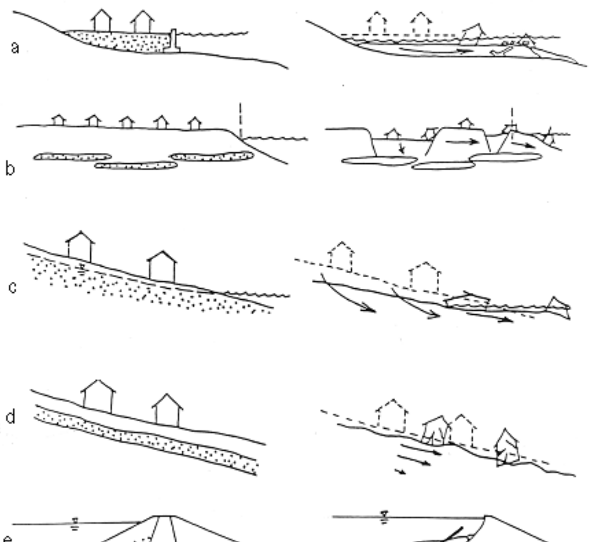

Fig. 1. Schematic examples of global instability of the area or "large" lateral displacement caused by the soil liquefaction [4], such as: a – lateral spread by flow; b – lateral spread by translational shift; c – flow of soil; d – translational displacement; e – variable or translational sliding

The most easily liquefiable soils typically include the following ones [2]:

1. All weakly binding soils of the specified age range in the water-saturated state (silty sands, sandy loams and light loams, including wet loess soils, ash, etc).
2. Sands of small and medium size.
3. Cohesive soils having metastable structures and low physical and chemical activity of a solid component (such as glacial-marine "quicksand" clays).

Assessment of the possibility of liquefaction of water-saturated and dispersed soils under expected earthquakes and its possible consequences is a very important task in the complex of findings for the design and construction of structures in seismic areas. A great number of special scientific publications, the review of which is given, in particular, in the monograph [3], is devoted to the analysis of the mechanism for seismic liquefaction of soils, principal factors influencing it, methods for experimental and expert evaluation of the possibility of liquefaction and its consequences.

Everything said is also fully applied to the technogenic alluvial soils in the tailing dumps of ore mining and processing enterprises. During the operation of mining enterprises, a large amount of wastes is formed which represent themselves as a chaotic alternation of sandy, sandy loamy and loamy technogenic formations.

When planning the placement, designing and exploiting of such objects as waste dams, tailings dumps and waste repositories, it is necessary to provide properly an estimation of engineering-geological risks and impacts on the environment, as well as management at all stages of the project cycle.

An increase in volumes of tailing dumps in some cases leads to the construction of bund walls of subsequent levels at the base of which dewatered technogenic soils lie.

If there are potential risks of liquefaction, related to the seismic activity, the maximum earthquake magnitude should be taken into consideration. Given that bund walls of tailing dumps refer to the class of hydrotechnical structures (HTS), according to the DBN B.1.1-12:2006 [5], seismic intensity and peak accelerations should be taken equal for the two levels: the design earthquake (DE) and the maximum calculated earthquake (MCE).

The DE should be perceived by the hydrotechnical structure without disturbance of its normal mode of operation. At the same time, residual displacements, cracks and other kinds of damage that do not affect the possibility of repairing the structure in the conditions of its normal functioning are allowed. The MCE should be perceived without any threat of the structure destruction or the breakthrough of the pressure front but the damage of the HTS and its foundations is possible [5].

The undercount of the factor of seismic liquefaction can lead to the fact that the result of seismic soil liquefaction is usually accompanied by severe accidents of even quakeproof buildings.

Analysis of the previous work and research methodology. To solve the question concerning the possibility of seismic soil liquefaction under the given characteristics of expected earthquakes the following methods can be presently used [2]:

- field methods for the assessment of dynamic properties of soils;
- laboratory methods for the dynamic tests of soils.

Laboratory dynamic tests of samples give a definite answer to the question about the possibility of soil liquefaction (on condition of adequate modeling of the baseline condition), herewith the field methods provide evaluation of the possibility of soil liquefaction with a certain probability. The reason of this is that the field methods used today are based on the empirical correlation dependences between directly measured characteristics of soils in the massif and their resistance to liquefaction, without modeling the expected seismic effects in the massif, that is, without conducting an experiment on the dynamic loading of the soil [2].

Laboratory methods for dynamic tests of physical models of geological bodies, earthworks, ground foundations include: tests on vibrating tables, centrifugal modeling of geotechnical centrifuges, etc.

A wide range of field methods for dynamic tests of soils can be divided into three main groups: seismoacoustic (geophysical), vibrational and geotechnical that differ fundamentally both by the set of estimated parameters and methods of their obtainment [3].

Presently, the most reasoned field method for the estimation of seismic liquefaction of sandy soils in natural bedding but not widely applied in Ukraine is the standard worked penetration [4]. The given method consists in the determination of the number of blows N under the immersion of a standard split-barrel to a depth of 30 cm. In the U.S., a standard split-barrel has a length of 32 inches (81.3 cm), an outer diameter of 2 inches (5.18 cm) and it sinks into the soil by blows of a hammer with the weight of 140 pounds (63.5 kg) when dropped from the height of 30 inches (76.2 cm).

The obtained values of N are normalized by the impact energy (the 60% level of the potential energy of a freely falling hammer is adopted as a standard) and by the effective value of the natural pressure (100 kPa is adopted as a standard), which makes it possible to compare data for different sampling points $N_{1,60}$.

The field technique for determining the potential of soil liquefaction during the seismic impact implies, in the first turn, determination of the cyclic stress ratio (CSR) in the section under the forecasted earthquake which suggests a cyclic load on the ground.

The value of the cyclic stress ratio (CSR) is determined for a specific area with account of the probability of occurrence of an earthquake shock of a given magnitude [6].

Empirical dependences between the number of blows $N_{1,60}$ and the critical value of the given cyclic stress ratio (CSRcrit) causing soil liquefaction under the earthquake with the magnitude (M) of 7.5 (the magnitude of a sufficiently intense shock has been chosen) were used for the assessment of the possibility of liquefaction. The value CSRcrit is determined in accordance with the recommended curves constructed by the results of the standard penetration tests in the areas previously subjected to seismic shocks, where with shocks of different intensity the soil liquefaction occurred or didn't occur (fig. 2). The curves CSR-$N_{1,60}$ differentiate the conditions of possible soil liquefaction (to the left of the given curves) and of impossible one (to the right of these curves).

Currently, a promising alternative or a supplement to the approaches based on the penetration properties has been developed methods of verifying the possibility of seismic soil liquefaction in allocated areas and their localization on the basis of shear wave velocities (V_S) according to the field and/or borehole seismic exploration. Criteria of soil liquefaction for field measurements of shear wave velocities have been proposed in the work [7] since both the V_S and the resistance to liquefaction analogically depend on numerous similar factors (such as porosity, stress state and geological age).

One of the important factors influencing the Vs is the stress state of the soil. Laboratory studies have shown that the shear wave velocity equally depends on the principal stress in the direction of wave propagation and in the direction of particle motion.

That is why in the calculations of seismic liquefaction estimation, reduction of the shear wave velocity Vs to the reference pressure is performed [8]

$$Vs_1 = Vs\left(\frac{Pa}{\sigma'_v}\right)^{0.25},$$

where Pa – reference pressure, adopted as 100 kPa; σ'_v – effective natural soil pressure.

The ability of using the information on the shear wave velocity V_S for the assessment of the likely soil liquefaction is based on the fact that the number of blows $N_{1,60}$ of the standard penetration test is equally dependant on such factors as porosity, stress state, geological age, etc. The sufficiently close relationship between Vs_1 and $N_{1,60}$ [8] obtained on the basis of a large number of experimental data serves as an example of this [fig. 3].

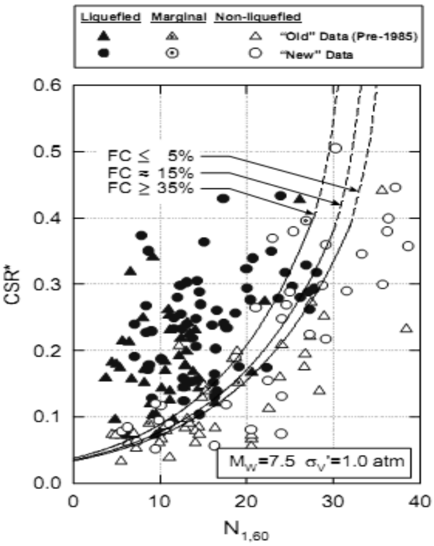

Fig. 2. Curves CSR-$N_{1,60}$ under a varying degree of content of silty-clay particles (FC) in the soil [4]: $N_{1,60}$ – number of blows; CSR – cyclic stress ratio; Mw – magnitude; σ'_v – initial effective vertical stress

The use of the value V_S as a criterion of soil liquefaction has certain advantages [9]:

1) the measurements V_S can be carried out in soils that are difficult to test by probing or taking samples (for example, gravel-pebble deposits), as well as in places where it is impossible to carry out prospecting;

2) the value V_S is an important indicator of physical and mechanical properties of the soil, directly related to its shear modulus at small strains. The shear modulus is required for the analytical evaluation of soil reaction on the dynamic impacts and interactions of soils and buildings in the conditions of such impacts.

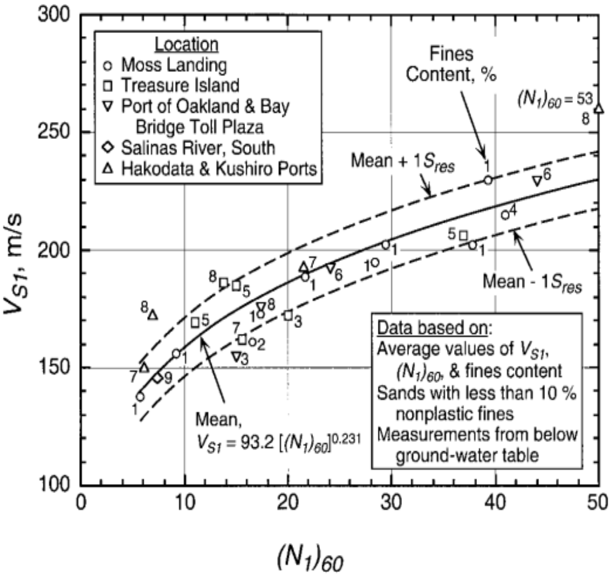

Fig. 3. Relationship curves for the shear wave velocity reduced to the model pressure (Vs_1) and the number of blows ($N_{1,60}$) 8

The second important characteristic which determines the possibility of liquefaction is the cyclic stress ratio (CSR). In 1971, Seed and Idriss proposed a method of assessment of the CSR on the basis of the peak horizontal acceleration on the surface of the array of soils, which makes it possible to use it in the method based on the measurements of V_S. According to this approach, the coefficient of cyclic stress ratio CSR can be determined from the equation [4]

$$CSR = \frac{\tau_{av}}{\sigma'_v} = 0.65\frac{a_{max}}{g} \times \frac{\sigma_v}{\sigma'_v} \times r_d,$$

where τ_{av} – the average value of expected cyclic shear stresses under the peak horizontal acceleration on the soil surface a_{max}; σ_v – the total natural soil pressure; σ'_v – the effective natural soil pressure; r_d – the coefficient of stress reduction with depth.

Peak accelerations a_{max} are assumed equal to the predictive values of maximum accelerations for the design and the maximum design earthquakes. The given characteristics are obtained when assessing the seismicity of the area of the object location taking into account seismic zonation.

The total natural soil pressure σ_v is assessed as the lithostatic pressure calculated at the investigated depth for the actual density of soils above and below the groundwater level.

The effective natural soil pressure σ'_v is calculated as a difference between the total natural soil pressure σ_v and the fluid pressure in the soil (hydrostatic pressure) which can also be easily assessed with the known groundwater level and the depth of the investigated point.

The value of the stress reduction coefficient r_d is estimated from the graph shown in fig. 4, built by Seed and Idriss. This graph has been determined on the basis of information about a variety of different soil conditions and earthquakes. Recommended analytical dependences of the stress reduction coefficient r_d can be represented in form of equations [8]

$$r_d = 1.0\text{-}0.00765z;\; r_d = 1.174\text{-}0.0267z;\; r_d = 0.744\text{-}0.008z,$$

where $z \le 9.15$ м; 9.15 м$< z \le 23$ м; 23м $< z \le 30$ м, accordingly; z – the depth from the surface to the point of the measurement, m.

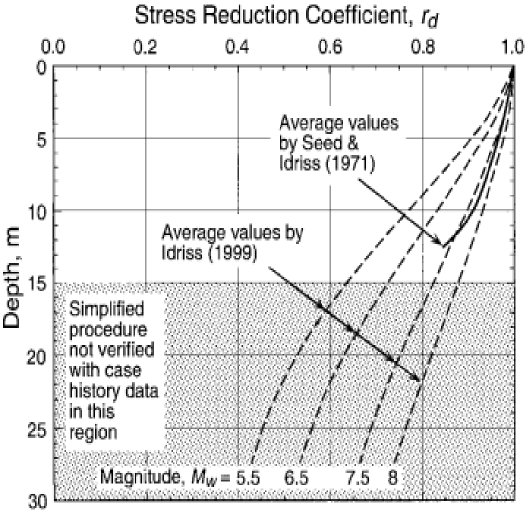

Fig. 4. Relationship between the stress reduction coefficient (r_d) and the depth 8

Investigations of the relationship between the cyclic stress ratio (CSR), velocities of shear waves (Vs_1) and soil liquefaction phenomena were made by various authors. These investigations made it possible to get curves which differentiate the field CSR-Vs_1 into two areas for which the liquefaction is possible and impossible (fig. 5).

Fig. 6 shows the recommended CSR-V_{S1} curves for the assessment of the possibility of soil liquefaction, proposed in 1997 at the seminar NCEER [9].

The value of the liquefaction potential which has the physical meaning of the factor of safety (FS) is used for the quantitative assessment of seismic soil liquefaction in the modern world practice [4]

$$FS = \frac{CRR}{CSR},$$

where *CSR* – cyclic stress ratio; *CRR* – cyclic resistance ratio.

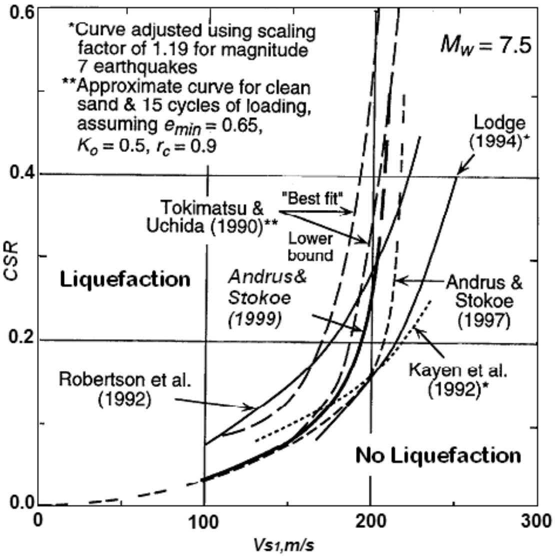

Fig. 5. Curves CSR–V_{s1} built by various researchers in different periods [8]

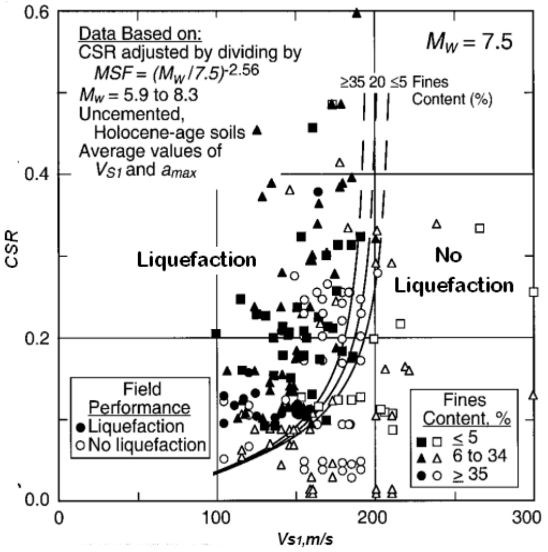

Fig. 6. Recommended curves CSR-Vs_1 4 obtained for soils with different contents of silty-clay grains

The parameter *CRR* can be determined on the basis of the reduced shear wave velocity to reference pressure (Vs_1).

The use of the shear wave velocity V_S as a field index of liquefaction is based on the fact that both V_S, and *CRR* are largely determined by the value of effective compressive stress, soil porosity, history of their loading and geological age of depositions. The use of the value V_S as a criterion for soil liquefaction has certain advantages (Youd et al., 2001) [9].

As a result of numerous studies the following relationship between *CRR* and V_{S1} [9] was proposed

$$CRR = a\left(\frac{Vs_1}{100}\right)^2 + b\left(\frac{1}{V^*s_1 - Vs_1} - \frac{1}{V^*s_1}\right),$$

where V^*_{S1} – critical for the liquefaction occurrence value of corrected shear wave velocity V_{S1}; *a* and *b* – curve parameters (Andrus, Stokoe, 2000) [7], for the construction of recommended curves 0.022 and 2.8 were taken, respectively.

The critical velocities V^*_{S1} depend on the content of silty clay particles in the soil and they are assumed to be equal [8]:

- V^*_{S1} = 200 m/s under the content of silty clay particles of FC ≥ 35%;
- V^*_{S1} = 215-0.5*(FC - 5) m/s when the content of silty clay particles reaches 5 % <FC < 35%;
- V^*_{S1} = 215 m/s with the content of silty clay particles of FC < 5%.

Liquefaction is predicted to occur when the $FS \le 1$ and does not occur when the $FS > 1$.

Results and conclusions. Tailing dumps of large ore mining and processing enterprises belong to the class of particularly important structures. One of the factors that influence their safety is connected with strong seismic impacts caused by earthquakes of technogenic and induced nature.

Under the progressive deposition of tailings, low-velocity and dewatered technogenic soils settle at the base of bund walls of subsequent tiers. When designing these facilities it is necessary to take into consideration the possibility of soil liquefaction at their base.

On the basis of the approach described above, the authors of this study have made investigations at a number of tailing dumps of ore mining and processing enterprises of Kryvyi Rig: InGOK, CGOK, and Northern GOK.

As an example, let us consider the assessment results, obtained by the authors, of the possibility of seismic liquefaction of low-velocity technogenic soils on the basis of the borehole and field seismology at one of the tailing dumps of Kryvyi Rig.

The initial data for the calculations included:

- maximum horizontal accelerations a_{max} for the design earthquake and the maximum calculated one;
- data on the changes in shear wave velocity *Vs* with depth;
- position of the groundwater level (GWL);
- values of rock density above and below the water table.

Quantitative assessment of the possibility of seismic liquefaction was carried out on the basis of the factor of safety.

Taking into account that the alluvial soils represent themselves as an alternation of soils with a different content of silty and clay particles, calculations of the *FS* were carried out for two boundary values of the critical velocity V^*_{S1}, namely [3]: V^*_{S1} = 215 m/s (Fs_1), and V^*_{S1} = 200 m/s (Fs_2).

The calculations were performed by using the materials of both field and borehole seismology (fig. 7, 8).

In the course of the studies it has been established the following. The main geophysical factors determining the possibility of liquefaction are the values of predictive peak horizontal accelerations of the soil surface as well as the law of changes in shear wave velocity with depth.

The depth of the point in the section has also made an essential contribution to the phenomenon. For the points willingly located below the groundwater level (GWL), variations of the ground water level position as well as of the soil density above and below the water level (for physically real situations) have far less effect on the potential liquefaction than the factors enumerated above.

Borehole seismic data make it possible to perform more detailed investigations of the changes in shear wave velocity with depth, and as a result, to divide the section into intervals for which liquefaction can be possible. At the same time, although the field seismic data don't allow researchers to build so circumstantial velocity models, they allow them to study the distribution of areas prone to liquefaction in the space which is impossible with borehole seismic data.

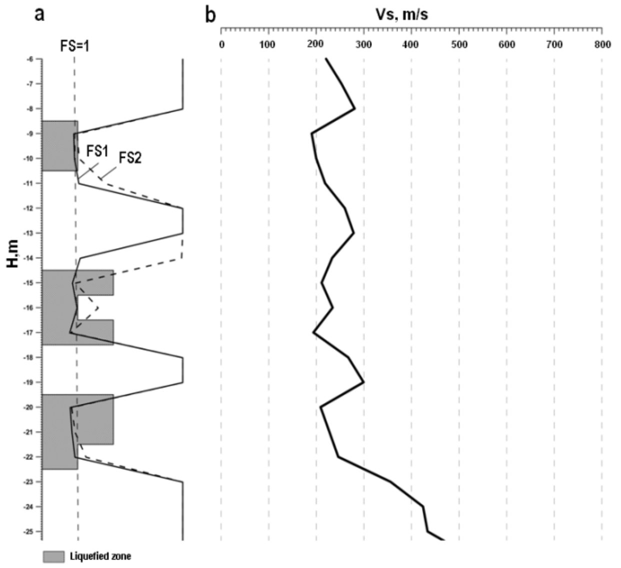

Fig. 7. Forecast of tehnogenic soil liquefaction zones based on the vertical seismic profiling: a – the graph of changes in the factor of safety FS with depth; b – the graph of changes in the shear wave velocity Vs

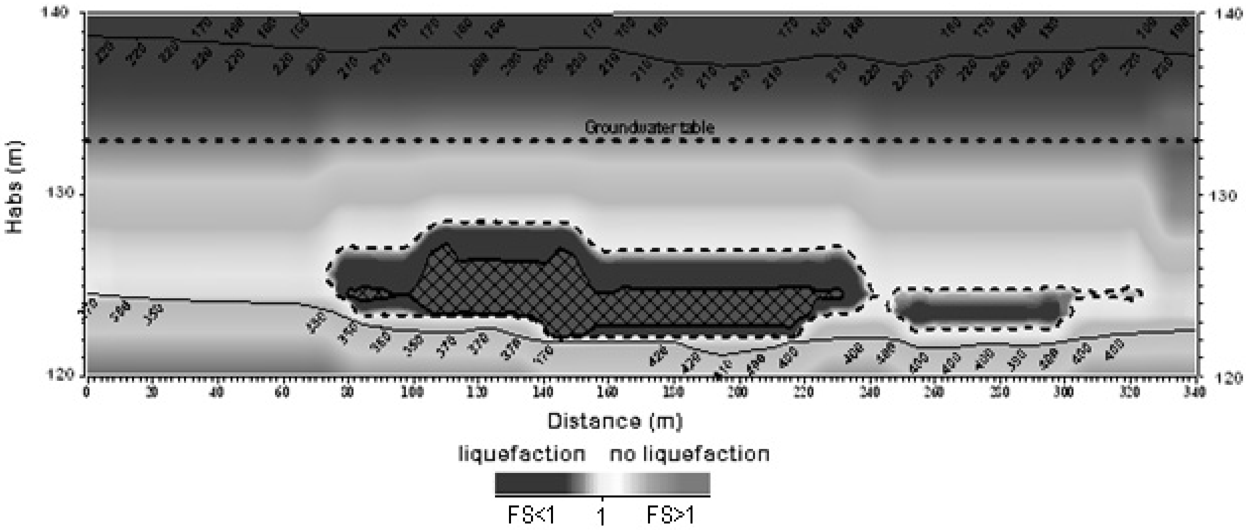

Fig. 8. Forecast of liquefaction of technogenic soils by the materials of field seismology

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Мета. Апробація підходів оцінки сейсмічного розрідження техногенних грунтів за геофізичними даними в умовах хвостосховищ гірничо-збагачувальних комбінатів (ГЗК) України.

Методика. Швидкісні моделі за даними свердловинної та польової сейсморозвідки використовуються для прогнозу можливого сейсмічного розрідження техногенних грунтів в основі огороджуючих дамб хвостосховищ ГЗК Кривого Рогу: ІнГЗК, ЦГЗК, ПівнГЗК. В основу методики покладено емпіричні залежності потенціалу розрідження від швидкісних властивостей ґрунтів і прогнозних значень пікових прискорень при землетрусах.

Результати. Встановлено, що основними геофізичними чинниками, які визначають можливість розрідження, є значення прогнозних пікових горизонтальних прискорень поверхні грунта та закон зміни швидкості поперечних хвиль з глибиною. Істотний внесок робить і глибина досліджуваної точки в розрізі. Для точок, розташованих свідомо нижче рівня грунтових вод (РГВ), варіації положення РГВ і щільності грунта вище та нижче РГВ (для фізично реальних ситуацій) впливають на потенціал розрідження істотно менше, ніж перераховані вище фактори.

Наукова новизна. Обґрунтовані перспективи геофізичної оцінки динамічної стійкості ґрунтів техногенних об'єктів. Уперше даний підхід був апробований на території хвостосховищ України.

Практична значимість. При нарощуванні обсягів хвостосховищ в основі огороджувальних дамб подальших ярусів розташовані низькошвидкісні, обводнені техногенні ґрунти. При проектуванні цих споруд необхідно враховувати можливість розрідження ґрунтів у їх основі. Використовуваний підхід є багатообіцяючою альтернативою або доповненням до підходів, що базуються на пенетраційних властивостях, який суттєво підвищить достовірність прогнозу можливості розрідження техногенних ґрунтів у випадку сейсмічного впливу різної природи.

Ключові слова: *хвостосховище, техногенні грунти, землетрус, розрідження, швидкість поперечної хвилі*

Цель. Апробация подходов оценки сейсмического разжижения техногенных грунтов по геофизическим данным в условиях хвостохранилищ горно-обогатительных комбинатов (ГОК) Украины.

Методика. Скоростные модели по данным скважинной и полевой сейсморазведки используются для прогноза возможного сейсмического разжижения техногенных грунтов в основании ограждающих дамб хвостохранилищ ГОКов Кривого Рога: ИнГОК, ЦГОК, СевГОК. В основу методики положены эмпирические зависимости потенциала разжижения от скоростных свойств грунтов и прогнозных значений пиковых ускорений при землетрясениях.

Результаты. Установлено, что основными геофизическими факторами, определяющими возможность разжижения, являются значения прогнозных пиковых горизонтальных ускорений поверхности грунта и закон изменения скорости поперечных волн с глубиной. Существенный вклад оказывает и глубина исследуемой точки в разрезе. Для точек, расположенных заведомо ниже уровня грунтовых вод (УГВ), вариации положения УГВ и плотности грунта выше и ниже УГВ (для физически реальных ситуаций) влияют на потенциал разжижения существенно меньше, чем перечисленные выше факторы.

Научная новизна. Обоснованы перспективы геофизической оценки динамической устойчивости грунтов техногенных объектов. Впервые данный подход был опробован на территории хвостохранилищ горно-обогатительных комбинатов Украины.

Практическая значимость. При наращивании объемов хвостохранилищ в основании ограждающих дамб последующих ярусов расположены низкоскоростные, обводненные техногенные грунты. При проектировании этих сооружений необходимо учитывать возможность разжижения грунтов в их основании. Используемый подход является многообещающей альтернативой либо дополнением к подходам, базирующимся на пенетрационных свойствах, и существенно повысит достоверность прогноза возможности разжижения техногенных грунтов в случае сейсмического воздействия различной природы.

Ключевые слова: *хвостохранилище, техногенные грунты, землетрясение, разжижение, скорость поперечной волны*

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