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# SOME FEATURES OF ASSESSING THE STABILITY OF HYDROTECHNICAL STRUCTURES GIVEN THE ANISOTROPY OF THE STRESS-DEFORMED STATE OF THEIR SOIL BASES

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***Abstract.*** *The processes that cause degradation of soil properties, decrease in their strength and increase in deformability was analized. Solving the problem of determining phase velocities and vectors of elastic displacements made it possible to establish the differential coefficient of elastic anisotropy of soils that form the basis of hydraulic structures. Experimental studies of soils, which are the basis of hydraulic structures, when using ultrasonic methods made it possible to determine the factors that cause the anisotropy of elastic waves. The most informative parameter of the anisotropy of soils, which are the basis of hydraulic structures,was established. The main indicators of the manifestation of azimuthal anisotropy of bulk elastic waves were determined. The study of samples of soil bases of hydraulic structures when using the invariant-polarization method made it possible to experimentally establish the type of anisotropy and determine the value of the coefficient of elastic anisotropy of the studied samples. The angle of deviation of the elastic displacement vector from the direction of the wave normal, exceeding 90°, is a sign of possible destruction of the soil base of a hydraulic structure and enables us to localize zones of limit equilibrium.*

*A study of sandstone samples was carried out when using atomic force microscopy to investigate the degree of change in the microstructure of the soil bases of hydraulic structures. The use of the acoustic emission method allowed us to obtain an image of the acoustic response during laser irradiation, which made it possible to evaluate the diffraction pattern of the studied sandstone samples. It was established that a characteristic feature of the acoustic emission spectrum of the studied samples of soil bases of hydraulic structures is the presence of numerous secondary maxima. Their occurrence indicates the complexity of the material composition and structure of soil bases, in particular, a specific combination of allotigenic and authigenic minerals, cementing substances and textural features. In the case of irreversible deformations, the influence of fluid saturation manifests itself through differential-elastic effects, caused by both the crystal structure and the nature of interphase bonds, as well as the temperature, pressure and other parameters of the soil base environment of hydraulic structures.*

***Keywords****: hydraulic structures, stability, soil base, acoustic emission, anisotropy*

**Relevance of the research.** Hydraulic structures are the structures subject to the water environment, designed for the use and protection of water resources, as well as for protection against the harmful effects of water [1]. The system “structure – soil base” can be represented as three sequentially connected elements: soil base, foundation and above-ground structure. When assessing the stability of a structure, the load transfer scheme is of direct practical importance, which depends on the structure design, the magnitude of the load on the column or on 1 $m^2$ of the foundation. And if the loads from the structure and equipment are more or less constant, then the structure itself changes over time: there is a gradual and irreversible change in the properties of building materials as a result of aging, corrosion, etc. [2]. The defining parameters of the foundation are its type (rigid, flexible), geometric dimensions, shape, and material strength [3]. During the operation of the structure, the foundation material changes the most as a result of fluctuations in temperature and moisture conditions under the influence of aggressive industrial effluents, etc. [4].

**Analysis of recent research and publications**. The most hidden and uncontrolled changes in the process of construction and operation of structures occur with the soil bases. When assessing the stability of structures, processes that lead to the deterioration of soil properties, a decrease in strength and an increase in deformability, which in turn leads to an increase in absolute and relative deformations, and sometimes to the destruction of soil bases and structures, are of great importance. Soils, depending on the type, physical state and structural strength, have different abilities for deformation developing. Numerous experimental studies show that under certain loads, when the stage of displacements begins, a compacted core is formed under the foundation in the shape of a wedge. The core is the foundation across the entire width, and the sides are formed by slip curves that pass along the edges of the foundation [5–7].

The stability of the structure depends on the type, size and depth of the foundation, as well as on the intensity of the load application. An increase in the size of the foundations and their depth leads to a decrease in the probability of bulging of the soil base and an increase in the stability of the structure. A rapid increase in additional pressure from the structure leads to a decrease in the magnitude of the destructive load, a slow increase in pressure – to the increase in destructive load. Uniform settlement of the entire structure does not cause additional stresses in the structures, but the difference in settlements of individual parts of the soil base especially affects the strength of foundations and above foundation buildings. Experience shows that the difference in settlements increases with an increase in the magnitude of absolute settlements. Deformations depend both on changes in volume (as a result of compaction, swelling, etc.) and on the deformation of individual phases that make up the soils (creep of the skeleton, compression of pore water, as well as inclusions of vapors and gases) [8–10].

Under the action of tangential stresses, local failure zones appear in the soil base, which, when the pressure from the structure increases, increase in size and form a sliding surface. The zones of limiting equilibrium of soil bases are the areas of the soil massif that are on the verge of destruction under the action of loads or other influences. Their dependence is determined by a combination of soil properties (its strength and deformability), load characteristics (magnitude, distribution) and geometric parameters of the structure resting on the soil. The determination of these zones is key to ensuring the stability of structures and preventing settlements and destractions. The limit states of the soil base manifest themselves in these zones. The information on the sizes of the zones of limiting equilibrium, where there is destruction of the soil base, allows:

– to assess the possibility of applying the theory of linearly deformed medium to calculate the stability of the structure’s foundation;

– to calculate the stability of the soil base and determine real ways to increase it.

When calculating the sizes of the zones of limit equilibrium (plastic deformations), it is first necessary to determine the depth of their development by comparing the maximum angles of deviation $\theta_{max}$ with the angles of internal friction φ, which vary within the soil base.

The boundaries of the zone of limit equilibrium can be traced based on the following dependencies:

– when $\varphi > \theta_{max}$ ($\tau_\alpha > \tau_{\theta max}$) – limit equilibrium is not observed;

– when $\varphi = \theta_{max}$ ($\tau_\alpha = \tau_{\theta max}$) – limit equilibrium is observed;

– when $\varphi < \theta_{max}$ ($\tau_\alpha < \tau_{\theta max}$) – soil destruction is observed [11–13].

The angle of internal friction of soil base φ is an angle that characterizes the resistance of the soil to shear, which arises from the interaction between its particles. This parameter is key for engineering and geological calculations of foundations, as it determines the stability of the soil massif and its ability to withstand loads.

1. Types of deformations and causes of their occurrence [5]

| Types of deformations | Causes of deformation |
|---|---|
| Elastic deformations:<br>– change in volume | Change in molecular forces of elasticity of solid particles, as well as thin films of water |
| – distortion of shape | Change in molecular forces of elasticity, change in structural lattice |
| Inelastic, residual deformations:<br>– compaction | Reduction in porosity |
| – swelling | Wedging effect as a result of electro-molecular forces |
| – creep | Mutual displacement of soil particles |
| – only residual | Destruction of structure, destruction of particles |

An important factor, the effect of which must be taken into account, is the difference in the mechanical soil properties in different directions, or the so-called mechanical anisotropy (for example, deformation anisotropy, strength anisotropy, swelling anisotropy), and sometimes the difference in filtration properties, or filtration anisotropy. The anisotropy of the mechanical properties of soils is explained by their ordered structure with a preferential parallel orientation of particles in a certain direction [14–16].

**The purpose of the study** is to test the use of the invariant-polarization method, atomic force microscopy and the acoustic emission method for assessing the stability of hydraulic structures, given the anisotropy of the stress-strain state of their soil bases by conducting experimental studies and subsequent analytical calculations.

**Materials and methods of the study**. Field and laboratory experimental studies on the elastic properties of the studied samples of soil bases of hydraulic structures were carried out using the invariant-polarization method, atomic force microscopy and the acoustic emission method [17–19]. The Hydrustab software and algorithmic complex developed by the author was used to process the results of experimental studies of samples of soil bases of hydraulic structures and to further construct stereo projections and diagrams.

**Research results and their discussion**. Experimental studies of the soil base using ultrasonic methods show that the anisotropy of elastic waves is due to the crystallographic orientation of minerals, the grain shape of oriented minerals and the location of microcracks. Depending on the nature of the orientation of the structural texture elements, soils are divided into three types: unidirectional, multidirectional within one plane and spatially oriented. The key indicator of anisotropy is the differential coefficient of elastic anisotropy, the value of which reflects the degree of deviation of the soil texture from the closest isotropic medium. Thanks to this coefficient, it is possible to compare the anisotropic properties of elastic media of different symmetry. In particular, the coefficient of transversely isotropic elastic anisotropy makes it possible to assess the degree of deviation of textures of rhombic symmetry from the elastic characteristics of a transversely isotropic medium.

The characteristic surfaces of the anisotropy parameters are constructed in the form of stereographic projections of isolines, which gives a complete idea of the spatial variability of the anisotropy parameters of bulk elastic waves and reflects the influence of the symmetry of the medium. Strict restrictions are imposed on the azimuthal dependence of the differential parameters, due to the anisotropy of the soil medium. The azimuthal anisotropy of bulk elastic waves manifests itself in the following forms [20–22]:

1) difference between the phase and radial velocities of elastic waves;

2) deviation of the elastic displacement vectors and radial velocity vectors from the direction of the wave normal;

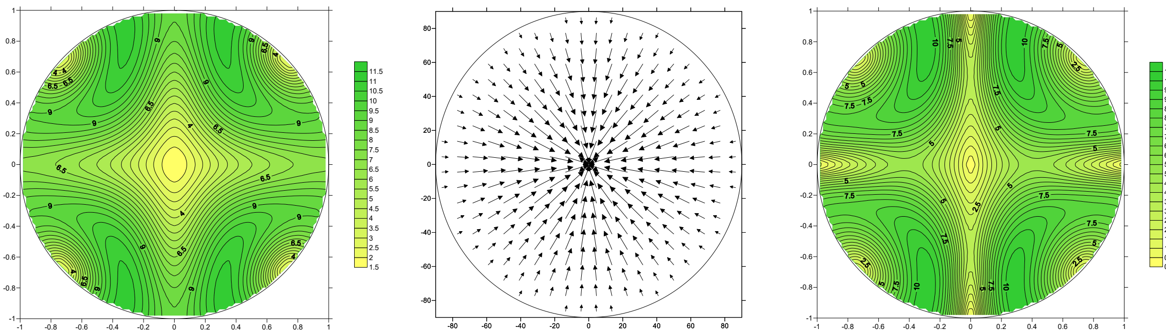
3) the presence of polarization effects, phenomena of acoustic birefringence, acoustic refraction and singular behavior of the elastic displacement vectors in the zone of the acoustic axes.

The use of stereographic projections made it possible to reflect the nature of the anisotropy of elastic waves in full, and not only in intersections selected when using coordinate planes. Fig. 1(a) shows a stereoprojection of the differential coefficient of elastic anisotropy $A_d$ of sandstone sample № 1 of the studied soil bases, which were selected in the area of the Kyiv HPP dam. In the wave theory for transverse waves in an elastic medium the vector of elastic displacements (polarization) is always perpendicular to the wave vector (normal to the wave front), but in a “pure” homogeneous medium, this vector lies strictly in the orthogonal direction, without deviations.

But in cases of anisotropy of the medium, boundary conditions (reflection, refraction at the boundary of the media) and diffraction at obstacles a deviation angle may appear between the direction of the wave normal and the actual direction of the elastic displacement vector.

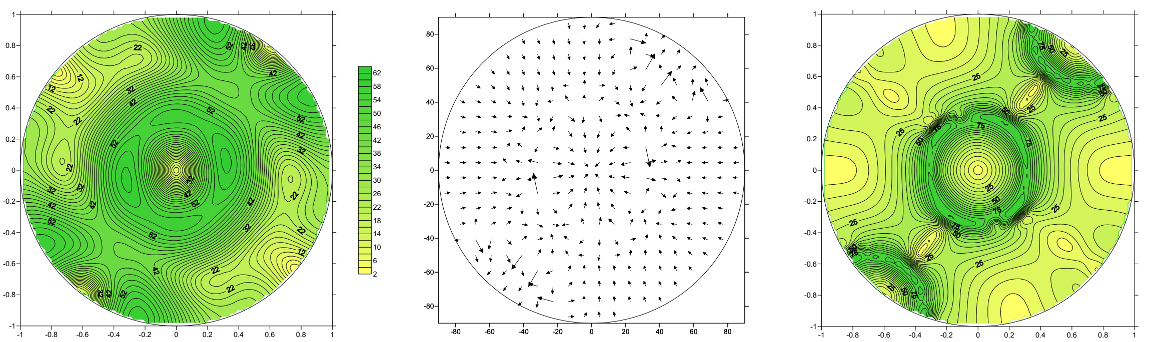
And this deviation that is an indicator of wave effects associated with diffraction and diffusion, which is a manifestation of non-orthogonal polarization or “mixed wave” (especially in anisotropic media) [23–25]. Fig. 1(b) shows a diagram of the distribution of polarization vectors of the “slow” quasi-transverse wave of sandstone sample № 1 of the studied soil bases. Based on the data obtained when constructing these stereo projections and diagrams, a stereo projection of the deviation angle of the elastic displacement vector from the direction of the wave normal $\left(\vec{U},\vec{n}\right)$ of sandstone sample № 1 of the studied soil bases was constructed, which is shown in Fig. 1(c).

The value of the elastic anisotropy coefficient varies from 0,48 % to 11,23 %. A particularly important factor determining the value of the elastic anisotropy coefficient is the spatial coincidence of the orientations of structural elements, primarily the crystallographic orientation, the orientation of sandstone grains by shape and the directions of microcrack development. The deviation of the elastic displacement vector from the direction of the wave normal varies from 0,44° to 10,63°. Fig. 2(a) shows a stereo projection of the differential elastic anisotropy coefficient $A_d$ of sandstone sample № 2 of the studied soil bases. Fig. 2(b) shows a diagram of the distribution of polarization vectors of the “slow” quasi-transverse wave of sandstone sample № 2 of the studied soil bases.



a b c

Fig. 1. Sandstone sample № 1:
a – stereo projection of epy isolines of the differential elastic anisotropy coefficient $A_d$ (isolines – in %);
b – diagram of the distribution of polarization vectors of a “slow” quasi-transverse wave;
c – stereo projection of the deviation angle of the elastic displacement vector from the direction of the wave normal $\left(\vec{U},\vec{n}\right)$ (isolines – in degrees)



a b c

Fig. 2. Sandstone sample № 2:
a – stereo projection of isolines of a differential elastic anisotropy coefficient $A_d$ (isolines – in %);
b – diagram of the distribution of polarization vectors of a “slow” quasi-transverse wave;
c – stereo projection of a of deviation angle of the elastic displacement vector from the direction of the wave normal $\left(\vec{U},\vec{n}\right)$ (isolines are in degrees)

Based on the data obtained when constructing these stereo projections and diagram, a stereo projection of the deviation angle of the elastic displacement vector from the direction of the wave normal $\left(\vec{U},\vec{n}\right)$ of the sandstone sample № 2 of the studied soil bases was constructed, which is shown in Fig. 2(c). The value of the elastic anisotropy coefficient varies from 1,67 % to 62,73 %. The value of the deviation of the elastic displacement vector from the direction of the wave normal varies from 0.47° to 95,46°.

Elastic anisotropy reflects the deformation history of the soils of the foundations of hydraulic structures. In the studied samples of deformed soils, a pronounced ordering of their internal structure is observed, which causes an even more intense manifestation of the anisotropy of elastic waves. Anisotropy and structural ordering of soils constitute interrelated fundamental properties that reflect the mechanisms of deformation formation and subsequent transformations. Thus, the stereo projections and diagrams obtained for the studied sandstone samples allowed us to quantitatively assess the influence of the anisotropy of the stress-strain state of the soil bases of hydraulic structures on the stability of these structures, and also demonstrate a direct relationship between the zones of limiting equilibrium and the angle of deviation of the elastic displacement vector from the direction of the wave normal $\left(\vec{U},\vec{n}\right)$. The obtained research results for soil samples that were not under the compaction pressure of the main part of the hydraulic structure confirm the efficiency of applying the methods used for studying the soil bases of hydraulic structures of various types.

In order to study the degree of change in the microstructure of a soil base sample of hydraulic structures caused by elastic deformations (in particular, shape distortion), a study of sandstone samples was carried out when using atomic force microscopy. The elastic $E$ and inelastic characteristics of soil bases significantly depend on the morphology of the near-surface layer. It is due to the development of flattened-lenticular layering and schistosity, the orientation of hinges and axial planes of linear folds, as well as the corresponding orientations of minerals both in their shape and internal structure. Using atomic force microscopy, 2D and 3D images of the surface of a sandstone in the (100) orientation plane obtained were obtained, which is shown in Fig. 3.

Fig. 4 (right) shows an image of the acoustic response that occurred during laser irradiation, which was accompanied by the formation of inhomogeneous thermomechanical stresses with the formation of a melt crater and the ejection of molten material onto the sample surface. The depth of the melt crater $\Delta h$, under conditions of constant power and duration of laser action, is determined by thermal conductivity (in particular, local) and a "quasi-equilibrium" spatial distribution of temperature gradients $\Delta T$ both in the direction perpendicular to the crater axis and along it. In our experiments, its value was about $h \approx 500$ µm. The complex structure of the recorded acoustic response indicates the action of several mechanisms for the transformation of localized thermal disturbance into mechanical stress waves (acoustic waves), which appear simultaneously or sequentially in time.

Comparison of the acoustic response in Fig. 4 (left) with the duration of the laser pulse and the geometric parameters of the sample indicates the probability of the second and third time maxima (pulses aligned in the time) occurring due to the acoustic emission mechanism (AE),

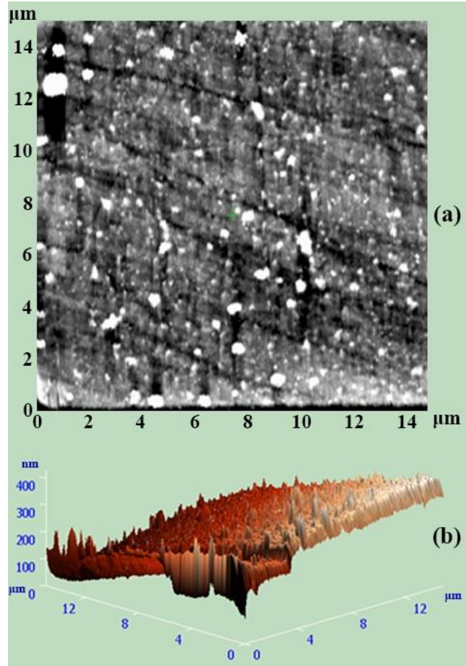



Fig. 3. Image of the microstructure of a sandstone sample in the (100) orientation plane obtained when using atomic force microscopy: (a) 2D image of the microstructure and (b) 3D image of the microstructure

since the time delays of their appearance and the length of the final pulse cannot be explained only within the photothermoelastic mechanism. An important task is to correctly determine the possible AE mechanisms accompanying the processes described above. The sequence of their manifestation in time can be presented as follows:

1. AE occurrence during the melting of the sandstone surface (phase transition- solid phase → liquid phase);

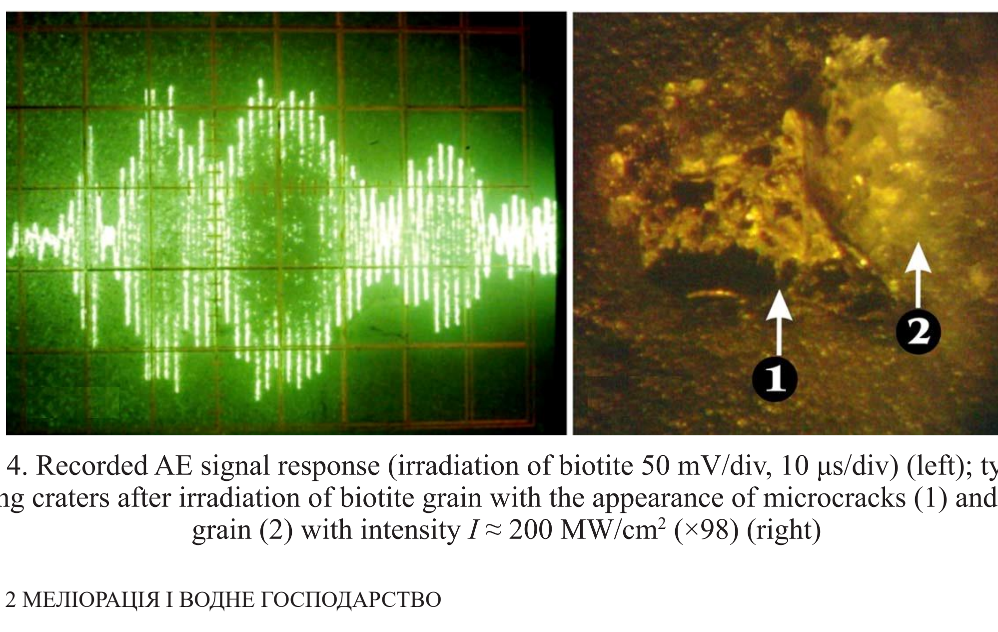



Fig. 4. Recorded AE signal response (irradiation of biotite 50 mV/div, 10 µs/div) (left); typical melting craters after irradiation of biotite grain with the appearance of microcracks (1) and quartz grain (2) with intensity $I \approx 200$ MW/cm$^2$ (×98) (right)

2. AE during the crystallization of the melt (phase transition – liquid phase → solid phase);

3. AE caused by crack formation.

Transition processes such as solid phase → gas and gas → solid phase can be ignored because they occur during a relatively "long" (nanosecond) laser pulse. Under the conditions of the experiments, phase transitions occur extremely quickly – for the time commensurate with the duration of the laser action ($\tau \approx 18$ нс). It is likely that it is crack formation that is the main source of the formation of the "acoustoemission component" of the acoustic response. Consideration of AE as two types of emission – discrete (high-energy) and continuous (low-energy) loses relevance in cases where the time of individual AE acts ($\tau$) exceed the time of wave transmission through the sample $t$, i.e. $\tau > t$, and the lengths of wave trains $\lambda$ exceed the typical dimensions of the base sample $L$, i.e. $\lambda > L$ [26–28].

The AE spectrum of fine-grained sandstones – cemented soils with granular porosity is characterized by the presence of numerous secondary maxima. Their appearance reflects both the diversity of the material composition and structural features of the soil base, including the combination of allotygenic and authigenic minerals, cement composition and specific texture, and to a certain extent reproduces the course of dia- and catagenetic processes. The soil bases, where the samples were taken, underwent mechanical deformations of varying intensity, which led to the formation of characteristic structural and textural features.

Under conditions of different tension or compression, massive textures arose, where high amplitudes of the main (primary) peaks were recorded in the AE spectra along with increased oscillations. In contrast, samples with directive structures generally showed lower averaged AE signal amplitudes, which is most pronounced in fine-grained varieties of sandstones. Another characteristic feature of samples with directive textures (soils formed in non-equilibrium deformation fields) is the dominance of AE spectra with inhomogeneous, stretched curves containing several signal trains.

**Conclusions.** The anisotropy of the studied soils is determined by their textural characteristics and the orderliness of the structural-morphological paragenesis, which is manifested in striation and linearity. An additional factor is the ordered system of microcracks formed as a result of the current state of the soil massif. The value of the deviation angles of the elastic displacement vector from the direction of the wave normal > 90° is an indicator of potential destruction in the soil base of the hydraulic structure and allows us to determine the zones of limit equilibrium.

The analysis of the acoustic emission signal allowed us to evaluate the diffraction pattern of the studied sandstone samples. In particular, the measured amplitude of the acoustic emission signal allowed us to quantitatively assess the intensity of polarization effects, phenomena of acoustic birefringence, acoustic refraction and singular behavior of elastic displacement vectors in the area of the acoustic axes of the studied soil base samples.

The conducted experimental studies and analytical calculations allowed us to test the use of the invariant and polarization method, atomic force microscopy and the acoustic emission method for assessing the stability of hydraulic structures given the anisotropy of the stress-strain state of their soil bases using the example of sandstones.

**Conflicts of interest:** the authors declare no conflict of interest.

**Use of artificial intelligence:** the authors confirm that they did not use artificial intelligence technologies during the creation of this work.

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# ДЕЯКІ ОСОБЛИВОСТІ ОЦІНЮВАННЯ СТІЙКОСТІ ГІДРОТЕХНІЧНИХ СПОРУД З ВРАХУВАННЯМ АНІЗОТРОПІЇ НАПРУЖЕНО-ДЕФОРМОВАНОГО СТАНУ ЇХ ҐРУНТОВИХ ОСНОВ

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***Анотація.*** *Проведено аналіз процесів, що спричиняють деградацію властивостей ґрунтів, зниження їх міцності та підвищення деформативності. Розв'язання задачі визначення фазових швидкостей і векторів пружних зміщень дало змогу встановити диференціальний коефіцієнт пружної анізотропії ґрунтів, які формують основу гідротехнічних споруд. Проведені експериментальні дослідження ґрунтів основи гідротехнічних споруд ультразвуковими методами дозволили визначити фактори, що обумовлюють анізотропію пружних хвиль. Встановлено найбільш інформативний параметр анізотропії ґрунтів основи гідротехнічних споруд. Визначено основні показники прояву азимутальної анізотропії об'ємних пружних хвиль. Дослідження зразків ґрунтових основ гідротехнічних споруд за допомогою інваріантно-поляризаційного методу дозволило експериментально встановити тип анізотропії та визначити величину коефіцієнта пружної анізотропії досліджуваних зразків. Кут відхилення вектора пружних зміщень від напрямку хвильової нормалі, що перевищує 90°, слугує ознакою можливого руйнування ґрунтової основи гідротехнічної споруди та дає змогу локалізувати зони граничної рівноваги. Проведено дослідження зразків пісковиків із застосуванням атомної силової мікроскопії з метою дослідження ступеня зміни мікроструктури ґрунтових основ гідротехнічних споруд. Застосування методу акустичної емісії дозволило отримати зображення акустичного відгуку при лазерному опроміненні, що надало змогу оцінити дифракційну картину досліджуваних зразків пісковиків. Встановлено, що характерною особливістю спектру акустичної емісії досліджуваних зразків ґрунтів основи гідротехнічних споруд є наявність численних вторинних максимумів. Їх виникнення свідчить про складність речовинного складу та структури ґрунтової основи, зокрема про специфічне поєднання аллотигенних і аутигенних мінералів, цементуючих речовин і текстурних особливостей. У випадку незворотних деформацій вплив флюїдонасичення проявляється через диференціально-пружні ефекти, зумовлені як кристалічною структурою і природою міжфазових зв'язків, так і температурними, тисковими та іншими параметрами середовища ґрунтової основи гідротехнічних споруд.*

***Ключові слова:*** *гідротехнічні споруди, стійкість, ґрунтова основа, акустична емісія, анізотропія*