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THREE-DIMENTIONAL MODEL OF THE DEFORMATION OF STRUCTURAL MERIAN BASIN BY STANDING WAVES

Purpose of the study. Analysis of the effect of standing waves on the bed of the water basin. **The research methodology**. When “standing” wave, the water masses carry out rotary-translational displacement. In the vertical cross section of the basin there are synchronous reversible water movements. Their greatest values are in the antinodes, in the vertical direction, and in the nodes, in the horizontal direction. Microseisms of seiche origin create a field of deformation in a vertical section of the basin, with maxima on the lines of projections of the antinodes at the bottom of the reservoir, and also on the lateral face. **Results**. Proceeding from the fact that the characteristic feature of oscillations is the conditionality of their period, with the linear dimensions of the characteristic side and the coexistence of vertical standing waves with horizontal flow of currents, in the calculations all three dimensions of the model rectangular basin with constant depth are considered. It is shown that in the presence of a “vertical” seiches, the threat of resonance excitation of the seiches is caused by the internal excitatory force – other seiches of the same basin. In the wet liquidation of mines, which are accompanied by the filling of the produced space with water, instead of layered aquifers, separated by water supply, a crack-collecting array is formed, which acts as the only cracked zone. Normal fluctuations of water masses can contribute to increasing the seismicity of the created depression zone. But, on the other hand – in mines it is possible to accommodate the underground pools of the pumped-storage power stations. The attractiveness of exhausted mines is to reduce or exclude excavation works when erecting underground energy objects. **Scientific novelty**. A modified Merian formula for calculating the seiche period in a rectangular basin of constant depth takes into account the presence of two horizontal and one vertical modes. It is shown that in the presence of a “vertical” seiches, the threat of resonance stimulation of the seiches is caused by the internal excitatory force – other seiches of the same water body. The danger of the resonance interaction of the unidirectional horizontal pairs of the “wave of horizontal mode – the current of the vertical mode” and “the wave of the vertical mode – the current of the horizontal mode” is determined. The hydrological danger, which is caused by possible resonance of the proper oscillations, as well as their resonance with the external excitatory force, is revealed. **Practical value**. Water objects have been discovered, the analysis of which requires taking into account the vertical mode of its normal oscillations. These are – mines with a vertical dimension, which are comparable to the horizontal ones.

Key words: hydroelectric pump storage power station, vertical mode of seiches; microseisms; wet liquidation of mine; seiches; seiche current; seiche wave; surf beat.

Introduction

One of the most powerful sources of lithospheric deformations is the pressure of standing waves, seiches and surf beat (see, for example, [Chekhov et al., 1994; Nesterov, 1996; Anakhov, 2016]). As a rule, deformations of the bottom, created by horizontal longitudinal and transverse waves, are considered.

However, information on the pressure of standing waves is also available on the vertical surfaces of the water bodies (underwater coastal slope). Fig. 1 shows the diagrams of the pressure of standing waves on the vertical wall from the open water area.

Purpose of the study

The purpose of the study is an analysis of the effect of activity of standing waves on the bed of the coastal slope.

The research methodology

The deformation field in the vertical cross section of the basin is created by the microseisms of seiches origin, with maxima on the lines of projections of the antinodes at the bottom of the reservoir [Anakhov, 2016], and, also, on the lateral face (see Fig. 1).

The water masses perform rotational-translational movements, as shown in Fig. 2.

In the vertical longitudinal (*L*) cross section of the rectangular basin with constant depth there are synchronous reversible displacements, with maxima in the vertical (in antinodes, with velocity $\vec{u}$) and horizontal (in nodes, with velocity $\vec{v}$) directions. Modes are calculated according to the Merian formula: $T_l = 2Ll^{-1}(gD)^{-1/2}$, where l – coefficient, that denote the number of standing half-waves of the field, laid along the side L of the water body; g – gravity of Earth (g=9.81 m/s^2).

In the perpendicular to the vertical transverse (*W*) section of the basin there are the same movements. Modes are calculated by the formula $T_w = 2Ww^{-1}(gD)^{-1/2}$.

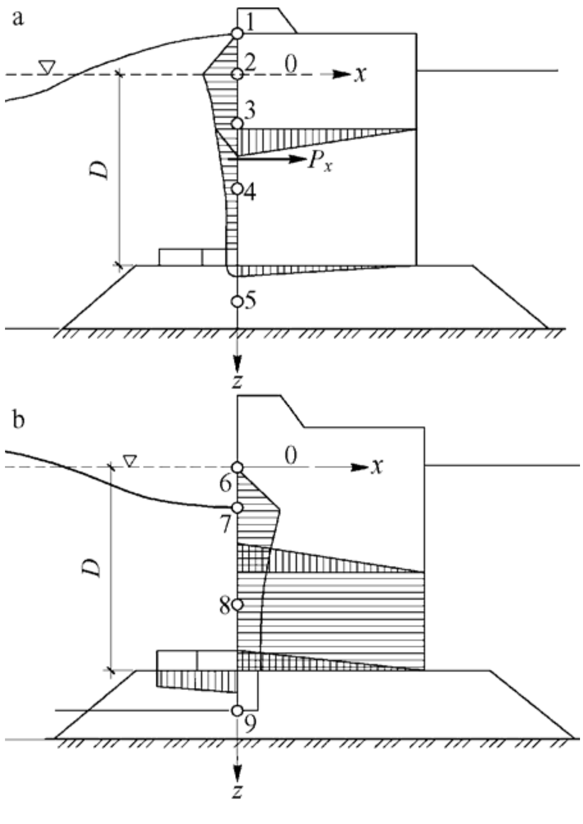

Fig. 1. Diagrams of pressure of standing waves on a vertical wall from the open water area at the ridge (a) and the sole (b) of the wave; P_x – horizontal linear load [TCP, 2011]

Proceeding from the fact, that the characteristic feature of the fluctuations of standing waves, firstly, is the conditionality of their period with the linear dimensions of the characteristic side, and, secondly, the coexistence of vertical standing waves with horizontal movements of currents, is a logical assumption concerning the existence of a pair wave/current with a period, which determines the depth of water: $T_d = 2Dd^{-1}(gD)^{-1/2}$.

The periods of normal oscillations in a bounded three-dimensional space are determined by all its linear dimensions [Knudsen, 1934].

Given this, we rewrite the Merian formula in the following form:

$$T_{lwd} = 2/\sqrt{gD}\sqrt{(L/l)^2 + (W/w)^2 + (D/d)^2}\ . \quad (1)$$

The stress in the Earth's crust, which is created by static loading, is [Anakhov, 2016],

$$\sigma = \rho g \overline{D}, \quad (2)$$

where ρ – water density ($\rho \approx 10^3$ kg/m^3).

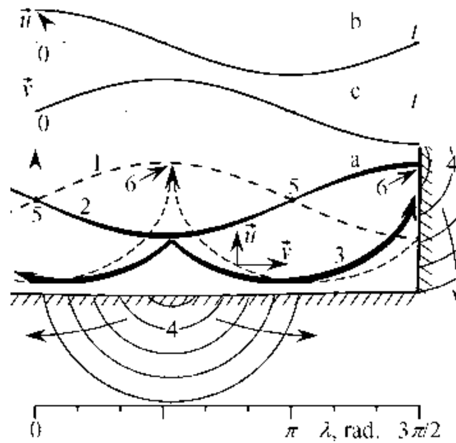

Fig. 2. Oscillations of the standing wave and the deformation field of the reservoir bed:

a – the profile of the standing wave at the characteristic moments of the oscillation cycle: 1, 2 – amplitude of the wave at times $t=0+2\pi k$ (v=0, u=max), $t=\pi+2\pi k$ (v=0, u=min), k=1,2,…, k; 3 – direction of the current immediately before the wave reaches the optimal value ($t\rightarrow\pi$); 4 – deformation field at time $t\rightarrow\pi$; 5, 6 – nodes and antinodes of wave (from [Anakhov, 2018], changed); b – changes in the rate of build-up of the level (water) in the beacon, starting at the time $t=0+2\pi k$; c – changes of the current velocity in the node, starting at the time $t=0+2\pi k$

Lithospheric deformations from the pressure of the seiche wave form a grid with lines of the antinodes. The maximum pressure at the bottom at times $t=0+2\pi k$ (see Fig. 2) can be calculated from the formula [Anakhov, 2016]:

$$\sigma_{an} = \rho g A\,. \quad (3)$$

Hydrostatic pressure on the top of the underwater coastal slope is zero, and at its lower edge is $P_{max}=\rho g D$.

The horizontal linear load P_x from broken waves must be taken equal to the area of the sidewall pressure diagram, with the maximum value of p for the value of ordinate D (see Fig. 1), to be calculated using the formula [TCP, 2011]:

$$p = \frac{2\rho g A}{\mathrm{ch}kD}, \quad (4)$$

where $k=2\pi/\lambda$ – wavenumber; λ – the wavelength.

Results

From the legitimacy of surface sea waves, it was known that the variations in pressure should be attenuated with depth in exponential law, and practically cannot affect depths equal to several wavelengths. M. Miche (1944) and M. Longuet-Higgins (1950) theoretically showed that under the action of standing waves there is a force that does not decay with increasing depth and is transmitted to the bottom for an “infinite” depth. This theory was perfected by J. Hieblot and J. Rocard (1959), and generalized by L. Brekhovsky (1966) [Tabulevich, 1986]. V. Tabulevich considered the effect of microseismic oscillations that arise simultaneously with standing water waves, which are generated in water areas in the rear parts of atmospheric cyclones. In particular, such a “one-sided approach” led to the consideration of the pressure of the wave only on the horizontal surface – the bottom of the reservoir (see [Roeloffs, 1988; Talwani et al., 2007; Anakhov, 2016]). Another explanation – the undeniable advantage of horizontal measurements above the vertical (Table 1).

The results of the study of the effect of standing waves, in comparison with the static pressure from the depth, are presented in Table 2 (at calculations the same amplitude for all reservoirs is accepted A=1 m).

Table 1

The ratio of the sides of the three deepest lakes in the world

Lake	Length L, km	Width W, km	Depth D, km	$L \times W \times D$, %
Caspian Sea	1.030	360	0.208	100×35× ×0.02
Lake Baikal	636	50	0.750	100×8× ×0.12
Lake Tanganyika	673	49	0.574	100×7× ×0.09

Table 2

Results of calculations of deformations of the structural basins of the deepest lakes in the world

Lake	Observation results		Results of calculations							
	T_{100}, min.	T_{010}, min.	T_{100}, min.	T_{010}, min.	T_{001}, min.	σ, MPa	σ_{an}, kPa	p_{100}, kN/m	p_{010}, kN/m	p_{001}, kN/m
Caspian Sea	750 [German, 1970]	282 [German, 1970]	760.06	265.65	0.15	2.040	9.810	47.163	47.163	47.158
Lake Baikal	277 [Smirnov et al., 2014]	11 [Smirnov et al., 2014]	469.32	36.90	0.55	7.358	9.810	13.080	13.080	13.080
Lake Tanganyika	270 [Kodomari, 1982]	Немає даних	496.62	36.16	0.42	5.631	9.810	17.091	17.091	17.090

The results of the calculations did not show a marked difference between the vertical pressure of the bottom and the horizontal pressure of the side faces. It is unlikely that the interaction between the waves is noticeable, the difference between periods of which is three orders of magnitude ($\{L \wedge W\} >> D$; $\wedge$ – logical conjunction).

Modern and perspective energy development involves the construction of capacities of the lower ponds of hydroelectric power stations (HPS) at large depths. Moreover, it is expected that the underground layout of energy objects will be 3–4 times (in conventional units) better than the ground layout [Kokosadze, 2017].

In the world experience of the mining industry, there are known overhead mines: TauTona (about 5 km), Witwatersrand (over 4.5 km), Western Deep Levels Mine (3.9 km), Mponeng (about 5 km), all – in Republic of South Africa. The deepest mines of Ukraine are located in the Donetsk region – Shakhtarskaya (Shakhtars'k, 1.546 km), Progress (Torez, 1.34 km), named after O. O. Skochinsky (Donetsk, 1.2 km), named of V. M. Bazhanov (Makiyivka, 1.2 km) [The largest, 2019].

All underground structures, listed above, may accommodate the underground basins of the HPS. The attractiveness of exhausted mines is, firstly, to reduce or exclude excavation works when erecting underground energy objects. It is intended to use products that are not secured, admitting rocks from the roof or the walls of workings, which can lead to a slight increase in the water level in the pool and will not change the hydraulic mode of the station [Kokosadze, 2017]. Secondly, the so-called wet elimination of mines, in which the volume produced is filled with water [Udalov, 2006]. Thirdly, the fluctuations of standing waves, which create microseisms, can also be used for seismic survey of subsoil [Anakhov, 2018].

However, when wet liquidation of mines instead of layered aquifers, separated by water supply, a crack-collecting array forms, which acts as a single cracked zone [Udalov, 2006; Kokosadze, 2017]. Normal fluctuations of the water masses can contribute to increasing the seismicity of the created depression zone [Anakhov, 2018]. We note in particular that the depth of the underwater pond becomes comparable to the horizontal dimensions ($\{L \wedge W\} \sim D$).

According to academician I. Kurchatov, in the hydrological life of any water basin one can find elements of the same period, and obviously these elements can always serve as an excitatory force for the water body. Moreover, the coincidence of the frequencies of their natural oscillations with external forces becomes of paramount importance [Kurchatov, 1982].

Seiche wave frequencies often close or coincide with the lunar-solar tides. This is a reason to expect the excitement and swing of a seiches by tidal wave. In the spectrum of waves of the Kandalaksha Bay of the White Sea (Russia), the fluctuations of the level with a period of 6 hours 12 minutes are pronounced. Academician V. Shulejkin determined that this phenomenon was caused by the resonance of the natural fluctuations of water in the bay with the first harmonic of the lunar tide [Shulejkin, 1968].

According to the results of the analysis of the Kamchatka (1952), Chilean (1960), Niigata (1964), Moneron (1971) and Akitsa (1983) tsunamis in the spectra of fluctuations in the water level of the Kholm Bay, there is a well-defined peak for a period of about 80 minutes, corresponding to a single-node longitudinal seiche. It is present in calm weather, and in stormy situations, its energy increases by about an order of magnitude [Shevchenko, 2006].

In a number of coastal seas there is an influx of double high waters – on the southern coast of England in the Solent and the port of Southampton, as well as about Portland, located 90 km west of Southampton; at Den Helder (Netherlands); and in Buzzards Bay (USA). The condition for the emergence of a double high waters is adding to the main tone of the lunar tide of oscillations of a higher frequency – a seiche wave [Bowers et al., 2013].

As a result of the analysis of materials of measurements of wave processes obtained from September to November 2008, in Alekseev Bay (Popov Island, Russia), the possibility of multiple (8–10 times) increase in the height of the waves of the Helmholtz, pumping mode, (T=630 s) has been confirmed. Generation of the more high frequency first mode (T=162 s) may be due to intense winds. This indicates a significant, approximately 30-time increase in the level of spectral density with increasing excitement on November 17–18, which compared to calm weather conditions [Shevchenko et al., 2010].

The study of frequency selective properties of specific water areas allows us to estimate the possibility of amplifying the coming waves, and the duration of significant fluctuations in the level [Kovalev, 2015]. It is noted that at resonance with natural oscillations of the water body there are waves of considerable height. Long-term observation of long-period waves on California Bay has shown, that when passing strong atmospheric disturbances, the value of the spectrum of ocean waves can increase 10 times, and when the tsunami passes – 100–1000 times [Rabinovich, 1993].

In order to excite strong seiche oscillations, it is necessary to fulfill three conditions: 1) high Q-factor of water area; 2) resonant proximity of the parameters of oscillations in the water area with external excitatory force; 3) the presence of a sufficiently strong long-period wave perturbation in the outer region [Rabinovich, 1993].

The relative amplitude of the excited external forces of the seiche wave is calculated by the formula [Rabinovich, 2009]:

$$A=\left[\left(1-\frac{T_{lwd}}{T_{out}}\right)^2+q^{-2}\left(\frac{T_{lwd}}{T_{out}}\right)^2\right]^{-1/2}, \qquad (5)$$

where q is the Q-factor of the reservoir, which determines the energy loss in the oscillatory system and the bandwidth of the resonance frequency; T_{out} is the period of the exciting external wave.

Any seiches are a resonance reaction of the water area to external influences, which manifests itself in the form of oscillations in their natural (“resonant”) frequencies [Rabinovich, 1993].

In the presence of a “vertical” seiches, the threat of resonant excitation of the seiches is caused by the internal excitatory force – from other seiches in the same water body. Thus, there is the possibility of interaction of unidirectional with horizontal pairs “the wave of horizontal mode – the current of the vertical mode” and “the wave of vertical mode – the current of horizontal mode”:

$$A=\left[\left(1-\frac{T_l\vee T_w}{T_d}\right)^2+q^{-2}\left(\frac{T_l\vee T_w}{T_d}\right)^2\right]^{-1/2}, \qquad (6)$$

where $\vee$ – logical disjunction.

Scientific novelty

We derived the modified Merian formula for calculating the seiches period in a rectangular basin with constant depth, which takes into account the presence of two horizontal and one vertical modes.

We have shown that in the presence of a “vertical” seiches, the threat of resonant excitation of the seiches is caused by the internal excitatory force – other seiches of the same basin. There is the possibility of interaction of unidirectional with horizontal pairs “the wave of horizontal mode – the current of the vertical mode” and “the wave of vertical mode – the current of horizontal mode”. Thus, the hydrological danger, which is conditioned by the possible resonance of the proper oscillations, as well as their resonance with the external excitatory force, is detected.

Practical value

We educed water objects, the analysis of which needs taking into account the vertical mode of natural oscillations. They are – liquidated undergrouned mines, the vertical size of which is compared to horizontal, or exceeds them. In case of wet liquidation of mines, the space is filled with water. Instead of the layer-by-layer located horizons, divide by waterproof layer, a crack-collector array is formed. It works as a single cracked zone. The natural modes of the water masses are able to assist the increase of seismicity of the created depressed zone. But, on the other hand – in the mines is possible placing of underground pools of hydroelectric pump storage power station. The attractiveness of the use of the liquidated mines making consists in reduction or exception of works at building of underground power objects.

Conclusion

When "standing" wave, the water masses carry out rotatory-translational moving with synchronous reversible motions of water in the vertical cross section of basin, with most values in the vertical direction in antinodes, and horizontal in nodes.

Coming from that the characteristic feature of vibrations is a conditionality of their period by the linear sizes of characteristic side and coexistence of vertical standing waves with the platforming's of currents, the modified Merian's formula of calculation of period is worked out seiche in the rectangular basin of permanent depth. The microseisms of seiche origin create the field of deformations in the vertical cross section of basin, with maximums on the lines of projections of antinodes on the bottom of reservoir, and also on a lateral verge.

Modern and perspective energy development involves the construction of capacities of the lower ponds of hydroelectric power stations at great depths. The attractiveness of the use for this purpose the exhaust mains consists in reduction or exception of works at erection of underground power objects. Previous sentence is not presented coherently. Wet liquidation of mines, separated by water supply, a crack-collecting array forms, which acts as a single cracked zone. Normal fluctuations of the water masses can contribute to increasing the seismicity of the created depression zone.

The cases of resonant excitation of standing waves are discussed, for the necessary implementation of three terms: 1) high Q-factor of water area; 2) resonant proximity of the parameters of oscillations in the water area with external excitatory force; 3) the presence of a sufficiently strong long-wave perturbation in the outer region. It is shown that at presence of "vertical" seiches is created a threat of resonant excitation seiches by internal excitant force from other seiches in the same basin. Possibility of cooperation of unidirectional appears with horizontal pairs a "wave of horizontal mode – current of vertical mode" and "wave of vertical mode – current of horizontal mode". A hydrological danger, that is stipulated by possible resonance of natural oscillations, and also their resonance with external excitant force, appears thus.

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ТРИВИМІРНА МОДЕЛЬ ДЕФОРМАЦІЙ КОТЛОВИНИ БАСЕЙНУ МЕРІАНА СТОЯЧИМИ ХВИЛЯМИ

Мета. Аналіз дії стоячих хвиль на ложе водного басейну. **Методика**. Під час "стояння" хвилі водні маси здійснюють обертально-поступальні переміщення, за яких у вертикальному розрізі басейну відбуваються синхронні реверсивні рухи води, з найбільшими значеннями у вертикальному, в пучностях, і горизонтальному, у вузлах, напрямках. Мікросейсми сейшового походження створюють поле деформацій у вертикальному розрізі басейну, з максимумами на лініях проєкцій пучностей на дні водойми, а також на боковій грані. **Результати**. Оскільки характерною особливістю коливань є обумовленість їх періоду лінійними розмірами характерної сторони і співіснування вертикальних стоячих хвиль із горизонтальними рухами течій, під час розрахунків розглядаються усі три сторони модельного прямокутного басейну постійної глибини. Показано, що за наявності "вертикальних" сейш створюється загроза резонансного збудження сейш внутрішньою збуджувальною силою – іншими сейшами цього ж басейну. За мокрої ліквідації шахт, яка супроводжується заповненням виробленого простору водою, замість пошарово розташованих водоносних горизонтів, розділених водоупорами, утворюється тріщино-колекторний масив, який працює як єдина тріщинувата зона. Власні коливання водних мас здатні сприяти підвищенню сейсмічності створеної депресійної зони. Але, з іншого боку – у гірничих виробках можливе розміщення підземних басейнів ГАЕС. Привабливість використання відпрацьованих гірничих виробок полягає у скороченні або непотрібності прохідницьких робіт під час зведення підземних енергетичних об'єктів. **Наукова новизна**. Розроблена модифікована формула Меріана розрахунку періоду сейш у прямокутному басейні постійної глибини, яка враховує наявність двох горизонтальних і однієї вертикальної мод. Показано, що за наявності "вертикальних" сейш створюється загроза резонансного збудження сейш внутрішньою збуджувальною силою – іншими сейшами цього ж басейну. Визначено небезпеку резонансної взаємодії однонаправлених із горизонтальними пар "хвиля горизонтальної моди – течія вертикальної моди" і "хвиля вертикальної моди – течія горизонтальної моди". Виявлено гідрологічну небезпеку, спричинену можливим резонансом власних коливань, а також їх резонансом із зовнішньою збуджувальною силою. **Практична значущість**. Виявлено водні об'єкти, аналіз яких потребує урахування вертикальної моди власних коливань. Це – ліквідовані гірничі виробки, вертикальний розмір яких порівнянний із горизонтальними або перевищує їх.

Ключові слова: гідроакумулююча електростанція; вертикальна мода сейш; мікросейсми; мокра ліквідація шахти; сейші; сейшова течія; сейшова хвиля; тягун.

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