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WEAK HYDROSEISMIC EFFECT OF LOCAL EARTHQUAKES IN HYDRAULIC BOREHOLES IN GEORGIA

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Preface

The hydroseismic variations observed in distant hydrologic boreholes are the result of the distribution of the planetary seismic waves generated after strong earthquakes with magnitude M≥7.The effect of hydroseismic variations is quite diverse and is expressed in either short-term or long-term variations in a borehole water level after a seismic phenomenon [1-5]. Their duration and intensity depend on geologic factors and the energy density of the seismic waves, which have reached the borehole. Hydroseismic effects of several distant strong earthquakes, like other places, have also manifested themselves in Georgia, which has an active network of hydrologic boreholes in recent years [6]. It is noteworthy that in distant hydrologic boreholes, besides strong hydroseismic variations, so called I type hydroseismic variations with small amplitudes are often observed. These variations cause weak disturbances in the water levels [7-9]. During an earthquake preparation process the increase in the seismic activity is usually accompanied with intensifying of the seismic background, which is formed by high-frequency $\boldsymbol{f}$=10-100Hz seismic waves. Their connection with weak high-frequency seismic waves at close distances seems natural in the viewpoint of energetics. However, besides seismic waves, emission of geo-acoustic waves from the hypocentral area of an upcoming earthquake is also possible. The intensity and frequency spectrum of these waves depend on the epicentral distance and earthquake magnitude [10]. Apart from seismic and geo-acoustic waves, the generation of low-frequency (VLF) electromagnetic terrestrial radiation is also possible and it is the obvious indicator for activation of seismic processes. It is natural that the reason of the generation of any kind of waves is the mechanical and thermodynamic changes accompanying geo-deformation processes taking place in a solid medium [5, 12, 13] for example, on the Kamchatka peninsula characterized with particularly high seismic activity, quite intense emission of geo-acoustic waves was recorded for more than 60 earthquakes with magnitudes M>5, the epicenters of which were located at L ≥250 km distance from the observation points. It turned out that approximately a day before the earthquakes, in the frequency diapason $\boldsymbol{f}$= /0.1-10000/Hz, during several hours, a manifold increase in the geo-acoustic noise took place, which together with the seismic waves, was the probable reason of the weak hydroseismic variations [11]. However, development of such phenomena in the hydrologic boreholes near epicentral areas is possible not only after strong but weak earthquakes (M≤5) as well. It must be especially noticeable in the hydrologic boreholes, where the activities of disturbance factors different from seismic ones are weak and not regular. In such boreholes the dependence of the water level change on the gravity force variation is expressed with a strong correlation between these values. In Georgia, these conditions are well satisfied, for example, by the boreholes in Marneuli (41.802° N,41.772° E), Nakalakevi (41.424° N, 43.317 °E) and Kobuleti (41.436° N, 44.755° E). In these boreholes the trends of water level variations quite precisely express the weak spontaneous disturbances of the periodic short-term variations of tidal forces. They can be caused by local seismic phenomena both before and after an earthquake in case the energy of the seismic waves is, at least, sufficient to generate the weakest, so called I type hydroseismic wave variations in boreholes. However, at extremely short distances, in a proper geologic medium, weak hydroseismic variations may also be caused by low-frequency geo-acoustic waves in infrasonic range.

The model of the mechanical eigen frequency of an earthquake focus

High frequency seismic waves, a so called wave tail, can be imagined as a harmonic set of primary P and secondary S seismic waves. The main characteristic of seismic wave spectrum is a so called “corner” frequency of aseismic focus, which is the lower limit of the frequency spectrum of the wave package constituent of the “tail”, i.e., the main frequency. The value of this parameter depends on the linear measure of an earthquake focus, as a whole body. Like the corner frequency, the main frequency of the geo-acoustic spectrum generated during the earthquake preparation process also must be determined by a certain characteristic measure. There must be a quantitative link, which is determined by the analysis model of the mechanical eigen frequency of an earthquake epicentral area [14]. According to this model an earthquake focus is composed of two, internal and external zones. In the first, internal area, which is a so called plasticity zone, an avalanche-like release of the earthquake energy takes place. The other, external area, from which seismic waves are emitted, is a linear elasticity zone. This model qualitatively resembles the well-known Bullen model, according to which there is a “maximum energy release area” in an earthquake focus [15]. Apart from this, an elasticity zone can be compared to an earthquake focus according to the Brune model [16]. However, we should note the significant difference between the models: the Bullen model is qualitative as far as without relevant quantitative assessment it is accepted that the volume of the “maximum energy release area” must be an order lower than the earthquake focus volume.

Radial symmetry approximation is suitable for approximating both weak and slightly stronger than moderate (M≤6) earthquake foci [17]. Therefore, according to the mechanical eigen frequency model an earthquake focus is a sphere with two characteristic radii. The first, internal radius corresponds to the plasticity zone, whereas the other, external radius determines the linear elasticity zone boundary and the whole volume of the earthquake focus. The physical basis of this model is the analogy between an earthquake focus eigen frequency and the eigen frequency of a weakly deformed water drop. This analogy is not new as it was used for the determination of the main period of the Earth’s natural frequency [18]. Generally, the task of the drop eigen frequency belongs to the classic task field of Hydrodynamics. The fundamental analysis method for determining the hydromechanical vibration frequency spectrum of liquid drop surface tension is well known [19]. According to the model of the mechanical eigen frequency of an earthquake focus, the elasticity force of geologic rocks is the analogy of water drop surface tension force. We used an additional physical condition at the boundary of the internal and external zones, according to which the mechanical vibration frequencies are imaginary in the plasticity zone. By use of the classic mathematical scheme and this condition we received a formula, which analytically defines the discrete spectrum of the mechanical eigen frequency of an earthquake focus:

$$f_n = \frac{V_p}{2\pi R}\left[(n-1)(n+2)\frac{\left(\dfrac{R}{R_0}\right)^{n-1} - \left(\dfrac{R_0}{R}\right)^{n+2}}{\dfrac{1}{n}\left(\dfrac{R}{R_0}\right)^{n-1} + \dfrac{1}{n+1}\left(\dfrac{R_0}{R}\right)^{n+2}}\right]^{1/2} \tag{1}$$

where R_0 is the elasticity zone radius, R varies from the center to the external boundary of the earthquake focus, V_p is the volumetric seismic wave velocity, $n = 2$ corresponds to the corner frequency, $n = 3,4\ldots$ corresponds to the corner frequency harmonics ($n = 0$ is stagnation, $n = 1$ is transitive motion).

Thus, according (1) formula, in the area, where $R \le R_0$, the mechanical vibration frequency spectrum is imaginary. It is natural that the avalanche-like release of the elastic tension energy, accumulated during the geo-deformation variation process in the plasticity zone, must be accompanied with the generation of shock waves. Consequently, the mechanical vibrations are virtual here. This condition is the cornerstone of the model, which enables to distinguish from each other the internal and external zones of an earthquake focus. Namely, by the use of (1) formula we can determine the correlation of the radii of the zones, which requires only two values – the corner frequency and its first harmonic. This task is especially simplified in the approximation of harmonic vibrations as far as in this case, only corner frequency f_2 is required to define the radii of the plasticity and elasticity zones and the whole frequency spectrum of the tail of the seismic waves. Namely, as $f_3/f_2 = 2$, the radii correlation is the root of the single-unknown equation obtained by the correlating of the first two expressions of (1) formula: $R/R_0 = 1.92$. This value is in quantitative accordance with theBullen hypothesis, according to which the volume of the "maximum energy release area" must be approximately an order lower than the whole earthquake focus volume.

Thus, according to the model, the correlation of the radii of internal and external zones is the universal characteristic of an earthquake focus. In case we make a change R=1.92 R_0in the first multiplier of the expression correspondent to $n = 2$ of (1) formula and use value $V_p/V_s \approx$ 1.65 characteristic of the correlation of the primary and secondary seismic wave velocities, then we will receive a well-known formula with empirical coefficient

$$R_0 \approx 0.37\frac{V_s}{f_2}, \tag{2}$$

which associates the corner frequency with the earthquake focus radius in the Brune model [16, 20]. This result must not be unforeseen as during the development process of geo-deformation phenomena the plasticity zone is the place of maximum mechanical tensions. Before an earthquake, this part of area can be imagined as a homogeneous elastic sphere, which emits weak seismic and geo-acoustic waves. Supposedly, at certain distances from the elastic sphere, the frequency ranges of high-frequency seismic waves and low-frequency acoustic waves, which seem to be associated with R_0 radius, must be in accordance with each other. In order to prove it let us make an asymptotic transformation with variation $R_0 \dashrightarrow 0$ in the (1) we receive expression

$$f_n = \frac{V_p}{2\pi R_0}\sqrt{n(n-1)(n+2)} \tag{3}$$

(3) formula is a precise analogy of the natural hydromechanical vibration frequency spectrum formula of a weakly deformed sphere-like liquid drop [19]. According to (3) formula, the main frequency of geo-acoustic waves ($n = 2$) is the first analogy of the first harmonic of the corner frequency of the voluminal seismic waves determined from (3) formula. Therefore, it must be difficult to unequivocally determine the type of the waves causing weak hydroseismic effect in hydrologic boreholes under the conditions of high seismic background.For example, in Oni the hydrologic borehole (42.573° N, 43.437° E) is located in a seismically active region near the Caucasus Ridge. At L≈50 km distance from the Oni bore hole there is a hydrologic borehole (42.187° N, 42.791° E) in Ajameti. During the last three decades there have been approximately 400 earthquakes near the Oni borehole. The magnitude of the strongest was M≈6.9 (1991, April 29, 9:12,42.453° N, 43.673° E, depth=17 km), whereas

the most of them belonged to moderate and weak earthquakes with magnitude M≤4.Due to the high seismic background the water levels in the boreholes of Oni and Ajameti, compared to other boreholes, more often undergo disturbances after earthquakes and during the time intervals between them. It is noteworthy that in these regions, earth rumblinggis periodically recorded, which becomes much stronger in the natural resonators of geo-acoustic waves, numerous grottos and karst caves [21].

Assessment of the energy density of the waves generated during a weak earthquake preparation process

The seismic energy density, on the value of which depends the type of the variations of the water level in hydrologic boreholes, decreases together with the increase in an epicentral distance. As mentioned above, before an earthquake in the boreholes near the upcoming earthquake epicenter, due to the coincidence of the frequency spectra of the high-frequency seismic waves and low-frequency geo-acoustic waves, separation of hydroseismic effects caused by them is practically impossible. Theoretically, the intensity of geo-acoustic waves may become commensurable to the one of the seismic waves immediately before the earthquake, when elastic tension energy sharply increases in rocks and the foreshocks defusing it are not observed. In such conditions, in boreholes in the epicentral area of an upcoming earthquake, besides hydroseismic variations, generation of atmospheric acoustic-gravitational waves may take places well [22].

It is established by an empirical method that the energy density of a seismic wave depends on the earthquake magnitude and hypocentral distance [23]

$$lgd_e = 0.48 * M - 0.33 * lge - 1.4 \tag{4}$$

where d_e is the distance from the earthquake epicenter to the observation point, e is seismic wave energy density, M is moment magnitude.

After distant strong (M≥7) earthquakes, for example, in the hydrologic boreholes on the Kamchatka peninsula, for the generation of I type hydroseismic variations causing weak wave disturbance s$e \approx 10^{-5}$ J m^{-3} is quite sufficient [7].This value of seismic wave energy density can be considered as a characteristic value, though it is not excluded that in the boreholes, which are located in a short distance from an epicenter, after earthquakes with shallow hypocentral depth and small magnitude (M≤5), for causing weak wave disturbance in water level, less energy density were sufficient. Moreover, in near boreholes the hydroseismic effect of weak seismic waves and geo-acoustic emission can be observed even before an earthquake in case the medium is sufficiently homogeneous and elastic, i.e., there are good conditions for surface distribution of geo-acoustic waves [13]. Although, (4) formula is eminently suitable for strong earthquakes with great hypocentral depths, it can be still used for weak earthquakes as for them the difference between local and moment magnitudes is slight. Therefore, it is correct to use (4) formula in combination with the model of the mechanical eigen frequency of an earthquake focus, according to which, as a result of geo-deformation changes, in the area of the plasticity zone of the upcoming earthquake, the increase in the elastic tension in rocks becomes especially intense. Consequently, the elastic energy density reaches characteristic value $e \approx 10^2$ J m^{-3} [17].During an earthquake preparation process a part of the elastic energy may be taken by the emission of seismic and geo-acoustic waves. Let us consider that there was an earthquake with corner frequency $f_2 \approx$ 7 Hz in the medium, where V_S ≈3.6 km/s. According to(2) formula these parameters are relevant to a plasticity zone with radius R_0≈200 m, in which $E_c = \frac{4}{3}\pi R_0^3 e \approx 3.3 * 10^9$ joule elastic tension energy may be accumulated. Let us imagine an earthquake with this strength. From the formula [24]

$$logE = 1.8 * M + 4 \quad (5)$$

The magnitude of this virtual earthquake is M=3. We know the value characteristic of the coefficient of seismic activity of weak and moderate earthquakes: $\acute{\eta} \approx 1\%$ [17]. Therefore, the magnitude of a real earthquake with $R_0 \approx 200$ m radius plasticity zone is M=3.9. Consequently, according to (4) formula the energy density value of the seismic waves generated by virtual and real earthquakes will be also different. Namely, the density of the seismic wave of an M=3 magnitude earthquake at d=50-200 km distance is: $e \approx /10^{-s} - 10^{-7}/J\ m^{-3}$, whereas the interval characteristic of an M=3.9 magnitude earthquake will be an order higher: $e \approx 3/10^{-4} - 10^{-6}$ /J m^{-3}. Consequently, the water level disturbances in near hydrologic boreholes at the last stage of the preparation periods of weak and moderate earthquakes should not be excluded. Generation of weak hydroseismic variations is more probable after earthquakes, when the energy density of seismic waves is significantly high.

Statistical analysis of hydrologic borehole data

The stability of the trend exposing the water level variations in a hydrologic borehole is manifested in regard to gravity (tidal) forces. It is obvious that in hydrologic boreholes with low background noise the water level variation trend must be rather stabile, for example, as a result of the Fourier transform of the data of one of the hydrologic boreholes on the Kamchatka peninsula the following regression equation was obtained [7]

$$H = (0.096 \pm 0.004) D + (0.083 \pm 0.247) \quad (6)$$

It, with standard 95% reliability expresses the linear correlation links between the amplitude ($H \leq 2$ cm) of the water level variation caused by diurnal periodic changes of tidal forces (tidal waves) and a theoretical areal deformation amplitude ($D \approx 10^{-9}$).The second coefficient of (6) equation is characterized with a quite large variation interval, which must be associated with non-constant disturbance factors. It is clear that their activities must be expressed in the trend of the water level variations in the borehole. A disturbance effect, besides seismic activities, may be caused by random mechanical phenomena and anomalous meteorological factors. In case their influence is minimized, we can expect that the hydro-seismic variation effect in the near boreholes caused by weak earthquakes will manifest itself in the coefficient variations of short-term regression equations, for example, the disturbance of the first (regression) coefficient expressing the linear correlation links between water level variation and tidal force variation can be revealed by the comparison of the values characteristic of the short- and long-term time intervals of this parameter. This task can be realized in two ways: 1) by the comparative analysis of the regression coefficients characteristic of the direct correlation links between the hydrologic borehole data and the tidal force variation synchronized with them; 2) by a correlative analysis of the statistical borehole data and the Fourier transforms of the theoretical values of the tidal force variations. In the case of the latter the disturbance effect caused by weak hydroseismic variations may be expressed in the frequencies characteristic of the short-term periodic variations of tidal forces.

As mentioned above, in Georgia, in regard to short-term trend stability of water level variation the hydrologic boreholes of Marneuli, Nakalakevi and Kobuleti are distinguished. In 2016-17 and 2019, due to technical conditions, 6-month time intervals were marked out for statistical analysis. The atmospheric pressure effect was preliminary removed from water level variation.

It was studied: a) correlation of amplitudes: water level vs. tidal; b) correlation of speeds: water level speed vs. tidal speed.

Here speed defined as $v(t) = \left[X\left(t + \frac{\Delta}{2}\right) - X\left(t - \frac{\Delta}{2}\right)\right]/\Delta t$ with $\Delta t = 360$ minutes.

For determining the momentary value of the vertical component of the gravity force we used https://geodesyworld.github.io/SOFTS/solid.htm, Dennis Milbert, solid-program.

During the process of the correlation analysis it turned out that despite the practically identical values of the regression coefficients, the correlation between amplitudes the borehole water level variation and the variation of the vertical component of gravity force was characterized with greater error than the correlation between the speed of water level variation (A) and the speed of change in the vertical component of the tidal force (Tidal Z).This fact is presumably sign of shortage of background noise in the second case compared to the first one. It appeared that, for example, in 2016-17 and 2019 the Marneuli hydrologic borehole was characterized with especially high Pirson correlation coefficient: r≈/0.97-0.99/. This means that the determination level reaches its absolute value in the borehole. For comparison, in the Nakalakevi borehole the correlation coefficient varies in interval r=/0.88-0.93/, whereas in the Kobuleti borehole it is r=/0.83-0.90/.Thus, correlation level is rather high in these boreholes as well. It also appears that despite the high seismic background the correlation between the water level variation and the change ofthe vertical component of the gravity force is quite noticeable in the boreholes of Oni and Ajameti as well.

Figure 1, as an example, shows the histogram of the Marneuli borehole, the horizontal axis of which depicts the variations in kilopascals(kPa/min) of the pressure correspondent to the tidal force variation interval, and the vertical axis shows the normalized number of the water level variation in /01.01-01.07/2019-time interval. According to the quite steep form of the normal Gauss distribution carve it becomes obvious that the correlation determined by the regression equation is very close to precise function relation.

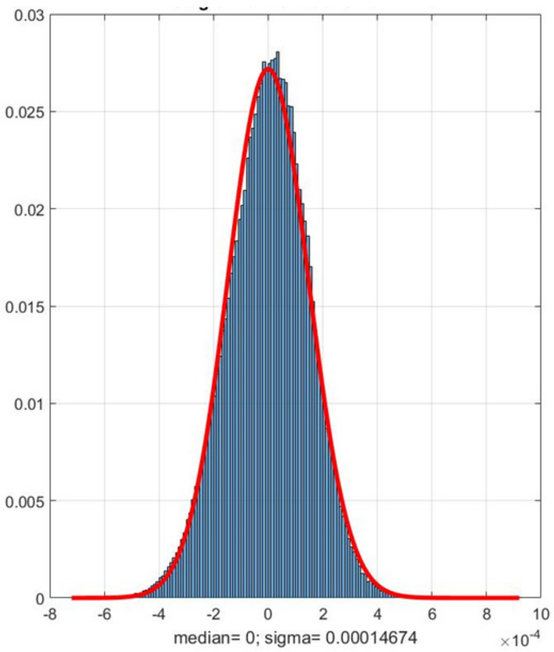

Fig.1 Marneuli. Histogram of deviations from line

The methodical basis of the work is an assumption that a long-term regression coefficient (A) can be considered as an individual characteristic of hydrologic boreholes. As shown in the second column of *Table 1* this parameter is different for each borehole and varies significantly in different time intervals. The purpose of the correlation analysis is to reveal the connection between the water level disturbances in boreholes and weak hydroseismic variations. Therefore, according to the first variant, for comparing with characteristic long-term regression coefficient, as a characteristic value, we determined short-term (three-day) regression coefficients by dividing the long-term time interval.

The third and fourth columns of *Table* 1 show the number of the three-day intervals characteristic of concrete boreholes. Here, numbers (P and p) of $\Delta \geq 5\%$ and $\Delta < 5\%$ relative disturbance of short-term regression coefficient in regards to the long-term coefficient are pointed out. According to the assumption the variations of characteristic three-day regression coefficient $\Delta \geq 5\%$ may probably be associated with weak hydroseismic variations. This means that in a concrete hydrologic borehole the water level disturbance might be generated either in a three-day interval or nearest days or hours before or after an earthquake or earthquake preparation period. In the latter case the weak hydroseismic variations, like some other phenomena, can be considered as a local indicator for an earthquake. As a result of the verification of this hypothesis, the hydrologic boreholes with stabile trends listed in the statistical analysis more or less react to near weak earthquakes in E= /40°-43°/ latitude line, which is adjacent to the Caucasus Ridge in the North and the Anatolian Ridge in the South. Taking into consideration this limitation, the penultimate column of *Table* 1 shows the common number (N) of $M \leq 5$ magnitude earthquakes, which occurred in a given time interval in $L \leq 200$ km epicentral distance from concrete boreholes.The last column shows the number (n) of earthquakes, which occurred in $\Delta \geq 5\%$ three-day interval.

Table 1.

Boreholes	Mean Value **A** for 6 months	P $\Delta \geq 5\%$	p $\Delta < 5\%$	Number of Earthquakes, **N**	n-have quake $\Delta \geq 5\%$
Marneuli					
2016	0.175	42	19	16	11
2017	0.185	33	28	12	6
2019	0.196	19	42	14	7
Kobuleti					
2016	0.129	42	19	12	9
2017	0.111	45	16	12	10
2019	0.119	35	26	10	6
Nakalakevi					
2016	0.117	15	6	5	5
2017	0.133	39	22	14	7
2019	0.164	42	19	11	10

According to the second variant of the correlation analysis, the tidal response of the water level variations in the boreholes can undergo corrections due to the activity of weak hydroseismic variations. This effect can be identified by tidal analysis of water level variation, which is especially noticeable in the frequencies of diurnal and semidiurnal tidal waves (short-period tidal waves) [25]. Based on this assumption, the Fourier transforms of variations in the water level of the boreholes and the vertical components of the tidal forces were subjected to correlation analysis. It is known that diurnal and semidiurnal variations of tidal acceleration are not simple harmonic variations, since they are combinations of the frequencies that depend on the parameters of the orbits of the Earth and the Moon. However, in the fine structure of the semidiurnal and diurnal tide spectrum, there are several fundamental frequencies corresponding to the periods of different waves. The main ones are the lunar semidiurnal wave $M2$($T \approx 12.42$h) and the solar semidiurnal wave $S2$ ($T = 12$h).There are also large lunar semidiurnal $N2$ ($T = 12.65$h) and small $L2$ ($T \approx 12.18$h) elliptical waves and a combined lunar-solar declination wave $K2$.It is a combination of two waves with the same period: the lunar semidiurnal declination wave $MK2$ and the solar semidiurnal declination wave $SK2$.The peculiarity of the diurnal spectral area is the absence of the main diurnal lunar wave $M1$ ($T \approx 24.83$h) and the main diurnal solar wave $S1$ ($T = 24$h). In their absence the main lunar declination wave $O1$($T = 25.8$h) has the maximum amplitude. The diurnal lunar-solar wave $K1$ ($T \approx 23.93$h) is shorter than it in amplitude, but exceeds the main solar declination wave $P1$ ($T \approx 24.07$h).At the frequency of the missing lunar-diurnal wave $M1$

there is a combination of low-amplitude wave modes, multiples of the semidiurnal elliptical waves *O1* and *MK1*.

Near the frequencies of the main short-period tidal waves, in addition to the indicated ones, other harmonics *(W)* with small amplitudes are observed. They can be neglected, though taking them into account can improve statistical reliability. Consequently, besides the frequencies of the main tidal waves, the harmonics of some combinations of these waves also participate in the regression equations, which reflect the correlations of Fourier transforms.

Table 2.

T, Day	T, Hour	Waves	Tidal Z, cm	Marneuli H, cm	Nakalakevi H, cm	Kobuleti H,cm	Ajameti H,cm
1.1217	26.92	*W*	1.034	0.333	0.210	0.121	0.075
1.0761	25.83	*O1K1*	5.710	1.330	1.063	0.736	0.616
1.0095	24.23	*W*	1.302	0.397	0.197	0.181	0.112
1.0047	24.11	*P1*	3.012	0.821	0.503	0.355	0.204
1.0000	24.00	*P1S1*	2.776	0.549	0.842	0.423	0.493
0.9953	23.89	*K1*	5.586	1.115	0.981	0.588	0.270
0.9907	23.78	*W*	1.790	0.317	0.325	0.165	0.046
0.5273	12.65	*N2*	1.312	0.299	0.217	0.197	0.048
0.5196	12.47	*SK2*	1.451	0.241	0.225	0.166	0.078
0.5183	12.44	*MK2*	3.738	0.665	0.520	0.497	0.331
0.5171	12.42	*M2*	6.686	1.238	0.955	0.894	0.490
0.5158	12.38	*W*	1.756	0.354	0.293	0.249	0.236
0.5147	12.35	*L2*	1.010	0.220	0.151	0.113	0.156
0.5000	12.00	*S2K2*	3.769	0.777	0.862	0.519	0.532

Table 2, as an example, shows the results of the Fourier analysis for four hydrological boreholes: Marneuli, Nakalakevi, Kobuleti and Ajameti for period 01.01-01.07 2019.For identifying the disturbing effect of high-frequency seismic and geo-acoustic waves, the Ajameti borehole is more reliable than the Oni borehole, which is located directly in the seismically active zone. The first columns of *Table 2* indicate the periods of short-period tidal waves in days and hours, the wave types and the corresponding dimension (H-cm) amplitudes of the linear deformation effect due to changes in tidal Z (at a specific point). The last four columns show the amplitudes (H-cm) of water level disturbances in individual hydrological boreholes.

According to the first variant of the correlation analysis, the degree of disturbance of the first coefficient of the regression equation caused by geo-acoustic and seismic waves was determined using a direct correlation between the speed of change in tidal forces and the speed of change in water level in hydrologic boreholes. In the second case, we can also use the correlation between the Fourier components of these physical factors. At the same time, in order to compose short-period regression equations and determine the coefficients, we should use a different, compared to the first case, division of the long-term data interval. Obviously, in order to improve accuracy, instead of a three-day interval, it would be more correct to use an interval with longer period, e.g., a six-day division, which is more consistent with diurnal tidal waves. As it turned out, as a result of this kind of change, the Pirson correlation coefficients obtained in the first case remained almost unchanged. Like the correlation coefficients, the regression coefficients are also almost identical to the coefficients obtained in the first case. Consequently, the probabilistic information presented in *Table 1*for assessing the degree of reliability of the relation between weak hydroseismic variations and local earthquakes remained practically unchanged. However, the advantage of the Fourier transform in comparison with direct correlation is manifested in the case of visualizing the data given in *Table 2*.*Figure 2*, as an example, shows the amplitudes of the water level variations corresponding to the short-period waves of tidal forces in two boreholes: Marneuli (circles) and Kobuleti (triangles).Here, a fairly high degree of approximation to the linear relation between the correlated values is obvious, which is not visible in the Ajameti borehole located near the seismically active zone (*Fig. 3*).This phenomenon is obviously caused by constant disturbances in the water level in this borehole. It can be assumed with a reasonable degree of probability that these disturbances are the result of weak hydroseismic variations constantly occurring due to the propagation of high-frequency seismic and low-frequency acoustic waves from the seismically active zone. The consistency of this statement can be confirmed by the Oni hydrologic borehole located immediately in the seismically active zone. In this borehole, the water level disturbances are so stochastic in nature that the Fourier analysis does not allow us to clearly distinguish the effect of short-period tidal waves.

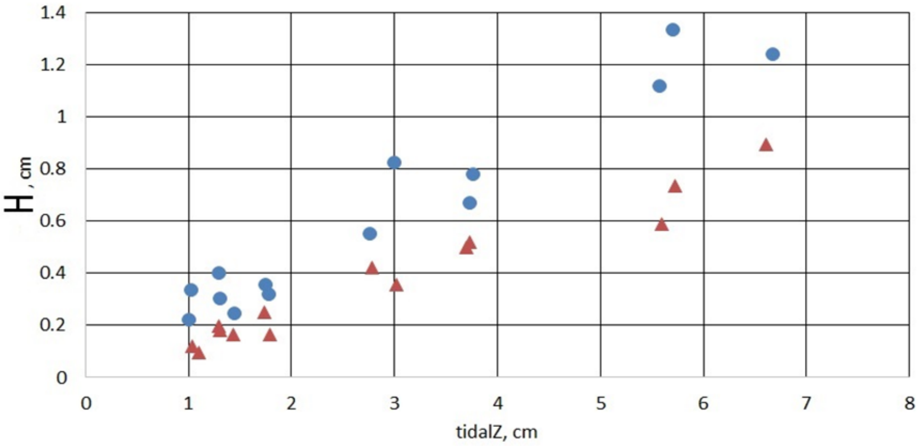

Fig. 2. Marneuli (circles) and Kobuleti (triangles), 2019

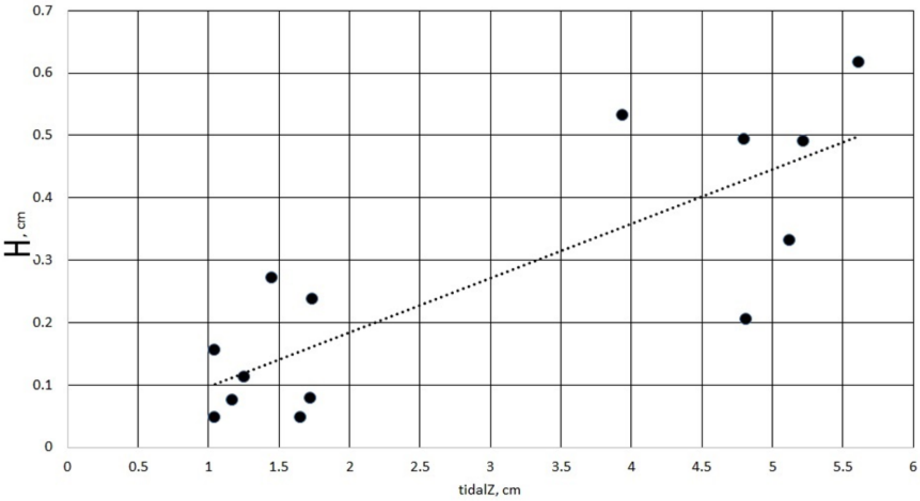

Fig. 3. Ajameti, 2019

Conclusion

In some cases, the energy density of seismic waves associated with weak earthquakes (M≤5) may be sufficient to generate weak hydroseismic variations in the water level in hydrological boreholes located not far from the epicenters of earthquakes. Analysis of data of 2016, 2017 and 2019 from several hydrological boreholes located in Georgia showed that a weak hydroseismic effect can occur not only after, but also before earthquakes. In the latter case, the reason of ahydroseismic effect can be high-frequency seismic and low-frequency geo-acoustic waves having the same frequency spectra. According to the model of the natural mechanical vibrations of an earthquake focus, the main frequency of the spectrum of these waves generated during the preparation of the earthquake is determined by the radius of so-called plasticity zone, in which an explosive release of seismic energy occurs after an earthquake. Using correlation analysis, the parameters of the relation between the rates of change in the water level in the boreholes and changes in the vertical component of the tidal forces were identified. It turned out that at small epicentral distances ($L \leq 200$ km), hydrologic boreholes quite often respond to local earthquakes that occur in a certain longitudinal interval. The value of the relative change in the regression coefficient in specific boreholes was used as a criterion. It turned out that in more than 50% cases the$\Delta \geq 5\%$ deviations of the first coefficient of short-term (3 days) regression equations with respect to the long-term (6 months) value of this parameter are associated either with earthquakes or with the process of their preparation. Such a result only proves the degree of weak hydroseismic variations as indicators for the activation of local seismic processes. However, in combination with other indicators for the increase in seismic activity, weak disturbances in the water level in hydrologic boreholes can be quite informative in regard to prediction of local earthquakes. This consideration turned out to be in an agreement with the result of Fourier analysis of the data from three boreholes located in the areas with relatively stable seismic background. In these boreholes, synchronicity was observed in the changes of the amplitudes of water level variation and short-period tidal waves. However, this effect turned out to be significantly weak in a borehole located near the boundary of a local seismically active zone, whereas in a borehole located immediately in this zone, it practically does not appear.

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WEAK HYDROSEISMIC EFFECT OF LOCAL EARTHQUAKES IN HYDRAULIC BOREHOLES IN GEORGIA

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Abstract

Strong earthquakes with magnitude $M\geq7$ often cause disturbances of various durations, i.e., so called hydroseismic variations, in the water level in hydrologic boreholes at distances of planetary scales. Besides strong earthquakes, moderate and weak earthquakes ($M\leq5$) also may be accompanied with such effects at short epicentral distances. Namely, in the hydrologic boreholes on the Georgian territory, before and after local earthquakes, against the background of so-called white noise, variations of weak waves with small amplitudes ($A\leq1$-2 cm) are quite often observed. Naturally, this is associated with seismic wave generation. At the same time, the geo-deformation processes in the hypocentral area of an upcoming earthquake, besides seismic waves, are often accompanied with the generation of low frequency (f=0.1-1000 Hz) geo-acoustic and very low frequency (VLF) electromagnetic waves ($f\geq$1kHz). The intensity of geo-acoustic waves compared to the one of seismic waves is considerably low. However, at the last stage of an earthquake preparation process the intensity of low frequency geo-acoustic waves may increase to such an extent that their amplitude becomes commensurable to the amplitude of high frequency (f=10-100 Hz) seismic waves. In this case, weak wave disturbances in hydrologic boreholes located at short epicentral distances, besides high frequency seismic waves, may be caused by geo-acoustic waves. The justice of this consideration is to some extent proved by the qualitative-quantitative analysis of the data of the hydrologic boreholes located in Georgia. Therefore, the goal of the research work is to reveal the probable reasons of the generation of high-frequency seismic waves and low-frequency acoustic emission, as weak hydroseismic variations, accompanying weak local earthquakes.

Key words: earthquake, hydroseismic effect, acoustic emission.

ლოკალური მიწისძვრების სუსტი ჰიდროსეისმური ეფექტი საქართველოს ჰიდროლოგიურ ჭაბურღილებში

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რეზიუმე

მძლავრი მიწისძვრები მაგნიტუდით $M\geq7$ დაშორებულ ჰიდროლოგიურ ჭაბურღილებში საკმაოდ ხშირად იწვევენ წყლის დონის სხვადასხვა ტიპის ჰიდროსეიმურ ვარიაციებს. ლოკალურად, ეპიცენტრიდან მცირედ დაშორებულ ჭაბურღილებში მსგავსი ეფექტი შესაძლებელია განვითარდეს აგრეთვე მცირე და საშუალო ($M\leq5$) მიწისძვრების შემთხვევაშიც. კერძოდ, საქართველოში მდებარე ჭაბურღილებში ასეთი მიწისძვრების წინ, ან მათ შემდეგ, საკმაოდ ხშირად დაიმზირება მცირე ამპლიტუდების მქონე სუსტი ტალღური ვარიაციები ($A\leq2$ სმ). ცხადია, რომ ისინი დაკავშირებულია სეისმური ტალღების გენერაციასთან. ცნობილია, რომ მომავალი მიწისძვრის ჰიპოცენტრალურ არეში მიმდინარე გეოდეფორმაციულ პროცესებს, სეისმური ტალღების გარდა, ხშირად თან ახლავს აგრეთვე დაბალსიხშირული გეოაკუსტიკური (f=0.1-1000ჰც) და ძალიან დაბალი სიხშირის ($f\geq$1კჰც) ელექტრომაგნიტური ტალღები. გეოაკუსტიკური ტალღების ინტენსივობა, სეისმურ ტალღებთან შედარებით, გაცილებით სუსტია. თუმცა, მიწისძვრის მომზადების პროცესის უკანასკნელ ეტაპზე შესაძლებელია, რომ დაბალსიხშირული გეოაკუსტიკური ტალღების ინტენსივობამ მოიმატოს ისეთ დონემდე, რომ მათი ამპლიტუდა მაღალ-

სიხშირული (f=10-100 ჰც) სეისმური ტალღების ამპლიტუდის თანაზომადი გახდეს. ასეთ შემთხვევაში დასაშვებია, რომ, მცირე ეპიცენტრალურ მანძილებზე მდებარე ჰიდროლოგიურ ჭაბურღილებში სუსტი ტალღური შეშფოთებები, მაღალსიხშირული სეისმური ტალღების გარდა, აგრეთვე შეიძლება გამოიწვიონ გეოაკუსტიკურმა ტალღებმაც. ამ მოსაზრების სამართლიანობას გარკვეულწილად ადასტურებს საქართველოში არსებული ჰიდროლოგიური ჭაბურღილების მონაცემების თვისობრივ-რაოდენობრივი ანალიზი. შესაბამისად, მოცემული ნაშრომის მიზანს წარმოადგენს სუსტი ლოკალური მიწისძვრების თანმდევი მაღალი სიხშირის სეისმური ტალღებისა და დაბალსიხშირული გეოაკუსტიკური გამოსხივების, როგორც სუსტი ჰიდროსეისმური ვარიაციების გენერაციის სავარაუდო მიზეზების, წარმოჩინება.

СЛАБЫЙ ГИДРОСЕЙСМИЧЕСКИЙ ЭФФЕКТ ЛОКАЛЬНЫХ ЗЕМЛЕТРЯСЕНИЙ В ГИДРАВЛИЧЕСКИХ СКВАЖИНАХ ГРУЗИИ

Кереселидзе З., Кобзев Г., Джимшелидзе Т.

Реферат

Сильные землетрясения с магнитудами $M\geq7$ в удаленных гидравлических скважинах довольно часто вызывают гидросейсмические вариации различных типов. Подобный эффект после слабых и средних по силе ($M\leq5$) землетрясений возможен также и в скважинах, находящихся на малых эпицентральных расстояниях. В частности, до и после таких землетрясений в скважинах, расположенных на территории Грузии, достаточно часто наблюдаются слабые волновые вариации уровня воды с амплитудами $A\leq2$ см. Очевидно, что они связаны с генерацией сейсмических волн. Известно, что геодеформационные процессы в гипоцентральной области будущего землетрясения, кроме сейсмических волн, часто сопровождаются также и геоакустическими (f=0.1-1000 Гц) и крайне низкочастотными ($f\geq1$ кГц) электромагнитными волнами. Геоакустические волны, по сравнению с сейсмическими волнами, имеют значительно меньшую интенсивность. Однако, на заключительном этапе подготовки землетрясения, можно допустить, что интенсивность низкочастотных геоакустических волн может возрасти до уровня, когда их амплитуды станут соизмеримыми с амплитудами высокочастотных (f=10-100 Гц) сейсмических волн. В таких случаях можно допустить, что в гидрологических скважинах, расположенных на малых эпицентральных расстояниях, слабые волновые возмущения могут генерировать не только сейсмические, но и геоакустические волны. Справедливость данного соображения подтверждают результаты качественно-количественного анализа данных гидрологических скважин, расположенных в Грузии. Следовательно, цель данной работы заключается в наглядном представлении высокочастотных сейсмических и низкочастотных геоакустических волн, сопровождающих локальные землетрясения, как вероятных причин генерации слабых гидросейсмических вариации.