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Relationship between the Velocity Parameters and Dominating Periods for the Stiffly Frozen Coarse Ground Layer

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Abstract: Consideration is being given to the correlation between theoretical concepts of the probability of occurrence of resonance phenomena and experimental data by the example of stiffly frozen coarse ground layer lying on the half-space that is also composed of frozen rocky grounds. An assessment of resonance frequencies is made in reference to relative frequency characteristics of the layer obtained for longitudinal and transverse waves from 14 earthquakes recorded in three sites. The velocities of the longitudinal and transverse waves vary in the frozen coarse grounds of Pribaikalye and Trans-Baikal area with regard to humidity and temperature. The generalized values of these velocities in combination with an equality of relationships between the resonance frequencies and velocities of longitudinal and transverse waves are used in the assessment of the probability values of velocities of lingitudinal and transverse waves alone in the investigated layer. It shows a possibility to determine the probability values of velocities of the wave propagation in a loose ground layer from the earthquake records with the availability of generalized data on the values of velocities alone obtained on the laboratory scale and through full-scale measurements.

Key words: Layer; Seismic signal; Frequency characteristics; Resonance frequencies; Velocities of longitudinal and transverse waves

硬化粗质地基冻土层的速度参数与卓越周期的关系

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摘 要：本文给出了对共振现象出现概率的理论分析与实验数据间关系的思考。样品取自位于半空间的硬化粗质冻土地基，包括石质冻层。参考从三个场地14次地震记录的纵、横波速求得的土层相对频率特征，进行了对其共振频率的评估。纵、横波速在前贝加尔和后贝加尔地区的粗质冻土层中随湿度和温度而变化。将这些概括化的速度值与一个共振频率和纵、横波度之间的关系式结合起来，用于评估被调查土层的纵、横波速的概率值。结果显示，通过综合在实验室尺度获得的速度值和现场测量获得的速度值的数据，则利用地震记录波来确定在松散土层内传播速度的概率值是可能的。

关键词：土层；地震信号；频率特征；共振频率；纵、横波速
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0 Introduction

The phenomenon of wave or constructive resonance in the layer during earthquakes[1] is invoked almost without exception to interpret the fact that

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the oscillation amplitudes recorded in the loose ground layer are more than twice as large as those recoreded in rocky ground. For example, seismic microzoning of the areas in the acoustic stiffness method involves the correction 2.5 units as a maximum for resonance phenomena in the layer to the value of seismic intensity increment ΔI determined directly from acoustic stiffness. ΔI_{res} tales the values from 0.1 to 1.3 units for rather moderate relationships between acoustic stiffness of the investigated layer and half-space $V_k \cdot \rho_k / V_3 \cdot \rho_3 = 0.3 \sim 0.6$ depending on the dominating period[2]. Taken alone, the error is calculated assuming a plane-parallel bedding of the loose ground layer on the half-space. Introducing the correction, as well as the correction alone, needs thorough experimental substantiation when it is considered that the plane-parallelism condition is not usually met by the native layer-half-space interface.

Since the theoretical concepts of wave resonance in the layer meet the requirements of the linear theory of elasticity, small earthquakes may well result in elastic ground motions. A short-lived seismic process and an ice that exerts a cementing effect on both loose ground layer and underlying half-space allow, as a first approximation, considering the latter as elastic bodies. So, the conditions of experiment may be thought of as being in complete agreement with theoretical concepts.

The earthquakes have been recorded in three sites in the layer of frozen coarse deposits. The layer of coarse deposits lying on granite basements is no more than 150 m in thickness. The temperature of ground (T) was $T = -3.1$℃ in the first site, $T = -2.0$℃ in the second site, and $T = -1.8$℃ in the third site. The largest distance between the sites is 1 200 m. The standard grounds are granites with $T = -3.5$℃. The velocities of longitudinal waves (V_P) are not lower than 2.0 km/s in the coarse grounds and 4.0 km/s in the granites. The variation of velocities of wave propagation in granites with depth did not exceed 0.5 km/s within the upper 150 meters. Each of the sites has been represented by three components: NS, Z, and EW. The seismometric channels had the magnification $V = 10\,000$ within the table-shaped part of amplitude-frequency characteristic on frequencies $f = 1 \sim 20$ Hz[3].

1 Determination of resonance frequencies

It is known[4] that the ground motions produced on the surface by seismic signal from an earthquake in a site can be derived in the form of a flowchart:

$$S^{i}_{n}(f) = H_{inst}(f) \cdot H^{i}_{gr}(f) \cdot H^{i}_{med}(f) \cdot S^{i}_{o}(f) \tag{1}$$

where index i determines a genetic type of the wave (P, S), $S_n(f)$ is a spectral presentation of seismic signal recorded on the surface, $H_{inst}(f)$ is a frequency characteristic of the instrumentation, $H^{i}_{gr}(f)$ is a frequency characteristic of local ground conditions in a site, $H^{i}_{med}(f)$ is a frequency characteristic of the medium describing the interaction between seismic waves and the medium with the wave propagation from the radiator to the layer-half-space interface when the medium is described by frequency characteristic $H^{i}_{gr}(f)$, and $S^{i}_{o}(f)$ is oscillation spectrum on the radiator boundary.

We write Equation(1) for one earthquake that is recorded in two sites spaced inconsiderably as compared to hypocentral distance. One site is therewith located on the frozen loose ground layer, and another one-on the rocky ground layer presented by the standard site:

$$S^{p}_{n\,gr}(f) = H^{p}_{inst}(f) \cdot H^{p}_{gr}(f) \cdot H^{p}_{med}(f) \cdot S^{p}_{o}(f) \tag{2a}$$

$$S^{p}_{n\,rck}(f) = H^{p}_{inst}(f) \cdot {'H}^{p}_{med}(f) \cdot S^{p}_{o}(f) \tag{2b}$$

Having divided Equation(2a) into Equation(2b), we obtain:

$$S^{p}_{n\,gr}(f) / S^{p}_{n\,rck}(f) = H^{p}_{gr}(f) H^{p}_{med}(f) / {'H}^{p}_{med}(f) \tag{3}$$

The stroke at $H^{p}_{med}(f)$ in the denominator is indicative of dissimilarity of the mediums described by values $H^{p}_{med}(f)$ and ${'H}^{p}_{med}(f)$. It is due to an additional effect that the rocky grounds of the upper section, equal in thickness to the investigated loose deposits, exert on dynamic characteristics of seismic signal. Because of this, $S^{p}_{n\,rck}(f)$ is not a spectrum of incident signal in relation to $S^{p}_{n\,gr}(f)$ as is required by physical definition of frequency characteristic of the system (in this case, the layer of frozen coarse deposits). By virtue of $H^{p}_{med}(f)$ is not equal to $'H^{p}_{med}(f)$, the ratio of $H^{p}_{med}(f)$ to $'H^{p}_{med}(f)$ will not be equal to 1 and, consequently, the ratio of spectra of motions recorded on the rocky and loose ground surface will not determine well the frequency characteristic of the layer. $S_{o}(f)$ characterizing the radiator according to the type of wave-S or P- is taken as the same for both of the sites. Setting $H^{p}_{cp}(f) = {}'H^{p}_{cp}(f)$ for the earthquake recorded at both sites, Equation(3) rearranges to the equation determining a relative frequency characteristic of the loose ground layer:

$$H^{p}_{gr}(f) = S^{p}_{n\,gr}(f)/S^{p}_{n\,rock}(f) \qquad (4)$$

Similar to Equations (2a, b) derived for P-wave, one can derive an equation for S-wave for the same sites. In the course of analogous operations we obtain:

$$S^{s}_{n\,gr}(f)/S^{s}_{n\,rock}(f) = H^{s}_{gr}(f) \cdot H^{s}_{med}(f)/'H^{s}_{med}(f) \qquad (5)$$

where the indexing of Expression(3) is hold. Obviously all limits set on P-wave are also true for S-wave, and on assumption of the equality $H^{s}_{med}(f) = H^{s}_{med}(f)$ we obtain:

$$H^{s}_{gr}(f) = S^{s}_{n\,gr}(f)/S^{s}_{n\,rock}(f). \qquad (6)$$

The effect of the uppermost section of rocky grounds on dynamic characteristics of seismic signal is not considered in solving practical problems rather often. For example, it is precisely this approach that the direct method of seismic zoning principally implies. That is why a frequency characteristic of a loose sedimentary layer is of a relative character.

The multiple reflection of waves will affect the gradient mediums, among which is the upper section of rocky grounds, to only a small extent as they do not have pronounced reflecting interface. Therefore, the components determined by resonance phenomena are essentially not expected in the spectrum of seismic signal recorded on rocky ground surface. For an extended discussion of influence of the deep-seated stratigraphic and irregular inhomogeneities on dynamic characteristics of seismic signal see[3,5,6].

The factor that motivates inequality of frequency characteristics in different sites is the scattering of seismic signal by inhomogeneities[7,8] for the scattered wave field imposed on the recorded seismic signal.

On small radiuses of correlation of the scattered wave field comparable with the distance between the sites the fluctuating wave field may reach 40% in the S-waves with regard to a wavelength. In such a situation, the frequency characteristic of loose ground can be essentially determined with 100% uncertainty and will not contain any useful information. Assuming a "resonant" scattering of the field on the marked inhomogeneity[9], the recorded seismic signal can be partially modulated even within the rocky ground. Then frequency characteristic of the loose ground layer as such may not reflect resonance phenomena in the latter. Finally, the form and level of frequency characteristic of a loose ground layer may depend on the character and "force" of the interaction between waves of different types(P and S) and regular and irregular inhomogeneities of the medium in which they propagate.

Elementary resonance condition in a loose ground layer with normal wave incidence on the layer-half-space interface is determined by relationship between wave length λ and layer thickness h

$$h = (2n-1)\lambda_{ij}/4,\ n = 1,2,3,\cdots \qquad (7)$$

with regard to the multiples; indexes i and j determine P- or S- waves. On incidence of the P- and S-waves at an angle to the bottom this relationship is somewhat complicated, but the physical essence would remain as before, like that of normal wave incidence on the layer-half-space interface.

The wavelength can be expressed as corresponding velocities of P and S seismic wave propagation V_{ij} and frequency f_{ij}. Substituting this expression in Eq. (7) shows that

$$f_{P}/f_{S} = V_{P}/V_{S} \qquad (8)$$

Thus, the ratio of velocities of longitudinal and transverse wave propagation can be determined in a loose ground layer on condition that the ratio of frequencies corresponding to resonance for P- and S-waves is known. Clearly f_P/f_S can be determined in the simplest way from the ratio of relative frequency characteristics of the investigated layer obtained from earthquake records.

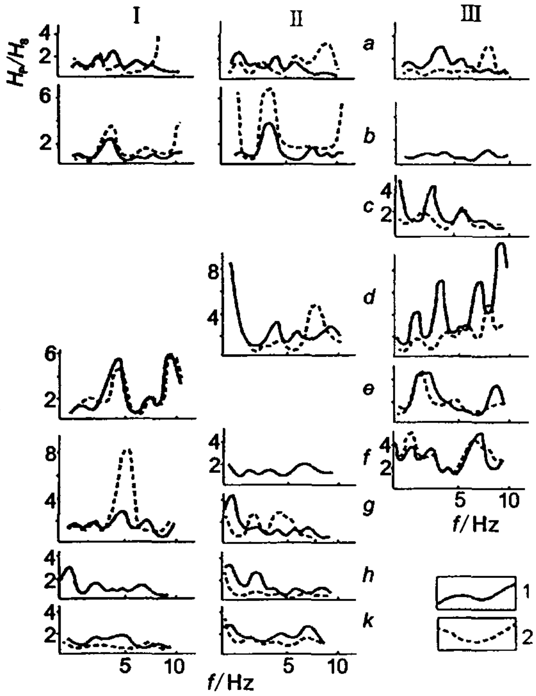

Fig. 1　A ratio of frequency characteristics $H_p(f)/H_s(f)$ for the frozen coarse debris in different sites(Ⅰ — Ⅲ) from P- and S-waves of simultaneously recorded earthquakes of different energy lasses $7 \leqslant K \leqslant 10$ and epicentral distances $7 \leqslant \Delta \leqslant 480$ km(a—k); 1—from S-wave records(NS-component) to P-waves(recorded by Z-component); 2—same as 1, from S-waves recorded by EW-component.

In practice, it is a curve with the average level close to 1 on alternating the maximums and minimums, as V_P is always more than V_S and hence f_P will be always more than f_S. Consequently, the ratio of the maximum frequency of this curve located at high frequencies to frequency of the minimum located at low frequencies will determine the V_P/V_S ratio. The V_P/V_S ratio has been determined from seismic signals ranging from 1.0 to 9.0 Hz in a broad frequency band, in which the amplitude spectrum is significant, i. e. when the signal/noise ratio is more than 2. The resolving power of the spectra on frequency is for the most part no less than 0.75 Hz. The resolving power of the curve of the ratio of frequency characteristics reached respectively 3.0 Hz, which results clearly in smoothing of the curve obtained from a single earthquake. The averaging of these curves from many earthquakes will yield curves all the more smoothed. Therefore the analysis is made of the ensemble of ratios of frequency characteristics obtained from each of the earthquake with different K and Δ. The basic criterion was the stability of recurrence of the first minimums and maximums[10,11] at certain frequencies. Fig. 1 shows that the most stable recurrence is typical of the first mimimums and maximums on the curves of ratios of frequency characteristics obtained from different earthquakes. Their values for each of the sites are accumulated in Table 1.

Table 1　Frequencies of the mimimums and maximums and their ratio

No.	Site 1			Site 2			Site 3		
	f_{min}	f_{max}	f_{max}/f_{min}	f_{min}	f_{max}	f_{max}/f_{min}	f_{min}	f_{max}	f_{max}/f_{min}
1	4.2	6.1	1.45	4.3	5.8	1.35	4.3	7.7	1.79
2	4.3	6.3	1.47	4.2	6.4	1.52	4.0	8.0	2.00
3	4.3	8.0	1.86	4.8	7.8	1.62	—	—	—
4	4.8	8.2	1.71	4.5	7.4	1.65	—	—	—
5	—	—	—	—	—	—	3.2	6.4	2.00
6		—	—	5.8	8.9	1.53	2.0	5.3	2.66
7	5.3	9.1	1.72	5.3	9.4	1.78	2.4	3.9	1.63
8	6.4	9.2	1.44	—	—	—	2.2	4.0	1.82
9	3.1	5.2	1.68	3.5	5.2	1.49	2.8	5.3	1.89
10	2.7	4.3	1.59	4.2	6.0	1.43	2.8	4.8	1.72
11	3.2	5.3	1.66	3.9	5.7	1.46	1.9	3.6	1.90
12	—	—	—	4.2	6.1	1.45	2.1	3.7	1.76
13	3.6	5.5	1.53	3.7	6.0	1.62	—	—	—
14	—	—	—	3.0	5.3	1.77	—	—	—

From the figure and table it appears that first minimums are characteristic of frequencies 2.7～5.3 Hz and the maximums-of frequencies 4.3～9.1 Hz for the first site with regard to resolving power of the curve of ratio of frequency characteristics. The ratio of frequencies is 1.6. The respective values for the second site correspond to frequencies 3.0～5.3 Hz; 5.2～8.9 Hz; 1.6, and those for the third site-to 1.9～4.0 Hz; 3.6～7.7 Hz; 1.9. The ratio of frequencies of the maximums to the minimums averages 1.70 for the whole layer. The level of minimum values of the curve of ratio of frequency characteristics range from 0. 3 to 1. 1, whereas its maximum values vary from 4. 0 to 9. 0 for different sites. Fig. 1 shows rather good recurrence of the form of ratio of frequency characteristics obtained from different components.

The seismic signal was tested for noise component through obtaining the curve of ratio of frequency characteristics determined from P- and S-waves that were recorded in different sties located on the perennially frozen rocky ground surface (Fig. 2). In doing so it emerges that the curve obtained in surch a way can be both smooth and substantially need in the frequency range from 1 to 10 Hz(Fig. 2). As it takes place, the curves of ratio of frequency characteristics of P- and S-waves do not coincide in details for the same earthquakes recorded in different sites located on the perennially frozen rocky grounds. Thus, the curve can be rather smooth for one site and have pronounced maximums and minimums for another. In the last case the levels of the first minimums are comparable with those for the curves obtained for loose grounds.

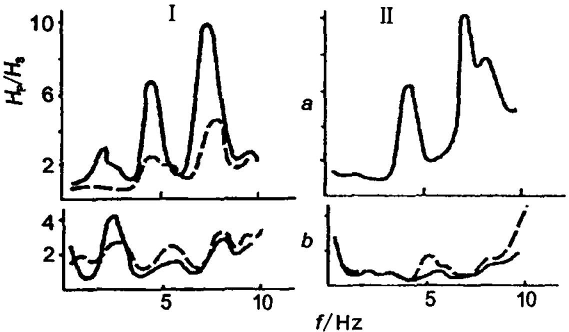

Fig. 2 A ratio of frequency characteristics $H_p(f)/H_s(f)$ for two sites located on the frozen rocky grounds distant from the standard frozen rocky ground for simultaneously recorded earthquakes(a and b corresponding to curves c and d in Fig. 1). The notations correspond to Fig. 1.

Note that the curves obtained from ratio of frequency characteristics of P- and S-waves for loose grounds become more smoothed at more than 100 km from the epicenter, especially on frequencies higher than 5. 0 Hz. But similar curves obtained for rocky grounds vary at random both from one earthquake to another and from one site to another without regard to the epicentral distance.

2 A possibility to determine V_P and V_S from dynamic characteristics

The velocities V_P/V_S obtained relative to frequency characteristics $H_p(f)/H_s(f)$ are well within the limits of distributions permissible in [12] for the investigated grounds. The V_P/V_S value equal to 1. 92 for site 3 is assigned to the extreme right values of the generalized distribution. Representing the grounds with $T=-1.8$ ℃, this site is in essence within the alluvial plain (stream) of the Sulban River($r \approx 50$ m), flooded by meltwater almost every summer due to an intensive snow melting that motivates a high degree of water saturation of its grounds. Numerous frost mounds degrading around this site testify to this fact. Consequently, high value V_P/V_S can be assigned to high water saturation (ice content) of the grounds.

This conclusion is in a rather good agreement with that made by V. I. Dzhurik[13] in result of numerous investigations of coarse grounds of various T^0 and W pursued from the laboratory and full-scale measurements. These data are presented in Fig. 3.

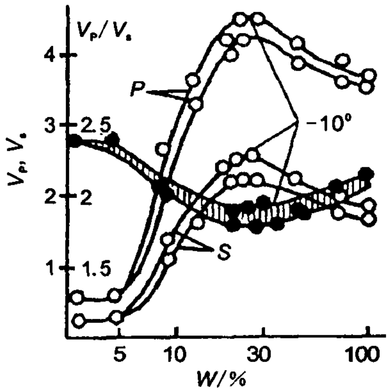

Fig. 3 A generalized curve of the variation of velocities of longitudinal (V_P) and transverse (V_S) waves and their ratio with regard to temperature(T ℃) and humidity (icy content)(W, %) for the frozen rudaceous grounds of Pribaikalye and Trans-Baikal area.

On measurements of velocities of seismic waves made on the laboratory scale the temperature of grounds varied from 0 to −10 ℃, and humidity-from 0～10 to 100%.

The full-scale measurements of velocities of P- and S-wave propagation were made with the use of 30- and 48-channel stations by the standard procedure[14]. The texture and condition of grounds were determined from the data on engineering-geological examination and borehole surveying.

The curves of the measured relationships $V_P = f(T,W)$; $V_S = f(T,W)$ and $V_P/V_S = f(T,W)$ can be arbitrarily divided into three segments (Fig. 3). Prior to ground cementing (frozen grounds) with humidity ranging from 0 to 5%, the first segments shows that velocities V_P and V_S depend almost not at all on temperature and their ratios equal to 2.3～2.4 are the highest as compared with the other parts of the curves.

The second segment covers humidity ranging from the beginning of cementation to full saturation of ground by ice. The velocities of longitudinal waves increase 7～8 times and those of transverse waves increase 10 times for this segment. The velocities' change of this type leads to decrease of their ratio of to consider the extreme values to 1.6～1.7/1.9. On decrease of the temperature on this segment the maximum velocities are noted with full water and ice saturation of ground and the ratio of velocities is minimum.

Increase of V_P and V_S values and decrease of their ratio characterize the third segment of the curve with humidity increasing to 100%. The velocities of transverse and longitudinal wave propagation do not increase in the same way with the decrease of temperature resulting in the decrease of their ratio with the increase of humidity. As it takes place, the V_P/V_S increases with the decrease of temperature reaching 2.1～2.3 at humidity 100%.

On the basis of V_P/V_S ratios obtained from the ratios of frequency characteristics it may be inferred that the ground investigated in sites 1 and 2 is entirely or almost entirely saturated with water and ice. The difference in V_P/V_S values for these sites can be assigned to the errors of V_P/V_S determinations (see Table 1). If so, V_P and V_S can also be determined from Fig. 3. As a result of it we obtain that the velocities of transverse wave propagation in the grounds presented by sites 1 and 2 should not exceed 2.5～2.6 km/s, and those of longitudinal wave propagation are to be no higher than 4.1～4.4 km/s. The respective velocities in site 3 are to be $V_S = 1.8～1.9$ km/s and $V_P \leqslant 3.5$ km/s assuming high humidity of the grounds. Actual velocities V_P and V_S can differ from the above-determined velocities due to granulomentric composition, filling material, saturation with saline solutions of ice etc.

From the foregoing it is seen that the ratio of relative frequency characteristics of grounds obtained from seismic signals of earthquakes allows determining not only resonance (leading) frequencies of the (frozen) loose ground layer but also the ratio of velocities of P- and S-wave propagation. In combination with the data of direct measurements of velocities V_P and V_S, the velocities alone can be determined around this ratio and known humidity (ice content) for this ground over a temperature range stretching from 0 to -10 ℃. In this article it is done by the example of frozen coarse grounds.

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1次，虚报3次，其中2004年出现的异常预报尚未到期。预报研究总时间为412个月，岗贝尔分布b值预报占用时间为80个月，其R值评分为0.47；泊松分布符合度Y_n值预报占用时间为132个月，其R值评分为0.56。

4　两种参数的不确定性探讨与结论

如同其它参数一样，岗贝尔分布b值和泊松分布符合度Y_n值在扫描中存在不确定性：岗贝尔分布b值缩短扫描窗长会出现异常次数增加，异常时间缩短，虚报率提高；增加窗长则会出现异常次数少，异常持续时间长的弊病。泊松分布符合度Y_n值在缩短窗长后异常出现率降低，异常时间缩短；加大窗长则会出现大面值异常，很难将异常和发生的地震相对应。

尽管这两种新参数还存在一定的不确定性，还需在实践中进一步检验和完善，但从我们将其应用于银川—河套地震带5级以上地震前和祁连山—六盘山地震带5.5级以上地震前进行预报检验的结果来看，两种参数在两个地震带均通过检验，对中强地震的映震效果较好，显示了应用前景。

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