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Strong Seismic Effects on Systems of "Ground-building" in the Presence of Softened Grounds

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Abstract: The macroseismic equation, giving the convergent solution (regardless of magnitude) for relative intensity at lg $R\sim0$, was derived. Investigation of seismically resistant characteristics of rocks in the Baikal region together with literary data and unified theory allowed one to evaluate the equipotential source surface. The constancy of earthquake intensity at the boundary of a source, the radiator of elastic waves in the crust, is established. This made it possible to carry out transition from the main parameter of an earthquake, the magnitude, to the quantitative calculation of intensity with distance from a source. Bilinear dependence of intensity (density of energy flux) on a distance is obtained. Correlation between density of energy flux and relative intensity is given.

Intensity of oscillatory loads depending on physical characteristics of grounds—building bases was derived.

The proposed method of quantitative prediction of large seismic effects in seismological aspect is one of the possible methods to provide the detailed seismic zoning and microzoning of the territories.

Key words: **Seismic intensity; Seismic effects; Seismic resistance**

软土地基上地表建筑系统的强震反应

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摘 要：本文导出了一种给出相对烈度在 lg $R\sim0$ 之间的收敛解(忽略震级)的小震方程式。结合在贝加尔地区岩石抗震特性调查与文字资料和统一理论，使人们可对震源等势面进行评估。确定了在震源区边界处的地震烈度稳定性和弹性波在地壳中的传播，使得推导出从地震主要参数震级向随震中距不同的烈度定量计算的转换成为可能。获得了烈度(能通量的密度)对距离的双线性相关，给出了能通量密度和相对烈度之间的关系。求出了取决于地表建筑地基的物理特性的振动载荷烈度。在地震学角度，这种强震的定量预测方法是一种提供详细地震区划和场地小区划的可能手段之一。

关键词：**地震烈度；地震反应；抗震**

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0 Introduction

The equations of a macroseismic field of Blake & Shebalin[8,11] expressed in terms of units and their "regional" modifications remain to be the only tool in evaluating the initial intensity of earthquakes to plan seismically resistant constructions. Since relative units of intensity are inadequate to maintain dynamical stability of structures, the en-

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gineering seismology solves the inverse problem. A correlation was made between macroseismic intensity and various elements of ground motion at earthquakes, including both strong and hazardous motions and the felt ones.

It should be noted that Shebalin's equation does not provide the solution for small distances adequate to the physics of destruction process. For small epicentral distances the hazardous design intensity actually reduces with decrease of the event magnitude(M). According to the Building Code[2], the design intensity at $M<4\sim5$ is referred to the safe level. However, by analogy with explosions the mass of a charge Q and the magnitude in seismic event determine only the volume of destruction area and damages, all things being equal.

1 Decrease in seismic intensity with distance from a source

The fact that decrease of dynamic level of oscillations at small distances R_i from a source with its size R_o is determined by $R_o/(R_i+R_o)$[8,11], is of basic importance in determining the level of hazardous intensity. The earthquake magnitude correlates with sizes of sources and the average radius R_o. Using correlation between the magnitude and the size of a source in[7], we find that

$$R_o(\text{km}) = 0.02 \cdot 10^{0.43M} \quad (1)$$

From the above it follows that classic equation of a macroseismic field[11] $J=1.5\,M-3.5\lg R_i+3$ must be replaced by the equality

$$J = 1.5\,M - 3.5\lg(R_i + 0.02 \cdot 10^{0.43M}) + 3 \quad (2)$$

Hence it follows that at $R_i=0$ the unit of intensity is constant and independent of a magnitude and is equal to 9.

Study of rock strength in the Baikal region as well as literary data allowed one to define the equipotential surface of an earthquake source. On its external boundary the oscillation velocity of particles of the medium (the bedrock in transition of elastoplastic deformations in elastic ones) is $0.7\sim0.8$ m/s. On this basis the constancy of earthquake intensity at the boundary of a source, the radiator of elastic waves in the crust, has been established. This allowed one to carry out transition from the main earthquake parameter, its magnitude, to quantitative calculation of intensity with distance from a source[3-4,6-7].

The joint study of influence of physical and geometrical nonliearity on intensity of seismic waves generated a need for division of the wave field into three zones[6]. The area in which oscillatory speed exceeds the elastoplastic limit of deformations are the sites where construction is impermissible. Following the Building Code[2], a specific design of constructions is required here.

Experimental results obtained in the Baikal seismic region together with the literary data[3-4,6-7] and unified theory enabled one to determine the relationship between intensity variation and distance from the earthquake source in the range of hazardous and felt seismic loads

$$I_{max} = 1/2[0.125 \cdot \bar{u}_{max}]^2\,\rho\bar{b}\,(8\,R_o/R_i)^p \quad (3)$$

Where $\rho\bar{b}$ is an average wave resistance of the medium equal to 10^7 kg/mc^2, R_o is a source size in spherical approximation, $R_i=R_o+R_r$, R_r is a hypocentral distance. Parameter $p=2$ at $R_i<8R_o$, $p=3$ at $R_i>8R_o$. Thus, on the basis of equation (2) the earthquake intensity can be estimated in absolute or relative units. We use MSK−64 scale and the correspondence $\bar{u}_{max}=0.7$ m/s is 10 units[5] that is valid for the Baikal region. It should be noted that when a factor of divergence is equal to two, the calculation agrees with the Shebalin's formula for intensity units $J>7$.

To reveal a correspondence between the calculated analytical relation and experimental data, we used EARTHQUAKE STRONG MOTION 3 − VOLUME CD − ROM COLLECTION (National Geophysical Data Center, 325, Broadway, E/GCI, Boulder, Colorado 80303 USA). We have analyzed the records of large earthquakes ($M=5\sim7.6$) with sources predominantly in California and Alaska. The overwhelming majority of the records used (~85%) was obtained on sedimentary rocks, ~15% on outcrops of magnetic rocks (fractured granites and basalts). More than 80% of sedimentary rocks are presented by alluvial deposits. Sandstone, schist, chalk deposits and volcanic breccia are observed among the other sedimentary rocks.

The data on oscillation velocities and accelerations were used. Once again, we took advantage of the relation between the magnitude and the source size R_o (following [7]), that was obtained by the author from the world brief reports. The relative distance has the following form:

$$R_{rel} = R_i/R_o = (0.02 \cdot 10^{0.43M} + R_r)/0.02 \cdot 10^{0.43M}$$

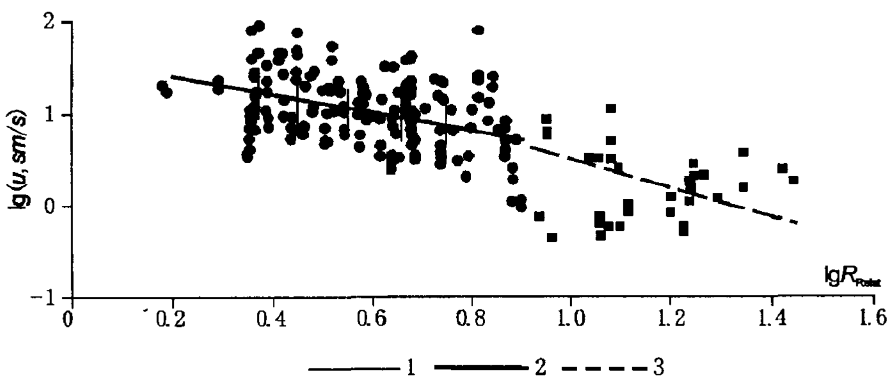
where R_r is a hypocentral distance, source size (R_o, km) is the equation (1).

The relation between oscillation velocities and relative distance is given in Fig. 1(A). In a linear approximation the function $u = f(R_{rel})$ breaks up into two branches which characterize near and far zones. The equation is:

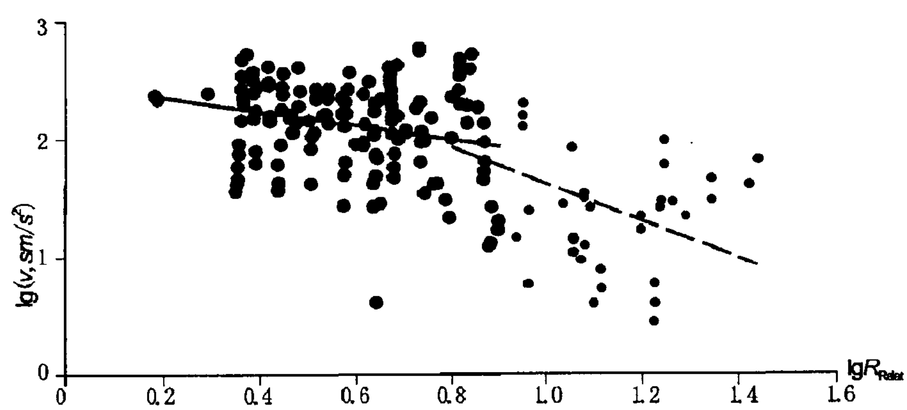
$$\lg(u, \mathrm{cm/s}) = 0.81 - p \cdot \lg(R_{rel}/6.4) \qquad (4)$$

Coefficient $p=0.95$ at $R_{rel}<6.4$ (in near zone) and $p=1.6$ at $R_{rel}>6.4$ (in far zone). Correlation coefficient is equal to 0.65. The equation (4) is in a good agreement with the above calculated analytical relation (3). In equation (3) the coefficient p is equal to 1 and 1.5 for near and far zones, correspondingly, and free term in this equation is 1. Values of the relative distance for inflection of bilinear relation are also in close agreement, 8 from equation (3) and 6.4 from equation (4).

Thus, as the wavefront of the source is widened, the level of maximum stresses ($\bar{u}\rho\bar{b}$) in a half-space (the earth crust) reduces to the distances $R_{rel}<6\sim8$ in inverse proportion to the relative distance to the source. Stress level decreases in inverse proportion $(R_{rel})^{1.5-1.6}$ with further increase in a distance. It should be noted that the value of oscillation velocity for inflection of bilinear relation is in agreement with the velocity range (5 ~ 10 cm/s) estimated by M. A. Sadovsky for a radiator[10].



(a)



(b)

Fig. 1 Relation between peak oscillation velocities (A) and accelerations (B) and the relative distance to the source(1 67% confidence interval of values of oscillation velocities in near zone; 2 linear set for near zone; 3 linear set for zone).

Relation between accelerations and a relative distance is given in Fig. 1(B). In linear approximation the function $v=f(R_{rel})$, like the relation between oscillation velocities and a distance, breaks up into two branches at $R_{rel}\sim 6.4$

$$v, \text{cm/s}^2 = 102.8 - p \cdot \lg(R_{rel}/6.4) \qquad (5)$$

Coefficient $p=0.61$ at $R_{rel}<6.4$ (in near zone) and $p=1.6$ at $R_{rel}>6.4$ (in far zone). Correlation coefficient for the relation in near zone is 0. 19 and −0. 57 for the relation in far zone. Taking into account the fact that correlation coefficient for the regression (5) for near zone is extremely low.

We find a mean value $\lg(v, \text{cm/s}^2)$ which is 2. 14 with a standard deviation 0. 17. Hence follows that mean acceleration in near zones is constant and is ~138 cm/s^2 with 67% confidence interval 93~204 cm/s^2. This interval practically corresponds to 7−unit range of the MSK−64 instrumental scale, which was used as a basis for elaboration of the Building code[2].

The level of accelerations in far zone, like the level of stresses, reduces in inverse proportion to (R_{rel}). However, according to the Building Code, zones with acceleration<100 cm/s^2 are considered to be seismically safe.

The use of equations (2) and (3) makes it possible to determine the intensity both in relative units and energy values, i. e. , by values of mass velocities and energy flux density. Here, it is worth noting that unlike the intensity of acoustic waves with the base 10 at the logarithm of absolute value for bels, the bases of logarithms for seismic units make 4 using intensity units, and correspondingly 2 from the values of mass velocities, that results from significant level of the intensity and the difference in frequency ranges.

2　Influence of local ground conditions on the level of intensity of effects

Of great importance is the problem of a consideration of the nonlinear effects in loose and waterlogged sedimentary grounds in the zone of transit earthquakes and rock differentiation with respect to strength characteristics. As stated in geomechanics, the range of seismic effects is rather wide and when it is exceeded nonelastic deformations can occur in grounds. The upper boundary of the range corresponds to monolithic rocks (mass velocity is 0. 8 m/s) and the lower one to the waterlogged loose grounds (0. 05~0. 1 m/s)[1]. We have obtained the experimental analytical dependence of oscillation velocity of a limit of elasticity in loose and waterlogged grounds[4]. The level of oscillatory loads in structure basements is given in Table 1, which is similar to Table 1 in the Building Code and [2].

The limit of elastoplasticity of rocks, depending on a degree of their preservation and water content, is indicated by values given in italics. Loss of strength of foundation bases of structures can take place when this limit is exceeded. The non−uniformity of residual deformations caused by inhomogeneity of ground beneath the foundations of buildings results in disturbance of static balance and stress redistribution in construction elements. Thus, in seismic microzoning of the territories the level of dynamic loads on construction elements and possible loss of bearing capacity of loose ground should be divided. The reinforced building which can take a load of nine intensity units, but which is constructed on the grounds unstable at loads of seven units (according to twelve−mark scale accepted in Russia), is really "a colossus on clay legs".

3　Discussion

M. A. Sadovsky advanced an energy approach to the evaluation of seismic effects. Using the experimental data as the base, he established the relationship between the destruction intensity and the value of mass velocity of seismically explosive waves and determined the functional dependence of oscillation velocity on the charge mass and distance to an explosion[10]. Investigation of the large−scale explosions have shown that, if the increase of oscillation duration is taken into account, these de

Table 1 Intensity of oscillatory loads (peak values of mass velocities in construction basements) depending on the physical characteristics of grounds

Rock in the basement of constructions	Average velocities of wave propagation/m·s^{-1}		$10^{-3}\rho$/ kg·m^{-3}	a/b	$\dot{u}$/ m·s^{-1}	$\dot{u}$/ m·s^{-1}	$\dot{u}$/ m·s^{-1}	$\dot{u}$/ m·s^{-1}
	P(a)	S(b)						
Magmatic, metamorphic, monolithic	5 800	3 400	2.65	1.71	0.8	0.4	0.2	0.1
Magmatic, metamorphic, fractured	3 300	1 800	2.6	1.83	0.8	0.57	0.28	0.14
Id, weathered	2 600	1 600	2.4	1.63	0.8	0.8	0.4	0.2
Gravel-pebbled-rubbly grounds with sandy filler	1 270	350	2.1	3.63	0.8	0.8	0.4	0.2
Fine-, medium-and coarse-grained sands, ari-dry	560	330	1.8	1.7	0.7	0.7	0.4	0.2
Sandy loam, ari-dry	430	210	1.8	2.05	0.7	0.7	0.4	0.2
Loam, air-dry	620	200	1.9	3.1	0.6	0.6	0.4	0.2
Gravel-pebbled grounds with sandy filler, waterlogged	1 660	380	2.1—2.2	4.37	0.4	0.4	0.4	0.2
Close sands, waterlogged	1 500	300	2.0	5	0.3—0.4	0.4	0.4	0.2
Loam-sandy loam grounds, waterlogged	1 600	170	1.9	9.5	0.1	0.1	0.1	0.1
Clay, waterlogged	1 700	130	1.7	13	0.05	0.05	0.05	0.05
Sands, waterlogged	1 600	160	1.6	10	0.1	0.1	0.1	0.1

pendencies are also valid for explosions comparable to large earthquakes in energy[1].

This method was not widely used in predicting earthquake intensity and effect for the lack of reliable methods for determining seismic energy of an earthquake in the near zone.

The above method of evaluation of seismic effects is based on successive differentiation of earthquake areas with respect to the mechanism of seismic effects determined by ultimate strength of rocks in natural occurrence. The distinctive feature of this method is that design loads are determined on a basis of relative instead of absolute distances from earthquake source hypocenter. When loads correspond to a range of mass velocities of 0.8～0.05 m/s, the problem is linear, excluding the territories with lower strength of rocks, and allows analytical solutions that makes it possible to predict not only intensity but also an earthquake spectrum on a basis of the data of field investigations of rocks and grounds which make up the territory of building.

Design factors of dynamics b due to oscillation velocities of buildings of general housing development were proposed earlier[7]. The distinctive feature of the plots b of accelerations and velocities (and thus stresses) is a displacement of the latter into more low—frequency field. The predominant frequencies of velocities (consequently, maxima of spectra) are 0.3 Hz, accelerations ——1/3 Hz. Hence, levels of dynamic stresses and deformations which determine various ultimate strengths of flexible (with large periods) constructions will be significantly higher than the similar levels of stability of rigid constructions. The higher is the floor of buildings, the greater are seismic loads, all other things being equal.

4 Conclusion

The proposed method of quantitative prediction of large seismic effects on the basis of mass velocities as a measure of earthquake intensity and hazard provides a unified building block to choose a specific design scheme in planning seismically resistant buildings and preparation of the bases for construction. The quantitative representation of intensity of a macroseismic field in seismological aspect is one of the possible methods to provide the detailed seismic zoning and microzoning of the territories.

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