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EXPECTED SEISMIC INTENSITY ASSESSMENT TAKING INTO ACCOUNT LOCAL TOPOGRAPHY SITE EFFECT

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ABSTRACT: The analysis of seismic codes of different countries shows accounting of seismic properties of soils caused mainly by their physical and mechanical properties but effect of the topography on site effect is not even considered. Exception is the Building Codes of France. The paper presents the results of experimental investigations of the influence of topographic features on the formation of the effect of strong earthquakes. Examples of amplification of seismic effect due to relief features are shown in the form of field, laboratory and numerical (mathematical modelling) investigations. It is defined that not only slope angle but also height of observation point significantly influences on site effect. It is shown that the intensity of the earthquake in mountainous areas is determined not only by the slope angle value, but also the specific location of the site in the hierarchy of the rock massif. Obtained instrumental data analysis showed that the influence of the relief on the seismic effect of the earthquakes can be most completely accounted by the parameter R, that is the product of the slope angle and the height. It has been defined that the intensity increment can be changed regardless of the constituent rock types from 0 to 1.5 points. It is found that the vibration amplitude varies considerably with the relief and this dependence is different for the displacements, velocities and accelerations..

Keywords: Topography, Relief, Site Effect, Microzonation

INTRODUCTION

The effect of seismic amplification caused by topography features of the surface relief was revealed in the analysis of the effects of many earthquakes, in particular, this is reflected in the works [1]-[8]. Formation of the seismic effect of the earthquake on the earth's surface is caused by geodynamic properties of soils, in other cases by combined action of these geotechnical hydrogeological conditions and the topography of the territory.

Increasing of vibrations amplitude on the surface is observed for such topographic features as hills, steep slopes, mountain ridges, sharp peaks, break zones of slope profile, canyon benches and sides.

In the area of elastic strain of the medium the seismic effect change on sites with rugged relief is caused by different factors: slope angle (steepness), ratio of the incident seismic wave length and the size of mountain structure, approach and departure angle directions of seismic waves, the nature of the relief the dense and loose media border line.

Currently there are no methods that would allow both taking all these factors into account and thus quantifying the spectral function and site amplification with sufficient accuracy. In this regard, investigation of various aspects of seismic effect formation caused by topography of any given territory under conditions of high seismic hazard remains an actual problem.

TAKING INTO ACCOUNT CROSSINGS OF RELIEF IN THE BUILDING CODE FOR SEISMIC MICROZONATION

The larger part of seismically active zones is located in mountain areas, which are characterized by complex topography and various engineering-geological conditions. Results of strong and destructive earthquake consequences show that exactly such features predetermine earthquake effect in many respects. Adequate accounting of topography and engineering-geological conditions of site is the base for realization of corresponding antiseismic measures on the built up and developed territories. Scientists and engineers traditionally pay greater attention to the study of influence of engineering-geological structure of site on seismic effect of earthquake.

Analysis of engineering macroseismic investigation of destructive earthquake consequences shows that degree of earthquake effect is in close correlation with the features of geomorphological conditions. Such dependence has the complex character: miltifactorial kind of correlations takes place what imposes definite constraints on direct usage of the data of macroseismic investigation, which has to a certain extent a formal character. It is caused by the undertime, which was given for the direct study of different engineering-geological situations and reducing earthquake consequences analysis to the formal or descriptive form. This leads to the necessity of special classification of observation data on a basis of corrective information. Such an approach will allow defining more exactly the reasons of earthquake intensity change in each definite case.

Seismic effect, i.e. the earthquake intensity, is formed by the factors mentioned above. One must keep in mind physical phenomena, which are formed by definite factor combination: intensification or weakening of the incoming seismic waves by soil stratum, non-uniform precipitations, soil-structure resonance phenomenon, etc.

The facts of how the geomorphological conditions of the site influence on earthquake effect intensity, are well-known on the data of macroseismic investigations of strong earthquakes. In particular, after the Racha earthquake (Georgia, 1991) a lot of buildings of rural type in Ambrolauri and Oni regions, situated at the foot of the hills, were damaged insignificantly (0–1 damage level) [7]. At the same time buildings, located on the hillsides with slopes exceeding 20° had considerably large damage (2–3 damage levels). For wide territories located on mountainous plateau the seismic effect is often predetermined exceptionally by relief influence, but attention to this is seldom paid. Partial or full failures of building-stock can prevail at that due to the nearness to the epicentre. For example, in 1991 in the village Bokva after the Racha earthquake damages of 4–5 levels took place, i.e. partial or full buildings failures prevailed. Here at the analysis of reasons of seismic effect forming the relief influence, namely location height of building stock, wasn’t taken into account.

The analysis of seismic codes of different countries of the world [9] shows that soil seismic properties caused mainly by their physical and mechanical properties, are taken into account while relief influence on site effect is not even considered. The exception is the Building Code of France (Paz, 1994). In the early building standards and regulations of the Former Soviet Union relief influence was taken into account (Building Code II-A12-69, 1970) and in the next following standards they were not taken into the consideration for unknown reasons (Building Code II-7-81, 1982; Building Code II-7-81*, 2000). Current recommendations on seismic microzonation (SMZ) (Recommendations on SMZ, 1985) determine the seismic conditions of sites, which have the slope more than 15°, as disadvantageous and recommend increasing of site intensity by one point. Such a simplified principle of the intensity assessment, which is not in the least typical for the SMZ, is explained by the absence of reliable methods for quantitatively realization of such assessments. Therefore, it is important from practical and scientific point of view to assess relief features influence on forming of earthquakes intensity.

TAKING INTO ACCOUNT RELIEF FOR EARTHQUAKE ENGINEERING. RELIEF COEFFICIENT (R)

Special investigations on the assessment of relief influence on earthquake seismic effect were carried out in different times. The materials of macroseismic investigations of several strong earthquakes lied in the base of the research. Field observations and investigations on models were executed.

In particular, field observations were carried out in the area of monastic cave complex David Garedzhi for the purposes of historical and cultural monument protection which is located near the military polygon (1988). Explosions were used as seismic source [10].

Physical modelling was performed for the territory of Sukhumi city. As the main conditions of simple similarity at creation of physical three-dimensional 3D model of the Sukhumi city (Fig. 1) the constancy of the values of wave propagation velocities, Poisson's ratio and the soil consistency was considered in the corresponding layers of the model relative to the on-site object.

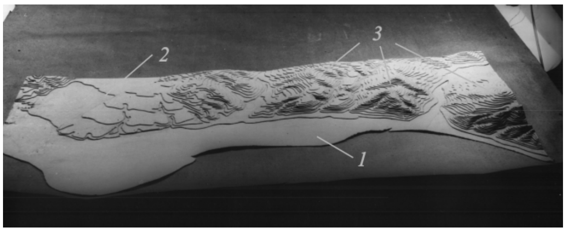

Fig. 1 General form of the model: 1 – shelf; 2 – valley; 3 – mountain range

City territory was 9×9 km in the plan. Model scale was M 1:10 000. The most hazardous vibration frequencies for the city are 1–10 Hz, what corresponds to the frequencies 10–100 kHz for the model with size 0.9×0.9 m. Bedrock of the corresponding massif is presented by fissured limestone, which are highly weathered from the surface. Gypsum was used as the model material. Wave field of surface Rayleigh waves, propagated from the seismic focus (in the shelf zone near Sukhumi city).

The experiment was carried out on the stand, consisting of ultrasonic waves generator with the period T = 3–20 ms and piezoelectric detectors (CTS-19). Frequency of generator vibrations during investigations was 62 kHz, what corresponds to the vibration frequency of real object 6.2 Hz. For the impulse with period T = 15 ms and Rayleigh waves velocity in gypsum V_R = 1.21 mm/s, wave-length for the model was λ = 18 mm.

The source of ultrasonic vibrations was located on a model surface in the shelf area on reference point. Model surface was divided on 96 squares and the wave field of Rayleigh waves was studied in 67 nodes. Up to 7 measurements were carried out on each picket and the results were averaged. The opportunity of reflections from model lateral faces (reverberation phenomenon) was taken into account in the experiments.

The influence of relief features on the Rayleigh wave propagation was assessed relatively to its amplitude on the reference-circle, i.e. relatively to vibration amplitudes on the corresponding distances on the similar model with homogeneous relief. Amplification coefficients were determined by displacing receiver along the profile on the model surface, and comparing measured amplitude with the reference point. The data analysis showed that at the relief slope angle $\alpha \geq 20°$ amplification reaches k = 2.0, what corresponds to the increase of intensity (in MSK scale) on 1 point. Sometimes the increase reached 2 and more points. The given points corresponded to the detached peaks. In some cases at $\alpha << 20°$the amplification, nevertheless, was large and also corresponds to 2 points. The analysis showed that such a phenomenon is caused by the location of the given points between the dominated peaks. Hence we can conclude that it is not enough to use only the relief slope angle. Especially as the relief slope angle not always adequately corresponds to the actual results of macroseismic observation of destructive earthquake consequences.

It was determined that the amplification of vibrations amplitude considerably varies (0–3.0) (Fig. 2) depending on the relief slope angle. On the other hand, the cross-sections (almost parallel to the coastline) show that besides the relief slope angle the proper height of observations considerably influences on amplification (Fig. 3). Moreover, even in the absence of local relief slope the amplification, nevertheless, was quite considerable.

The analysis of corresponding dependences showed that it is necessary to take into account both factors simultaneously in order to increase the observation results reliability. It led to the introduction by V.B. Zaalishvili [10] in 1989 of the so-called “relief coefficient” R, which allows taking both factors into account (Fig. 4).

The analysis of the data, obtained as the result of experimental investigations and also as the result of macroseismic observations of the Racha earthquake, showed that relief influence on seismic effect is the most fully taken into account by the R coefficient:

$$R = \alpha H, \qquad (1)$$

where α is the relief slope angle, degrees; H is the observation height, m.

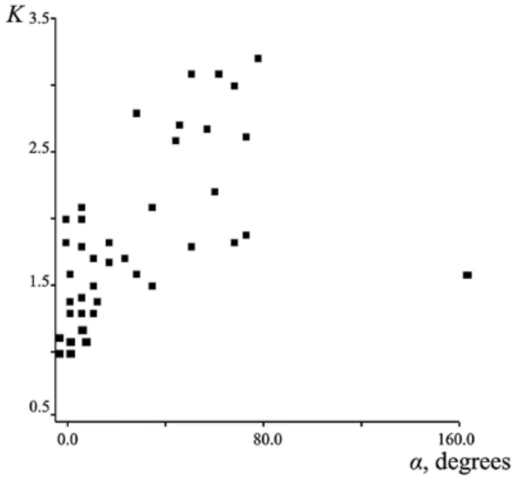

Fig. 2 Dependence of soil vibration amplification on relief slope angle

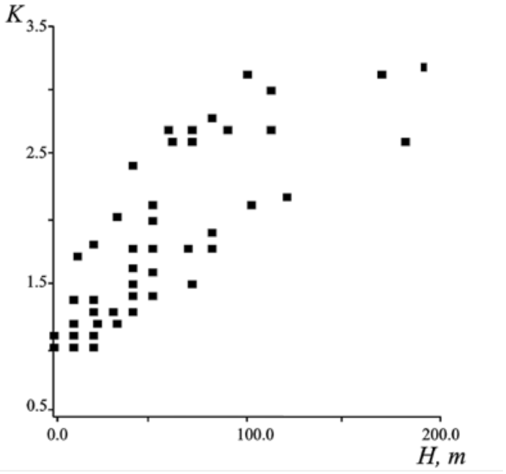

Fig. 3 Dependence of soil vibration amplification on observation height

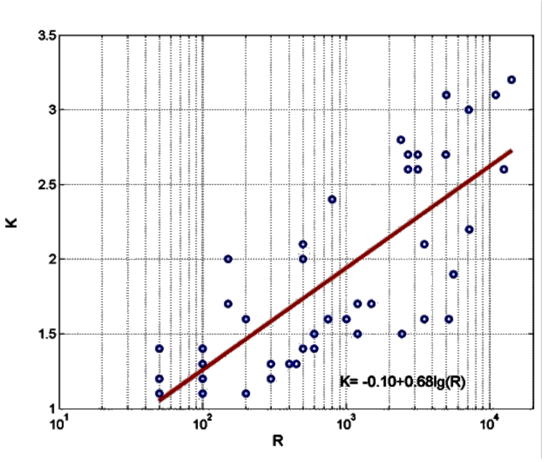

Fig. 4 Dependence of soil vibration amplification on relief coefficient

According to the Building Code [11] positive increment on 1 point corresponds to the twofold acceleration amplitude increase. Then at $\alpha = 10°$ and $H = 65–70$ m, i.e. at $R = 650–700$ (degree·m) intensity increment will be 1 point. It must be noted that according to some reports the intensity increment can change, depending on the fact what investigated index of motion is chosen (displacement, velocity, acceleration). Increase by 1 point corresponds to the displacement amplitude increase (amplification) in 4 times, etc. This supposes to use the investigation results warily, without formalism and continue active investigations in the given direction.

Usage of relief coefficient R in the practice of earthquake engineering allows taking into account definite conditions of location of the investigated area fully, what increases the foundation of the determination of mechanisms, on which the earthquake intensity in mountainous regions is formed.

RELIEF INFLUENCE ON THE EARTHQUAKE INTENSITY IN SMZ PROBLEMS

On the basis of the analysis of numerous macroseismic observations of strong earthquakes consequences S.V. Puchkov and D.V. Garagozov offered the empirical formula for the intensity increment calculation (ΔI) depending on the relief features [12]:

$$\Delta I = 3.3\lg(W_s / W_{et}) + 3.3\lg(W_t / W_f) \qquad (2)$$

where W_s, W_{et} are the accelerations of vibratory motion on soil and etalon; W_t, W_f are the accelerations on the top of mountain structure and its foundation.

As a result of the instrumental and theoretical investigations it was determined that the increment of seismic intensity for the microrelief increases from the foundation of mountain structure to its top and can reach approximately 1.8 point. For mesorelief the tendency of the increase of seismic vibration intensity from foundation to the top remains. The increment of seismic intensity for the relief mesoforms is about 0.3 point. It was shown that weak hilly relief, with the inclinations less than 10°, does not influence on the seismic vibrations intensity.

The investigations of S.V. Puchkov and D.V. Garagozov [13] showed that at vibrations of mountain range, composed by volcanic tuff, the amplitude of seismic vibrations in S-waves increases on the height 15 m in 1.46 times in comparison with the foundation. For the massif, composed by loamy sand and loams on the same height marks the vibrational amplitude increased in 1.8 times for P-waves and in 3.2 times for S-waves.

Slope steepness considerably influences on the increment of seismic intensity. The increase of slope steepness, composed by incoherent gravel-pebble and sabulous-loamy grounds is conductive to the sharp worsening of engineering-geological and seismic conditions of the territory. So, for example, it is determined that slope steepness more than 19°–15° (for dry sandy-argillaceous and gravel-pebble varieties) produces the intensity increment of up to 1 point and at variation of slope steepness from 10° to 40° the amplitudes of seismic vibrations increase approximately in 2.5 times.

It is known that the increase of slope steepness from 40° to 80° produces the increment of seismic intensity equal to 1.5 point [10].

Correlation analysis of the dependence of seismic intensity increment on true altitude, slope steepness and relief roughness showed that the main factors, which change the value of seismic intensity, are the first two indices [12]. It conforms well to investigation results of V.B. Zaalishvili, who introduced the new parameter of the relief coefficient [10].

Later the data analysis allowed to I.L. Gabeeva and V.B. Zaalishvili to offer the empirical formula for calculation of possible amplification K and intensity increment ΔI, which are conditioned by the relief (Fig. 4) [12]:

$$K = -0.1 + 0.68\lg R \qquad (3)$$

where $R = \alpha \times H$ is the relief coefficient; α is the relief slope angle, degrees; H is the height, m.

The analysis of the experimental data shows that intensity increment can vary at that independently of the type of composing rocks, from 0 to 1.5 point.

There are sites on the territory of Vladikavkaz city "unfavorable" for construction in accordance with Russian Building Codes (SNiP II-7-81*) [11] - slopes more than 15°.

At the first stage the slope on the right bank of the river Terek in Vladikavkaz city was selected for investigations (Fig. 5, slope angle 25-35°). Recording of microseismic vibrations was performed on this site.

Two seismic stations were simultaneously used; recording duration was 10 minutes and stations were moved to next point on slope one by one. Usage of such scheme allows accounting temporal variations of amplitude level of microseismic field during performance of the work.

Before recording calibration tests were performed and amplitude adjustment coefficients were obtained (for the second station relatively to the first one): KZ=1.36; KX=2.19; KY=1.13. Due to a large value of adjustment coefficient for X-component (> 1.5) this component was not used in the analysis.

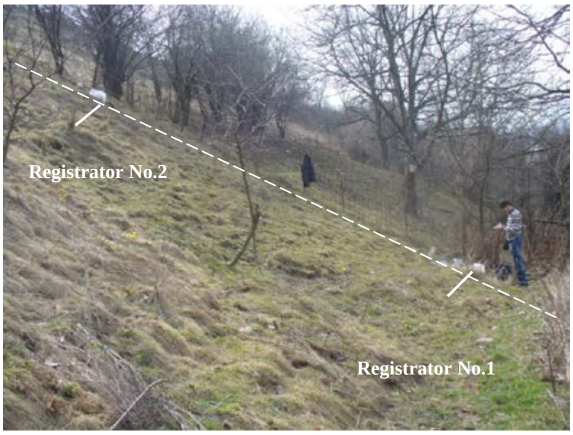

Fig. 5 The part of the slope during microseisms recording

Considering that slope is oriented in West-East direction the maximum relief influence must be registered on Y-component, oriented in the same direction.

Mean amplitudes of microseismic vibrations (microseisms amplitude level) were referred to the point at the base of the slope – Table 1. The corresponding scheme and the curve are presented in the Fig. 6.

Table 1 Maximum amplitudes of microseismic vibrations

Com-ponent	Distance L, m					
	0	20	40	60	80	100
Z	1.00	1.17	1.21	2.03	0.85	1.46
Y	1.00	1.28	1.78	2.96	2.97	2.22

Intensity variation of strong earthquake on the data of maximum amplitude of microseismic vibrations was calculated by the next formula [17]:

$$\Delta I = 2\lg\frac{A\max_i}{A\max_e}, \qquad (4)$$

where Amax$_i$ and Amax$_e$ – maximum amplitudes of microseismic vibrations on investigated and etalon sites correspondingly.

Results of intensity increments relatively to the base of the slope calculation are given in Table 2.

Table 2 Intensity increments calculated on the microseismic data

Com-ponent	Distance L m					
	0	20	40	60	80	100
Z	0.00	0.13	0.16	0.61	-0.14	0.33
Y	0.00	0.21	0.50	0.94	0.95	0.69

Calculations for vertical component (Z) show that there can be expected 1 point intensity increment at the distance of 40 meters from the base of the slope. Amplification at the top of the slope (L=100 m) is not so clear. Horizontal component (Y) analysis gives more stable and sustainable results.

Finally, amplification of vibrational amplitude, which is caused by relief, was assessed with the help of the calculation method of finite elements analysis (FEM) [14].

FEM model of slope with angle of 30° equivalent to the site used for instrumental investigations was constructed (Fig. 6b). The next parameters were used for the slope material Vs=300, ρ=1800, μ=0.28 and for bedding gravel soils – Vs=900, ρ=2200, μ=0.28. Loma Prieta strong motion record was used as an input motion.

Results of horizontal component amplification along profile are shown in the Fig. 7.

Accordance of the both curves is observed in all points except those ones located in 60 and 100 m. It must be noted that the impacts of different level and spectral content are comparing and this has effect on resulting amplitude level on the surface. Differences may also be explained by local soil differences of registration point and some reflection phenomena may not appear in FEM modelling procedure.

Maximum values from both methods were used for the further seismic hazard assessment of this part of the city.

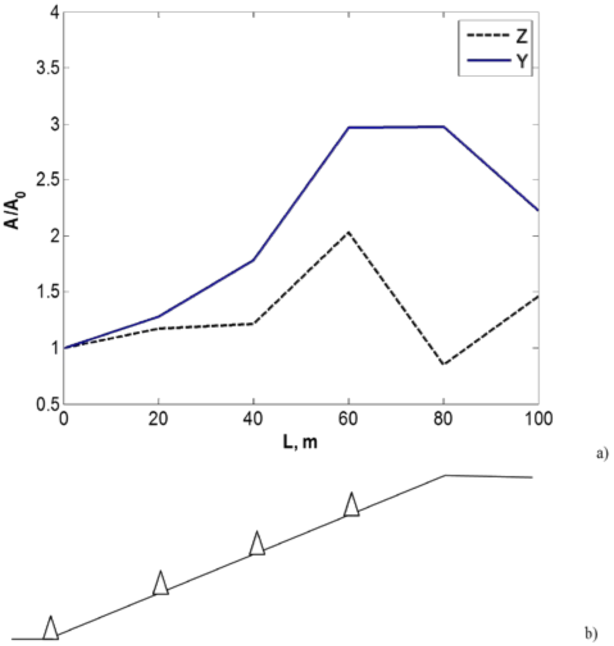

Fig. 6 Amplification of microseisms amplitudes A/A0 (a) along the slope (b)

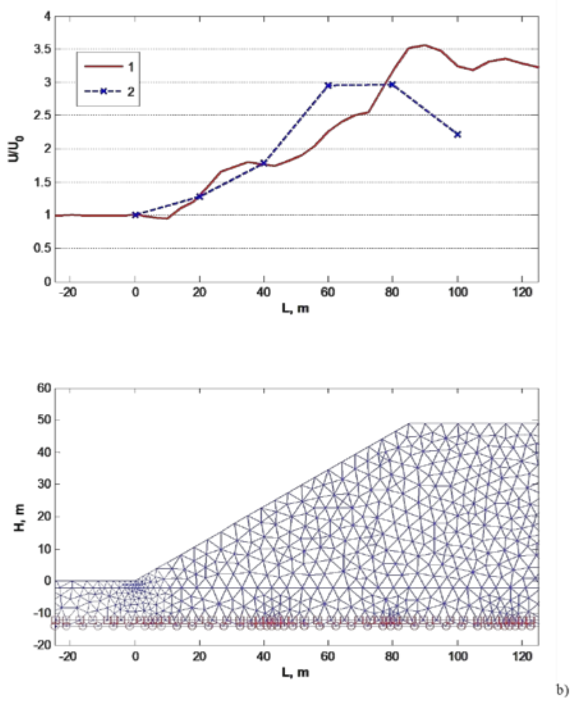

Fig. 7 Amplification of vibrations along the slope – a (1 – calculated; 2 – instrumental) and calculational model of slope – b.

Thus, at the realization of SMZ works in the mountain regions or under the conditions of high relief, it is necessary to pay a special attention to the influence of surface or underground relief on the intensity forming. It is necessary to continue the investigations in order to obtain statistically proved ratio for the calculation of intensity increment, caused by relief.

CONCLUSIONS

Analysis of engineering macroseismic investigations of destructive earthquake consequences shows that the intensity of earthquake effect is in close correlation with the features of geomorphological conditions. Moreover such dependence has well-defined multifactorial correlation relationships.

It is shown that earthquake intensity is determined not only by the value of a relief slope angle, but also by the height. There are given the results of full-scale and laboratory experiment. It is noted that the relief has definite potential energy from the physical point of view. For the assessment of the mentioned energy phenomenological index in the form of the so-called “relief coefficient”, which is represented by the product of a relief slope angle and the corresponding height, is introduced.

It is shown that the intensity is determined not only by the value of relief slope angle, but also by definite area location in the massif hierarchy. There are given the results of investigations which were carried out previously and connected with the necessity of practice and also the results of experimental investigations (full-scale and laboratory experiments). The impact was set in the form of explosions and monochromatic vibrations in ultrasonic range. In spite of considerable differences of investigation conditions the results were mainly characterized by high degree of final results conformity.

It is necessary to realize accounting of locality geomorphological conditions by usage of the so-called “relief coefficient”. It is noted that at R = 650 (degree·m) the intensity for acceleration reaches 1 point.

Usage of the relief coefficient R in the practice of earthquake engineering allows taking into account fully definite conditions of location of investigated area, what increases the foundation of the determination of mechanisms, by which the earthquake intensity in mountainous regions is formed.

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