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# BEHAVIOUR NONLINEAR, ABSORBING SOIL ENVIRONMENTS IN CONDITIONS OF STRONG MOTIONS

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## SUMMARY

During research we have obtained parameters, closely fixed with absorption and non-linearity of soils or any physical system. It was shown the difference of absorption phenomena of seismic energy in soft and hard soils. We received expression for the direct determination of the intensity modification at the changing power for soft soils of different sites of the territory.

The results of the work give opportunity to conclude that in spite of using type of equipment, the main properties of ground strong motion is similarly reflected in corresponding recordings, from earliest to the recent. From the other hand it is necessary to pay special attention to the range of resolution in high-frequency area of spectrum of vibrations. It gives opportunity to register significantly high accelerations, if they accompany strong motion. As it seems they accompany them. Besides, it is necessary to increase radically the level of resolution of record of strong motion for obtaining momentary and "short-living" ultra-high accelerations. And, at last, it is preferred creation of these strong motion instrumentation, that will give opportunity to register directly passing seismic energy, e.g. to create so-called "energometer".

## INTRODUCTION

It is known, that damage of structures, buildings (and any physical system) during earthquake is caused by their inability to absorb corresponding seismic energy. Then, after partial damage, the system obtains an extra absorption ability, which preserves the system from future damages at the given level of impact. During the exceeding impact, the system will be damaged in bigger degree or absolutely destroyed. Another type of system's behavior is the well-known building/structure's leaving from resonance condition by the way of partial damage followed by changes of rigidity and correspondingly of natural vibration frequency of buildings/structures. In this connection it is very important the issue of appraisal adequacy of seismic energy absorption by different types of physical systems (soils, buildings, structures, etc.). The theoretical solutions in this field is often differed from the real results. Such uncertainty appraisals are especially significant at strong motions. This leads to big scientific and practical interest to the results of analyses of strong motion instrumental records.

Not less important is the phenomena of non-linearity during strong motion. The quantitative assessment of non-linearity degree of materials or any physical system presents sufficiently complex and uncertain problem.

Non-linear distortions of wave shapes, occurred in so-called "bimodular" medium, is shown itself in "spreading" of spectrum in the area of low and high frequencies. These mediums are real soils, the compression module of which is significantly differed from strain one. The simple quantitative degree of "spreading" process is the width or area of normalized spectrum.

## SOFT AND ROCK SOILS

What's the difference between soft and hard soils? Give consider the recordings of Racha earthquake (Georgia, 1991). On the basis of analysis it was obtained that area of normalized spectrum in rock soils (Oni station) is increasing, and in soft soils (Ambrolauri station) insignificantly decreasing, as the average weighted vibration frequency of soils is increasing (Fig.1a). Amplitude of spectra of soft and hard soils is directly proportional to acceleration of soil vibration (Fig.1b).

The value of acceleration is widely used in very different analyses of engineering seismology and theory of dynamics of structures. At the same time it is well-known its often wrong correlation with seismic energy, which is inverse proportional to the frequency of vibration (easily obtained from the recordings). This fact provided the research of dependence of vibrations maximal frequency on acceleration. It should be noted very fastidious property of this dependence at some areas (Zemo Bari, Iri stations). So, it is significant the conclusion about opportunity of existence of high frequencies as for low accelerations, as for high ones (Fig.1a), appreciating the fact that the frequencies themselves are linked tightly, as a rule, with values of magnitude, it is clear the dissimilarity of correlation between magnitudes and accelerations. During high accelerations the characteristic of dependence of areas frequencies, contained in soft soils is close to rock ones. So, at low initial values of acceleration, as they are increasing, the curve (acceleration - maximal frequency) declines and the vibrations are characterized by low frequency. Further, as the acceleration is increasing, the frequency of corresponding vibrations increases. This fact explains the existing concept [1], that during low frequencies, the building is damaged by acceleration (e.g. the amplitude level of acceleration is significantly high), and the absorption of energy is minimal, because the frequency of vibrations is low. "Average amplitude level" of acceleration can cause the significant damages in sufficiently elastic buildings, and at the same time accelerations of high frequency (considerably high), have exceeded some "elastic area" of its quantity, are fading fast because of high absorption. Perhaps, by this fact can be explained, sometimes, little damages during high-frequent vibrations.

In Fig. 2 dependence of real spectra areas on acceleration for rock soil vibration (Fig. 2a) and for soft soil (Fig. 2b) are shown. It is evident, that in rock soils area of spectrum is increased with increasing of accelerations and is decreased in soft soils.

It should be noted that during research it was obtained for the behavior of viscous-elastic body that the real part of motion equation solution corresponds to the increasing of rigidity on frequency [2]. Imaginary part of equation's solution corresponds to insignificant decreasing of value of parameters on frequency (Fig.2c).

Comparison of experimental and theoretical data shows their good coincidence. Thus, area of the real spectrum of vibration is, firstly, reliable indicator of physical state of medium and, secondly, characterizes its deformability or degree of its behavior's deviation from Hoock's linear-elastic law.

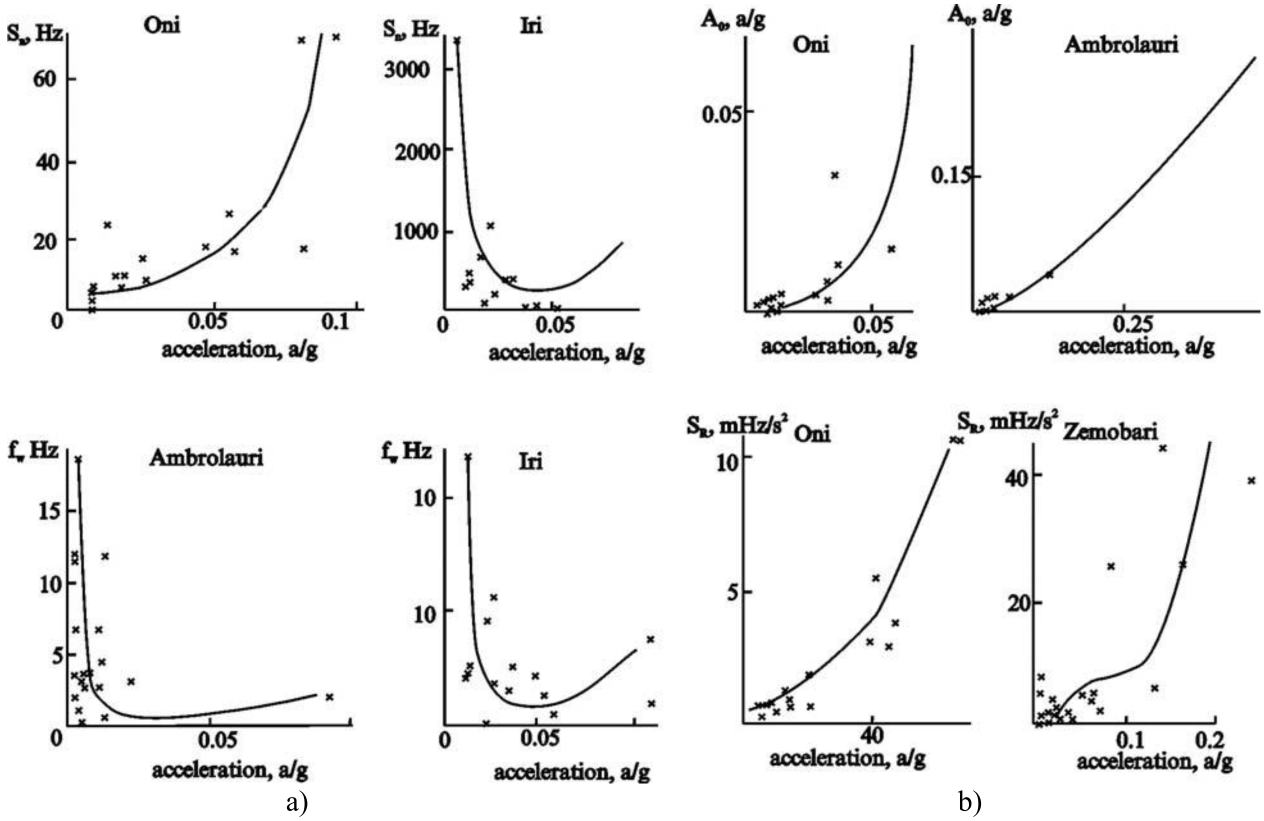


**Fig. 1. a) Dependence of normalized spectrum area and vibrations' average-weighted frequency on acceleration (Racha Earthquake, 1991); b) Dependence of spectrum maximal amplitude and vibration real spectrum area on acceleration**

In Fig.3 is shown the dependence of real spectrum's area of vibration on acceleration (Array SMART-1, Taiwan). It is clearly shown a sharp turns at acceleration a=0.1g. It is interesting to note, that according to [3] the change of shear to longitudinal waves velocity ratio (this quantity directly characterizes physical condition of medium) has two sharp turns at acceleration 0.1g and 0.2g (Fig.4). Comparing with Fig.1b (Zemobari) shows clear correspondence

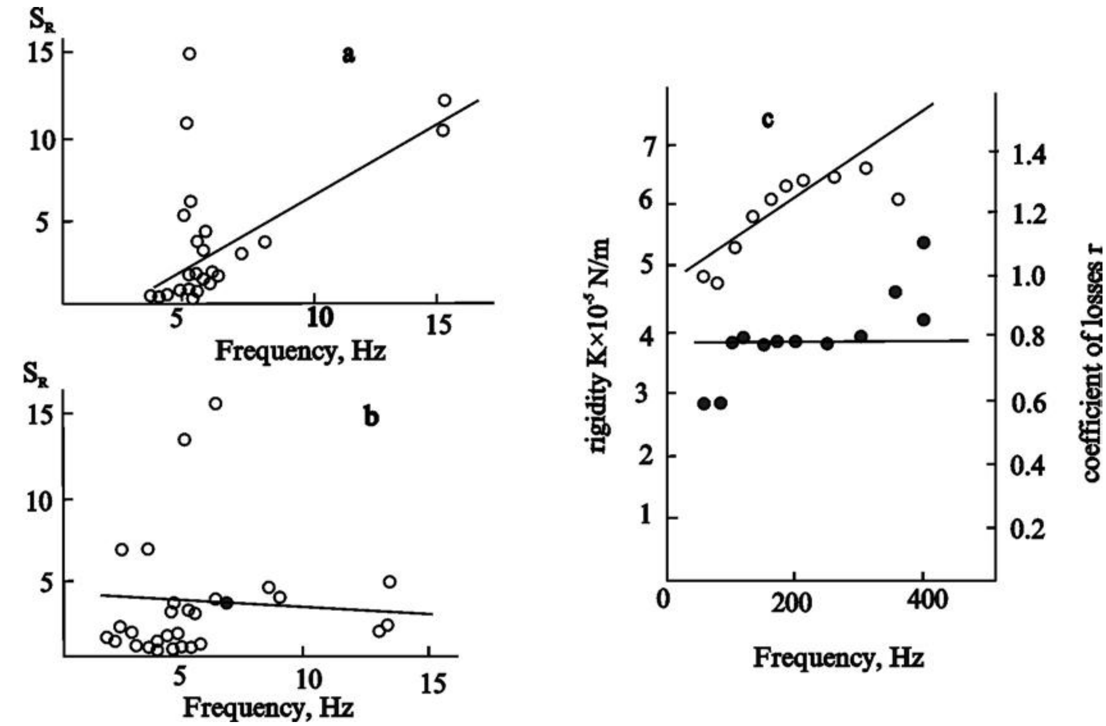


**Fig. 2. Dependence of real spectrum area for rock (a, Oni) and soft (b, Ambrolauri) on soils' vibration frequency. c) Dependence of rigidity and material loss coefficient on frequency of vibrations**

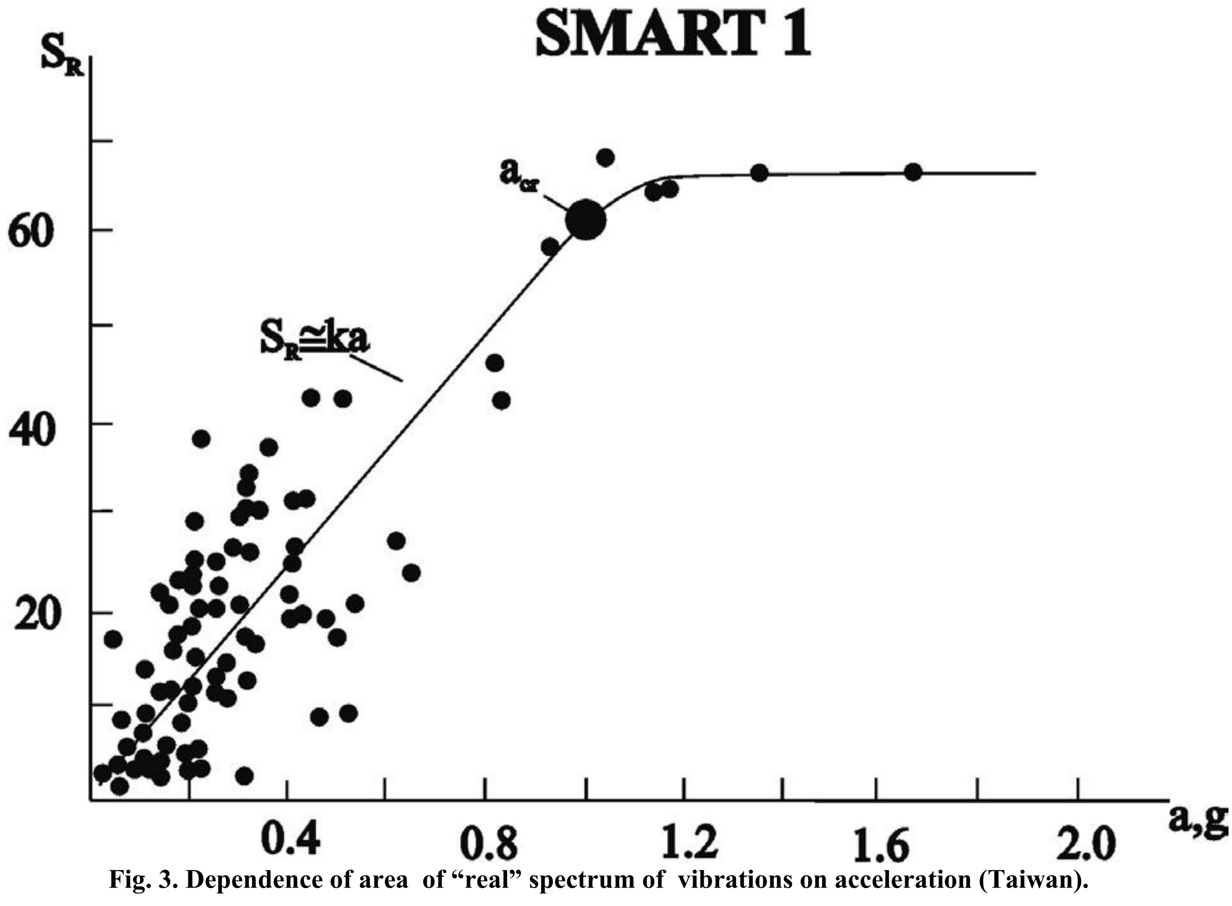


**Fig. 3. Dependence of area of "real" spectrum of vibrations on acceleration (Taiwan).**

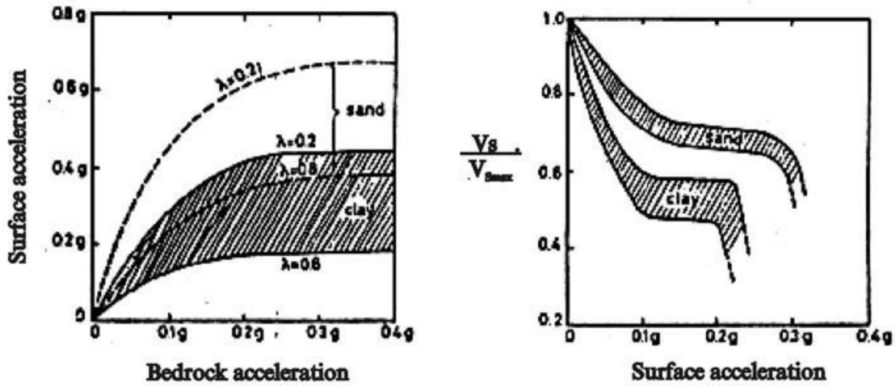


**Fig.4. Dependence of shear wave to longitudinal wave velocity ratio on soil acceleration [1].**

So, the area of real spectrum is important indicator of soils' behavior properties at different level of excitation

## GROUND STRONG MOTION

What is strong motion and how it differs from weak? Why the rigid, weight building destroys ? Currently is well known the significant influence of non-linear phenomena on seismic effect or intensity of earthquake.

The first research in this field, in fact, was the investigation, conducted under direction of A. Nikolaev from United Institute of Physics of the Earth (Moscow) in the end of fifties in Russia. Much later, he has published with the great difficulties the first theoretical research dedicated to the problem of non-linearity [4]. This was explained by the fact that the non-linear effects are presented by most of seismic events as insignificant because of number of factors, determining the intensity of earthquake.

In 1988 K. Aki wrote, that except of case of liquefaction, nonlinearity practically is not significant in seismological data. Later he recognized the necessity of existence of visible non-linearity in soils' behavior and the necessity of non-linearity accounting during seismological analysis of events [5]. So, non-linearity of soils is expressed in dependence of all parameters of soil vibration on intensity of earthquakes.

In 1987 I carried out an experiment on study of soils' behavior under high dynamic unexplosive loading. This experiment was carried out in the region of the new by-pass highway near Tbilisi city. Soils presented an artificial embankment with 40 m thickness. Seismographs were set – one at a depth of 1m and second at a depth of 5m into the embankment soil. On the surface of the embankment an impulse impact of a moving part of the scraper was applied. In the seismogram one can see a predominant peak of high frequency, which attenuates quickly with depth.  It is known that nonlinear distortion of signal is appeared in its enrichment in high-frequency spectrum. Thus, high frequency peak is due to nonlinear deformations in the embankment. In other words, at intensive effect in near zone of earthquake a high frequency excitation can predominate in soft soils. At that it is clear, that a rigid structure can be destroyed because of resonance phenomena in a high frequency diapason of spectrum.

a) b) c)

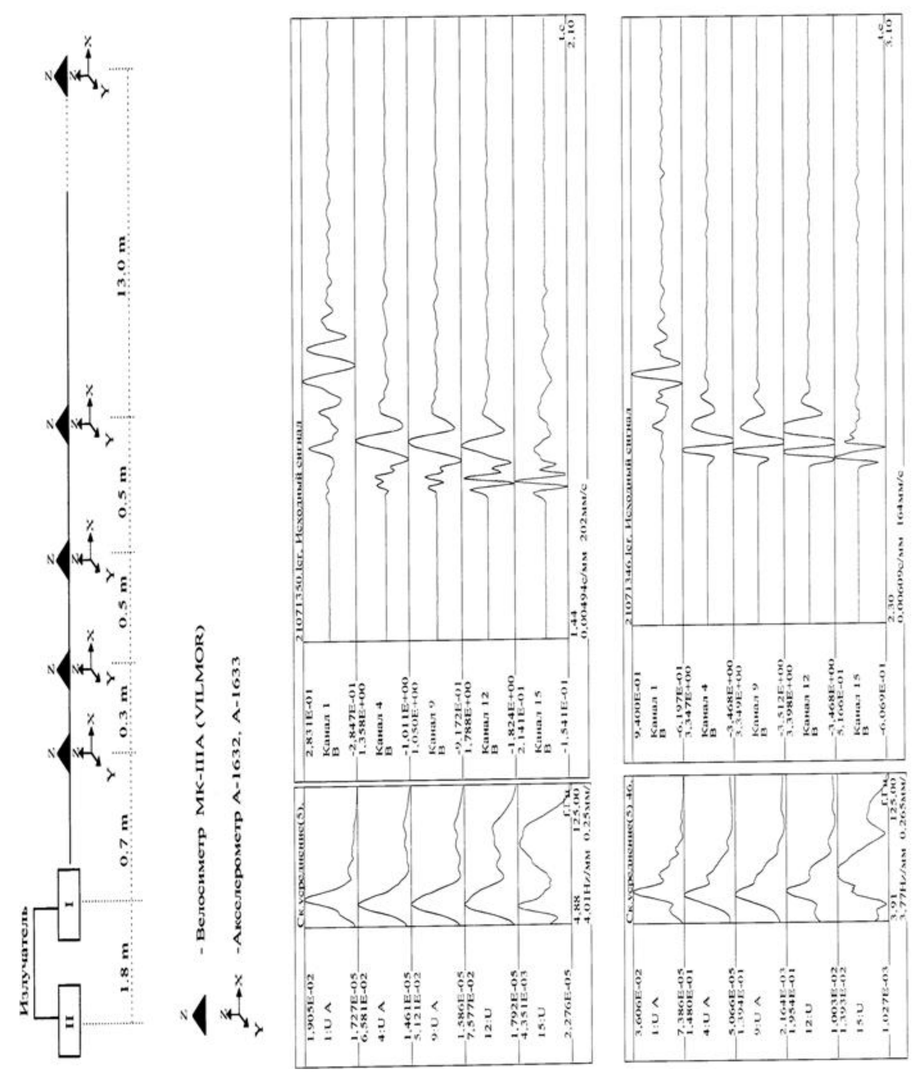


**Fig. 5. a) Profile of measurements.**
**b) Record of soil vibrations (I exciter)**
**c) Record of soil vibrations (II exciter).**

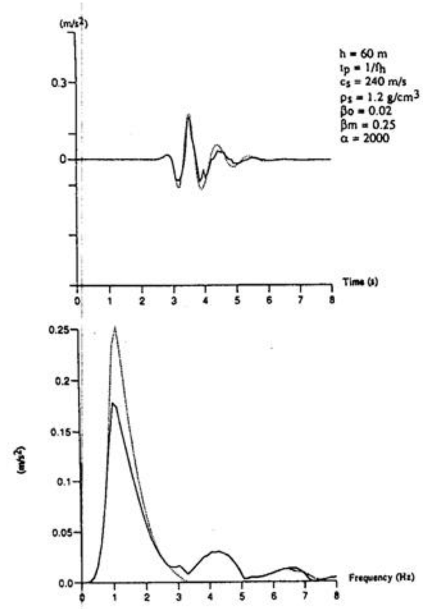


**Fig. 6. Comparison of accelerograms and Fourier spectra with or without taking into account the non-linear effect. The dotted line is for the linear solution.**

At the sector contained from powerful sediments of sands, in 1996, Russia, we made experimental research dependence of spectrum changing on level of influence [6]. As a source of vibration we have experienced the powerful pulse, source with two exciter. In Fig. 5 is presented the vibrations of soils caused by near (b) and far (c) exciters. During close strike HF peak is domain in vibration spectrum, and which is absorbed upon increasing of distance. As the seismo-recievers we used Russian, special developed, three-component accelerometers and English one-component Willmore accelerometer. Recording and data processing was carried out with special GEMIS-WIN software [7].

In this connection, it is interesting to compare the obtained data with calculations (Fig.6). It is clearly shown, that during elastic non-linear deformations, the energy "downloaded" to HF area of spectrum. It should be noted, that during change from linear-elastic deformations to non-linear-elastic ones, the square of real spectrum remains the same. At the same time the square of real spectrum is decreasing during non-elastic deformations, characterized buy losses of energy.

At the basis of buildings' damage analyses during earthquakes, some engineers explain damages by significantly high accelerations, much bigger than 2g. In every case, it can be said, that in some conditions in soft and especially in rock soils, the main energy can be situated in HF spectrum area.

## SEISMIC IMPACT AND RESPONSE OF SOIL.

As a result of analysis of instrumental entries of strong earthquakes and special experiments the following expression was obtained [8-10]:

$$\alpha \sim S_n / f_w \qquad (1)$$

where: $\alpha$ - the parameter of an absorption of vibrations by a soil;

$S_n$ - the area of the normalized spectrum of vibrations;

$f_w$ - average-weighted frequency vibration.

It has been determined that the area of a peak Fourier spectrum $S_R$, is related to the normalized area by a following relationship:

$$S_R = S_n A \qquad (2)$$

where: $A$ - a peak amplitude of a spectrum of vibrations.

The peak of amplitude of the spectrum characterizes a parameter of nonlinearity of soil. Then from (1) and (2) we receive, that:

$$S_R \sim \alpha A f_w \tag{3}$$

A spectrum area is integrated performance of the phenomena of an absorption and nonlinearity. A parameter of absorption, excluded, we shall obtain "pure" nonlinearity (parameter of nonlinearity of a soil):

$$S_R / \alpha \sim \alpha A f_w \tag{4}$$

Thus, the product of maximum amplitude of a spectrum of vibrations of a ground by average weighted frequency of vibrations is an elementary and easily measurable quantity describing the special property - soil nonlinearity.

On the basis of account is of nonlinear - elastic behaviors of grounds, the following relationship is obtained:

$$\Delta I = K \lg \frac{A_i f_{wi}}{A_0 f_{w0}} \tag{5}$$

where - $A f_{wi}$ and $A f_{w0}$ are soil nonlinearity of investigated and firm (standard) soil or of site correspondingly.

Thus the formula for direct calculating of intensity modification on the basis of account of nonlinear properties of grounds with obligatory use of artificial high-power impulse or vibration sources were obtained.

Then as a result of account of the inelastic phenomena, the expression is obtained [6]:

$$\Delta I = K \lg \frac{(A_i f_{wi})_n (A_0 f_{w0})_f}{(A_i f_{wi})_f (A_0 f_{w0})_n} \tag{6}$$

where: $(A_i f_{wi})_{n,f}$, $(A_0 f_{w0})_{n,f}$ - parameters of nonlinearity of investigated and firm soils in near and far zones of source.

By special correlational researches was obtained, that in soft soils the absorption within 10-40 km from a source (of earthquake aftershocks with $M = 1.2\text{-}6.3$) is proportional:

$$\alpha \sim \frac{f_w t}{\sqrt{M}} \tag{7}$$

where: $t$ -duration of vibrations,
$M$- magnitude of earthquake.

In rocky or rigid grounds (for example, pebbles)the absorption is proportional:

$$\alpha \sim f^2 t \sqrt{\mathrm{a} r} \tag{8}$$

where: $a$ - peak ground acceleration;
$r$ - epicentral distance.

Thus, the absorption in soft soils practically does not depend on acceleration. Its level completely is determined by magnitude - the more magnitude, the less absorption. In rocky grounds the absorption is directly proportional to acceleration. The relations are valid within the given soils statistical number.

On the other hand, on the basis of comparison of parameters of nonlinearity for soils as $S_R$, we shall obtain for soft soils from (3) and (7), taking into account that $A \sim M^{2.5}\sqrt{a}$ the following relationship:

$$\Delta I = K \lg \frac{f_{wi}^2 M_i^2 t_i}{f_{w0}^2 M_0^2 t_0} \sqrt{\frac{a_i}{a_0}} \tag{9}$$

where: $f_{wio}$ - peak ground acceleration at different magnitudes, correspondingly;
$M_{io}$ - epicentral distance at different magnitudes, correspondingly;
$t_{io}$ -duration of vibrations at different magnitudes, correspondingly;
$a_{io}$- peak ground acceleration at different magnitudes, correspondingly.

The formula (9) allows to assess the influence of a modification of power (influence) to the intensity modification for given soil at different values of magnitudes. More exactly we received the relationship for direct calculation of nonlinear intensity modification of the given soft soil.

Then we received expression for the direct determination of the influence of a modification of power to the intensity modification for soft soils of different sites (*i*-site and *o*-site) of the territory:

$$\delta I = 2\{\lg \frac{M^2{}_1 t_{i1} f^2{}_{wi1}}{M^2{}_2 t_{i2} f^2{}_{wi2}} \sqrt{\frac{a_{i1}}{a_{i2}}} - \lg \frac{M^2{}_1 t_{01} f^2{}_{w01}}{M^2{}_2 t_{02} f^2{}_{w02}} \sqrt{\frac{a_{01}}{a_{02}}}\} \quad (10)$$

where: $\delta I$ - the intensity modification at the changing power, $\delta I = \Delta I_{ni} - \Delta I_{n0}$;

$\Delta I_{ni}$ - the nonlinear intensity modification at investigated soils, degree;
$\Delta I_{n0}$- the intensity modification at firm soils, degree;
$M_1$, $M_2$ - magnitudes of (*n*) and (*n+1*) earthquakes, correspondingly;
$M_1 >> M_2$;
$t_{i01}$, $t_{i02}$ - duration of vibrations investigated and firm soils at (*n*) and (*n+1*) earthquake (at magnitudes $M_1$ and $M_2$) correspondingly, *s*;
$f_{wi01}$, $f_{wi02}$- average-weighted frequency vibration of investigated and firm soils at (*n*) and (*n+1*) earthquake, correspondingly, Hz;
$a_{i01}$, $a_{i02}$ – peak acceleration vibrations of investigated and firm soils at (*n*) and (*n+1*) earthquake, correspondingly, m/s$^2$;

Then shall consider of relationship (9) again. Let $M \sim E$ (energy of effect of an artificial source). Taking into account, that for a typical artificial vibrator $M_i \approx M_0$, $t_i \approx t_0$, $a \approx A^2$, we obtain expression which is similar to expression (5):

$$\Delta I = K \lg \frac{A_i f_{wi}}{A_0 f_{w0}} \quad (11)$$

It is very important result. We could receive the same express in other way. If frequencies do not differ much, then $f_{wi} \approx f_{w0}$, also we shall obtain an expression:

$$\Delta I = K \lg \frac{A_i}{A_0} \quad (12)$$

Received expression is similar the expression of S. Medvedev [11].

The seismic hazard or earthquake intensity is defined by magnitude, seismic focus depth, epicentral distance from faults. This is the so-called “averaged” or initial intensity of the given territory. At the same time, variations of intensity on a territory are defined by other, no less important parameters. These are a soil types, power of soil thickness, surface relief, underground relief of bedrock, soil physical condition, etc. Damages of buildings and constructions, caused by soil conditions, may take place due to amplification of the arriving vibrations (from the bedrock) by weak medium or due to the uneven settling of buildings and constructions. In the first case, soil-construction interaction presupposes elastic deformation, and in the second case-unelastic one. Amplification of vibrations will be the highest in case of coincidence of natural frequencies of vibrations of buildings and constructions with natural frequency of soil substance under the foundations. Damages will also increase in case of the above mentioned effect similar of soil liquefaction. Of course, technical state of structures, separate constructions, orientation of buildings in relation to the arriving seismic impact etc. significantly define the level of damage of the building-stock, too.

## CONCLUSIONS

1. At the bases of strong motion instrumental recording analyses, have been obtained parameters, closely fixed with absorption and non-linearity of soils or any physical system.
2. It was shown the difference of absorption phenomena of seismic energy in soft and hard (rock) soils. In soft soils absorption is mainly caused by magnitude of earthquake and in rock soils by acceleration. By the way, in common types of soils the absorption is directly proportional to average-weighted frequency and duration of vibrations.
3. During strong motion the main energy in soft and especially in rock soils is situated in high-frequent part of spectrum. During changing linear-elastic deformation to non-linear-elastic deformation the energy of vibrations remains constant. During non-elastic deformation the energy of vibrations decreases. It is clear, that in conditions of large strain it should be the most significant decreasing.
4. We received expression for the direct determination of the intensity modification at the changing power for soft soils of different sites of the territory.
5. The modern level of strong motion instrumentation is considerably high (USA, Japan, Switzerland, etc.). Its opportunities are used non-fully. The obstacle is from one hand the low information density of analyses of data, that have traditionally used, and from the other hand - properties of measuring-resolution of system itself.
6. The results of the work give opportunity to conclude that in spite of using type of equipment, the main properties of ground strong motion is similarly reflected in corresponding recordings, from earliest to the recent. From the other hand it is necessary to pay special attention to the range of resolution in high-frequency area of spectrum of vibrations. Here it should be upped the level of soils acceleration registration from widely used value of 2g. It gives opportunity to register significantly high accelerations, if they accompany strong motion. As it seems they accompany them. Besides, it is necessary to increase radically the level of resolution of record of strong motion for obtaining momentary and "short-living" ultra-high accelerations. And, at last, it is preferred creation of these strong motion instrumentation, that will give opportunity to register directly passing seismic energy, e.g. to create so-called "energometer". This will give opportunity to exclude the necessity using the big number of parameters of instrumental recordings and simplify calculations of buildings and constructions upon seismic influence. In last years, it was a number of trials to present in such calculation the seismic influence in energy type.

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