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SPECTRAL CHARACTERISTICS OF SEISMIC WAVES AT STRONG GROUND MOTIONS

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ABSTRACT: Introduction of the value of the weight-average period of ground vibrations significantly improves the differentiation quality of various types of soils. The dependence of the spectral composition of the seismic waves on power, physical and mechanical properties of soils that compound a ground stratum and hydrogeological conditions are considered. On the basis of data analysis a conclusion about high usefulness of powerful pulsed and vibration artificial nonexplosive sources for seismic microzonation is made. A particular attention was paid to the investigation of the absorption indexes of seismic energy in different types of soil. It is shown that the use of the extended type of soil indexes, in particular, to include the standard spectral characteristics can significantly improve the accuracy and reliability of the establishment of engineering and geological cross-section of a ground stratum and its hydrogeological conditions.

Keywords: Soils, Spectra Analysis, Seismograms, Active Zone, Weighted Average Period of Vibrations, Soil Density, Absorption

1. INTRODUCTION

Soil thickness, consisting of one or several layers, has selectivity; it singles out and increases vibrations in the definite wave range. The interference of seismic waves repeatedly reflected in layers and the existence of natural vibrations of soil layers are the reason of selective intensification. Moreover, the amplitude-frequency vibration spectrum on the thickness surface depends on the spectral composition of the coming wave, the approach angle, the thickness power, the physical and mechanical properties of the soils, composing this thickness and the hydrological conditions.

2. SPECTRAL ANALYSIS OF SEISMOGRAM

The size and the shape of the volume source active zone are determined by density and viscosity of soil, composing the top of thickness, source directivity etc. The active zone depth (allocation zones of residual deformations) can be calculated according to the approximate formula [1]:

$$h = 3d, \tag{1}$$

where d is the plate diameter.

The mass of active zone is added mass of soil, which participates in systems motion. Taking into account the fact that the plate diameter of SI-32 source is d = 1.0 meter and the soil (loam) density is $\rho = 1.8$ t/m^3 the added mass can be calculated according to the formula:

$$m = 2.4\rho d^3. \tag{2}$$

The added mass of soil for the given case is 4.3 t. At usage of a disc with the diameter d = 0.3 meter for a hammer the added mass is m_a= 110 kg. A high power source can be presented in the form of a sphere with the pick in the point of power influence attack. Beyond the bounds of the active zone only elastic seismic waves will be observed.

Thus, the more powerful the source is the more soil massif volume sets in vibratory motion.

The program, made for decomposing of non-sinusoidal process in a line, is used for the spectrum analysis of seismograms of soil vibration.

Because of the fact that measuring equipment with comparatively small intensification was used at the investigations it was necessary to find out the influence of the investigated seismogram segment length on the major spectrum characteristics. As an initial seismogram the seismogram of comparatively loose soil was used (loams of Rustavi city, area 2). (The initial duration of the seismogram t = 0,65 seconds, the number of reference points N = 139). Specimens of the spectra of the sequentially cut off seismogram (from the end of the record) are given in the Fig. 1–2. The number of reference points at that was decreasing up to N = 9 of the even pitch of digitization. One can see that the irregularity of spectral characteristics is changed by a more gradual (smooth) envelope curve of frequency line; the weight of the high-frequency part of spectrum decreases. This points to the fact, that in the next after the main wave record part the refracted-reflected waves come from deep seated horizons in the form of high-frequency vibrations with low amplitude (due to the distances on small heterogeneities). It is clearly seen that the decrease on nearly 70% of the used segment length does not almost influence the spectrum composition up to the harmonics n = 4 (Fig. 3).

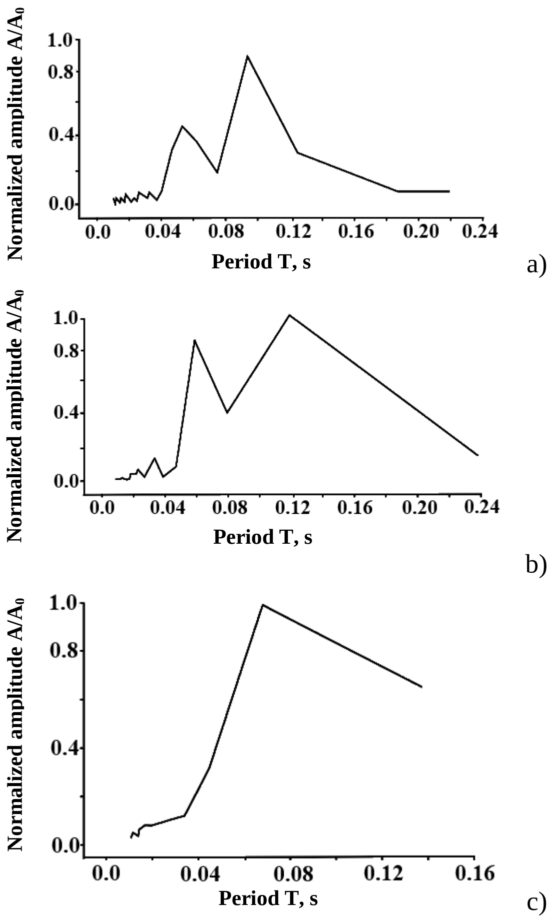


Fig. 1 The spectra of seismograms' segments (number of reference points N = 139 – 29)

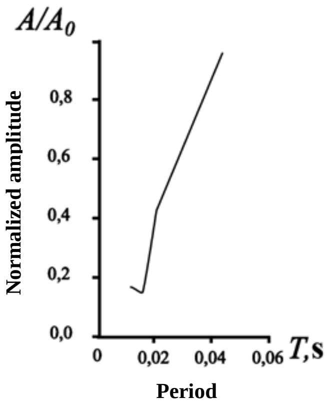


Fig. 2 Spectrum of seismogram segment (9 reference points)

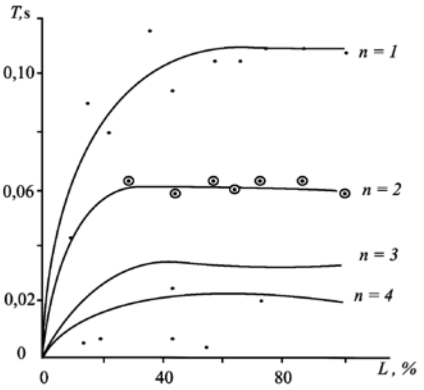


Fig. 3 Change of maximum periods with the seismogram segment decrease

This is obviously explained by the fact that the major information of the impulsive energy source is contained in the first 20–30% of the total record length. At the same time a more appreciable decrease of weight-average period is observed. Therefore the whole segment of seismogram with visible vibration amplitudes was used at spectrum plotting.

3. WEIGHT-AVERAGE VALUE OF PERIOD

The spectrum analysis of the seismograms of soil vibrations excited by a low-powered source allowed to establish that close values of maximum periods are observed for quite different soil types (for example, turf (peat) soils and pebbles with sandy-argillaceous filler more than 30%) (Fig. 4, a).

It can be explained by the fact that low-powered sources on areas, composed with different soil types, in fact, excite vibrations in the region practically equal in depth (difference in values of their active zones is insignificant). Besides, high-frequency signal components quickly attenuate (in pebbles due to the dispersal, in turf due to the absorption). And elastic waves, close on maximum period values, come to the point of observation.

Taking into account that maximum values of periods are mainly used at seismic microzonation the following must be noted. Obviously, it is more reasonable to use the weight-average value of the period (i.e. the spectrum power-consuming or representativeness), which is calculated according to the Zaalishvili' s (1986) formula [2]:

$$T_{aw} = \frac{\sum A_i T_i}{A_i} . \tag{3}$$

where A_i and T_i are the amplitude and the corresponding period of the spectrum.

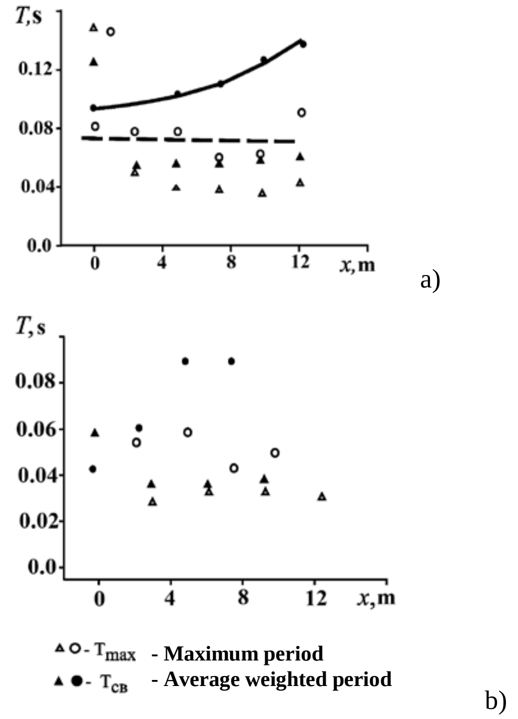


Fig. 4 Weight-average period of vibrations: a – pebbles with sandy filler more than 30% and turfs; b – pebbles with sandy filler less than 30% and loams

It is shown in the Fig. 4 that the value increase of the weight-average period of the spectrum for turf is a sufficiently big value (ΔT_1) relative to its maximum period. For pebble the increase (ΔT_2) is less. That's why the weight-average period value can be used as an additional index of soil characteristics. Statistical analysis of the facts, obtained on areas, composed by different soil types, allowed getting a graphic chart (curve) of weight-average values of periods (for the one-type low-powered source) on S-wave propagation velocity. The values of S-wave velocities directly characterize physic-mechanical properties of the given soils at that (Fig. 5, a).

The considered chart (curve) can be approximated by the expression:

$$T_{aw} = a + b\mathrm{e}^{-c\lg v_S}, \tag{4}$$

where a = 0.016; b = 1.447; c = 1.245.

The formula of A. Maksimov [4] for the calculation of intensity increment is well-known:

$$\Delta I = 0.8\frac{\rho_0 v_0 f_0^2}{\rho_i v_i f_i^2}, \tag{5}$$

where: $\rho_{0i}v_{0i}$ are acoustic rigidities of compared soils; f_{0i} is predominant frequencies of soil vibrations.

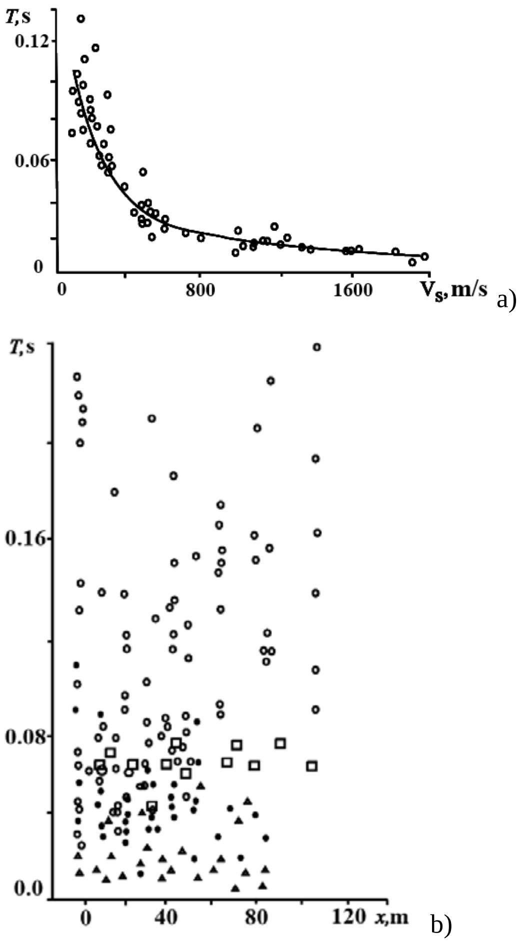


Fig. 5 Weight-average periods of soil vibrations: a – change of the weight-average periods at S-wave velocity increase; b – change of the weight-average periods with distance depending on type and power of soils

Taking into account the obtained dependence (4) and introducing approximation $\alpha \approx 0$ we have:

$$\Delta I = \lg\frac{\rho_0 v_0}{\rho_i v_i} e^{2.5(\lg v_0 - \lg v_i)}, \tag{6}$$

At the absence of data about soil density ρ next dependences for density of sandy-argillaceous and large-detailed soils

$$\rho = 2.4 v_S^{0.2}, \tag{7}$$

and Basement density

$$\rho = 2.4 v_S^{0.4}, \tag{8}$$

can be used and the formula for the calculation of intensity increment will look like this:

$$\Delta I = \lg \frac{a_0 v_0^{1+n_0}}{a_1 v_1^{1+n_1}} e^{2.5\left(\lg v_0 - \lg v_1\right)}, \qquad (9)$$

where a_{01} are coefficients, equal to 2.4 for sandy-argillaceous and large-fragmental soils and 2.0 – for basement rocks; n_{01} is an exponent, equal to 0.2 for sandy-argillaceous and large-fragmental soils; and 0.4 – for basement rocks.

Thus, the formula of intensity increment calculation at usage of low-powered sources is obtained (taking into account three soil characteristics). Practically it is necessary to determine the value of one quantity (i.e. S-wave propagation velocity) for calculations. This, undoubtedly, will allow receiving on-line and at the same time proved information about the properties of the investigated soils in case of need.

The analysis of weight-average period values showed, that the soil type of under-layer influences the frequency characteristics of seismic waves at surface observations at surface layer power $H \leq \lambda/4$ (λ is wavelength). So, if the under layer is composed with firm soils (limestone, conglomerate etc.), then the periods of seismic waves decrease with moving off from the source. At comparatively loose soil type, composing the under-layer (slit, turf, loose loam etc.) the periods increase. This is obviously explained by the fact that with moving off from the source in the region of the first events the refracted seismic waves, which are warbled by underlying layers, come out on the obtained seismograms. It can be noted that each soil type is characterized by a definite range of values. At their approximation by lines we have the so-called «frequency levels» (Fig. 6) for different soil types (for the one-type source). It must be noted that for sources of low intensity the soil power doesn't virtually influence the values of weight-average periods.

The analysis of weight-average period values of excited by powerful nonexplosive sources soil vibrations shows, that:

- each soil type of equal power is characterized by a definite level of weight-average period (T_{wa});
- values of T_{wa} change depending on power and type of soil;
- presence of loose topsoil (arable land or tilled soil, etc.) generates the presence of big values of T_{wa} in immediate proximity from the soil vibration source;
- in the distance of 30–40 meters from the source the T_{wa} values approximate to predominant period of sesmic vibarations T_0 values for thickness power 8–10 meters ($T_0 = 4H/v_S$);
- uneven increase of T_{wa} (approximating to corresponding T_0) is observed at distance for high-power soils (H > 10 m) in the distance more than 40 meters; T_{wa} increase with the distance more than 30–40 meters is small for soils with power $H \approx 8$–10 m.

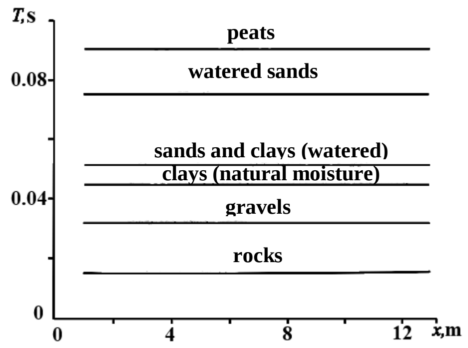


Fig. 6 Experimental values of the periods of soil vibrations, generated by standard source – "frequency levels"

Thus, the investigation of weight-average periods allow to study physic-mechanical soil properties as well as their resonance properties, which are determined by equality between weight-average and predominant vibration periods.

4. DEPENDENCE OF SEISMIC WAVE SPECTRAL DISTRIBUTION ON POWER, PHYSICAL AND MECHANICAL SOIL PROPERTIES, COMPOSING SOIL THICKNESS, AND HYDROGEOLOGICAL CONDITIONS

The vibration spectrum in the observation point Si(f) is connected with the vibration spectrum in the arriving wave by the proportion $S_i(f)=S_0(f)K_i(f)$ [2]. Thus, the frequency characteristics of the medium in i-observation point is determined if the vibration spectra on the medium surface $S_i(f)$ and on underlying loose medium bedrock $S_0(f)$ are known. In practice amplitude-frequency soil characters of investigated area are calculated directly referring their vibration spectra to the vibration spectra of the etalon area soils. The etalon area is composed at that with bedrocks which come out onto the surface [2].

First of all the vibration spectrum in the observation point must be considered. The analysis of the spectral features of the waves excited on the soil thickness surface shows that the type of the spectral envelope curve of periods and their values are closely connected with the type and the power of soils, composing thickness. So, at usage of a low-powered source (a hammer impact) the spectrum width and the definite period value change depending on soil type. At observation changing from rocks to turf soils the spectrum width increases 6 times as large (Fig. 7).

It must be noted that the data on the difference between the vibration spectra of pebbles and sands which corresponds to the obtained data is given in A. Levshin`s work [3]. Even if the soil is under a three-meter layer of bedrock, spectrum type in the region of maximum remains practically invariable.

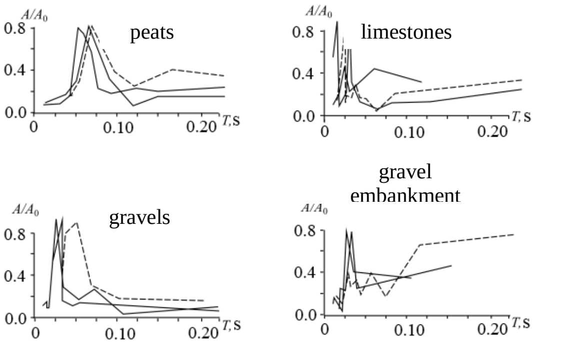


Fig. 7 Spectra of vibrations, generated by low-powered source

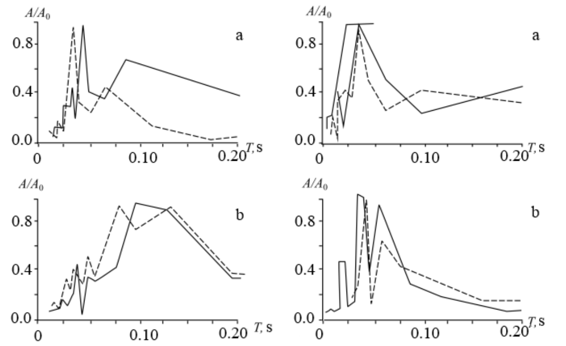


Fig. 8 Spectra of soil vibrations, caused by powerful impulse source SI-32: a – near zone; b – far zone

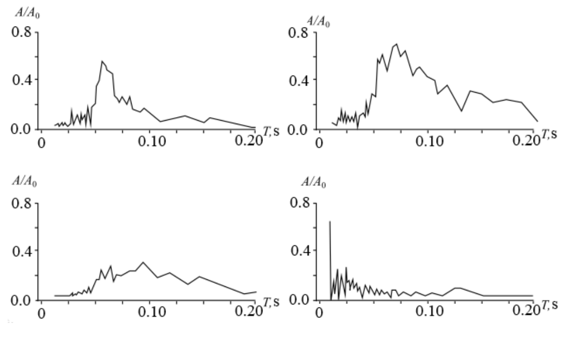


Fig. 9 Spectra of vibrations, generated by powerful vibrator SV-10/100

It must be noted that the spectrum shape has mainly the form of an isosceles triangle for any soil type at usage of a low-powered source, and one can clearly see, that the spectra, as a rule, move to the high-frequency region (without changing the spectrum occupied square) with moving off from the source (1–4). Taking into account the fact that the distances are standard, it is possible to assess intensity increment of the described soil on the square occupied by their spectral characteristics and also to assess seismic wave absorption in soils.

At the analysis of the vibration spectra of watered soils excited by a low-powered source it was determined that the values of maximum periods are directly connected with the depth of groundwater standing. In such soil type (for example, in clay soil) the vibration period of thickness increases with the growth of groundwater standing depth. Comparing vibrations from different sources, one can see that the level of amplitude spectrum vibrations excited by a powerful impulsive source considerably exceeds the spectrum of vibrations excited by a hammer impact (Fig. 10).

At the analysis of soil thickness spectrum vibrations, excited by nonexplosive sources with high power SI-32 (Russia), it was determined that spectral characteristics of soil thickness vibrations are a stable value (Fig. 8). This is right at vibration spread with the distance at a fixed source as well as at fixed observation points with the source location change (oncoming observation system) with the opposite (reverse) source location. The mentioned features are also true for vibration sources SV-10/100 (Russia) or VSH-8 (USA).

Spectral composition of the investigated vibrations was a monochromatic signal f = 10 Hz and also a sweep-signal with an emission band f_h–f_k= 5–30 Hz. At the monochromatic signal of the source of generated vibrations in thickness of clay soils (alternation of loam and clay) the seismogram represents a record of harmonic (saw-shape, to be more exact) vibrations with frequency f = 10 Hz. In that case soils behave like systems with one degree of freedom. The initial and the final parts of the record, connected with transitional influence phenomena are exceptions. Time duration of signal sending coincides with forced vibration duration in the region of direct joining to the source. Signal spreads with moving off from the source due to the dispersion phenomena and the total signal duration increases insignificantly.

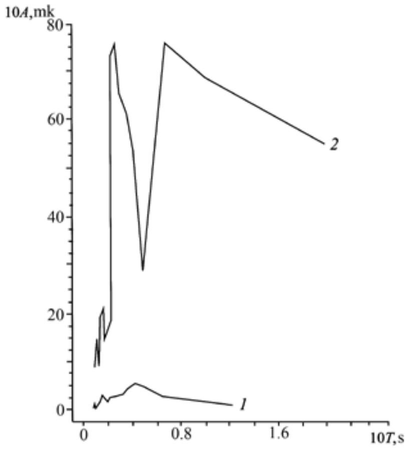


Fig. 10 Spectra of vibrations generated by hammer (1) and powerful impulse source SI-32 (2)

At the similar vibration excitation in complex-composed thickness (alternation of thin-layer loam and weathered basement rocks of different type) high-frequency hashing, caused by frequency features of the lower layers, appear on the corresponding seismogram. It must be noted that this hashing is highly absorbed and practically disappears with distance. Nevertheless, harmonic vibrations with the frequency f = 10 Hz are rather clearly displayed on all seismogram propagation paths. This allows comparing (correlating) directly the amplitudes of harmonic vibrations in order to calculate the intensity increment of the areas composed with different soils, in future. It must be noted that the influence of the surface layer decreases just next to the source at vibration influence.

This is explained by the fact that remanent plastic strains in the near zone of the vibration source (in contrast to the impulsive energy source) are significantly less. Frequencies, which were not set by the generator, were observed in the corresponding area. So, vibrations with frequencies 1–3 Hz on seismograms of clay soils and of rocks – 40–80 Hz appear at sweep-signal sending with parameters Δf = 5–30 Hz. As it was mentioned above, the initial signal duration was t = 2.0 seconds. It must be noted that the vibration duration in soils was t = 2.0 seconds at that. The insignificant decrease of duration in unweathered rocks (2%) and the increase in loose clay thickness (5%) was observed. Thus, the difference between the reaction duration and the initial signal in different soil types doesn’t exceed 3%. With moving off from the source the signal duration distortion increases and already in the distance of 20 meters obtains 8%.

The analysis of spectra seismograms, which were excited by vibration sources, displays the picture, analogous to spectra seismogram of soil vibrations, excited by powerful impulsive energy sources. Spectral distribution curves (sub-spectral area, to be more exact) for powerful thickness of clay sediments are more representative. And spectral distribution curves for clay thin-layer soils, which are subjacent by basement rocks, are more indented and their representativeness is less (see Fig. 9).

Thus, the square of a spectral distribution curve is directly connected with physical and mechanical and, therefore, seismic properties of soils, composing the thickness. Usage of powerful vibration sources (for example, VSH-8) allows investigating spectra constituents on periods 1–1.5 s. Increase of signal duration expands the boundaries of soil frequency features investigations. Thus, each soil type has definite influence features. Record keeping of such indexes will allow using at SMZ this or that type of source, depending on work conditions or detail of necessary data receiving.

At data analysis, obtained with the help of a low-powered source it is determined, that the geometric size of soil thickness insignificantly influences the spectral distribution of excited vibrations. Each soil type is characterized at standard observation by a definite type of spectral distribution curve and weight-average value of periods. The sum-total of different soil types causes the existence of their frequency level. The worse on seismic properties the soil is the higher the weight-average value of periods of its vibrations. This difference reaches larger values than the change of corresponding maximum periods.

If ground is underlaid with firm soils its weight-average vibration period decreases with distance. In case of loose soils the period increases. The spectral distribution curve has a triangular form which insignificantly changes with distance (0–20 m.) in the area of maximum amplitude values. With seismic soil properties deterioration the width of the corresponding spectrum increases. Soil spectral characteristic is a stable value for each type of soil. So, spectral characteristics of investigated soil (in the area of maximum values) at overlapping by natural embankment (h = 2.5 m) practically remains constant. Embankment influence is only expressed by adding of a long-period representative (on a square) area to the vibration spectrum. At mainly elastic soil deformation the vibration spectrum is determined by the whole soil volume and the influence of the near-surface layer decreases with moving off from the source. The fill-up soil iterates the movement of the lower layer and the spectral distribution curve form in its main part is similar to the soil vibrations without embankment. Embankment influence is expressed by an insignificant increase of the amplitude level of vibrations. This phenomenon can be used in order to specify the type and the power of soils on investigated areas. The spectral distribution curve becomes representative at the loose lower layer and the main maximum moves to the low-frequency region.

The decrease of the groundwater standing depth generates the displacement of spectral characteristics to the high-frequency region and the increase of the amplitude level almost in two times at water standing change from 8 to 2 meters. At the analysis of soil vibrations, excited by powerful nonexplosive sources, it was determined that spectral characteristics of vibrations within a typical area with definite engineering-geological conditions have stability at observation point displacement as well as at source displacement. At very inclined (slanting) boundaries (which is rarely observed for the investigated depth) the amplitude can significantly vary, but the spectral distribution curve shape remains the same. In case of thin-layer mixed soils general vibrations of thickness as a whole can be observed. That’s why the form of the spectral distribution curve plateaus with distance. Longitudinal profiling with oncoming observation systems gives an opportunity of identification of the spectral distribution curve sudden change.

The type of spectrum vibrations, excited by a powerful source, is directly connected with the power of the surface layer of thickness. And the higher the power of soil is the larger the square of the sub-spectral area. At comparing soil vibrations with equal power spectrum, sharing in different frequency domains of the spectrum is observed, depending on the type of the investigated soil. The presence of a loose near-surface layer causes increase of low-frequency spectrum constituents in immediate proximity to influence zone in case of an impulsive source. With moving off from the source its influence decreases and the form of the spectral distribution curve is practically determined by the features of the engineering-geological composition, physic-mechanical properties and hydrogeological conditions of thickness on the whole.

Weight-average periods are practically predominant periods of soil vibrations of the corresponding power. They coincide with predominant periods ($T_0 = 4H/v_S$) [4] for loose soils in the distance of 30–40 meters for soil power $H \approx 8–10$ meters and corresponding S-wave propagation velocity. At further moving off from the source the values of weight-average periods of vibrations for the given powers of thickness insignificantly increase (in the distance up to 100 m). Weight-average periods for loose soils with power $H = 15–20$ meters are close to the corresponding predominant periods at the distance of 30–40 m. And with moving off to 80–100 m. they coincide with predominant periods. This is explained by the fact that waves cover greater thickness volume with distance.

The comparison of the results of nonexplosive sources usage (both impulsive and vibratory effect) allowed determining the following. Despite the fact that at usage of the impulsive energy source the natural damped vibrations of thickness are observed and at usage of vibration sources – forced vibrations, soil thickness reaction to a standard signal is similar.

For loose thickness of clay soils the sub-spectral region of vibrations excited by both source types significantly exceeds the sub-spectral region of firm thickness vibrations. At usage of vibration source the influence of the surface thin layer is insignificant in the given frequency range and in the near zone. Correspondence of the final results of both source type usage is the basis for generalization of the obtained data. It increases the results proof. Thus, one can draw a conclusion about high utility of powerful impulsive and vibration artificial nonexplosive sources usage at SMZ.

4.1 Investigation of soil spectral characteristics on models

The most complete information about the investigated object behavior at different external influence can be obtained at full-scale experimental investigations. But it is practically impossible to change any parameters of full-scale object (change of engineering-geological structure of thickness, hydrogeological conditions, etc.) at such investigations. Moreover, the increase of force action, for example, is also connected with definite technical difficulties and economic costs. There are different types of modeling: visual; symbolic (sign); mathematical mental; full-scale; physical and analog-digital modeling [5].

Physical modeling appropriates to our aims most of all. This type of modeling is first of all characterized by the fact that investigations are made on equipment having physical similarity i.e. fully or mainly preserving the nature of the phenomena. It is possible to obtain all the characteristics of the original on model characteristics by recalculation with the help of scale factor coefficients. The main purpose of modeling is to investigate spectral features of soil thickness vibrations, composed with different soil types.

Engineering-geological profiles of two typical areas of Rustavi city territory were chosen as originals. Vibrations were excited by a powerful impulsive energy source on these areas at SMZ. Corresponding soils of areas were used in models, i.e. they had a mere similarity which significantly simplifies the task. Similitude relationships for such model will be automatically held at any complicated stress condition, as the link between stresses and deformations for the model and the original is identical in similar points ($\sigma_m = \sigma$, $\varepsilon_m = \varepsilon$) and all the parameters only depend on the scale factor coefficient ξ [5].

In order to exclude the influence of the model shape on the final results and to obtain proportional dynamic influence a cylindrical shape was used. Soil layer system, composing thickness, is stable to a little extent. And in order to shape the model it was formed in a special cylindrical template. The bottom of the template was in rigid connection with a concrete pedestal (base). In order to exclude the influence of the waves reflected from the template sidewall the walls were covered with thin figured foam-rubber. The layer powers and the value of the dynamic influence were chosen by taking into account the template size and the scale factor coefficient. Pressure sensors were located on the corresponding soil layers of the model. The impact was made with the help of a special impact vibro-stand (Fig. 11).

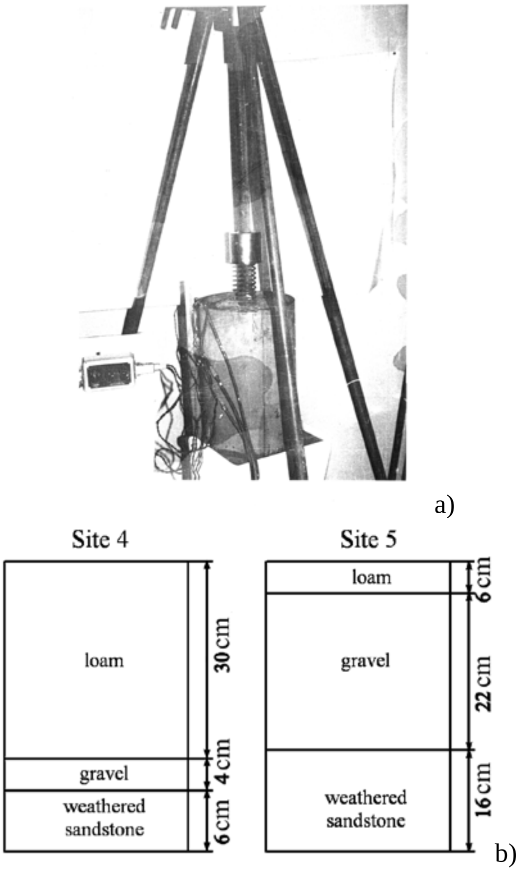


Fig. 11 Vibration spectra investigation (study) on models: a – equipment of the experiment; b – schemes of thickness models

In order to decrease local plastic deformations, the impact was made on a metallic disc. The soils were selected in places of full-scale investigations realization. Spectral characteristics were calculated with the help of the obtained seismograms. At the analysis of experimental material the following was determined:

- the type of spectral characteristics (Fig. 12) directly depends on the power of a loose homogeneous layer. The more the power is the more the sub-spectral region;
- the spectrum moves to the low-frequency region with the increase of the impact force;
- each soil type is characterized by definite spectral characteristics of vibrations;
- spectral characteristics of vibrations are sustainable with depth;
- the type of spectral distribution curves of the model is similar to the spectra of full-scale observations on the corresponding prototypes of models.

On basis of the mentioned data one can draw a conclusion about the availability of investigations on models. Variation of the engineering-geological structure of the place of load imposing and its value allows solving many problems of soil dynamic.

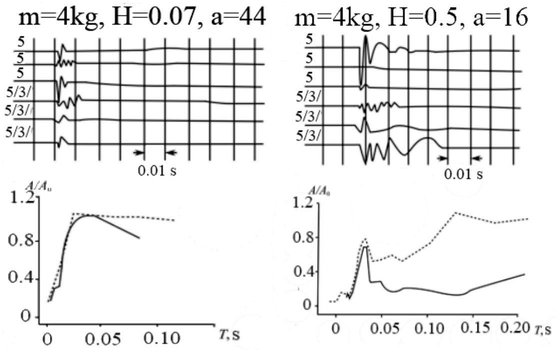


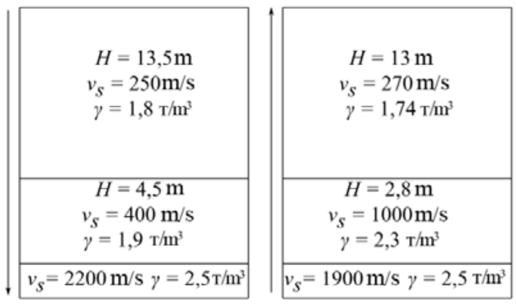
Fig. 12 Seismograms of soil vibrations and corresponding spectral characteristics

4.2 Usage of numerical method for calculation of soil vibration spectrum

In order to investigate the factors, which determine the type of spectral characteristics of soil vibrations, excited by a powerful nonexplosive source, making a theoretical seismogram and getting its spectral decomposition on basis of engineering-geological and instrumental data (lithological profile of thickness; seismic wave velocities etc.) is of great interest. Further, the calculated seismogram for basement rock was re-counted for the surface of typical area of Gory city territory (Fig. 13, b).The power of layers, the soil density and the S-wave propagation velocities (experimentally received in definite soil profiles) were given as initial data. The spectrum of the calculated seismogram is practically similar to the experimentally obtained amplitude-frequency characteristics of the profile (Fig. 14). It must be noted, that the predominant engineering-geological conditions from the surface of thickness for the compared areas (Rustavi and Gory cities) are practically identical and the vibration spectra differ significantly. This, obviously, is caused by the lower layer type influence. Correspondence of calculation and experimental spectra of vibrations was also observed at the introduction of vibration seismograms of rocks into the thickness foundation, composed with pebbles (H = 14.2 m).

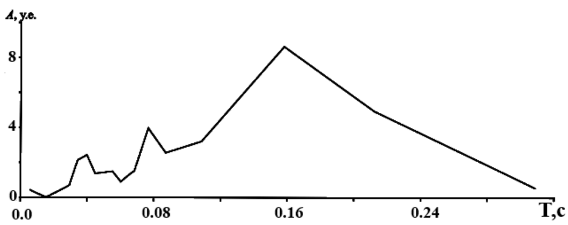
For this purpose the seismogram of soil vibrations, recorded on the surface of typical area of Rustavi city (Fig. 13, a) was recalculated for the bedrock with the help of the program of numerical solution of direct and inverse problem of earthquake engineering, using multiple-reflected plane waves [4]. The following conclusions can be made at the analysis of the obtained material. The correspondence of the calculated spectrum and the amplitude-frequency characteristics of soil thickness have been determined. It proves the validity of the initial data, in particular, formation of the thickness velocity profile. In spite of the fact, that the calculation results are practically similar to the experimental data, nevertheless, the value of the experimental observation on a definite area in conditions of natural soil bedding is undoubted. Significant differences are observed for multiplex composed thicknesses.

At the analysis of the experimental data there is an opportunity of taking into account not only the properties of the thickness profile but also different impurities, complications of soil conditions, non-horizontality of boundaries, specification of soil type, its main seismic characteristics, etc. But the most important is the fact that the initial data of the numerical method are just determined experimentally. It is advisable to compare the spectra, excited by a powerful nonexplosive source, with the calculated spectrum of the earthquake. Depending on epicentral distance, wave angle of incidence and their attenuation the obtained experimental spectra can be used for studying real seismic source properties, its focus etc.

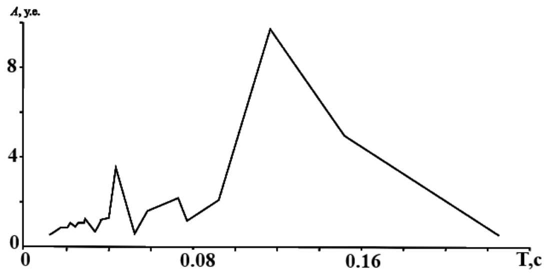


a) b)

Fig. 13 Engineering-geological and velocity profiles



a)



b)

Fig. 14 Vibration spectra on the thickness surface: a – experimental spectrum; b – design spectrum

5. ENERGY OF SEISMIC WAVES EXCITED BY A NONEXPLOSIVE SOURCE. SEISMIC WAVE ABSORPTION

Considerable part of nonexplosive source energy is emitted in the form of seismic waves. Let's assess the total influence energy of a powerful impulsive source [6], [7], which will make doubled value of kinetic energy:

$$E = E_k + E_n = 2E_k. \tag{10}$$

Taking into account the fact that the mass of the impulsive source (SI-32) active part m = 553 kg and the influence velocity $v \approx 13$ m/s, source kinetic energy can be calculated:

$$E_k = \frac{mv^2}{2} \approx 50 \text{ kJ}. \tag{11}$$

The source energy, emitted in the form of seismic waves, can be assessed through the spectrum of the excited vibrations. Total amount of the energy, which passed in a unit of time, i.e. energy density is:

$$\varepsilon = 2\pi^2 \rho \int_0^t v_S \left(\frac{A}{T}\right)^2 dt, \tag{12}$$

where: ρ is medium density; v_S is S-wave velocity; A is wave amplitude; T is vibration period.

Because of the fact, that the displacement is a complex function of time, integration can be replaced by summing for simplification, dividing record into groups. Within the group we have sinusoidal vibrations with the constant amplitude and period. Then we have

$$\varepsilon = 2\pi\rho v_S \sum \left(A_i / T_i\right) \Delta t_i. \tag{13}$$

Total amplitude vector is $A = \sqrt{A_x^2 + A_y^2 + A_z^2}$.

At source presentation in the form of a sphere the source energy can be calculated according to the formula:

$$E = 2\pi R^2 \varepsilon, \tag{14}$$

where R is the distance from the source.

Let's calculate the wave energy on the total vibration spectrum on the area, composed with loose soils (H = 14 m) in the distance R = 2.5 m from the source. The spectrum fragment is shown in the Fig. 15, a .The total duration of vibrations comes up to t = 0.63 s (curve 1). The total energy comes up to the value E = 27 300 joule, which makes 55% from the excited energy in the influence point. For rocks (the spectrum fragment in Fig. 15, c) the energy comes up to E = 35 400 joule, i.e. 70% of the total energy changes into the seismic wave energy on rocks.

Determination of absorption coefficients is a sufficiently complex problem. Most data is obtained for a high-frequency range (50–100 Hz). The presence of powerful sources of multiple actions allows reducing the frequency range in the direction of real frequencies of earthquakes at determination of absorption coefficients. The absorption coefficients were determined on amplitude spectra of the dependence of coefficients' difference on frequency [8]:

$$\alpha_{f_1} - \alpha_{f_2} = \frac{\ln\left(\varphi_{x_1} / \varphi_{x_2}\right)}{x_2 - x_1}, \qquad (15)$$

where φ_{x1} is amplitude ratio of the spectrum components, obtained on base of x_1; φ_{x2} is amplitude ratio of the spectrum components, obtained on base of x_2.

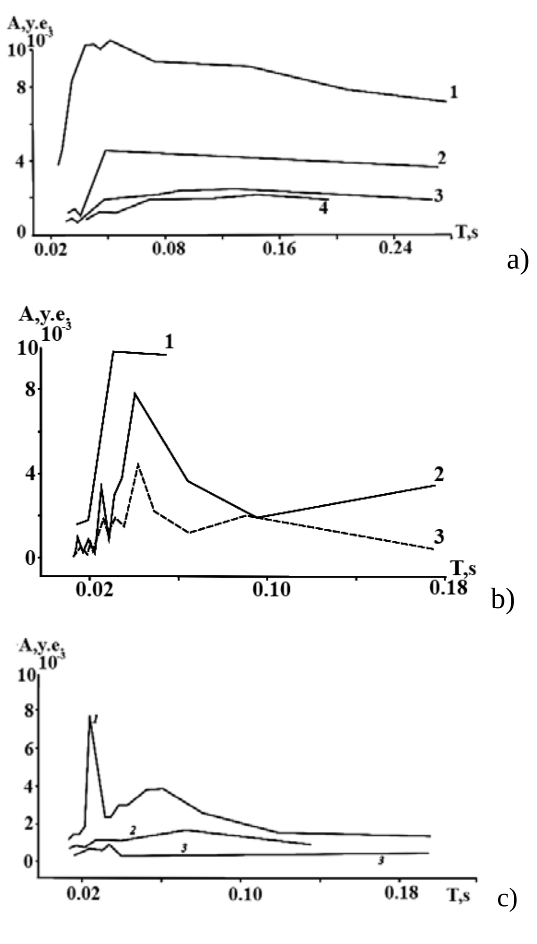


Fig. 15 The change of amplitude level of vibration spectrum with distance: a – loams; b – pebbles; c – rocks (weathered from the surface)

Absorption coefficient significantly depends on frequency. Thus, α1 = 0.3 for loams at the frequency f_1 = 50 Hz, whereas α2 = 0.08 for frequency f_2 = 10 Hz. At the same frequencies for rocks α1 = 0.07 and α2 = 0.003, accordingly. The examples of the absorption coefficient calculations in clay soil are given in the Fig. 16. Dependence α (f) for rocks has a complex type (Fig. 17, b). It must be noted, that the absorption coefficients differ for near and far zones of source. This is explained by a high index of energy absorption due to plastic deformations near the influence zone.

Absorption coefficient can be calculated in another way. Let's suppose that vertically oriented dynamic influence F (t) of nonexplosive source is applied to homogeneous soil thickness surface with power H. The phenomena of wave reflection and refraction will be observed at the wave incidence on the top of the basement rock.

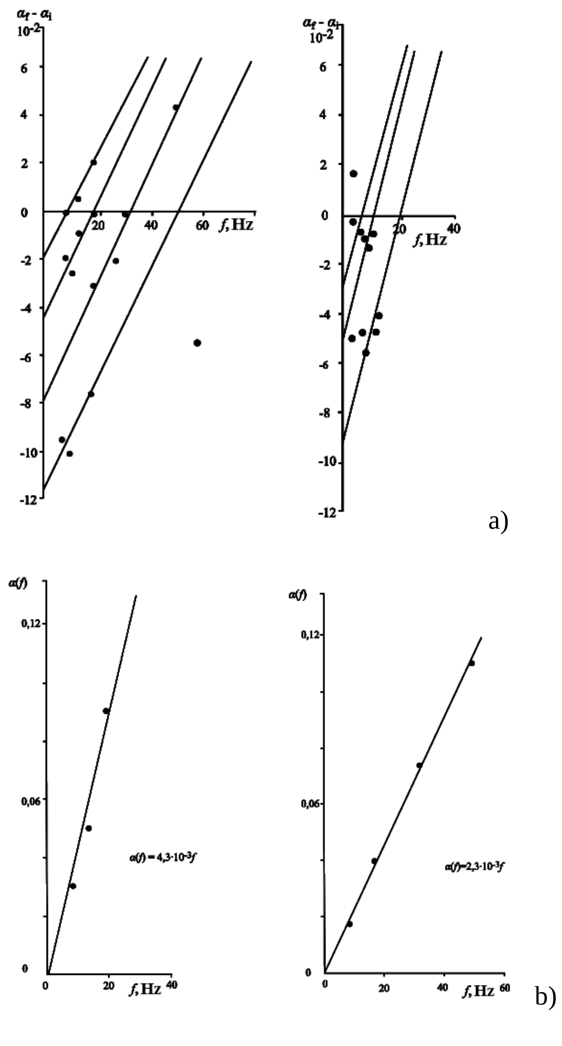
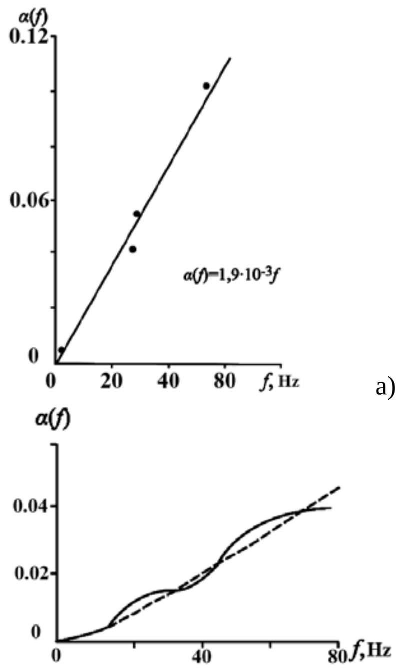


Fig. 16 Seismic waves' energy absorption: a – dependence (α_{f1}-α_{f2}) on frequency f; b – dependence of absorption coefficient on frequency (for near and far zones)

Let`s calculate the absorption coefficient of seismic energy of the thickness on the obtained dependences of absorption coefficient from frequency (Fig. 17 b) for T = 0.06 s (f = 17 Hz)

$$\begin{cases} \alpha_1(f) = 4{,}3\cdot 10^{-3}\, f \quad (\textit{near zone}), \\ \alpha_2(f) = 2{,}3\cdot 10^{-3}\, f \quad (\textit{far zone}). \end{cases}$$

Substituting the frequency 17 Hz, we obtain $\alpha_1(f) = 0.071$ m^{-1} и $\alpha_2(f) = 0.038$ m^{-1}, whereas their average value will be 0.056 m^{-1}. At absorption calculation for the sum-total of the soil vibration spectra one can also make up the dependence k(f). The problem of the absorption coefficient study in different soils wasn't specially posed in the present work. At the same time the opportunity of direct determination of absorption coefficients in a comparatively low-frequency region of measures is shown. It must be noted that the data will be more proved at usage of vibration equipment as sources of soil vibration. And it will be easier to obtain the data. Thus, on amplitude level change one can obtain the dependences of energy absorption on frequency in different soil types at consecutive sending of a monochromatic signal with different frequency to the soil thickness, at its registration in different distances from the source. In order to increase data reliability it is possible to use oncoming observation systems.



a)

b)

Fig. 17 Absorption coefficient dependence on frequency: a – large-fragmental soils; b – rocks

Therefore, it is interesting to consider the change of the square of normalized spectrum of vibrations at change of the dynamic influence value. If soil vibrations are generated simultaneously by four sources SI-32 then the spectrum of vibrations of loams changes significantly (Fig. 18) and region of the spectrum envelope increase 4 times.

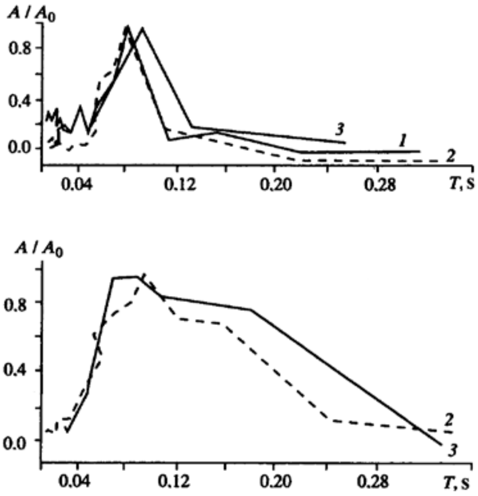


Fig. 18 Spectra of vibrations, generated by the source SI-32: a – one source; b – four sources

It must be noted that the sources can`t be located sufficiently near, therefore the appearance of plastic deformations is practically excluded. On the other hand, elastic nonlinearity of reaction can quite take place. Watering of clay and large-fragmental soils causes the narrowing of vibration spectrum. Nevertheless, the change of influence causes the similar increment of the square of the soil vibrations spectrum. Results of investigations allow creating base for prognosis of spectral features of soil vibrations at strong motions.

Summarizing results of the study problems of estimating the possible dangerous processes of strong seismic impacts on various grounds, such as urban areas can be formulated. Considered parameters can be successfully used for practical purposes of seismic risk management and thus create the basis for the forecast of the features of the spectral composition of the ground motion at the strong motions caused by strong earthquakes. The spectral characteristics of various types of ground vibrations which are, at the same time, in different physical states, largely determine the behavior of different physical systems constructed in the ground (buildings, overhead and underground constructions) and devastating earthquake itself [9].

CONCLUSIONS

Independently of influence energy at standard observations each soil type is characterized by a definite spectral distribution curve. The sub-spectral region increases at seismic properties deterioration. The maximum values of amplitudes of the spectral distribution curve move to the high-frequency region and the vibration amplitudes increase at decreasing of the groundwater standing level. Good stability of spectral characteristics of soil vibrations is observed at the source displacement. Low-powered sources don't allow using spectral characteristics of the vibrations excited by them for the assessment of influence of the soil thickness power change. At the same time such spectral distribution curve gives the information about the lower layers properties with moving off from the source. Thus, if the lower layers are solid, then the spectrum moves to the high-frequency region and vice versa. The spectrum has a simple triangular form in the region of maximum amplitude values. It must be noted that the width and the type of the spectrum remain even at three-meter covering by embankment of considered soils. Correlation dependences between the S-wave velocity and the weight-average value of the vibration period of the corresponding soils and the intensity increment have been obtained.

Powerful sources have their own inherent features of application. Weight-average values of periods are practically close to the values of predominant periods for corresponding soil thicknesses. The sources allow investigating the properties of thickness up to the depth 15–20 meters without special amplifying devices. At increase of loose soil power the spectrum square accordingly increases and can be the index of soil seismic properties. The spectrum of soil vibrations, excited by an impulsive source is similar to the spectrum of soil vibrations, generated by an earthquake in the high-frequency part of the spectrum. The analysis of the vibrograms shows the picture which is similar to the results of the impulsive source usage, and subordinate maximums appear in a lower-frequency region (T~ 1–1.5 s).

The investigations on the models confirmed the dependence of the spectral characteristics on physical and mechanical properties and the power of soil thickness and showed the stability of the spectral distribution curve with depth. The usage of the numerical method allows obtaining calculated spectra of vibrations, similar to the experimental spectra. This proves the validity of the velocity profile making up. The opportunity of the assessment of absorbing properties of soils in a low-frequency range has been shown. The question of the specification of engineering-geological and hydrogeological conditions has been investigated. The increase of additional indirect characteristics considerably raises the reliability of final results.

With the help of low-powered sources there exists the opportunity of the detailed investigation (without usage of amplifying devices) of soil medium properties up to the depth of 5–10 meters. At the same time powerful nonexplosive sources allow to study the properties of practically the whole soil thickness, which is of practical interest for seismic microzonation purposes. Totality of all the types (on power) of sources allows obtaining necessary information on seismic properties of the investigated medium. Results of investigations allow creating base for prognosis of spectral features of soil vibrations at strong motions. Wherein spectral features of vibrations in soils of different type and physical state in many respects define behavior of different systems constructed on soils (buildings, overground and underground constructions) and devastating earthquake itself.

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