Accounting for nonlinear soil properties in the computational method of seismic microzoning

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Abstract. The paper notes that in recent years, attention to the study of nonlinear phenomena in engineering seismology has sharply increased. The problem of accounting for nonlinear phenomena can be solved using instrumental and computational studies, as well as collaterally. In the latter case, the possible level of soil nonlinearity is estimated using the instrumental method, then the possible features of soil movements are calculated numerically. An algorithm for taking into account the nonlinearity of soils when calculating vibrations of the soil strata under intense seismic influences is proposed. The algorithm was developed on the basis of the known empirical relationships between the soil types and their indicators. The number of plasticity was chosen as an indicator of the soil type. Additionally, the necessary criteria and refinements have been introduced to correctly take into account the normal stress and calculate the deformation. The value of the shear wave propagation velocity in the soil, closely related to the physical state of the soil, is considered as a modulated indicator. The way of using the proposed algorithm for the method developed on the basis of the multiple-reflected waves theory and the method developed on the FEM basis is shown.

1. Introduction
In recent years, the list of studies, in which instrumental measurements are very actively used in various, very different fields of geophysics, has significantly expanded. This undoubtedly raised the quality of the results obtained and their reliability [1-9]. In this regard, it became possible to directly study such subtle effects as nonlinearity, which is clearly manifested during macro-seismic and other field surveys of various hazardous natural and man-made processes’ manifestations. At the same time, it should be noted that the manifestations of physical nonlinearity of soils under strong impacts have been insufficiently studied. The influence of the soil conditions of the territory on the earthquakes’ manifestation is well known. Many authors studied various aspects of the local conditions’ influence: the dependence of the earthquakes’ manifestation on the topographic, lithological, hydrogeological features of the territory. At the same time, the influence of each individual factor on the earthquake intensity formation is still taken into account rather formally. Relatively few works are known on the direct assessment of the soils’ physical state influence on the intensity formation. With rare exceptions, there were almost no works devoted to the impact level influence on soils’ behavior, i.e. – the studies of soil nonlinearity assessments [11]. On the one hand, this is explained by the greater complexity of the problem and, on the other hand, many leading scientists of the world believed that the nonlinearity...
influence on the earthquakes’ manifestation features is insignificant [10]. Analysis of the survey data of strong earthquakes that have occurred in recent years has shown that the nonlinearity effect can be very significant. This led to a radical change in the attitude to this problem [10, 12].

This problem can be solved using the instrumental and computational studies, as well as collaterally. In the latter case, the soil nonlinearity level is assessed using the instrumental method.

Possible features of soil movements (the soil layer natural vibrations’ frequency, etc.) are calculated by the calculation numerical methods.

2. Calculation method of seismic microzoning.
When carrying out seismic microzoning, it is necessary to simulate the real soil conditions, which are diverse. It is equally important to develop and use the principles of accounting for the nonlinear soil properties using the calculation method. The use of the computational method makes it possible to simulate any conditions observed in nature and evaluate the features of nonlinear phenomena deep in loose sediments. Such programs exist abroad. But, first, they are quite expensive, and second, the use of a ready-made program does not allow taking the results of our own research fully into account.

When solving such a problem, it seems that the half-space describing the rocky soil behaves like a linear elastic medium, and the loose soil overlying it, exhibits strong nonlinear properties under intense seismic or dynamic influences.

Half-space and loose soil can be characterized by the propagation velocity of the shear waves $V_s$, attenuation coefficient $\beta$ and shear modulus $G$.

The nonlinear behavior of soils is most often assessed by the nonlinear relationship between stress $\tau$ and soil deformation $\gamma$ [13]:

$$\tau = G(\gamma)\gamma$$

At present, on the basis of the existing modifications [5-12], the Institute has developed two numerical methods for calculating the soil layer vibrations: the first is based on the well-known theory of multiple-reflected waves (MRW) [14-21], and the second is the finite element method (FEM) [20]. Currently, the new modifications of both methods have been developed [22]. In these ways, the medium still appears to be linearly elastic. In addition, a method to take into account the nonlinearity of soils [22], based on high capabilities FEM, was developed. When implementing this method, it is possible to set any type of stress-strain relationship obtained from the laboratory research data or physical assumptions and calculate the corresponding reaction on the soil strata surface.

At the same time, when solving the scientific and practical problems, it is necessary to rely on the initial data obtained directly from the field observations (shear wave velocity in the soil, soil density, etc.), although if necessary, it is also possible to use this, well-known in earthquake-resistant design, approach.

2.1. Method of multiple-reflected waves of seismic microzoning
Let us have a seismic wave falling on the soil strata surface. Let us assume that the soil mass is a nonlinear, absorbing infinite medium with a density $\rho$ and the propagation velocity of shear waves $V_s$. The shear modulus of the medium $G$ can be determined from the relation:

$$G = G_{\text{max}} = \rho V_s^2$$

In most practical problems, in particular, when drawing up a high-velocity section of a soil stratum, the values of the shear wave velocities obtained at small deformations are used. Hence, the shear modulus will correspond to the maximum value of the shear modulus for a given environment (soil).

In the process of applying a monotonically increasing seismic or dynamic load to the soil, several different stress-strain states of the latter will be observed. Initially, with the growth of small (for a given
soil) deformations, the stresses in the soil increase in direct proportion to them. The process is linearly elastic. Then, upon reaching a certain value (specific for each material or soil), the material exhibits its nonlinear properties. The nature of the process becomes nonlinear elastic. In this case, there are no inelastic phenomena, the soil simply changes some of its elastic characteristics (for example, the prevailing frequency of the natural soil vibrations can go into the high-frequency region, etc.). With the nonlinear elastic nature of the relationship "stress-strain", as the deformations increase, the stresses slightly slow down the growth. But the process is still reversible. With a further increase in deformations, the process can become inelastic. In this case, stresses significantly reduce growth, may not change, or even have negative increments until the material is hardened or destroyed, respectively, i.e., before the change in physical condition.

In accordance with the noted stages of physical states, the propagation velocity of the shear seismic wave, which is a quantity closely related to the state and changes of the soil. From the formula (1) it can be seen that any, arbitrarily small, change in velocity leads to a noticeable change in the soil shear modulus. The change in soil density at the first stage can, in general, be neglected. At the same time, the soil density can be quite reliably determined for various types of soils directly from the shear wave velocity using the empirical dependences obtained by us for the conditions of Georgia [23]. Such connections are well known from the data of other authors. [24].

1. The behavior of soil under intense loads depends on the type of soil and the specific physical condition. The latter, in turn, is determined by a number of soil parameters: the degree of water cut, existing internal stresses, the past loads chronology, etc.

2. A very important factor is the magnitude of the normal stress caused by the lithostatic pressure of the overlying soil [12]. In this case, the normal stress can reach noticeable values. Thus, it is necessary to take into account the location of the soil in depth.

3. Next, we determine the expected deformations from the vibration velocity of soil particles in accordance with the corresponding level of intensity for a given area [23]. In the latter case, the intensity predicted for a given area can be used according to maps of general seismic zoning, detailed seismic zoning and even seismic microzoning.

If we estimate the indicated intensity directly from a seismic zoning map or detailed zoning, i.e., without taking into account the engineering-geological, hydrogeological and geomorphological conditions, then it should be attributed to the so-called medium soils. Such conditions should be carefully selected. Otherwise, the intensity and deformation will accordingly be underestimated or overestimated. The vibration velocity is determined from the tabular data for the corresponding intensity.

a) Further, in the ideal case, an accelerogram can be found from the database of strong movements, recorded on similar grounds and with the corresponding developed intensity. Then we recalculate the record from the strata surface onto the rocky ground (bedrock) The resulting accelerogram (or a set of them) will be the initial one for entering the soil sections into the bedrock for all areas in the study area. It is easier to select the records recorded directly on the rocky grounds with appropriate characteristics or create the synthetic accelerograms.

b) Another solution is as follows. We carry out the work using the instrumental method of seismic microzoning, determine the intensity level for the soils of the selected site (this also determines the level of possible nonlinearity) and estimate the vibration velocity according to the tabular data (Table 2) for the corresponding intensity [24]. Then the process is repeated.

When using the maps of seismic microzoning, the problem of the numerical method is somewhat narrowed and as a result, we study only the dependence of the vibrations frequency on the intensity. Then, if, for example, we have the soils in the 8-point zone of the city, on which the intensity calculated by the methods of seismic microzoning can be 9 points, then we use the corresponding value from the database or the specified table.

The calculation should take into account the characteristics of the soil type. This is realized on the basis of soil differentiation according to such indicators, which are especially characteristic for certain types of soils. Such indicators include: consistency indicator, porosity coefficient, plasticity number,
deformation modulus, etc. By choosing the appropriate indicator, it is possible to reliably take into account the soil type and its expected behavior under intense loads.

It should be noted that the role of watering is to change the physical state of certain soil types. Therefore, the formal accounting of the groundwater level as one of the soils seismic properties indicators, which is still widely used in some modifications of seismic microzoning, can lead to errors [12]. On the other hand, watering is taken into account directly by the corresponding change in the physical soil state.

We define further, for a given level of deformations, the change in the shear modulus due to the above-mentioned factors, for example, $a_1 a_2 a_3 a_4$ etc. It should be borne in mind here that an increase in the number of factors that determine the soil type and its physical state, on the one hand, leads to greater concretization, but on the other hand, it seriously complicates the calculations due to the lack of appropriate analytical relationships. In this regard, in such studies, as a rule, the amount of soil deformation and one or two indicators of the soil itself are taken into account. To solve such problems, the results of special studies of the soils behavior under varying loads are used [12, 13, 26]:

$$\frac{G}{G_{\max}} = \prod(a_1 a_2 a_3 a_4 \gamma)$$

(3)

where $G$ is a current shear modulus.

7. In the considered method, one of the main parameters is the shear wave velocity. In this regard, we further determine the changes in the current velocity of the shear wave ($\rho$-represent constant or calculated from empirical dependence) for a given level and take into account in the corresponding calculations:

$$V_S = \sqrt{\frac{G}{\rho}}$$

(4)

8. If it is necessary to take into account absorption, its calculation is carried out according to the corresponding dependence:

$$\xi = \prod(a_1 a_2 a_3 a_4 \gamma)$$

(5)

Thus, the module $G$ and absorption $\xi$ are calculated based on the change of $V_S$.

$$G = \varphi(V_S)$$
$$\xi = \varphi(V_S)$$

(6)

The data obtained are the direct basis for taking into account nonlinear phenomena in the soil. At the same time, during the development, the well-known research results are used.

9. In the case of a layered soil stratum, a corresponding change in shear velocity is calculated for each layer. At the same time, seismic vibrations, already modulated by soil nonlinearity, will come to each subsequent layer from the depth. They are expressed by the corresponding accelerograms. As a result, on the soil layer surface, we obtain an accelerogram representing the integral effect of taking into account physical nonlinearity.

10. The algorithm was developed on the basis of the well-known empirical relationships between the soil types, the corresponding indicators and the indicators values’ dependence on deformations. The number of plasticity and the corresponding dependence were chosen as an indicator of the soil
characteristics [26]. Additionally, the necessary criteria and refinements were introduced to take into account the normal stress and calculate the deformation.

2.2 Seismic microzoning FEM method

1. To make the calculations, it is necessary to know the values of Young's modulus E and Poisson's ratio \( \mu \), which are calculated according to well-known formulas. The main indicator is again the measured shear wave velocity. The values of the propagation velocities of longitudinal and transverse waves in the soil mass are determined without any special difficulties in field observations. In a methodical analysis based on the known shear wave velocity, the longitudinal wave velocity can be approximately determined. This is realized from the known ratios of the longitudinal and transverse waves' velocities [23, 27]. As noted above, the soil density can be determined from the empirical relationship between the shear wave velocity and the density obtained by us for the conditions of Georgia. Next, the Poisson's ratio (\( \mu \)) and Young's dynamic modulus (E) are calculated. The calculations of these values are carried out using the longitudinal and transverse waves' velocities.

2. With a layered thickness, we calculate E and \( \mu \) for each layer according to the above-depicted formulas. The calculation makes it possible to directly take into account the change in the soils' behavior due to their nonlinearity under intense loads.

3. In conclusion, it should be noted that the behavior of "weak" soils under intense loads is characterized by a significant difference in compression and tension. Moreover, non-cohesive soils (such as sand or gravel) near the earth surface have nearly zero Young's modulus and tensile shear modulus. This can and does lead to a decrease in the bearing capacity of the soil during multicyclic seismic vibrations, to its destruction (for example, the phenomenon of cavitation). The absence of a dataset does not allow to take into account directly the bi-modularity of a particular environment in the calculations at present. At the same time, if necessary, it is possible to take into account the bi-modularity of the environment based on the specified dependencies of the type:

\[
G_- = \varphi(V_{s_-}) \tag{7}
\]

\[
G_+ = \varphi(V_{s_+}) \tag{8}
\]

Summary

A new algorithm has been developed based on the use of the method of multiple - reflected waves and the FEM method by taking into account the empirical relationships between the soil types, the corresponding indicators and the magnitude dependence of the indicators on deformations. The number of plasticity and the corresponding dependence were chosen as an indicator of the soil characteristics. The values \( \mu \) of Young's modulus E and Poisson's ratio are also used. Additionally, the necessary criteria and refinements were introduced to take into account the normal stress and calculate the deformation.

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