The vibrations of a nonlinear, absorbing soil ground calculation by the method of the seismic microzoning multiple-reflected waves

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Abstract. A nonlinear version of the program ZOND (nonlinear) has been developed based on the dependence of the shear and absorption modulus values on the seismic impact intensity, as well as on the introduction of ratios for calculating various indicators of soil movement (normal stress, deformation, etc.). The program algorithm is based on the multiple-reflected waves theory. An accelerogram of an earthquake, recorded on a rocky ground in Japan with earthquake characteristics similar to those for the territory of Tbilisi (magnitude, epicentral distance, spectral features, etc.), was chosen as an accelerogram set into the bedrock from the generated strong motion database AGESAS. The results of linear and nonlinear calculations with and without absorption are presented. It is clearly seen that with an increase in the intensity of the impact, the nonlinearity manifestation increases. At the same time, absorption increases. In this regard, the resulting movement at very high levels of impact may be below the initial level. This corresponds to the facts known from the analysis of the consequences of strong earthquakes that have occurred in recent years.

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 [1-6]. 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 physical nonlinearity manifestations of the soils under strong impacts have been little studied. Accounting for the nonlinear soil properties in engineering seismology problems can be carried out in two ways: instrumental and calculated. Despite the fact that the instrumental method of seismic microzoning is the main one, nevertheless, very often it becomes necessary to solve such problems using the computational method.

2. Modeling nonlinear and absorbing soil properties
The use of the computational method makes it possible to simulate practically any conditions observed in nature. The solution of the problem of calculating the vibrations of the soil strata for the conditions of linear elastic deformations was implemented in different years by many authors [7-14]. The author and his students previously developed a linear version of the program ZOND (linear) [15].
At the same time, the needs of practice lead to the need to calculate soil vibrations for the conditions of nonlinear deformations (nonlinear elastic and inelastic deformations.). We believe that the elastic half-space is a linear elastic medium, and the soil overlying it exhibits strong nonlinear properties under intense seismic influences [16].

The solution of this nonlinear problem in an analytical form for soils is based on significant assumptions for such a complex medium as soil [16], and therefore the solution of nonlinear computational problems is based on the correlations established by the experimental studies. In other words, computational programs for solving nonlinear problems are essentially analytical-empirical. The most adequate programs have these peculiarities (SHAKE etc.) [17].

Let us have a seismic wave falling on the soil strata surface. Let us assume that the soil stratum is a nonlinear absorbing infinite medium with a density \( \rho \) and the propagation velocity of shear waves \( V_s \).

With small deformations, the shear modulus \( G \) will be maximum for a given soil:

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

(1)

With an increase in deformation, the shear modulus initially remains constant, but upon reaching a certain value (specific for each material or soil), it is characterized by a noticeable change, i.e., the soil starts showing its nonlinear properties. With a continued increase in deformation, the growth of stresses slows down and then may not change until the destruction or hardening of the material, i.e., before the structural change.

The value of the plasticity number was chosen as the main indicator of the soil, characterizing its type and behavior under intense loads \( PI \). On the empirical relations basis, the parameters necessary for the calculations are determined [18]:

\[
k(\gamma, PI) = 0.5 \left\{ 1 + \tanh \left[ \ln \frac{0.000102 + n(PI)}{\gamma} \right]^{0.492} \right\}
\]  

(2)

where

\[
n(PI) = \begin{cases} 
0.0 & \text{for } PI = 0 \\
3.37 \times 10^{-6} PI^{1.404} & \text{for } 0 < PI \leq 15 \\
7.0 \times 10^{-7} PI^{1.976} & \text{for } 15 < PI \leq 70 \\
2.7 \times 10^{-5} PI^{1.115} & \text{for } PI > 70 
\end{cases}
\]

\[
d = 0.272 \left\{ 1 - \tanh \left[ \ln \left( \frac{0.000556}{\gamma} \right) \right]^{0.4} \right\} e^{-0.0145 \gamma^{1.5}}
\]

Next, the change in the shear modulus is determined based on the following relationship:

\[
\frac{G}{G_{\text{max}}} = k(\gamma, PI)(\sigma)^d
\]  

(3)

where \( G \) - is a current module,

\( \sigma \) - is normal voltage.

The seismic energy absorption is calculated by the formula [18]:

...
\[ \xi = 0.333 \frac{1 + \exp(-0.0145 Pt^{1.3})}{2} \left[ 0.586 \left( \frac{G}{G_{\text{max}}} \right)^2 - 1.547 \frac{G}{G_{\text{max}}} + 1 \right] \] (4)

On the basis of the indicated and introduced ratios to determine the required parameters (normal stress, deformation, etc.), a nonlinear version of the program ZOND (nonlinear) was developed. As an accelerogram set into the rock base from the database of strong movements AGESAS we have created [19], the earthquake accelerogram was chosen, recorded on a rocky ground in Japan, with characteristics similar to the territory of Tbilisi (magnitude, epicentral distance, spectral features, etc.) [20].

**Figure 1.** Plot 16. I=7. Non-linear calculation without absorption

**Figure 2.** Plot 16. I=7. Nonlinear calculation with absorption
**Figure 3.** Plot 16. I=8. Linear calculation without absorption

**Figure 4.** Plot 16. I=8. Non-linear calculation without absorption
3. Summary
The results’ analysis of linear and nonlinear calculations with and without absorption for the models of specific sites in the territory of Tbilisi confirms the adequacy of the calculations to the physical phenomena observed in the soils under intense loads (Fig. 1-6). It is clearly seen that with an increase in the seismic impact intensity, the manifestation of nonlinearity increases (Fig. 2, Fig. 4). At the same time, absorption increases. Hence, the resulting movement at very high levels of impact may be below
the initial level (Fig. 4). This corresponds to the facts known from the consequences analysis of the strong earthquakes that have occurred in recent years (for example, the Notridge earthquake, 1994).

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