Dynamic Deformation Characteristics of Soil in the Tasks of Seismic Micro Zoning

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ABSTRACT

The article discusses a technique for determining the nonlinear characteristics of the layers of computational models of the soil profile for the equivalent linear and nonlinear modeling of its response to seismic effects. The results of studying the factors influencing the curves of the strain-dependent shear modulus $G(\gamma)$ and damping ratio $D(\gamma)$ are analyzed. Based on the results of the analysis, the main parameters have identified that control the shape of the curves and allow you to quickly select the corresponding curves from the existing database with acceptable accuracy for each layer of the soil profile model. For clayey rocks: this is the plasticity index PL and the depth of occurrence; for sandy rocks: particle size, percentage, and depth. The paper presents the results of studying the effect of relative errors that arise when choosing the curves $G(\gamma)$ and $D(\gamma)$ for the soil layers of the computational seismic-geological model on the parameters of the frequency response of the soil, calculated using the equivalent linear modeling of ground vibrations during earthquakes. It was found that errors in determining the strain characteristics of soil layers in the calculation model lead to a shift in the maxima of the amplitude-frequency characteristic, to a change in the amplification factors of oscillations, as well as to the appearance of "false" maxima at high frequencies.

The methodological approach to the formation of computational seismic-geological models of soil strata, by introducing the curves $G(\gamma)$ and $D(\gamma)$, which reflect the nonlinear properties of the soil, makes it possible to improve the computational methods for determining the resonance properties of soils under construction sites. The most accurate values of the frequency characteristics of the soil strata under construction sites are necessary for the development of effective measures to ensure the seismic resistance of the designed and existing facilities.

As a result, the validity and accuracy of determining the quantitative parameters of seismic hazard at the construction and operational sites under study are increased.

Keywords: Seismic effects, Earthquakes, Resonant amplification, Seismic waves.

I. INTRODUCTION

The degree of damage to an object during an earthquake depends not only on the level of seismic effects, but also on the quality of seismic design and construction. Ensuring the required quality is possible only if the quantitative parameters of the seismic hazard of the site are correctly predicted, which is carried out using a set of works on seismic microzoning [3], [4], [20]. The purpose of the seismic micro-zoning of construction sites is to predict the behavior of soils during an assumed strong earthquake. Despite a large number of works in this area, predicting the behavior of soils under seismic impacts remains one of the topical problems of seismology.

The nature of soil behavior during earthquakes depends on many factors [3], [4], [20]. Research in the field of soil behavior under seismic loads is actively developing, which is largely facilitated by laboratory and field studies of changes in the strain characteristics of soils under the influence of dynamic loads.

It is known that the strain characteristics of the soil under significant loads are nonlinear [2], since the value of the shear modulus $G$ and the damping ratio $D$ change, depending on the amplitude of the shear strain $\gamma$ under seismic effects. At small deformations, the shear modulus is considered to be maximum and is denoted by $G_{\text{max}}$. It is related to the shear wave velocity $V_s$ by the ratio $G_{\text{max}} = V_s^2 \rho$.

When calculating soil response to seismic effects, using equivalent linear and nonlinear modeling using software such as: EERA [10], NERA [11], PROSHAKE [27], [30], DEEPSOIL [14], etc. – you must have empirical data on the
curves of the shear modulus $G$ and the damping ratio $D$ on the shear strain $\gamma$ for each layer of the soil model. These curves are determined as a result of field or laboratory studies of changes in the strain characteristics of soils under the influence of dynamic soil tests.

The results of laboratory and field studies of the curves of the strain-dependent shear modulus $G(\gamma)$ and the damping ratio $D(\gamma)$ are presented in [17], [26], [28], [31], [41] etc. According to the research results, it was found that with an increase in the amplitude of shear strain, the shear modulus $G$ decreases, and the damping ratio $D$ increases. In this case, the law of the rate of change of these quantities for each type of soil turns out to be different.

The authors of the article have collected stock and published materials on the study of the curves $G(\gamma)$ and $D(\gamma)$, obtained by various researchers and published in various sources [9], [26], [28], [33] etc. The materials are analyzed and systematized in a computer database, which allows for each layer of computational soil models to automate the selection of the appropriate curves of the strain-dependent shear modulus $G(\gamma)$ and the damping ratio $D(\gamma)$. The database continues to be replenished with dependencies generated for individual layers and for their units, which are characterized by different lithology, physical and mechanical properties, thickness, and depth of occurrence.

II. FACTORS THAT AFFECT THE DECREASE IN SHEAR MODULUS AND DAMPING RATIO

As a result of laboratory tests carried out in the 70s of the XIX century, the first curves of the strain-dependent shear modulus $G(\gamma)$ and the damping ratio $D(\gamma)$ were established. The results were presented in papers [13], [31]. Their authors showed that the nature of the curves of the strain-dependent shear modulus $G(\gamma)$ and the damping ratio $D(\gamma)$ value depends on the soil composition, moisture content, structural bonds between particles, the depth of the layers, and the like.

Modern field and laboratory methods for determining the curves of the shear strain-dependent shear modulus $G(\gamma)$ and the damping ratio $D(\gamma)$ are described in detail, for example, in the review works of S. Kramer [25] and EA Voznesensky [1]. In general, field and laboratory methods for determining these soil characteristics differ for small and large seismic deformations.

A. Influence of the Porosity Coefficient on the Shape of the Curves of the Shear Modulus and Damping Ratio with Shear Strain

When studying the dependence of the damping ratio and shear modulus on various influencing factors, the researchers B. Hardin and V. Drnević [13] found that one of the main factors is the coefficient of porosity. The results of their experiments on a resonant column with undisturbed soils indicate a decrease in the damping ratio with an increase in the porosity coefficient. At the same time, the results of studies of normally compacted clays carried out by K. Stoki and V. Eisenhower in 1981 using improved equipment, on the contrary, did not reveal a noticeable dependence of damping ratio and shear modulus on porosity [16].

In works [18], [19], [22] presents the results of detailed studies of the dynamic properties of soils, depending on the strain, on the standard Japanese sand "Toyora". The studies were carried out under conditions of all-round compression of samples up to 100 kPa of different porosity. The research results showed that the decrease in the shear modulus with strain practically does not depend on the value of the porosity coefficient for sandy rocks, and the damping ratio $D$ increases with an increase in shear deformation and reaches ~ 0.25 at a shear strain of 0.5%. The relationship between the damping ratio and the shear strain is independent of the porosity of the sample. Similar results were obtained for non-cohesive soils in the experiments of S. Sagaset [29]. In his work, S. Sagaseta notes that the damping ratio and shear modulus of the sand studied by him, which depend on the shear strain and compression stress, turned out to be practically independent of the porosity coefficient. At the same time, in a generalized series of field studies by other researchers, for example [5], it is noted that in water-saturated sandy soils, the damping ratio increases linearly with an increase in the porosity coefficient.

B. Influence of Acidity of the Medium on the Shape of the Dependence of the Shear Modulus and Damping Ratio with Shear Strain

The nature of the influence of the acidity of the medium on the damping properties are considered in the work of Yu. Wang and V. Sue [42]. It is noted that the minimum value of the damping ratio decreases with decreasing soil pH.

C. Influence of the number of load cycles on the shape of the dependence of the shear modulus and damping ratio with shear strain.

Iwasaki [18], [19] and Kokusho [22] also studied the effect of the number of load cycles on the change in the dynamic parameters of Toyora sand. According to the research results obtained, the values of the shear modulus obtained during the 2nd and 10th load cycles differ by no more than 10% with a shear strain of up to $10^{4}$. Approximately the same dependence is characteristic of the damping ratio. It should be noted that when the number of cycles exceeds 10, the influence of their number becomes insignificant. Hence, an important conclusion follows that in almost all cases of calculating the response of sandy soil to seismic effects, it is possible to neglect the change in shear modulus and damping ratio due to an increase in the number of load cycles. An exception is the case of undrained sandy soil with large shear strain, at which there is a significant increase in pore water pressure [2].

The effect of compression stress from deformation was studied by Japanese scientists [18], [19], [22], [37]. In particular, Kokusho [22] generalized the results of studies on triaxial cyclic compression. The samples were compacted under a pressure of 20...300 kPa and then subjected to cyclic axial loading without drainage. According to the research results, it was found that the rate of decrease in the shear modulus increases along with deformation with a decrease in compressive stresses. This pattern can be explained by considering the dependence of the compressive stress on the strength and the initial shear modulus $G_{0}$.
D. Theoretical Explanation of the Change in the Shape of the Curves of the Shear Modulus and the Damping Ratio with Shear Strain when a Decrease in Uniform Compression

Let the sand strength be expressed through the Coulomb-Mohr fracture criterion:

\[ \tau_f = \sigma'\gamma g\phi, \]  \hspace{1cm} (1)

where \( \phi \) is the angle of internal friction.

The formula for calculating the shear modulus at small deformations will be written as:

\[ G_o = 8400 \frac{(2.17 - e)^2}{1 + e} (\sigma'_u)^{0.5} \]  \hspace{1cm} (2)

where \( e \) – is the porosity coefficient.

Substituting (1) and (2) into the equation for determining the reference strain \( \gamma_r = \tau_f/G_o \), we obtain for clean sands the ratio of the reference strain to the compression stress:

\[ \gamma_r \sim (\sigma'_u)^{0.5} \]  \hspace{1cm} (3)

From equation (3) it can be seen that the reference strain increases with the stress of uniform compression. Accordingly, an increase in the compressive stress leads to an increase in the shear modulus at a given level of deformation, which is confirmed by the results of empirical studies.

The damping characteristics for Toyora sand obtained during similar studies are presented in [22]. Their analysis shows that the damping ratio increases with decreasing compression stress. This fact becomes clear if we assume that the damping ratio is related to the modulus ratio \( G/G_0 \) by the dependence:

\[ D = \frac{2r - 1}{\pi r + 1} \left( 1 - \frac{G}{G_0} \right) \]

The research results presented in works [18], [19], [22], indicate the presence of a relationship between the ratio of the shear moduli \( G/G_0 \), the damping ratio \( D \), and the amount of shear strain \( \gamma \), which is taken as an operating parameter.

E. Influence of Drainage on the Shape of the Curves of the Shear Modulus and Damping Ratio with Shear Strain

The results of the above studies describe the response of sand to cyclic loading in undrained conditions. Kokusho [22] also carried out a series of triaxial loading of samples in the presence of drainage. The results of these studies showed that at strain values from \( 10^{-6} \) to \( 5 \times 10^{-3} \), drainage practically does not affect either the shear modulus or the damping characteristics of Toyora sand. This is quite logical if we take into account that the effect of dilatancy begins to manifest itself when the strain exceeds the values of \( 5 \times 10^{-3} \) [2].

F. Investigation of the Influence of the Plasticity Number of Clay Rocks on the Shape of the Curves of the Shear Modulus and Damping Ratio with Shear Strain

Large-scale laboratory studies to identify the dependence of the strain characteristics of cohesive soils on deformation have been carried out by many researchers. The main results are presented in papers [9], [13], [24], [31], [33], [38] etc. All of them indicate that the shear modulus for clays decreases significantly when stresses exceed the elastic threshold.

When conducting comprehensive studies on samples of five types of clays with an undisturbed structure, Anderson and Richart [6] found that clays with a small number of plasticity (from 20 to 45), selected by researchers in US laboratories, were characterized by the value of undrained shear strength in the range of 70...85 kPa. Only one clay sample had a shear strength of 15 kPa. The generalized results of studies using a device for resonance testing of soil columns, published in [6], [8], show that the shear modulus begins to decrease when the strain exceeds \( 5 \times 10^{-5} \). This phenomenon is not manifested in the behavior of non-cohesive soils, where the shear modulus begins to decrease when the deformation exceeds values of about \( 10^{-5} \).

In the work of Andreasson [7], [8], the results of studies of the strain-dependent shear modulus on plastic clay samples taken at three sites in the region of Gothenburg (Sweden) are presented. The plasticity number of the clays varied from 20 to 60. Samples of the undisturbed structure were examined in the laboratory using an instrument for resonance testing of soil columns. From the results of field and laboratory studies presented in [7], [8] on the change in the value of the shear modulus for clays at different levels of deformation, it follows that the curve of the decrease in the shear modulus of Gothenburg clay is similar in shape to the curve on the graph constructed by Andersen and Richard [6] for American clay samples.

In the work of Kim, Novak [21], [22], and Kokusho [23], the results of studies of the effect of the stress of uniform compression on the change in the shear modulus and damping ratio under conditions of sample consolidation with an increase in the shear strain are presented. According to the results of cyclic tests, it is indicated [23] that a change in the stress of uniform compression in the range from 45 to 500 kPa practically does not affect the deformation of cohesive soils of an undisturbed structure with a plasticity number of 35–55 turned out to be insignificant.

It was shown in [18], [19] that the decrease in the shear modulus is influenced by the effective stresses of uniform compression, especially for soils with low plasticity: with an increase in the effective stresses of uniform compression, the threshold of "nonlinear behavior" appears at high values of shear deformation.

G. Theoretical Dependence of Effective Compressive Stresses \( \sigma_m \) and Plasticity Index \( PL \) on Shear Modulus \( G \)

In [17], a theoretical analysis of the dependence of the effective stresses of uniform compression \( \sigma_m \) and the plasticity index \( PL \) on the shear modulus \( G \). The dependence has the form:

\[ \frac{G}{G_{max}} = K(\gamma, PL)(\sigma'_u)^{m(\gamma, PL)} - \beta, \]

where \( K(\gamma, PL) = 0.5 \left[ 1 + \tanh \left( \frac{0.000102 + m(PL)}{\gamma} \right) \right]^{0.492} \),

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As a result of a series of studies carried out on samples of crushed rocks [23], a tendency to a decrease in the shear modulus and an increase in the damping ratio with an increase in shear strain was found. It was also confirmed by the research of Studer [29].

The results of studies of the effect of the magnitude of compression on the shear modulus and on the damping ratio on samples with 25 and 50% gravel content, presented in [36], indicate a high degree of nonlinearity of the behavior of such soil even at low stresses of uniform compression. This is explained by a sharp decrease in the shear modulus and an increase in the damping ratio with decreasing stresses. Shear modulus and damping ratio begin to change at a low level of a shear strain than is observed in previously considered cohesive and non-cohesive soils. With an increase in the number of loading cycles, the shear modulus begins to decrease at a low level of strain. However, these soil properties are not constant. They only characterize a specific state.

As a result of the analysis of a large amount of experimental data presented in [35], [41], etc., it was concluded that the shape of the shear modulus decrease curve is more influenced by the value of the plasticity index than other indicators.

After analyzing a large number of results of dynamic tests of various clay soils, Vucetic [39], [40] proposed a relationship that links the threshold shear deformation and the number of plasticity for such soils. According to the established dependence, the damping ratio begins to increase when the shear strain leaves the elastic section.

Based on the results of the work performed, the dependences of the shear modulus and the damping ratio on the magnitude of the shear strain for soils with different plasticity indices Pl are plotted in Fig. 1 and 2.

According to many authors [26], [41] etc., it is the plasticity number that can affect the change in the shear modulus and damping ratio. It is it that controls the shape of the curves of the shear strain-dependent damping ratio. The study of Lanzo [26] for clays with plasticity numbers 15 and 30 showed that under the same conditions, a lower plasticity number, as a rule, corresponds to a higher damping ratio. This is clearly manifested when the amplitude of the shear strain starts from 0.01%. In [23], [44], it was noted that the shear moduli of soils with high plasticity decrease more slowly than the shear moduli of low plastic soils.

**I. Strain Characteristics of Gravel Sands**

The results of studies of the strain characteristics of sands with gravel content are presented in the work of Studer [34]. His research was prompted by the need to study the seismic hazard of sites for the construction of such important facilities as retaining dams and nuclear power plants. The selected samples were compacted into molds with a diameter of 15 cm and a height of 30 cm, less than for clean sands. Therefore, when modeling the response of the soil to seismic effects, taking into account nonlinear properties, when choosing for calculations the dependence of the shear modulus on strain for gravelly soils, one should not use the dependencies obtained for sands, which, for example, was allowed in [32] etc. The damping ratio for gravelly soils begins to increase at approximately the same level of deformation, and for sandy ones.

As a result of a series of studies carried out on samples of crushed rocks [23], a tendency to a decrease in the shear modulus and an increase in the damping ratio with an increase in shear strain was found. It was also confirmed by the research of Studer [29].

![Fig. 1. Shear strain-dependent shear modulus for clay soils with different plasticity indices (according to [41]).](http://dx.doi.org/10.24018/ejgeo.2021.2.3.142)
From the graphs in Fig. 1 and 2, based on the results of studies [41], it can be seen that the threshold of “nonlinear behavior” of soils with high plasticity is in the area of higher values of a shear strain than for soils with low plasticity. This conclusion is important in predicting the response of the soil to seismic impacts.

For practical use, it can be assumed that for soils with a plasticity index $PL = 0$, the dependence of the shear modulus and damping ratio on the amplitude of shear strain will be close to a similar dependence for coarse-grained soils.

Based on the results of studies carried out in the 90s of the XX century, Idriss [15] refined the dependences $G(\gamma)$ and $D(\gamma)$ presented in [41] for soils with the plasticity index $PL = 30$, 50, and 100. Differences in the values of the dependences $G(\gamma)$ and $D(\gamma)$ from [41] and [15] are presented in Tables I and II.

### TABLE I. THE RATIO OF THE SHEAR MODULUS G TO THE MAXIMUM VALUE $G_{\text{Max}}$ FOR SOILS WITH DIFFERENT PLASTICITY AT DIFFERENT VALUES OF SHEAR STRAIN ACCORDING TO THE DATA [41] AND [15]

| Shear strain (%) | $Pl=30$ | $Pl = 30$ | $Pl=50$ | $Pl = 50$ | $Pl=100$ | $Pl = 100$ |
|------------------|---------|----------|---------|----------|---------|----------|
| [41]             | [15]    | [41]     | [15]    | [41]     | [15]    | [41]     |
| 0.0001           | 0.0001  | 0.0001   | 0.0001  | 0.0001   | 0.0001  | 0.0001   |
| 0.0005           | 0.0005  | 0.0005   | 0.0005  | 0.0005   | 0.0005  | 0.0005   |
| 0.001            | 0.001   | 0.001    | 0.001   | 0.001    | 0.001   | 0.001    |
| 0.003            | 0.003   | 0.003    | 0.003   | 0.003    | 0.003   | 0.003    |
| 0.01             | 0.01    | 0.01     | 0.01    | 0.01     | 0.01    | 0.01     |
| 0.03             | 0.03    | 0.03     | 0.03    | 0.03     | 0.03    | 0.03     |
| 0.1              | 0.1     | 0.1      | 0.1     | 0.1      | 0.1     | 0.1      |
| 0.3              | 0.3     | 0.3      | 0.3     | 0.3      | 0.3     | 0.3      |
| 1                | 1       | 1        | 1       | 1        | 1       | 1        |
| 3                | 3       | 3        | 3       | 3        | 3       | 3        |
| 10               | 10      | 10       | 10      | 10       | 10      | 10       |

### TABLE II. DAMPING RATIO FOR SOILS WITH DIFFERENT PLASTICITY AT DIFFERENT VALUES OF SHEAR STRAIN ACCORDING TO THE DATA [41] AND [15]

| Shear strain (%) | $Pl=30$ | $Pl = 30$ | $Pl=50$ | $Pl = 50$ | $Pl=100$ | $Pl = 100$ |
|------------------|---------|----------|---------|----------|---------|----------|
| [41]             | [15]    | [41]     | [15]    | [41]     | [15]    | [41]     |
| 0.0001           | 0.01    | 0.01     | 0.01    | 0.01     | 0.01    | 0.01     |
| 0.0005           | 0.03    | 0.03     | 0.03    | 0.03     | 0.03    | 0.03     |
| 0.001            | 0.3     | 0.3      | 0.3     | 0.3      | 0.3     | 0.3      |
| 0.003            | 1.4     | 1.4      | 1.4     | 1.4      | 1.4     | 1.4      |
| 0.01             | 3.7     | 3.7      | 3.7     | 3.7      | 3.7     | 3.7      |
| 0.03             | 5.8     | 5.8      | 5.8     | 5.8      | 5.8     | 5.8      |
| 0.1              | 8.6     | 8.6      | 8.6     | 8.6      | 8.6     | 8.6      |
| 0.3              | 12.25   | 12.25    | 12.25   | 12.25    | 12.25   | 12.25    |
| 1                | 16.86   | 16.86    | 16.86   | 16.86    | 16.86   | 16.86    |
| 3                | 20.80   | 20.80    | 20.80   | 20.80    | 20.80   | 20.80    |
| 10               | 24.00   | 24.00    | 24.00   | 24.00    | 24.00   | 24.00    |

From Tables I and II it can be seen that the shear modulus in [41] and [15] differ, starting with a shear strain above 0.003%, and the damping ratio, according to [15], is much less than the damping ratio determined from the data of [41] at strain values in the range of 0.0001% ÷ 0.1%. The indicated difference in the values of the shear modulus and the damping ratio obtained in different years indicates the need to use as much new data as possible when calculating the response of the soil to seismic effects. As a rule, data were obtained in the last century less accurate due to the use, as it turned out later, of insufficiently accurate equipment and data processing methods. Changing the parameters in the specified range of shear deformation can make significant adjustments to the results of calculations of seismic effects for areas in weakly seismic areas, which include a significant part of Ukraine.

### J. Influence of Particle Size and Percentage in Sandy Rocks on Shear Modulus and Damping Ratio

The results of studies of the effect of the particle size of sandy rocks with different percentages on the dependences $G(\gamma)$ and $D(\gamma)$ are presented in [28]. In Fig. 3 and 4 show the graphs of the dependence of the shear modulus and the damping ratio based on the data of [28].

![Fig. 3. Shear strain-dependent shear modulus for soils with a content of less than 30% of particles with sizes $d <0.075$ mm for different depths of soil layers (according to [28]).](image-url)
It is noted in [43] that the shear strain-dependent shear modulus and damping ratio, calculated using records of real earthquakes, are in good agreement with the curves obtained in laboratory and field conditions. Due to this, the stock and published empirical curves shear strain-dependent shear modulus and damping ratio, collected over the last period of time (1996-2016) in the database, can, with a high level of reliability, be used in modeling the response of soils to seismic effects, taking into account the nonlinear properties of soils.

III. INFLUENCE OF ERRORS ARISING WHEN CHOOSING THE CURVES OF THE STRAIN-DEPENDENT SHEAR MODULUS AND DAMPING RATIO ON THE FREQUENCY RESPONSE OF THE SOIL

The paper investigates the influence of errors introduced when choosing the appropriate curves of the strain-dependent shear modulus and damping ratio on the parameters of the calculated frequency response of the soil model.

In Fig. 5 shows the amplitude-frequency characteristic of the soil under the construction site in Kyiv, calculated using equivalent linear modeling using the PROSHAKE software product. The nonlinear properties of the layers of the soil model were approximated by the curves $G(\gamma)$ and $D(\gamma)$ in two ways: 1) taking into account the lithological composition and physical and mechanical properties of each layer, 2) without taking into account the lithology and physical and mechanical properties of each layer (i.e., with errors in the description of the physical and mechanical properties and lithology of the soil model).

Fig. 5 it can be seen that in the case when the lithological composition and physical and mechanical properties when approximating the nonlinear characteristics of each of the layers by the curves $G(\gamma)$ and $D(\gamma)$ are set with errors, in the calculated frequency response of the soil in the frequency range from 1 to 10 Hz additional maxima appear and an increase in the amplification is observed at all maxima. Table 3 shows the numerical values of the maxima of the frequency response (amplification) shown in Fig. 5.

![Fig. 5. The frequency response of the soil under the construction site in the Pechersk district of Kyiv was calculated taking into account the nonlinear properties of soils: 1) the choice of the curves $G(\gamma)$ and $D(\gamma)$ was carried out taking into account the lithology of each of the layers, 2) the curves $G(\gamma)$ and $D(\gamma)$ are calculated with the presence of errors in the lithological composition of the layers of the soil strata.](image)

The following follows from the table. If the approximation of the layers of the soil model by the curves $G(\gamma)$ and $D(\gamma)$ was carried out with errors in the description of the lithological composition and physical and mechanical properties of each layer, then the calculation of the frequency response can lead to results with significant errors, namely:

- to the appearance of a larger number of frequency response maxima (some of which will be false)
- to an uncontrolled shift of the frequency response maxima, both towards lower frequencies and towards higher frequencies;
- to a significant change in the gain.

Investigation of the influence of relative errors, which are contained in the curves $G(\gamma)$ and $D(\gamma)$, obtained without using an improved hardware-methodological base, for example [31], and using similarly refined curves from [28], lead to the results shown in fig. 6. When calculating the frequency response, a model of soil strata under the construction site in Kyiv was used. The calculation was performed using an equivalent linear simulation using the PROSHAKE software.

![Fig. 6. The frequency response of the soil under the construction site in Kyiv is calculated taking into account the nonlinear properties for soil layers composed of sands according to the data: a) [28]; b) [31].](image)

| Frequency Hz | Amplification factor | Frequency Hz | Amplification factor |
|--------------|---------------------|--------------|---------------------|
| 1            | 0.44                | 0.56         | 11.37226            |
| 2            | 1.32                | 1.2          | 9.7236              |
| 3            | -                   | 3.58         | 2.58074             |

TABLE III: NUMERICAL VALUES OF FREQUENCY RESPONSE PRESENTED IN FIG. 5

Using curves $G(\gamma)$ and $D(\gamma)$ taking into account the lithological composition and physical and mechanical properties of each layer

Using curves $G(\gamma)$ and $D(\gamma)$ without taking into account the lithology and physical and mechanical properties of each layer (i.e. with errors in the description of the physical and mechanical properties and lithology of the soil model).
formulated.
- When using outdated numerical curves $G (\gamma)$ and $D (\gamma)$, one can underestimate the frequency range of the resonant amplification of seismic motions.
- The curves $G (\gamma)$ and $D (\gamma)$, obtained from the results of laboratory and field studies using an imperfect instrumental and methodological base, require clarification of information on the main parameters that determine the nature of the curves of the strain-dependent shear modulus and damping ratio: number plasticity for clay rocks, particle size and percentage for sandy rocks.

IV. CONCLUSIONS

Under conditions of significant seismic loads, the strain characteristics of the soil become nonlinear. This property of soils is expressed through the shear modulus $G$ and the damping ratio $D$, the values of which can vary significantly, depending on the amplitude of the shear strain $\gamma$. In the case of equivalent linear and nonlinear modeling of the soil response to a possible earthquake, it is necessary to specify additional parameters for each layer in the calculated seismogeological models of the soil, which characterize the nonlinear properties of soils, namely, the curves $G (\gamma)$ and $D (\gamma)$. It is practically impossible to obtain such curves in laboratory or field conditions for each layer of soil in the upper part of the section under the construction site under the conditions of Ukraine. In this regard, it is necessary to use stock and published materials.

The results of a detailed study of research materials on changes in the values of the dynamic parameters of soils with strain are summarized in the database on the curves $G (\gamma)$ and $D (\gamma)$ for various types of soils characteristic of sites located on the territory of Ukraine. On its basis:

- the influence of the lithological composition and physical and mechanical parameters of the soil on a decrease in the shear modulus and an increase in the damping ratio was investigated;
- the main parameters are highlighted by which it is possible to effectively approximate the nonlinear properties of each of the layers of the soil profile model by the corresponding curves $G (\gamma)$ and $D (\gamma)$: for clayey rocks, this is the plasticity index PL and the depth of occurrence; for sandy rocks - particle size, percentage, and depth;
- the influence of relative errors that may arise when choosing the curves $G (\gamma)$ and $D (\gamma)$ for the soil layers of the computational seismic-geological model on the parameters of its frequency response has been investigated.

The methodological approach to the formation of computational seismic-geological models of soil strata, by introducing the curves $G (\gamma)$ and $D (\gamma)$, which reflect the nonlinear properties of the soil, makes it possible to improve the computational methods for determining the resonance properties of soils under construction sites. The most accurate values of the frequency characteristics of the soil strata under construction sites are necessary for the development of effective measures to ensure the seismic resistance of the designed and existing facilities.

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