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Interaction of the base and construction under seismic action, with considering various characteristics of soil damping

Evgeny Sobolev* and *Armen* Ter-Martirosyan

Moscow State University of Civil Engineering, Yaroslavskoe shosse, 26, Moscow, 129337, Russia

Abstract. In this paper, we determine the characteristics of the physical damping of sand and clay soil by the results of special laboratory tests. The transition from parameters obtained directly from the results of triaxial dynamic tests to parameters of mathematical models of soils used in modern software complexes is shown. The solution of several dynamic FEM problems is exemplified by PLAXIS PC taking into account different damping characteristics of the ground base of a multi-storey building with a developed underground part. Recommendations are given for selecting a soil model for dynamic impact and dynamic soil parameters, and an analysis of the solutions obtained.

1 Introduction

For the qualitative and quantitative description of the stress-strain state and the interaction of the «foundation – construction» system under dynamic loads, it is required to determine the dynamic properties of soils with subsequent use of these properties in numerical modelling, the results of which will then be analyzed and used to develop structures and technology of erection underground part of buildings and structures [1, 2].

The experience of numerical simulation by the finite element method of various dynamic problems of interaction between the base and the structure shows that the main characteristic affecting the result is the physical damping of the system, that is, the ability to absorb the forced oscillations applied to it [3, 4, 5]. In geotechnical software complexes (PC), this phenomenon is most often modelled by Rayleigh damping, the quantitative characteristics of which are the proportionality coefficients α and β, which depend on the proper cyclic frequencies and the modal damping of the modes of natural oscillations.

In finite element calculations (FEM), when carrying out a geotechnical forecast, the dynamic properties of soils are either specified in accordance with the recommendations of software developers, or are not specified at all. Meanwhile, the damping characteristics of the ground base and the materials from which the structures of the aboveground and underground parts of the building are erected play an important role in the dynamic analysis of the «foundation – structure» system. This situation reduces the reliability and reliability

* Corresponding author: e.s.sobolev@mail.ru

of the geotechnical forecast of the «foundation – construction» system under dynamic impacts.

In this paper, we determine the characteristics of the physical damping of sand and clay soil by the results of special laboratory tests. The transition from parameters obtained directly from the results of triaxial dynamic tests to parameters of mathematical models of soils used in modern software complexes is shown. The solution of several dynamic FEM problems is exemplified by PLAXIS PC taking into account different damping characteristics of the ground base of a multi-storey building with a developed underground part. The recommendations for choosing a soil model for dynamic impact and dynamic soil parameters are presented, as well as an analysis of the solutions obtained.

2 Dynamic tests of soils

Dynamic parameters of the soils of the foundations of buildings and structures can be determined in laboratory conditions following the results of special tests. The main installations for such tests are triaxial compression devices with the possibility of creating static and dynamic loads (dynamic stabilometers, figure 1), as well as triaxial compression devices with the possibility of creating torsion oscillations (resonance columns, figure 2).

Fig. 1. Dynamic triaxial machine (laboratory REC «Geotechnics» NRU MSUCE)

Fig. 2. Resonance column (laboratory REC «Geotechnics» NRU MSUCE)

In the present work, the results of a series of sand and clay soil tests performed in a dynamic stabilometer are used. A laboratory installation was used, which is a servo-hydraulic load frame with a maximum axial force of 63 kN, a triaxial compression type «A» chamber, a servo-hydraulic drive control unit, a data processing unit coming from pressure, force and displacement sensors, a pneumatic pressure control unit and a personal computer , through which the initial data for the test are given and information on the progress of the test is displayed, as well as its results.

The software of the facility allows in automatic mode to carry out triaxial tests of soils under different loading paths for given initial geometric parameters of the soil sample and the characteristics of static and dynamic effects. The measuring channels of the installation, in addition to the standard equipment provided by GOST 12248, include the control of vertical displacements on the local sample base (two LVDT-sensors, which are fixed diametrically opposite to the sample at a distance of half its height - the range of displacement measurements: 0–10 mm, accuracy measuring deformations 10^{-5}) and changing the circumference of the specimen at the half-height level (LVDT-sensor attached to the chain - measuring range 0–10 mm, strain measurement accuracy of 10^{-5}).

The specified features of the equipment allow carrying out static and dynamic tests of soils to determine the parameters of soil models in the range of small deformations (up to 10^{-4} %). Determination of soil parameters is performed in accordance with the national Russian standards GOST 12248, GOST 56353 and the American standard ASTM D3999 on the graphs of strain loops built in the coordinates «shear stress τ - shear deformation γ».

3 Calculation of soil parameters

Dynamic shear modulus G_d and attenuation (damping) factor D are calculated according to formulas

$$G_d = \tau_a / \gamma_a \ , \tag{1}$$

where G_d - shear modulus, in kPa; τ_a - shear stress amplitude τ, in kPa; γ_a - shear strain amplitude γ, in u.f.

$$D = \Delta W / \left(4\pi W \right), \tag{2}$$

where D - coefficient of damping, in u.f.; ΔW - loss of energy in one «load – unload» cycle, quantitatively equal to the area of the hysteresis loop; W - maximum stored energy per cycle.

Measurements of the vertical displacements of the sample on the local base make it possible, at the initial stage of the deviator loading of the sample, to determine the shear modulus at small deformations of G_0 (at $\varepsilon \le 10^{-4}$), and also the value of the threshold deformation $\gamma_{0.7}$, which are used in the hardening soil model for small deformations or HSS.

The shear modulus for small deformations was calculated using the following formula

$$G_0 = \Delta\tau / \Delta\gamma \ , \tag{3}$$

where $\Delta\tau$ - change in shear stresses; $\Delta\gamma$ - change in shear strain.

A shear deformation of $\gamma_{0.7}$ is adopted as the threshold, at which the shear modulus is reduced to 70% of its initial value G_0.

Calculation of the Rayleigh damping parameters was performed on the basis of work [6] by calculating the coefficients α and β for calculating soil mass oscillations on the basis of the stiffness data ($G_0, \gamma_{0.7}$) and damping properties of soils (D) obtained from laboratory soil tests.

If the coefficients α and β are known, then the damping of the soil D is calculated as follows

$$D = \frac{1}{2f}\alpha + \frac{f}{2}\beta \ , \tag{4}$$

where $f_1 = \hat{f}$, $f_2 = \sqrt{R}\,\hat{f}$, $f_3 = R\,\hat{f}$ at parameter $R > 1$.

Let us give an example. For clay soil (plasticity index $I_p = 0,2$, density $\gamma = 18$ kN/m^3, modulus of deformation $E = 20$ MPa) at a frequency of dynamic action from 0,25 Hz to 1 Hz, in the range of deformations $10^{-3}...10^{-4}$, with the coefficient damping 0,1 the Rayleigh parameters determined by the presented procedure are R = 4; α = 0,0444 and β = 0,1778. These parameters were subsequently used in dynamic numerical calculations of the PLAXIS PC.

4 Numerical simulation of a dynamic problem

The essential influence of Rayleigh parameters on the behavior of the soil massif is illustrated by calculating the natural oscillation frequency of a nine-story building under the influence of a seismic load and free oscillations.

The building has nine over ground floors and two underground floors. Its width is 10 m, and the height together with the underground part is 33 m (the height from the base level is 9×3 = 27 m, the height of the underground floors is 3 m). The load from the self-weight of the floors is assumed to be 5 kN/m^2. The building is built on a layer of clay soil (layer No. 1) with a thickness of 15 m, under which the sand layer lies to a greater depth. In the model, we will take into account the upper 25 m layer of sand (layer No. 2). Both soils are modeled using a hardening soil small strain (HSS) model. The main physical and mechanical properties of soils are presented in Tables 1 and 2. Consider several calculation cases in which soils have different hysteresis damping conditions.

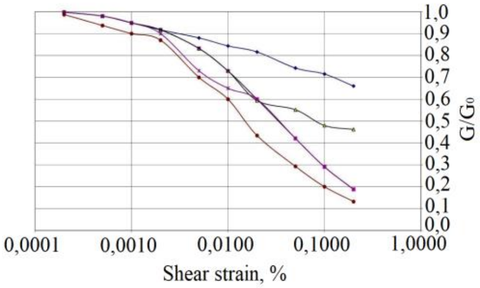
Table 1. Soil parameters (model HS)

Name of the soil layer	Secant modulus [kN/m^2]	Tangential odometric module with primary loading [kN/m^2]	Stiffness during unloading / reloading [kN/m^2]	Angle of internal friction [°]	Cohesion [kN/m^2]
Upper clay layer	$2.0\cdot10^4$	$2.561\cdot10^4$	$9.484\cdot10^4$	18	10
Lower sand layer	$3.0\cdot10^4$	$3.601\cdot10^4$	$1.108\cdot10^5$	28	5

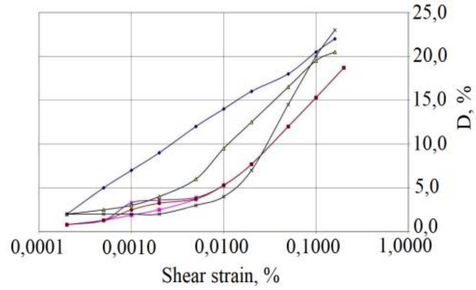
Table 2. Additional soil parameters (model HSS)

Name of the soil layer	Shear modulus for small deformations [kN/m^3]	$\gamma_{0,7}$ [-]	The exponent for the dependence of rigidity on the stress level [-]	Poisson's ratio [-]
Upper clay layer	$2.7\cdot10^5$	$1.2\cdot10^{-4}$	0.5	0.2
Lower sand layer	$1.0\cdot10^5$	$1.5\cdot10^{-4}$	0.5	0.2

When a seismic load is applied, which is characterized by shear strains, the HSS model exhibits hysteresis characteristics. As the shear strain amplitude increases, the actual shear stiffness will decrease in comparison with the stiffness at small deformations, while the damping of the system, characterized by the damping coefficient, will increase. Figure 3*a* shows the curves characterizing the decrease in the shear modulus as the strain increases. Figure 3*b* shows the dependence of the damping coefficient on the shear strains for soils used in numerical simulation. The curves were obtained from the results of several series of soil tests in the laboratory. A more detailed description of the decrease curves of the shear modulus and the order of the transition from it to the damping curve can be found in the literature [7, 8, 9, 10].



a



b

Fig. 3. Dependence of the normalized shear modulus (*a*) and the damping coefficient (*b*) on shear strains. Received according to the results of special experiments in the laboratory of REC «Geotechnics» NRU MSUCE

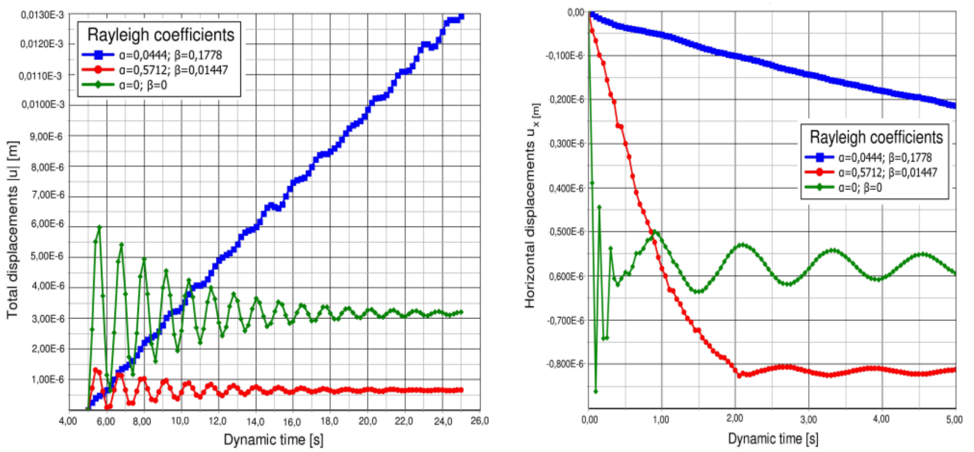
Plates representing the walls and floors of the building are linearly elastic. To illustrate the free vibrations of the building, two different data sets were used: the underground structures of the building are more rigid than the above-ground ones. Physical damping of oscillations in the building is modeled by means of Rayleigh damping. Parameters are taken in accordance with the recommendations [12].

The results of the calculations presented in Figures 4 and 5 are performed for various versions of the problem of the interaction of the base and the structure under seismic action. In the first case, there was no damping of the ground base (Rayleigh parameters $\alpha = 0$ and $\beta = 0$). In the second case, damping was set in accordance with the recommendations of PC developers ($\alpha = 0,5712$ and $\beta = 1,447 \cdot 10^{-3}$). In the third case, damping was set in accordance with the results of laboratory investigations ($\alpha = 0,044$ and $\beta = 1,778 \cdot 10^{-1}$).

A comparative analysis of the presented variants shows that the damping characteristics significantly influence the damping of the oscillations with time as a result of energy absorption in the base soil (Figure 4 *b*) and the building structures (Figure 4 *a*). In this case, if the parameters obtained from the results of laboratory experiments are taken into account, undamped horizontal displacements of the superstructures are observed at the level of the upper floor (mark +27.00 relative to the ground level). Probably, this feature is due to a slight dampening of the base, and as a consequence, a large period of damping of free oscillations after the end of the phase of forced oscillations (seismic action).

The deformed net of finite elements clearly shows the result of free oscillations of the superstructure after the end of the seismic action (Figure 5). This image is exaggerated 200 times the normal scale. Analysis of the forms of free oscillations shows that the damping has a significant effect on the magnitude of displacements of the superstructures during the phase of free oscillations. It is noted that the greater the damping of the ground base, the smaller the values of the total displacements of superstructures are nabbed in the end.

Here we give only the main results. Undoubtedly, the obtained data need additional analysis and will be presented in the future works of the authors of this article.



a *b*

Fig. 4. *a*) Dependence of total displacements on time at the top of the building. The phase of free oscillations after the seismic action. *b*) Dependence of shear strain on time at the bottom of the foundation. Phase of seismic action Results of calculations in PC PLAXIS 2D 2018.0

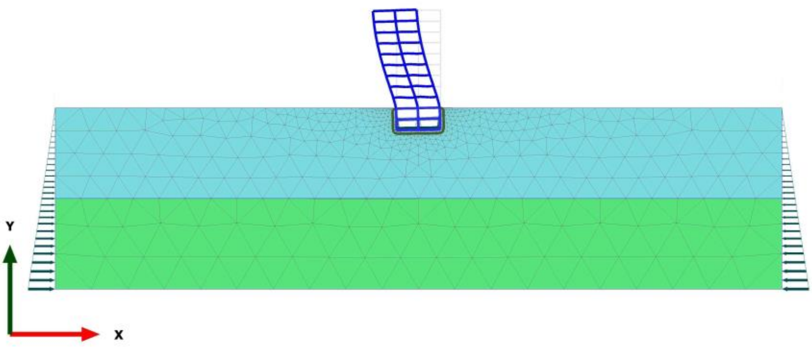


Fig. 5. Deformed mesh of finite elements. The phase of free oscillations after the seismic action. Results of calculations in PC PLAXIS 2D 2018.0

5 Conclusions

The construction of industrial and civil buildings and structures in complex engineering and geological conditions requires increased attention to engineering surveys that precede the design stage. For the foundations of multi-storey buildings and unique structures, special types of studies of soil properties are required to describe the operation of the «foundation – construction» system. Especially often, such special research should be carried out if the designed structure is subjected to dynamic effects of various genesis, both natural (seismic impacts, wave effects on hydraulic structures) and technogenic (heavy transport and mechanisms, explosive effects).

Summarizing the experience of numerical simulation of geotechnical problems, a thorough analysis of the results of specialized laboratory testing and examination of test problems presented in this paper, allow the following general conclusions.

1. The reliability and accuracy of the geotechnical forecast of the interaction of the foundation-structure system under dynamic influences depends on the precise determination of the mechanical properties of soils, the correct analysis of the results of the

tests performed, the rational approach to mathematical modeling, and the careful consideration of the results of the fulfilled forecast.

2. For the numerical simulation of dynamic problems of the dynamic parameters of the soil should be guided by the results of tests of soil from the site of the construction of the planned facilities, taking tabulated values or recommendation software developers only if preliminary calculations.

3. The account of the physical characteristics of the damping is important not only to analyze the behavior of the system «foundation – structure», but also for the calculation of underground and aboveground structures designed buildings and structures. Selection of materials, physical and mechanical characteristics of structures of buildings and structures, built with due regard for dynamic effects, must be carried out taking into account the interaction of the proposed structure with the base.

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