Analysis of the seismic stability of foundations according to laboratory soil tests

Armen Ter-Martirosyan and Evgeny Sobolev

Moscow State University of Civil Engineering, Yaroslavskoe shosse, 26, Moscow, 129337, Russia
E-mail: e.s.sobolev@mail.ru

Abstract. Seismically hazardous areas are widespread on the territory of Russia. These are the North Caucasus, Altai, Sayan, Eastern Siberia, Kamchatka, Sakhalin. The issues of earthquake-resistant construction in difficult engineering and geological conditions, design in new earthquake-prone zones and construction in already developed territories are important aspects of the increasing intensity of development. Against this background, the problem of assessing the dynamic stability of soils becomes a priority task of modern soil dynamics and geotechnics. The article focuses on highlighting the main stages of the analysis of the dynamic stability of the foundations of structures of increased responsibility, taking into account complex geological conditions. The work contains the theoretical foundations of the methodology for assessing stability under dynamic loads, a description of laboratory equipment and test methods, the process of processing the experimental results. The study uses the results of assessing the dynamic stability of foundations obtained in the course of practical activities of the Scientific and Educational Center “Geotechnics” of the Moscow State University of Civil Engineering.

1. Introduction
The main goals of earthquake-resistant construction are the construction of foundations, taking into account the necessary safety margins in case of earthquakes, as well as reducing the possible costs of strengthening the foundations to ensure a given level of strength and stability. When designing such foundations, an assessment of the dynamic stability of soils is required. Currently, there are many different methods for such an assessment, both field tests and laboratory ones. Each method has its advantages and disadvantages. In this work, we will use the results of laboratory tests. The task of such tests is to determine the relationship between the load acting during an earthquake and the dynamic strength of soils.

2. Methods
The most dangerous type of dynamic action during an earthquake is shear stress. The dynamic shear stresses acting in the soil during an earthquake when a shear wave passes from below can be determined using the method proposed in the studies of Sid H.B. and Idriss I.M. [1-6]. It is assumed that a soil massif with a height $h$ in an earthquake moves horizontally. In this case, the maximum tangential stress $\tau_{\text{max}}$ acting on the lower face of such a massif will depend on the horizontal acceleration $a_{\text{max}}$ on the massif surface and the specific gravity of soils $\gamma$ in accordance with the formula:
max
max dz
a r g  ,

(1)

where: \( a_{\text{max}} \) is the maximum horizontal acceleration at the ground surface during a predicted earthquake, in \( \text{m/s}^2 \); \( g \) is the acceleration of gravity, in \( \text{m/s}^2 \); \( \gamma \) is the specific gravity of the soil, in \( \text{kN/m}^3 \); \( r_d \) is coefficient of stress reduction with depth, taking into account the deformability of the soil mass during an earthquake, the value of which is less than one [7-8].

Figure 1. Results of laboratory tests of soils in the dynamic triaxial compression mode. Dependences of soil shear deformation on shear stress when determining the strength (a) and for the given parameters of seismic action (b).
Since soils are always saturated with water to one degree or another, the pore pressure has a significant effect on the results of determining the effective shear stresses. For water-saturated soil masses, it is necessary to take into account the effective values of the acting stresses. The effective stress values $\sigma'_z$ are obtained by subtracting the pore water pressure from the total effective stress.

Dividing each part of formula (1) by the effective vertical natural stress $\sigma'_z$, we obtain a modified formula that takes into account the distribution of total and effective stresses in the soil mass

$$\frac{\tau_{\text{max}}}{\sigma'_z} = \frac{a_{\text{max}}}{g} \frac{r_d}{r_z} \frac{\sigma_z}{\sigma'_z},$$

where: $\sigma_z = \gamma h$ is the total vertical stress; $\sigma'_z = \sigma_z - u$ is the effective stress, $u$ is the pressure in the pore fluid.

Formula (2) is used in many works [5, 6] when calculating the effective shear stress during an earthquake. Of course, it has many disadvantages, such as the lack of taking into account the duration of the earthquake, the spectrum of operating frequencies, the distance from the epicenter of the earthquake. However, it also has a significant advantage, since there is a significant amount of accumulated data on horizontal accelerations on the ground surface in various seismically hazardous regions.

The analysis of the dynamic stability of soils is carried out on the basis of comparing the shear stresses arising in the soil mass during an earthquake and the dynamic strength of the soil corresponding to the maximum shear stresses in the soil sample at the moment of destruction under the action of a dynamic load. The moment of destruction is considered either the physical destruction of the sample, which usually corresponds to vertical deformations of more than 10% [9], or such a level of deformations that is considered unacceptable for the designed structure [10-11]. Another criterion for sample destruction is a sharp increase in pore fluid pressure. To assess this factor, the concept of reduced pore pressure is used, i.e. the ratio of the pressure of the pore fluid $u$ to the lateral pressure on the ground $\sigma_z$. This parameter is called the pore pressure ratio (PPR) and is determined by the formula:

$$\text{PPR} = \frac{u}{\sigma_z}.$$  (3)

If this value reaches 0.9, then we can talk about dynamic liquefaction.

Using formula (2), it is possible to determine the stress in the soil acting during a predicted earthquake $\frac{\tau_{\text{max}}}{\sigma'_z}$, and the dynamic strength of the soil $\frac{\tau_{\text{max},L}}{\sigma_{z,L}}$ can be determined from the results of laboratory tests of soils in devices of dynamic triaxial compression. Thus, the liquefaction potential $F_L$ can be calculated using the formula [12]:

$$F_L = \frac{\frac{\tau_{\text{max}}}{\sigma'_z}}{\frac{\tau_{\text{max},L}}{\sigma_{z,L}}}.$$  (4)

If the liquefaction potential $F_L$ is less than one, then liquefaction occurs. In all other cases, the soil is dynamically stable [13-16].

The relative level of tangential stresses acting in the soil $\frac{\tau_{\text{max}}}{\sigma'_z}$ is often called the cyclic stress ratio (CSR), and the value of the cyclic strength is called the cyclic resistance ratio (CRR). Most of the field and laboratory dynamic resistance methods are based on comparing CSR and CRR values. Taking these changes into account, formula (4) takes the following form:

$$F_L = \frac{\text{CSR}}{\text{CRR}}.$$  (5)
3. Results
Determination of the dynamic strength of soils [4] according to the results of laboratory research consists in the analysis of tests of dynamic triaxial compression. A cylindrical soil sample with a diameter to height ratio of 0.5 is compacted under the action of an isotropic stress corresponding to natural pressure. Then an initial shear stress is applied to the sample, corresponding to the additional vertical pressure from the designed structure. After stabilization of vertical deformations, a vertical dynamic action is applied to the specimen with a predetermined number of "load - unload" cycles. In this case, several series of vertical loads are performed in the absence of drainage of pore fluid with an increasing amplitude. This process is repeated until the specimen failure conditions mentioned earlier are reached. At the moment of fracture, the maximum shear stress is recorded, which becomes the value of the dynamic strength. The frequency of application and the number of loading-unloading cycles during the tests depend on the parameters of the design earthquake and are determined by seismic zoning.

![Figure 2](image.png)

**Figure 2.** Graphical representation of the assessment of the dynamic stability of soils. Dependences CRR (red line) and CSR (blue line) (a) and liquefaction potential (b) on the distance to the soil surface.

Comparison of the results of determining the dynamic strength and the values of the predicted shear stresses during an earthquake can be represented in graphical form in the form of a diagram of the liquefaction potential with the distribution along the depth of the studied soil mass (Figure 2)

In such studies, it should be borne in mind that the possibility of dynamic instability of soils decreases with increasing depth. The generally accepted is the depth of the studied soils up to 20 - 25 m [6]. Deeper, as a rule, the danger of dynamic instability does not arise [7-8] due to significant natural pressure.

4. Conclusions
Based on the results of tests, the following conclusions can be drawn:
A geotechnical forecast when designing buildings in difficult geological conditions and taking into account the increased responsibility of buildings cannot be carried out without taking into account the dynamic stability of soils.

To analyze the dynamic stability of soil massifs during earthquakes, it is necessary to assess the level of design impact and the dynamic strength of soil.

Having completed the calculation of the effective shear stresses, it is necessary to correlate them with the dynamic strength obtained from the results of special laboratory dynamic soil tests.

The specified method for assessing the dynamic stability of foundations makes it possible to take into account a significant amount of accumulated data on the characteristics of seismic impact (frequency of impact, frequency, acceleration, magnitude, duration of impact, etc.)

The technique makes it possible to estimate the potential for liquefaction, taking into account the distribution over the depth of the soil massif and to highlight the thickness of the soil, which, during an earthquake, may lose dynamic stability.

References
[1] Voznesensky E.A., Funikova V.V., Kushnareva E.S., Kovalenko V.G. Seismic liquefaction of soils: mechanism, consequences and engineering assessment for the purposes of seismic microzoning of the territory / Exploration and protection of subsoil, No. 12, 2005 - pp. 61-65. (In Russian)
[2] Mirsayayov I.T., Koroleva I.V., Zaripova G.Z. Assessment of the seismic stability of the bases composed of clays and water-saturated sandstones. Soil mechanics in geotechnics and foundation engineering: materials of the international scientific and technical conference, Novocherkassk May 13-15, 2015 / South-Russian State Polytechnic University (NPI) named after M.I. Platova. - Novocherkassk: SRSPU (NPI), 2015 - 31-37 p. (In Russian)
[3] Stavnitser L.R. Seismic stability of bases and foundations / Monograph. - M .: Ed. Association of Construction Universities, 2010 - P.448. (In Russian)
[4] Ter-Martirosyan A.Z., Mirny A.Yu., Sobolev E.S. Features of determining the parameters of modern soil models during laboratory tests / Geotechnics, No. 1, 2016, pp. 66-72. (In Russian)
[5] Ishihara K. Behavior of soils during earthquakes: Per. from English. / Ed. A.B. Fadeeva, M.B. Lisyuka / NPO "Georeconstruction-Fundamentproekt." - SPb., 2006 - P.384. (In Russian)
[6] Seed H.B., Idriss I.M. Simplified procedures for evaluating soil liquefaction potential. Journal of Soil Mechanics and Foundation Engineering, ASCE, Vol. 97, 1971 - 1249-1273 pp.
[7] Seed H.B. Soil liquefaction and cyclic mobility evaluation for level ground during earthquakes. Journal of Soil Mechanics and Foundation Engineering, ASCE, Vol. 105, T2, 1996 - 201-255 pp.
[8] Iwasaki T., Tokida K., Tatsuoka F., Watanabe S., Yasuda S., Sato H. Microzonation for soil liquefaction potential using simplified methods / Proc. 3rd Int. Conf. On Microzonation. Seattle. 1982. Vol. 3.1319-1330 pp.
[9] Ter-Martirosyan A.Z., Sobolev E.S. Maintenance safety of the foundations of buildings and structures exposed to dynamic loading // Vestnik MGSU, Vol. 12, No. 5(104), 2017. pp. 537-544. (In Russian)
[10] Clayton C.R.I. Stiffness at small strain: research and practice // Geotechnique, Vol. 61, No. 1, 2011. pp. 5-37.
[11] Kottke A.R., Keene A., Wang Y., Shin B., Stokoe II K.H., Lewis M.R. In Situ and Laboratory Measured Dynamic Properties of a Marine Clay // Geotechnical Frontiers 2017, 2017. pp. 337-346.
[12] Abramova T.T. Protection of soil masses from dynamic and seismic loads // Symvol Nauki, Vol. 4, 2016. pp. 41-49. (In Russian)
[13] Abramova T.T., Valieva K.E. Complex issues of technogenic safety, Proceedings of international research and practice conference // Overview of modern technologies aimed ad
lowering dynamic impact on soils. Voronezh, Russia. 2017. pp. 33-37. (In Russian)

[14] Abramova T.T., Voznesensky E.A. Modern methods of managing properties of soils on the sites exposed to high dynamic loads // Geotechnics, Vol. 4, 2015. pp. 6-25. (In Russian)

[15] Ilyin S.V., Zhevzhikov I.I. Technologies for strengthening soft soils of foundations used at the facilities of the State company Avtodor // Dorozhniki, T. 2, No. 10, 2017. P. 6-11. (In Russian)

[16] Sobolev E.S., Ter-Martirosyan A.Z., Morev D.S. Experimental studies of elastic shear waves speeds in soil-cement depending on density // Geotechnics, Vol. 11, No. 3, 2019. pp. 6-21. (In Russian)

[17] Kiyota T., Wu C. Evaluation of Liquefaction Resistance from In Situ and Laboratory-Measured Shear Wave Velocities // Geotechnical Earthquake Engineering and Soil Dynamics V, Jul 2018. pp. 237-243.

[18] Chang W.J. Evaluation of Liquefaction Resistance for Gravelly Sands Using Gravel Content–Corrected Shear-Wave Velocity // Journal of Geotechnical and Geoenvironmental Engineering, Vol. 142, No. 5, May 2016. P. 04016002.

[19] Ertelev O.O., Sidorin A.Y., Sokolova E.Y., Lukk A.A., Nikonov A.A., Aptikaev F.F., Shvarev S.V. Methods for Assessing the Seismic Hazard of Stable Continental Areas Using Combined Paleoseismological and Geophysical Data // Seismic Instruments, Vol. 55, August 2019. pp. 464-485. (In Russian)

[20] Chernov Y.K. Preliminary analysis of possibility of seismogenic soil liquefaction (as exemplified by water saturated sandy and agrilaceous deposits in the settlement Kudepsta of Adler region, Sochi) // Geology and Geophysics of the South of Russia, Vol. 9, No. 1, 2019. pp. 58-70. (In Russian)