A crucial step towards ensuring the seismic resistance of critical facilities and the mitigation of earthquake risks involves the accomplishment of site response studies. The selection of a model of stress-strain state of soil under seismic loads is considered. The paper presents the results of a study of the influence of the sedimentary layer on seismic oscillations on the surface using the example of the territory of the Yagotin compressor station (Ukraine). In the calculations, the equivalent linear ground response analysis to seismic impact was used. The frequency range of the resonant amplification of the soil under the site is determined. The analysis of the influence of the sedimentary layer on the frequency composition of the oscillations of the upper layer is carried out. The study of the site effects allows you to make design decisions that do not allow the frequencies of structures on the site to coincide with the frequencies of the soil amplifying seismic vibrations.
Introduction

Earthquakes over the past decades have shown that the role of the site effects in the distribution and magnitude of the damages associated with a seismic event to be paramount. Site effects play a very important role in characterizing seismic ground motions because they may strongly amplify (or reduce) of the seismic motions at the last moment just before reaching the surface of the ground or the basement of man-made structures. During the Michoacan Earthquake in Mexico (e.g., Anderson et al. 1986; Singh and Ordaz 1993; Cruz-Atienza et al. 2016) amplification induced from site effects has been recognized as the major cause of the structural collapse. Work on seismic microzoning is carried out to take into account the influence of local soils on the intensity, shape of recording and spectrum of vibrations on the surface. In contrast to the general and detailed seismic zoning during seismic microzoning, it is not the sources of seismic hazard that are studied, but the response of the soil to seismic influence.

For earthquake resistant design, it is necessary to know not only the magnitude of oscillations and the values of maximum peak accelerations but also information about the distribution of seismic effects by frequency. It is known that the soil strata behave as an amplitude-frequency filter: at some frequencies, the oscillations are almost unchanged, while at others, they are either amplified or absorbed. When designing earthquake-proof buildings and structures, it is important to avoid that the maximum frequency characteristics of the soil thickness coincide with the eigenfrequency of buildings and structures. The seismic effects vary with the softness and thickness of the sediment. As seismic waves travel through the ground, they move faster through hard rock than soft soil. When waves transition from hard to soft layer, they increase in amplitude. A bigger wave causes stronger shaking.

Basically, the frequency range from 0.05 to 20 Hz is considered. This range is of greatest interest in seismic microzoning, since this range contains the vibration frequencies of the main types of buildings, structures and their critical structures, as well as the maximums of the vibration spectra during strong earthquakes. Local site effects are considered the most significant factors in the microzonation of ground motions.

The representation stress-strain relation in seismic loading

When analyzing the response of soil to seismic effects within the framework of the theory of wave propagation, it is important to represent the soil reaction in the form of a model that establishes the ratio of shear stresses and shear strain (Semenova and Kendzera, 2019). Modeling the reaction of the soil under seismic load makes it possible to obtain deformation characteristics in the considered strain range.

Soils’ responses subject to earthquakes are controlled by the mechanical properties of the soil, which basically include shear modulus (shear wave velocity), damping, Poisson’s ratio, and density (mass). Of these, shear modulus and damping are the most important material properties with which to characterize the dynamic behavior of soils (Jia, 2017). Both these properties are affected by effective stress and over-consolidation ratio. Furthermore, both shear modulus and damping depend on the strain level, while the strain response level also depends on the modulus and damping. All the issues above complicate the seismic ground response analysis and challenge analysis accuracy requirements.

If we assume that the soil deformations will be small (below 10^{-6}), then the use of a linear (elastic) model will be justified. Then the main parameter for an adequate analysis will be the shear modulus $G$.

If average deformations are assumed (10^{-5} - 10^{-3}), the soil reaction becomes visco-plastic (Ishihara, 1996) with shear modulus $G$ decreasing as the displacement deformation $\gamma$ increases. In the process of loading, energy dissipation occurs which in the soils has a hysteresis character. The $G/G_{\text{max}}(\gamma)$ curve, which shows a decrease in the shear modulus with increasing strain, conveys the same information as the skeletal (characteristic) curve. To estimate the energy-absorbing properties of the soil, the dimensionless relative absorption coefficient $D$ is used.
Medium strains do not cause a progressive change in soil properties, therefore $G$ and $D$, in this case, are independent of the number of cycles. This kind of soil reaction is characterized by the presence of hysteresis of the “stable” type (non-degraded hysteresis type). In this case, an equivalent linear model based on the concept of viscous elasticity is used as an analytical tool. In the equivalent linear approach, linear analyses are performed with soil properties that are iteratively adjusted to be consistent with an effective level of shear strain induced in the soil. In the equivalent linear approach, the shear modulus is taken as the secant shear modulus which, approximates an “average” shear modulus over an entire cycle of loading. As the level of shear strain increases, the secant shear modulus decreases. The relationship between secant shear modulus and shear strain amplitude characterized by the modulus reduction curve [ProShake…, 1998].

For shear deformation, which exceeds $10^{-2}$, a significant change in soil characteristics can be associated not only with an increase in $\gamma$, but also with the presence of a number of repetitions (cycles) of a load. This kind of soil reaction is characterized by hysteresis of the “progressive” type (degraded hysteresis type). It is believed that the magnitude of the change in $G$ and $D$ during cyclic loading depends on the magnitude of the change in the effective stress of comprehensive compression with an irregular application of shear stresses over time. After establishing the pattern of change in effective stresses, it is necessary to determine the pattern for establishing the stress-strain state at each stage of the process of loading, unloading, and reloading. One of the most common approaches that are used for this is the Masing law. To analyze the reaction of the soil, the stress-strain state of which is characterized by large deformations close to the fracture boundary, it is necessary to use a numerical method with step-by-step integration. In this case, nonlinear modeling is used as an analytical tool.

The use of software products for equivalent linear and nonlinear modeling requires additional parameters in seismic geological soil models in the form of empirical dependencies $G(\gamma)$ and $D(\gamma)$. These dependencies can be obtained as a result of dynamic soil tests during field or laboratory studies.

**Local site effects of the station (Ukraine)**

This paper investigates the local amplification of seismic waves (site effects) of the site of the Yagotin compressor station (Ukraine).

The site of the Yagotin compressor station is characterized by a flat relief and is located in the left-bank part of the Dnieper River valley. In engineering-geological terms, the studied area is located within the Dnieper-Donets depression. The upper part of the geological section is represented by deposits of aeolian and glacial genesis. Mostly these are loess loams, overlain by moraine loams. Groundwater lies at a depth of 7-12 m. The thickness of the sedimentary layer to bedrock is almost 900m.

During seismic microzoning within the site of the Yagotin compressor station one zone of seismic effect was identified. Accordingly, one seismic-geological model was built. One frequency characteristic of this model was calculated.

Figure 1 shows a velocity model of a section of soil to bedrock under the study site. It can be seen from Fig. 1 that the velocity model is characterized by rather a low shear wave velocity values. Especially low values up to 500 m/s in the upper 50-meter layer.
Figure 1. The velocity model of a section of soil to bedrock under the site of the Yagotin compressor station

Equivalent linear model was used in the calculations. Equivalent linear site response analyses were performed using Proshake software (ProShake…, 1998). The behavior of each layer was specified by the Kelvin-Voigt model (viscoelastic). The nonlinearity of soil stress-strain behavior means that the shear modulus of the soil is constantly changing. For each layer, the shear modulus reduction and damping ratio curves were chosen in order to take into account the nonlinearity.

In fig. 2 shows the amplitude-frequency characteristic of the soil stratum model under the site of the Yagotin compressor station
An analysis of the frequency response shown in Fig. 2 showed that seismic oscillations can be amplified by the soil under the studied area in the range 0.18–2.66 Hz. The maximum amplification coefficient is 3.8 at a frequency of 0.9 Hz. The frequency response has a wide range of resonant amplification of seismic oscillations by soils. The highest amplifications are observed in the low-frequency range. This is due to the large thickness of the sedimentary layer of about 900m.

Taking into account the amplification of seismic vibrations in the low-frequency range is necessary for earthquake-resistant design of high-rise and extended structures since they are characterized by low natural frequencies of vibrations. Such objects located on the territory of Ukraine may suffer damage under the influence of strong subcrustal earthquakes from the Vrancea zone. Seismic effects from these earthquakes are characterized by low-frequency long-period oscillations and propagate over long distances without significant attenuation, which can lead to dangerous resonant effects.

The frequency response most fully reflects the influence of the soil on the transformation of the input motion from the bedrock. Information about the seismic site effects allows increasing the seismic resistance of structures by developing design solutions that prevent the natural frequencies of the designed building from coinciding with the maxima of the frequency characteristic of the soil.

**Conclusion**

The issue of the influence of sedimentary deposits on seismic hazard parameters has been relevant for a long time. It has been established that surface geology, which strongly affects the propagation of a seismic wave, is one of the main factors that determines the seismic effect on the surface. Under intense seismic impacts, the soil response becomes non-linear and the problem of evaluating the soil response is significantly complicated. The paper considers and analyzes the results of a study of the influence of the sedimentary layer on seismic vibrations on the surface using the example of the territory of the Yagotin compressor station (Ukraine). The sedimentary layer of the studied site has a thickness of 900 m and is characterized by rather low values of the shear wave. As a result of an equivalent linear analysis, the frequency response of the soil stratum of the studied site was calculated. The frequency response has a fairly wide range of resonant gain. The highest gain is mainly in the low-frequency range from 0.2 Hz to 2.2 Hz. This is due to the rather high thickness of the sedimentary layer and low shear wave velocities. The results obtained were used to assess the seismic hazard of the site of the Yagotin compressor station (Ukraine). An analysis of soil properties of enhancing seismic oscillations under the study site is important for further study of the site effect and improve their research methods.
References


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