Experimental and FEM Calculation of Spectral Characteristics of Near-surface Layers under the Seismic Station "Uzhgorod"

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Abstract—**The purpose of this work is to calculate theoretical transfer characteristics of the sedimentary layers under the seismic station of the Carpathian seismic network "Uzhgorod" by finite element method. These results will be used for comparison with the dynamic parameters of the near-surface layers obtained experimentally. Based on the correlation of the resonance properties obtained by these methods, the possibility of their use in regional seismological studies was substantiated. In this work, the simulation was carried out by solving the direct dynamic seismic problem by the finite element method. Using the developed wave field simulation technique, oscillations for models of the seismic section under the «Uzhgorod» station were investigated. According to the simulation results for this seismic station, theoretical spectral relations were calculated. The results obtained by the experimental and model methods showed identical behavior throughout the frequency range. According to these graphs, a stable source of noise within the city was allocated. The knowledge about the dynamic parameters of the upper sediment layers under the seismic station, which are the largest filter of oscillation frequencies in the spectral range, will allow more accurate interpretation of registered by this station occurrences. The calculated spectral ratios give a possibility to estimate the degree of environmental influence on station's seismic signals recording, which will be the largest at frequencies corresponding to the received resonance maxima and minima. These results should be taken into account when evaluating the parameters of possible seismic effects on the territory.**

Index Terms—**modeling, finite element method, transfer characteristic, Nakamura's technique, resonance frequency, interference**

I. Introduction

The long experience of seismological research has proved that local geological conditions are a decisive factor in the magnitude and extent of earthquake-related destruction. The need to take these conditions into account when assessing the seismic hazard and the parameters of the possible seismic impact is quite evident even when it comes to separate construction sites and structures. Examples of complete destruction of the certain building, located very close to the other, with the same seismic safety level but completely surviving often occur [1].

The increase in the amplitude of seismic oscillations is primarily due to the accumulation of their energy in near-surface layers of the environment, where the velocity of the oscillations propagation is much smaller than at a greater depth. Due to the presence of contrasting boundaries, there is also an interference enhancement of oscillations at frequencies, depending on the layers' elastic characteristics, the geometry of their boundaries and the angles of oscillations propagation.

The most reliable and complete consideration of these and many other factors of seismic impact is possible only when large-scale and complex geological, geophysical, seismological, geotechnical and engineering studies are conducted. They draw significant costs, sometimes involving adequate material and technical resources and the appropriate number of specialists [2].

One of the most common approaches to the estimation of the resonant frequencies is to compare oscillations' spectra, aroused by weak sources (small earthquakes, noise) and registered on the sites at the outlet of the rock base and on the sedimentary layer lying on the same rock base [3, 4]. As an alternative to this approach, limited in the use by the fact that the outcrops of rock bases near the estimated site are not often encountered, the so-called Nakamura's technique is proposed [5]. Using it, the resonant frequency is measured by the spectral ratio of horizontal and vertical components (H/V) of oscillations, aroused by weak sources.

Nakamura's technique, often referred to as QTS (quasi-transfer spectra technique), has become widespread in world practice of seismological research due to its convenience and low cost. It does not require much time, a large amount of equipment or drilling wells to reach the rock base. Thus it can be used nearly on any site. However, the theoretical foundations of this purely empirical technique are still not properly substantiated. Although the author of the technique claims that the maximum values of the spectral ratio H/V for microseisms are due to the amplification and repeated reflection of transverse oscillations SH [6], the question regarding the influence on the shape of the H/V spectrum of surface oscillations etc. still remains [7].

It is known, however, that the H/V spectral ratio has a clear physical content both in the spectral areas and in time space (in the case when the environment is horizontally-layered and the source of oscillations is a plane wave (longitudinal or transverse), extending from the depth). For a certain wave number (corresponding to the angle of incidence of a plane wave), this function depends only on the parameters of the environment (thickness of the layers, their densities, velocities of longitudinal and transverse waves' propagation through them) [8]. And the maxima of its spectrum correspond to the frequencies on which there is an interference enhancement of the horizontal vibrations relative to the vertical ones. In the case of their coincidence with the frequencies of the building's (or its parts) own fluctuations, dangerous phenomena of resonance amplification and even destruction can occur.

In the case of the simultaneous fall of several plane waves, the H/V ratio will depend not only on the parameters of the environment but also on the amplitude and phase of oscillations. In each of them, the assumption of a horizontal-layered structure of the environment and a plane wave as a source of oscillations is quite adequate and acceptable for solving many practical problems. Indeed, the location of earthquakes' focal zones, which can be a real danger in a particular area, is usually known. In the case of known parameters of the environment, this allows to estimate the wave front angle with the greatest energy of oscillations and to calculate the corresponding theoretical spectral ratio H/V. Comparing the theoretical H/V ratio with the experimental ones, one can assess the feasibility of using only the latter when the data on the environmental parameters necessary for the calculation of theoretical H/V is poor.

For horizontally layered environment it is most convenient to calculate spectral ratio H/V directly in the frequency and wave numbers region using the so-called matrix method, first proposed by Thompson and Haskel [9, 10], as well as its numerous modifications. If the geometry of seismic boundaries substantially deviates from the horizontal-layered, for the simulation of seismic wave fields the FEM (Finite Element Method) is often used [11]. FEM is much more versatile in capability and scope of application than the matrix method. Since computations in the FEM are carried out in real-time space, but not frequencies and wave numbers as in the matrix method, difficulties with the coinciding of the results obtained by both methods in solving the same tasks may arise. This may include, in particular, the computation of H/V spectra for a horizontal-layered environment. The achievement of this convergence is an important component of the methodological guidelines for the use of FEM development for determining the resonance frequencies in environments with a more complex structure. In particular, this applies to so-called sedimentary basins, where reflections from their boundaries can produce a significant influence on the resonant maxima formation. Account of such reflections is still remains the actual task in assessing of seismic influences.

II. Theory of Nakamura's technique

The technique of determining the proper resonance frequencies of the sedimentary strata by the ratio of the horizontal to the vertical components of natural noise spectra was developed by the Japanese scientist Yutaka NAKAMURA. In this case, borehole strong-motions studies for various geological conditions of the studied section were used. He advanced the hypothesis that the vertical component of the geological environment natural noises contains the characteristics of the environment throughout the way from the source to the sediment surface, with the relative influence of Rayleigh waves in the sedimentary thickness. Therefore, it can be used to eliminate the source and the Rayleigh wave effect from the horizontal component. This allows us to determine proper resonant frequencies of the sedimentary layer together with the amplification factors (i.e. amplitude-frequency characteristic). They will more realistically reflect the characteristics of the environment than those obtained from the ratio of the sedimentary thickness to rocks. As shown by the works of many researchers, the H/V technique can be successfully used to determine proper resonant frequencies and the amplification factors of the sediment strata. Also in the work of the technique's author, it was shown that the maximum values of the horizontal to the vertical component of the microseisms spectra ratio are explained by multiple reflections of the SH wave.

III. Basics of the dynamic problem of elasticity theory by finite element method solution for wave field modeling in complex environments

To model wave fields in complex structure rocks, we solve the dynamic problem of the elasticity theory, taking into account nonlinear phenomena.

The essence of the FEM consists in the approximation of continuous quantities by piecewise-continuous functions on a finite number of sub-sections - elements. These functions can be polynomials that are defined for each element in particular. The order of the polynomial depends on the form of the element and the number of nodes in the element. The problem is reduced to a system of linear algebraic equations, which is solved by known methods. As a result, we get seismic waves simulation in the studied environment.

IV. Results

Using the developed technique of wave field simulation by finite element method, oscillations for a seismic section model under the "Uzhgorod" seismic station were simulated. The theoretical spectral ratios for the station were also calculated according to the simulation results.

In this work, the calculation of the experimental spectral ratios of the Carpathian Seismological Network's "Uzhgorod" station for the recordings of the earthquakes of this network was completed [12]. The theoretical spectral ratios obtained with the finite element method will be compared with them.

On the graphs obtained experimentally and by the theoretical method, we see practically the same behavior of two curves, except for the maximum at a frequency of 15 Hz which is present on the experimental, but not on the theoretical graph. This situation suggests a stable source of noise that is present within the city. In case of some inadequacy in the model construction, experimental and theoretical graphs would not have such a similar form on almost the entire range of frequencies. The sources of seismic oscillations at high frequencies are of low-power and have a low permeability in the environment. Therefore, we can talk about quite a short distance from the source of perturbation to the seismic station.

From this point of view, one can draw the following methodological conclusion. Such an approach should be used to distinguish noise of technogenic origin from frequency records of seismic stations located within densely populated areas with possible objects that generate constant fluctuations during their operation. For such studies, the presence of a complete engineering-geological section under the station and the accurate construction of the environment mathematical model is the necessary condition.

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