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CONTENT

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A METHODOLOGY OF DETERMINING THE NATURAL FREQUENCIES OF LOW-RISE BUILDINGS

MIRJANA KOCALEVA AND VLADO GICEV

Abstract. We live in a world that is constantly faced with natural disasters such as earthquakes, floods, tsunamis and other geological processes. These catastrophes, besides causing material damage, are sometimes fatal to people's lives. Therefore, different types of measurements are performed, various studies are made, with the same goal - to predict disasters, to mitigate and their consequences, and to find a way to protect ourselves from them. One of the most important parameters for designing earthquake resistant structures is the natural frequency of the structure. The main purpose of our research is to find the natural frequencies, i.e. the fundamental periods of objects. By determining natural frequencies, we can find dynamic forces acting on the structure so we can design the constructive elements to resist to these forces. We will do this in order to determine which frequencies of excitations are dangerous to the construction at certain excitation (such as explosions or earthquakes). Because, if the predominant frequency of the excitation is close l to the natural frequency of the structure, the dynamic forces are large and the structure will not only have some damage, but may, in the worst-case scenario collapse. Our attention is focused on disasters caused by earthquakes. For this purpose, we will measure the existing structure - a weekend house in Berovo. Using measurements and data processing, we will try to obtain its natural frequencies.

1. Introduction

The earthquake, as the name implies, is a shaking of the earth. Hundreds of thousands of earthquakes occur each year across the planet Earth. Earthquakes can be caused by a variety of factors, but usually they occur due to a displacement of the earth's tectonic plates that traverse, underlie one beneath another or separate, and thereby create excessive stresses at the contact points. When these stresses exceed a certain critical value, cracks and slides between the plates occur and a sudden relaxation (annulment) of the stresses generates seismic waves. These waves propagate in the space from the earthquake source, transmitting seismic energy. When they reach the surface of the Earth, one part of this seismic energy is transferred to existing objects, which may lead to serious damaging or even collapsing. An earthquake can be triggered by volcanic activity as well. It can also be caused by human activity. Fortunately, for human safety and material goods, a large number of earthquakes are weak and can only be registered with seismological measuring instruments. The part of physics that studies earthquakes is called seismology. The instrument that measures earthquake displacement is called a seismograph, and the record of displacements over time is called a seismogram. The instrument that measures acceleration over time is called an accelerometer, and the records it registers over time are called accelerometers [11].

Earthquakes are manifested by the movement of the earth's surface and are measured by intensity or magnitude. Intensity is a descriptive measure of the magnitude of the earthquake on people and buildings in a specific location. One of the most commonly used earthquake intensity scale is the Mercalian scale or the Mercalli - Cancani - Sieberg (MCS) scale of 12 degrees. When the intensity value is greater than 5, the earthquake can be sensed and at higher values damage to objects may also occur. The Richter scale is used to measure magnitude, i.e. the amount of energy released during the seismic event. This scale is based on an empirical formula. The scale measures the magnitude of an earthquake on a scale of 0 to 9. Tremors of magnitude 4.6 and above are strong enough to be recorded by the most remote seismographs in the world.

The energy released by earthquakes is harmful to buildings and humans, and, to protect them, people study earthquakes and their effects on buildings. Seismology is a part of physics that studies the sources of earthquakes and the propagation of seismic waves across the earth's layers. Earthquake engineering is a multidisciplinary technical science that studies the behavior or response of objects to seismic wave excitation.

The traditional design of earthquake resistant buildings is based on the determination of the total seismic force $S = S_d(T_1) \cdot W$. This force depends on the weight of the building W and the fundamental period of the fixed-base building T_1. For the period T_1, one reads the ordinate of the response spectra, $S_d(T_1)$ from the codes and multiplying this ordinate with the peak ground acceleration and the total weight of the building, obtains the total seismic force. Further, this force is distributed on the floors of the building, increasing linearly with the height. Further, the analysis of the response can be linear - spectral analysis and nonlinear - pushover analysis. The intensity of the seismic force S is defined by the total seismic coefficient K and the weight of the object, G so $S = K \cdot G$. G is the sum of the constant, variable loads and the snow load.

The design of earthquake resistant structures in N. Macedonia is still based on the old YU codes from 1981. The total seismic force is estimated as a product of four coefficients and the total weight of the structure $S = k_o \cdot k_s \cdot k_p \cdot k_d \cdot W$. The coefficient k_o depends on the category of the structure and can have values in the range $0.75 \leq k_o \leq 1.5$. Next, the seismic coefficient, k_s depends on the seismicity of the site and has values of 0.025 for seismic intensity VII to 0.1 for seismic intensity IX on MCS scale. The coefficient of ductility k_p depends on the constructive system of the building and has values of one to two and the dynamic coefficient, k_d depends on the soil properties and fundamental period of the building on the fixed base T_1. From above, it can be noticed that all codes use natural periods of the building on the fixed base, T_1. For that reason, it is important to estimate T_1 accurately.

There are many research projects for obtaining empirical equations for building periods [1], [2], [3], [6], [7]). In most cases, the researchers use ambient vibration tests and the empirical equations of the building periods are functions of geometric (height, length), material and structural properties of the buildings. As in different regions of the world the constructive systems, the materials, the building codes and the soil properties are different, there is no unique equation which will successfully estimate building periods for different regions. Because of this, it is important to develop an original equation for estimating building periods in a specific region. Further, the obtained equations estimate system periods Ts, which depends on the soil properties. This means that the same building, on a different location will have a different system period. For that reason, besides the fundamental system period Ts, it is important to obtain the fundamental period of building on the fixed base, T_1. Using impulse response analysis and wave travel times, [8] uncoupled period of building on the fixed base T_1 from period of coupled soil-structure system Ts and [8], [9] uncoupled T_1 from coupled period of horizontal and rocking response of the soil-structure system. The fundamental natural period of building on the fixed base, T_1 is especially important for structural health monitoring.

2. Research purpose

The purpose of earthquake engineering is to design earthquake resistant objects. Early modern earthquake engineering was appointed by Maurice Biot with his method of spectral response. The purpose of our research is to obtain the fundamental frequencies or fundamental periods of solid structures such as buildings and bridges. We will do this in order to determine which frequencies of the motions are dangerous to the construction itself in certain excitations (such as explosions or earthquakes). Because, if the frequency of the excitation is approximately the same as the natural frequency of the construction, the construction will not only have some damage, but may, in the worst-case scenario, also collapse (causing permanent damage).

Our main goal is obtaining empirical equations for estimating the fundamental period of the soil-building system T_s and ultimately, using impulse response, obtaining the fundamental period of building on the fixed base, T_1.

To achieve our goal, we will work according to the following concept:

- We will record ambient vibrations of selected buildings in Skopje and Stip using two accelerometers, one at the base (basement or ground floor) and the other at the top of the buildings (at the attic). The obtained data will include photos of the building taken from at least two normal directions, the building plan, the date of construction, the type of building construction system and the material of the foundations. With these instruments we will measure the horizontal accelerations at the base and at the top resulting from ambient excitations (traffic, wind, movements in the building etc.) versus time. These recordings will last about thirty minutes per building.
- Using the Fourier transform, the obtained acceleration records at the base $a_0(t)$ and at the top $a_T(t)$ will be transformed into frequency domain $F_0(\omega)$ and $F_T(\omega)$ respectively. Having these values in frequency domain, we get the transfer function as $H(\omega) = F_T(\omega) / F_0(\omega)$. The reciprocal values of the angular frequencies ω corresponding to peaks of the transfer function scaled by 2π, determine natural

periods. The highest period is the fundamental period of the soil-structure system. Alternatively, the fundamental system period can be obtained as a ratio of power spectral densities at the top and at the bottom of the building.

- Simultaneously, with deploying instruments near the edges on the roof and with recording ambient vibrations in directions of length and width of the building, with the same procedure we can determine the torsional periods of the measured buildings. Besides determining building periods with measuring ambient vibrations, in parallel we will create a database with keeping records of each measured building. The database record will consist of:
    - location of the building (latitude and longitude),
    - height and number of stories,
    - materials of the foundations,
    - codes with which the building is designed,
    - structural and geometric irregularities,
    - building age,
    - recorded accelerations versus time obtained from two instruments during ambient vibration tests.
- Analysis of the data from ambient vibration tests. Based on this data, using a regression formula, we will propose empirical equations for determining natural periods of soil-building system, T_s in cities in N. Macedonia. Ultimately, using the impulse response analysis, the fundamental period of buildings on fixed base, T_1 can be determined. The periods T_1 and T_s will be compared and an empirical equation for T_1 will be proposed for buildings in N. Macedonia.
- Analysis of the data from ambient vibration torsion test. The benefit of the proposed research is obtaining reliable equations for the estimate of building periods in N. Macedonia. The existing equations of building periods in Macedonia are based on the old YU code. They are not based on instrumental recordings and they consider only the height, or number of stories of the building. With this research, we will propose more detailed empirical equations for estimation of fundamental periods.
- These periods further, together with the maps of microzonations based on the Uniform Hazard Spectra (UHS) method, will be used for estimation of the physical vulnerability of the buildings. Based on it, estimation of funds for building new, or retrofit of the damaged buildings can be determined.

3. Research methodology

In this research, we will work with the data obtained by field measurements using EQResponder120 accelerometers. We first set up the accelerometers using an internet connection and connect them with GPS antennas. We placed the GPS antennas on the windows to be open-air and to receive a good satellite signal to synchronize the time of both instruments.

The working methods will be divided into two parts: Field work and Laboratory work. The fieldwork will consist of measurements of the natural frequency of buildings in the cities of Stip and Skopje. The accelerometers are usually placed at the basement level and at the attic level (Figure 1). Accelerometers record data in multiple files, which are closed every 30 minutes, 1 hour, 2 hours or 6 hours, depending on how it is selected in the settings. It is more suitable if the test data are in a single file. If the sensors are set to a continuous mode, we should wait for the file to close and reset the sensor. Data is never lost.

Laboratory work will consist of creating a database of the measured buildings, analyzing data to obtain empirical formulas for calculating natural frequencies, obtaining a relevant equation for determining the torsional periods of buildings and, based on that, assessing the physical vulnerability of buildings.

4. Case study weekend house in Berovo

On October 19, 2019, we conducted test measurements of the ambient vibration of a weekend house located on the shore of Lake Berovo in Berovo. The house in Berovo is a two-storey reinforced concrete building with a partially buried basement and attic at 41 degrees 40 minutes 34.99 seconds and 22 degrees 53 minutes 54.75 seconds. The house is founded on a slope dipping from North-East towards South-West. Figure 1 shows a view of the house from the South-West (part a) and from North-East (part b).

The measurements of the ambient vibration were performed using two EQR 120 accelerometers. The EQR 120 accelerometers are highly sensitive and therefore able to register the smallest ambient movements.

Accelerometers were set one in the basement (Slave) and the other in the attic (Master). The accelerometers were set to continuous operation mode and each was synchronized with UTC (Universal Coordinated Time) from its own GPS receivers (with the accuracy of 1µs). The length of the analyzed segments was approximately 30 minutes.

Figure 1. Weekend house at Berovo lake (a) North-East view (b) South-West view

After the measurements, we processed the data and obtained the results presented in Figure 2. The upper row presents the Fourier spectrum of acceleration a (t) obtained from the "Master" instrument in the attic, the middle row shows the Fourier spectrum of acceleration a (t) obtained from the "Slave" instrument in the basement, and in the lower row is the transfer function in x direction (east-west), y direction (north-south), and z direction (vertical).

In the Fourier spectrum of the EW component of the response in the attic, extremes of about 35 Hz, 50 Hz and 77 Hz can be identified. In the NS component, extremes of about 50 Hz can be identified. Vertically, extremes are identified at 50 Hz and 82 Hz. In the Fourier spectrum of the EW component of the basement response, peaks of about 10 Hz, 54 Hz and 78 Hz can be identified. In the NS component, peaks of about 58 Hz can be identified. Vertical peaks are identified at 28 Hz and 67 Hz. The transfer function between the attic and basement responses has the following peaks: at EW 25 Hz, 67 Hz and 82 Hz, at NS is 50 Hz and at vertical 85 Hz.

Because the frequency of electricity in our country is 50 Hz, the extremity that occurs at 50 Hz in all records of the upper instrument is a consequence of the interference with the power source (cable in the wall near the instrument).

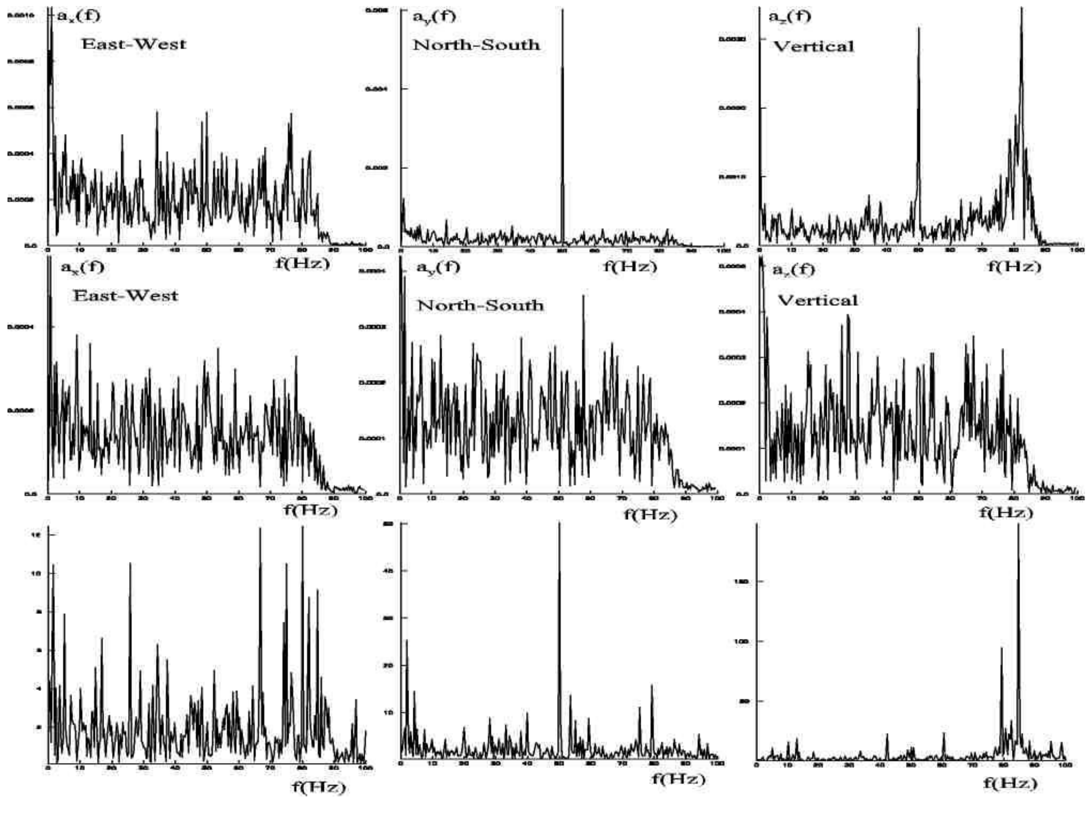

Figure 2. FFT of acceleration a (t) in three orthogonal directions obtained from the ambient vibration test with two accelerometers EQR 120 at Berovo lake weekend house.

From Figure 2 we can see that the results go up to frequency of 100 Hz. This is the critical frequency of the Nuyquist that depends on the sampling rate of the signal and its value is $f_N=1/2\Delta$. In our case, for a chosen discretization interval of 0.005 seconds $f_N=1/2\Delta=1/(2\cdot0.005)=100$ Hz. But, as most objects vary to a frequency of about 20 to 30 Hz, our next goal will be to remove frequencies greater than 20 - 30 Hz using a low-pass filter and to work only with those up to 20 - 30 Hz.

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