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ASSESSMENT OF FUNDAMENTAL PERIODS OF VIBRATION THROUGH ANALYTICAL AND EXPERIMENTAL IN-SITU MEASUREMENTS

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Abstract

The structural response due to the seismic load depends on the dynamic structural properties and incoming ground motion. Although for low amplitude ground motions the material behaviour is assumed to be linear, as the amplitude increases the dynamic properties of the structures are changed so that the nonlinear effects should be considered. In determining the nonlinear characteristics of structures, the vibrational periods are important step to be followed. On the other hand, the local site effects have impact on earthquake motion alteration which in most cases contribute to the dynamic amplification of the ground motions. The definition of natural periods of existing buildings including the foundation structure of the whole system can be done by in-situ experimental methods. These experimental methods being cost-effective are constituted by various techniques relating the measurement of structural natural vibrations. This work sums up the experience of UKIM-IZIIS in measuring the in-situ dynamic characteristics of different types of buildings in N. Macedonia. The measurements are based on ambient vibration using the newest technological methods. The established database apart from the vibrational periods includes the geometrical and structural properties of the measured structures which are shown in this paper. The results have shown that apart from geometry the material characteristics play important roles in definition of dynamic characteristics of the structures. The inclusion of brick masonry infills in the final establishment of the dynamic properties plays important role and should be considered in the analysis of the structural analysis. Last but not least is the definition of representative hazard which indirectly influences the dynamics of the structures.

Keywords: Ambient vibration measurements; Period of vibration, RC Buildings, N. Macedonia

1. Introduction

Overall behaviour of structures is directly affected by their dynamic characteristics, for instance eigenvalues, eigenvectors, and damping. In this sense, non-destructive techniques appear as useful tools to provide information about the structural behaviour of the building. In particular, dynamic properties provided by ambient vibration techniques have proved to be quite well-suited to validate and update numerical models. In the last years this technique has attracted the interest of many researchers [1, 2], because no excitation equipment is needed, involving minimum interference with the normal use of the structure. The experimental "in situ" testing method has very wide application especially in structures from where identity card of the structure can be obtained accounting for all dynamic characteristics [3, 4]. The advantages of this method are the light equipment easy for transportation and management and the non-destructive procedure without altering the normal operation of structures. So, using this non-

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destructive method fundamental dynamic characteristics for the structure can be obtained, such as natural frequencies and corresponding mode shapes, as well as damping in each mode, without altering their normal operation [5-9]. Having this data as a valuable parameter, leads in the correlation of experimental and analytical results as a confirmation for accurate mathematical model formulation. In the beginning of this century, significant improvement of sensors and data acquisition system technologies was evident. The analogue recording and acquisition of data were replaced by digital systems providing the large analytical possibilities. Also, the software's for data processing were adequately upgraded. Considering "in situ" experimental testing, ambient vibration testing methods prevailed, being applicable for all types of structures, components, and materials in practice as a reason for getting more realistic evaluation of dynamic properties of structures. This method is based on recording and processing of structural response to wind and other ambient excitations, like traffic noise, some other microtremor and impulsive forces like wave loading or periodical rotational forces of some automatic machines. The experimental and theoretical procedure is based on the assumption that the exciting force is a stationary stochastic process with a relatively flat amplitude spectrum. In such conditions, the structures will vibrate and their response will contain all their normal modes. The Institute of Earthquake Engineering and Engineering Seismology (UKIM-IZIIS) from Skopje has an extensive experience in the field of ambient vibration testing starting from 1978 with more than 500 tests performed during this period [10-14]. The subject of this paper is to present the summary of natural vibration period measurements from ambient vibration signal records for 169 representative buildings with different structural characteristics. The influence of height of the building and infill wall effects are evaluated and commented further.

2. In-situ ambient vibration measurements

UKIM-IZIIS in the last decade has been performed several hundreds of in-situ measurements of ambient vibrations on buildings for different investigations and research purposes. For the need of this paper, 169 representative measurements have been selected and analysed. It must be pointed out that those measurements were performed for the purpose of rapid screening with one three-component measurement mostly on the highest assessable level of the related buildings. Dominantly, the recording instrument was placed in a central position with respect to the layout, where applicable.

The measurements were performed with a portable TROMINO® velocimeter (https://moho.world/en/tromino/) from the first generation (Fig. 1) with measurement duration of 10 minutes and certain pre-defined parameters as given in Tab. 1.

Fig. 1. Some photos from the performed measurements with TROMINO instrument

TROMINO® instruments, originally conceived for the dynamic characterization of subsoils, has been increasingly used for the operational modal analysis of structures to such an extent that this has become its primary application over the years. TROMINO® has been extensively used worldwide for ambient vibration measurements, not only on regular structures but also on some of the most iconic structures

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worldwide, such as the Eiffel tower, the Golden Gate Bridge in San Francisco, the Shanghai tower, the leaning tower of Pisa, the landmark skyscrapers in Abu Dhabi and many more.

Table 1 - Standard Site Measurement and Processing Parameters

Site Measurement Parameters		**Processing Parameters**	
Record (trace) length	10 min	Window length	20 sec
Sampling frequency	128 Hz	No. of windows	60
Nyquist frequency	64Hz	Tapering	Bartlett window (20 sec, 2561 points)
Frequency range of interest	0.1 - 32 Hz	Smoothing function	Konno – Omachi, b=20, or Triangular window (5% smoothing)

Amplitude spectra of the different components (channels N-S, E-W, Z) of the recorded ambient vibration motion are computed by MOHO's software package GRILLA™ (http://www.tromino.it/soft-database.htm). The results derived in terms of average velocity amplitude spectra, have been studied in all details for defining the building modal parameters. They are relevant for linear (elastic) behaviour of studied structural system, only. The ambient vibration measurements have been performed on a fully constructed structure, thus incorporating not only the fundamental modal characteristics of the structural system itself, but also the influence of internal and external walls and other non-structural elements.

The results are summarized in the direction for which the vibration periods are obtained. For the analysed buildings, a correlation analysis was performed with the dynamic characteristics, i.e., the basic periods of vibration extracted from the design documentation. The created database was composed in tabular format in which, in addition to the dynamic characteristics of the buildings, the type of structure, total area of the building and the number of stories were included as well. For a certain number of buildings, two types of vibration periods from the project documentation were presented i.e., on a fixed and on an elastic base.

3. Analysed and inspected structures

The database established in UKIM-IZIIS for this study allows detailed classification of the structures. The types of structures considered are mainly reinforced concrete (RC) buildings built in the last decade while the biggest part of the buildings are located in the Skopje area. The reinforced concrete structures are predominantly frame structures with and without shear walls. All the buildings in the established database are build and constructed according to the latest design regulations. In the last years, efforts have been made to improve detailing and increase inelastic capacity of the building to resist potential earthquake ground motions. Although not very common but in some cases the buildings have been built over soft soil deposits in which the dynamic characteristics of the structures are influenced by the presence of soil stiffness characteristics making the soil structure interaction phenomenon important to be considered. Moreover, the ground floor in some of the structures is used for commercial purposes, thus increasing the height and decreasing the stiffness of the ground floor, creating the conditions for appearance of soft-story effect. The height of the analyzed buildings varies from one to 14 floors.

The majority of analyzed buildings are of frame type structures in which the column-beam connections have been given special importance in order to resist the seismic forces, thus preventing the columns of collapse assuring life safety design criteria. The principal structural system for buildings with 1-3 levels is reinforced concrete frame with beams and columns, and the structures with more than 4 storeys are reinforced concrete frame with shear walls in both directions. The dynamic characteristics of these domestic RC buildings show periods in relation of 0.1 times the number of the floors which is a rule of thumb and is a widely accepted worldwide practice.

All investigated structures are designed according to the Code of Technical Regulations for the Design and Construction of Buildings in Seismic Regions (OGoSFRY No. 31/81 of June 5, 1981 with

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Amendments 49/82, 29/83, 21/88 and 52/90), where the total horizontal seismic force acting on a building is given with the equation (1)

$$S = K \cdot G \tag{1}$$

where:

K = the total seismic coefficient for the horizontal direction

G = the total weight of the building and its equipment

The seismic coefficient for the horizontal direction K depends directly by the coefficient of building category, coefficient of seismic intensity, coefficient of dynamic response, and coefficient of ductility and damping. The coefficient of ductility and damping, depends on the type of structure under consideration (modem reinforced-concrete structures, steel structures, reinforced masonry, and for braced steel structures masonry structures, strengthened by means of vertical reinforced-concrete tie-beams' for reinforced-concrete shear-wall structures etc).

4. Investigations results

A total number of 169 newly built reinforced concrete structures are considered in this study. All the structures were measured using ambient vibration testing method. Ambient vibration collected data have been used to extract dynamic characteristics of the structures. As an addition, numerical analyses were performed for all examined structures.

(a) (b) (c) (d)

Fig. 2. Selected measured structures in Skopje (a) Bitola (b), Veles (c) and Ohrid (d)

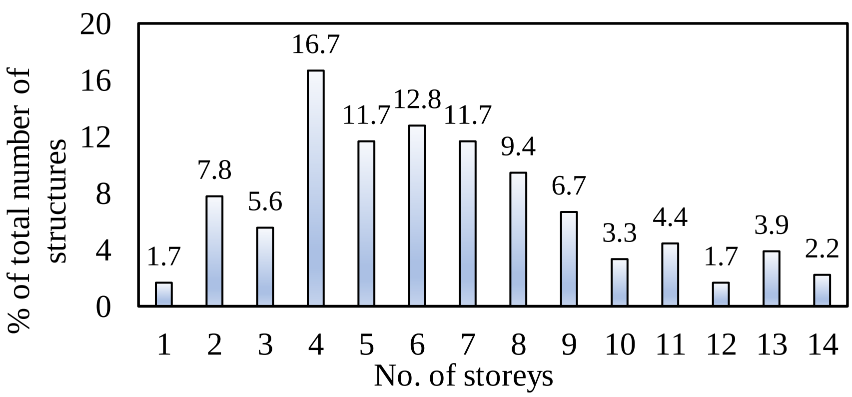

Fig. 3 Percentage of structures with different no. of stories

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The buildings are with 1 to 14 storeys. The principal structural system for buildings with 1-3 levels is reinforced concrete frame with beams and columns, and the structures with more than 4 storeys are reinforced concrete frame with shear walls in both directions.

Some photos of the measured buildings are shown on Fig. 2. Regarding the number of stories, most of the buildings have between 2-9 levels. Larger number of them are with 4 (16.7%) and 6 stories (12.8%) (Fig. 3).

Ambient vibration spectrum graphs of some selected sample buildings are shown in Fig. 4.

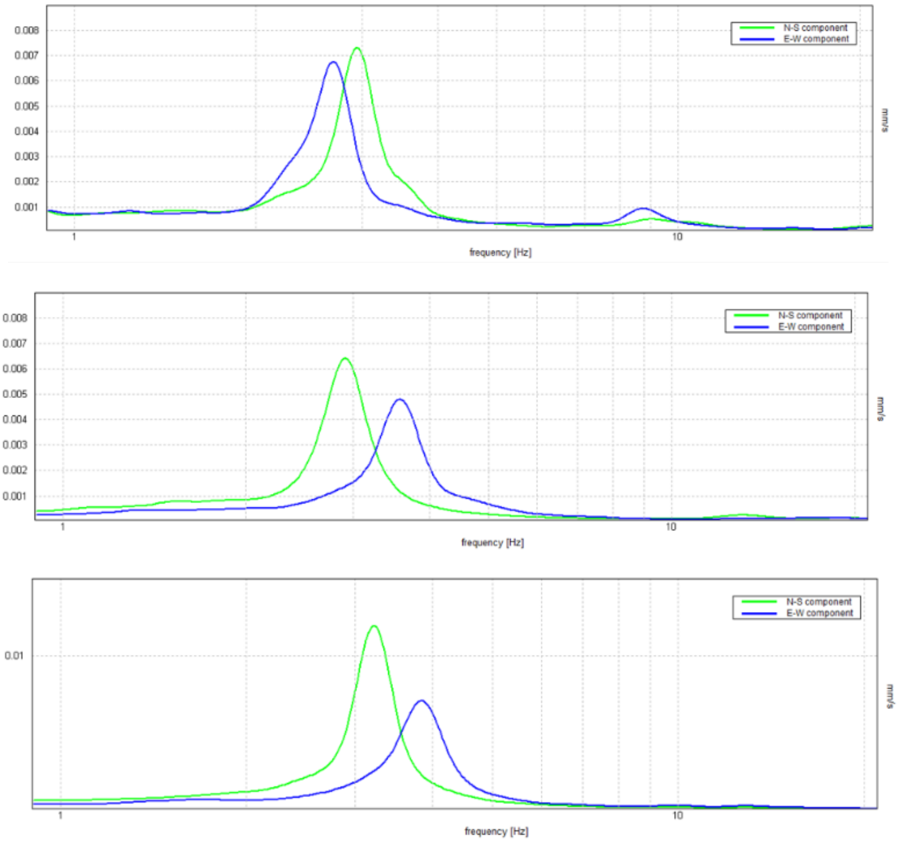

Fig. 4 Two-component ambient vibration spectra's of selected buildings in from database (N-E: north-east, E-W: east-west)

The vibration periods obtained from ambient vibration measurements were compared with the periods obtained by analytical models. The buildings were modeled with infill walls as dead loads in 3-D models. Aerated concrete blocks are used in the buildings as infill wall elements. All other infill walls with openings that prevent diagonal strut formation were considered as dead loads. Other dead loads such as slab weight were also considered as a distributed load.

Concrete compressive strength, steel properties, and size of structural members were taken from construction drawings. Most of the buildings higher than 3 levels were reinforced concrete frame-type structures with shear walls. Structures with lower heights are without shear walls.

A database with all measurement results and results from the numerical analyses which contains the fundamental characteristics of those structures and their most important geometric and structural properties with the aim of setting correlations between structural typologies and fundamental periods or frequencies has been created. The distribution of natural vibration periods obtained for all structures with respect to the building's height is shown in Fig.5. These results are related to building structures with infill walls. As expected, building periods increase with respect to height. Fig.5 shows that the measured fundamental periods are higher than the analyzed (numerically obtained), what is expected due to level of the construction of the infill walls.

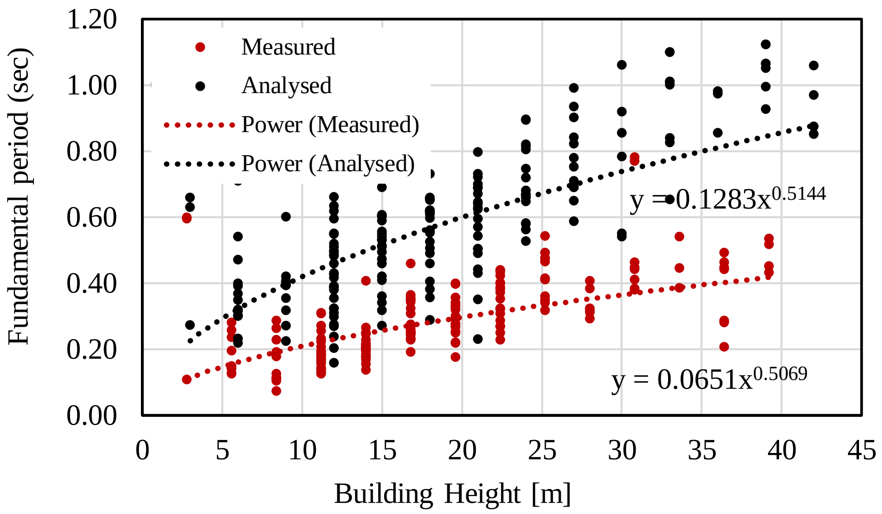

Fig.5. Fundamental period of measured and analyzed structures as a function of building height (m)

The height-period curve parameters are defined in many design regulations as well as in Eurocode 8 [15]. Ambient vibration signal measurements were compared to evaluate the consistency of obtained data with other results available in the literature (Fig. 6). Empirical equation derived by Eurocode 8 is given in equation (2). T defines the building period and H defines the building height in the following equation

$$T = 0.075H^{0.75} \tag{2}$$

Gallipoli et al. [16] derived equation (3) by using ambient vibration signal records taken from 244 buildings located in various regions in Europe:

$$T = 0.016H \tag{3}$$

Based on the measurements in this study, we propose an empirical equation (4) with respect to height-period parameters given in the following form

$$T = 0.0651H^{0.5069} \tag{4}$$

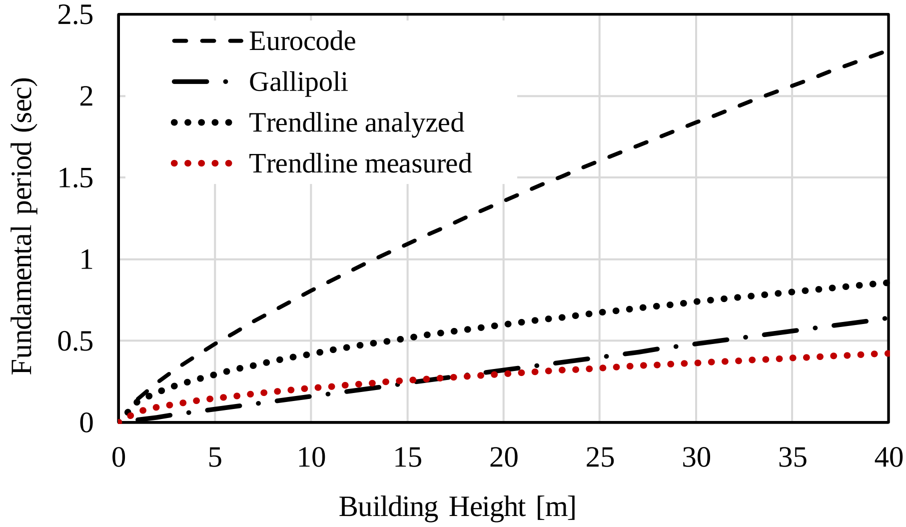

Fig. 6 Distribution of fundamental periods with respect to building height

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When results are compared, it is observed that the data obtained from these measurements have a similar tendency to the equation proposed by Gallipoli et al. [16]. The Eurocode 8 code height-period curve resulted in estimations much higher than expected for all ranges due to omitting the stiffness contribution of infill walls. Another significant point is that buildings used in this study are residential buildings of similar characteristics. These buildings have reinforced concrete frame structures, are constructed in accordance with current design codes and do not have great differences. For buildings with a higher amount of shear walls, lack of such a high-level relationship between height and period can be expected depending on the amount of shear walls [17].
The period/height ratio of the measured and analytically obtained results are given in Tab. 2.

Table 2 - Period/height ratio

Period/height ratio	Analytical	Measured
max	0.118	0.065
min	0.001	0.006

The strength of infill walls is influenced by many parameters such as material and mortar properties and production quality. Therefore, it is reasonable that under large displacements, building periods even in elastic regions can be higher than the period values determined based on ambient vibration records.

5. Notes and conclusions

The ambient vibration measurements from the 169 new buildings have been evaluated. More than, half of the residential buildings that have been tested were measured after the construction of infill walls. All the obtained results and the authors experience during many years of work in this field with in-situ measurements of structures under the most varied conditions (in construction, full occupancy, using various sources of excitation, etc.) and numerical modelling for typical structures, has led to the following conclusions:

- The measured fundamental periods of all structures are lower than the analytically obtained, which is expected due to the influence of general stiffness contribution of infill walls.
- There is a close correlation between natural vibration periods and building height in RC frame buildings with and without constructed infill walls.
- Based on the measurements in this study, an empirical equation with respect to height-period parameters is derived as eq. (4).
- The obtained results revealed a similar distribution with height-period equations in the selected literature by using ambient vibration signal records, especially to the Gallipoli et al. [16]. The relationship used in Eurocode 8 (1) revealed higher natural vibration period estimates than the measured periods.
- The highest period/height ratio from analytical results was found to be 0.096 and the value for minimum ratio is 0.008. The measured minimum and maximum values are 0.005 and 0.060 respectively. The uppermost values are so low, that are appropriate for newly building structures.
- It is relatively easy to identify the two basic modes using a single instrument for the structures which are regular to a certain extent, the first two modes in each horizontal direction.
- The effect of infill brick walls in RC structures, is larger for more flexible structures.
- Analytical modelling can reach results remarkably close to the measured ones if infills and stairways are modelled.

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