Analysis of Seismic Waves Generated by Blasting Operations and their Response on Buildings

S. Ziaran, M. Musil, M. Cekan, O. Chlebo

Abstract—The paper analyzes the response of buildings and industrially structures on seismic waves (low frequency mechanical vibration) generated by blasting operations. The principles of seismic analysis can be applied for different kinds of excitation such as: earthquakes, wind, explosions, random excitation from local transportation, periodic excitation from large rotating and/or machines with reciprocating motion, metal forming processes such as forging, shearing and stamping, chemical reactions, construction and earth moving work, and other strong deterministic and random energy sources caused by human activities. The article deals with the response of seismic, low frequency, mechanical vibrations generated by nearby blasting operations on a residential home. The goal was to determine the fundamental natural frequencies of the measured structure; therefore it is important to determine the resonant frequencies to design a suitable modal damping. The article also analyzes the package of seismic waves generated by blasting (Primary waves – P-waves and Secondary waves S-waves) and investigated the transfer regions. For the detection of seismic waves resulting from an explosion, the Fast Fourier Transform (FFT) and modal analysis, in the frequency domain, is used and the signal was acquired and analyzed also in the time domain. In the conclusions the measured results of seismic waves caused by blasting in a nearby quarry and its effect on a nearby structure (house) is analyzed. The response on the house, including the fundamental natural frequency and possible fatigue damage is also assessed.

Keywords—Building structure, seismic waves, spectral analysis, structural response.

I. INTRODUCTION

CURRENT experience confirms that seismicity generated by technology can cause severe problems even in regions with little natural seismic conditions, therefore it is important to analyze and generalize the response of seismic waves on buildings and industrial structures with the intention to reduce its effects. The response of buildings and industrial structures on seismic events depends on the type of excitation, because there are differences between earthquakes and mechanical vibrations and/or shock or impact (dynamic loading) resulting from human activities which effect the conditions of the measured data. Sources of earthquakes are dimensionally large and much deeper than most vibration sources caused by human activity. Earthquakes cause damage over large distances, are characterized by a much larger flow of seismic energy, duration, and different types of seismic wave propagation. Therefore, for the same evaluating parameter, for example, the peak values of the measured objects parameters vary. In this respect, seismic measurements are affected by the

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source of the dynamic loading (shock, impact, vibration) and thus its frequency, duration and amplitude, where the low frequency vibration must be considered: earthquakes, wind, explosions [1], aerodynamic and mechanical impacts, machines installed in buildings or industrial structures and/or in the vicinity of these structures [2]-[4], technological processes such as forging, shearing and forming [5], chemical processes [6], transportation, construction activity and other sources of unwanted seismic excitation.

II. INVESTIGATION AND MEASUREMENT METHODS

The goal of the experimental tests is usually to determine the effects of seismic waves (shocks, mechanical impact, random or periodic low frequency vibration) on the effected structures/objects and any resulting damage to them, as well as any effects on human beings in the area of these objects with respect to their comfort and disturbance [7]-[10]. In order to realize such an experimental test it is necessary to:

- determine the location of the monitored structure with respect to the source of the seismic waves, if it is known (see Fig. 2 (a));
- appropriately select three (or in some special cases two) measurement directions, one in the vertical direction and two perpendicular directions to each other in the horizontal plane. In the case that the object is placed at a known location to the source of the seismic waves, two measurement areas can be sufficient, where the measurement in the horizontal direction coincides closely to the direction of the surface wave rays (see Fig. 2 (b));
- measurement of the seismic waves (source of the dynamic load on the structure) including FFT analysis, during the exposition of the structure [11], [12];
- measurement and analysis of secondary vibrations (background) and their assessment;
- analyze the source of the generated seismic waves (vibration) with respect to the important value, which can affect the measurements of the structure.

A. Measurement Equipment

Measurement of the seismic waves (vibration) was performed by using the PULSE Analyzer, Dyn-X, FFT, MI 3560-B-X10 made by Bruel & Kjaer. This analyzer represents an open system, which allows for new possibilities and more information with reliability in the measurement processes, analysis, and evaluation. Part of this system is the piezoelectric accelerometer with a frequency range of 1 Hz to 10 kHz (amplitude ±10%), a microphone, display and memory module (laptop PC). It is necessary to emphasize that, as a

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general rule, measurements are performed in three directions, two perpendicular directions in the horizontal plane and one in the vertical direction, usually measured by a geophone (Fig. 1) [13], [14], which are more sensitive to very low frequencies. The number of measured areas is relative to the size (length and height) of the measured structure [15].
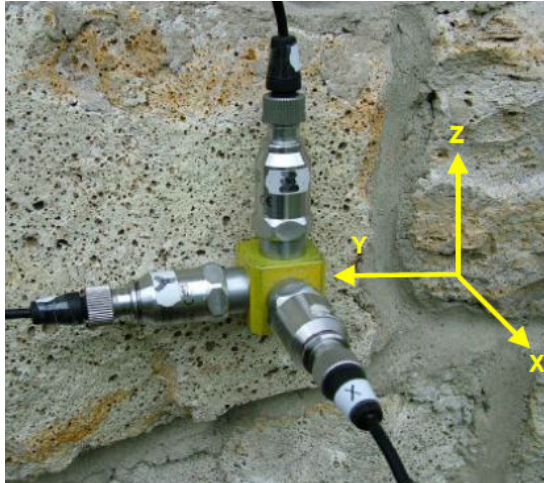

Fig. 1 Mounting of sensor to the structure of a building

In the event that seismic events location is known, measurements in the horizontal directions can be taken by one single-line sensor positioned such that its sensitive axis is positioned towards the seismic source [15]. When measuring responses of structures on impacts resulting from blasting operations the sensors sensitive axis was placed parallel to the ray of the seismic wave (see Fig. 2 (b)) [16]. If the source is unknown, it is advised to use a tri-axial vibration sensor.

Sensor mounting on structural elements of the building must coincide with the ISO 5348 standard with respect to accelerometers [17]. The goal is to ensure that the sensor correctly reproduces the motion of the structural element or foundation without interfering with the response, thus the upper areas of the foundation were selected as a suitable element. It should be taken into consideration that any aid used in measuring kinematic parameters of seismic events in the horizontal direction are considered to be not acceptable.

B. Location of Seismic Waves and Objective of Dynamic Analysis

The structure measured is a three story house, for which the first floor is built into a sloping landscape where the garage and basement are at the same level (see Fig. 2 (b) for floor plan). The location of the house with respect to the source of the blast (seismic waves) is shown in Fig. 2 (a). Fig. 2 (b) shows the floor plan of the house, measurement locations for the vertical and horizontal directions, and location of the source (approximately 1250m away). The plan also shows the seismic waves direction of progression. The energy absorbed by each external wall of the structure can be determined from the direction of the seismic wave. The source of the seismic wave is from an explosion in a quarry not far away.
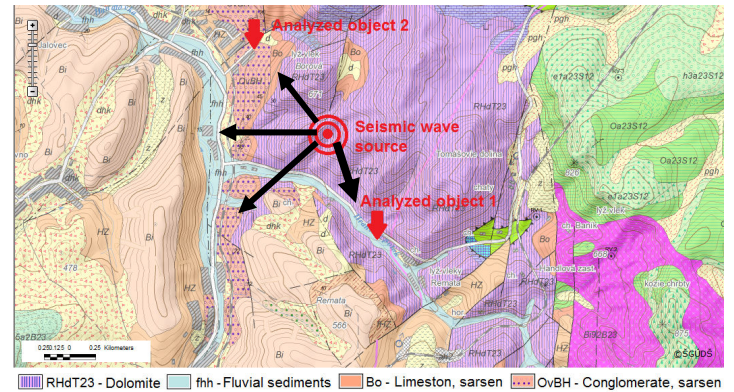
(a)
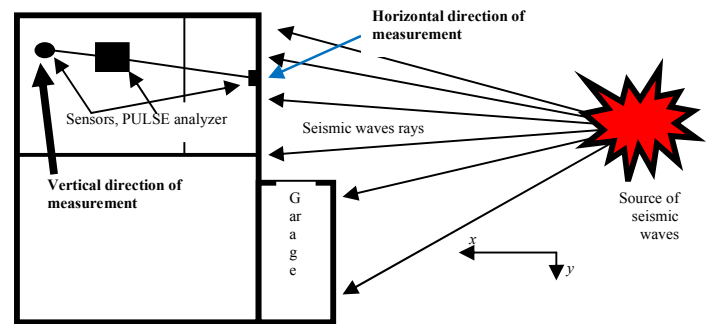
(b)

Fig. 2 Source of the seismic wave with respect to the measured object (a) source position of seismic wave with respect to longer wall and measurement points within the measured object (b)

C. Measured Parameters and Procedures

The measurement device and its technical parameters must be calibrated before measuring any seismic event. Proper calibration and setup is very important in measuring short non-repeating seismic events. Other than the frequency range, for the type of signal, it is also very important to select the appropriate type of averaging as well and number of averages per unit time as well as a suitable time window [12]. Definition of the measured parameter, such as the vibration acceleration, velocity (strength of vibration) and other performance parameters must be done. For short non-repeatable seismic events caused by human activity (blasting in a quarry) it is indispensable to setup the time interval of the measurement such that the signal is measured before the event occurs (background signal), during the seismic event, and after the seismic event (background signal) the time interval of the seismic signal is the basis for determining the strength of the vibration, since this energy parameter is used to evaluate the effect of the seismic event on the structure. For example, basic parameters for vibration induced by blasting can be seen in [15]. Before and after the measurement of non-repeatable seismic events it is beneficial to measure any secondary vibrations from external and/or internal sources of dynamic loading.

Throughout the measurements other variables are recorded that are essential to the frequency analysis, identification of measurement location and their corresponding frequency

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spectra, such as possible unique effects during measurements (random impacts and shocks caused by human activities in the surrounding areas). Such unique events, which can impact the correctness of the results, are an essential part of seismic measurements. By means of FFT analysis, the natural frequency of the measured building and/or segments is determined.

Overall, six auto spectrum are recorded from the defined measurement locations by means of contact vibration sensors (accelerometers), and coincidentally, the time history can be saved in memory for both measurement locations. Two auto spectrum and time history represent the blast itself and the remaining secondary dynamic loading (background).

### III. RESPONSE ANALYSIS OF THE SEISMIC WAVES AND DISCUSSIONS

The fundamental natural frequencies of a building or industrial structure or the parts of these structures influence their response and need to be known to allow the several methods of analyzing dynamic loading to be applied. This may be achieved by spectral analysis of low-level response to ambient excitation. Experimental studies have indicated the range of fundamental shear frequency of low-rise buildings 3m to 12m high to be from 4 Hz to 15 Hz [15], [18], [19]. Damping behavior is generally amplitude dependent.

Seismic waves are beneficial to analyze with respect to the frequency distribution of the signal, which allows for the determination of the structures fundamental natural frequencies, the energetic acting on structures as well as time history, which records the maximum amplitude of vibration acceleration and/or velocity and is used also in the further laboratory processing of the signal.

The environment of the analyzed object was seismically quite which means that there were no other sources of dynamic loading, such as from transportation, industry or other human activities. The measured object is located in a quite valley of mountains, which the frequency analysis of the background proves (no secondary vibrations from external sources was measured).

A. Frequency Analysis of Background and Seismic Waves

The frequency analysis of secondary vibration (background) from either measurement locations clearly confirms that no significant source of dynamic loading existed internally or externally (Fig. 3). Significant vibration amplitudes at higher frequencies are caused by human activities, who were dwelling within the home but these activity had no effect on the analysis the response of the building structure (pump of heating, refrigerate etc.). From the frequency analysis of the background and seismic waves, it is possible to state that the structure is sensitive to internal excitation in vertical direction (Fig. 3 (b)), while in the horizontal direction it is sensitive to the seismic event (Fig. 3 (a)).
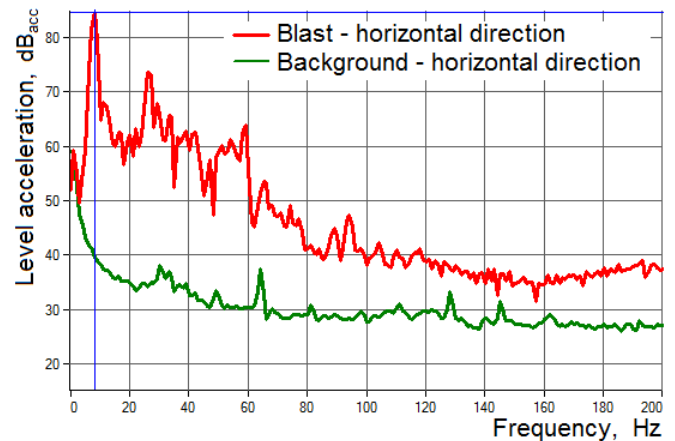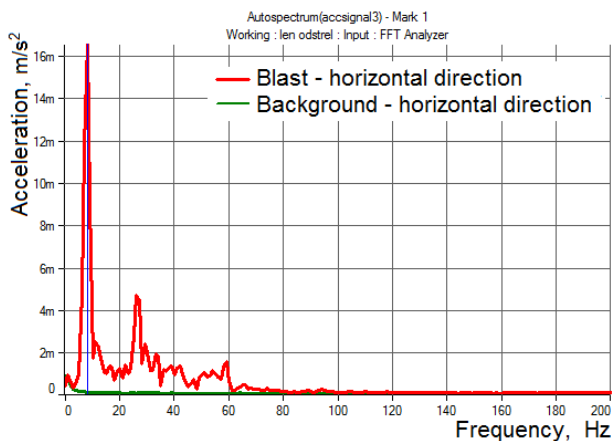
(a)
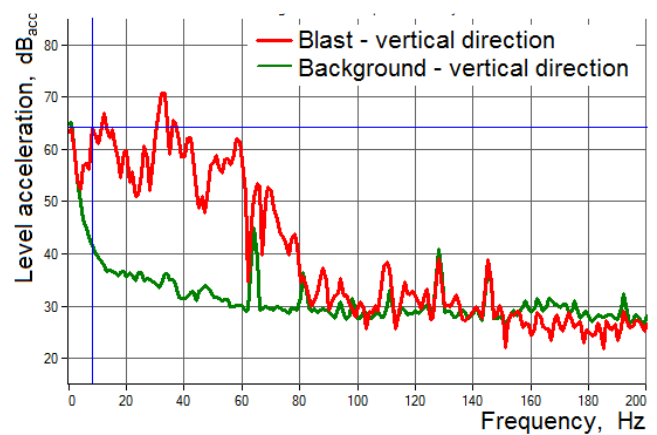
(b)

Fig. 3 Comparison of the frequency spectrum of background and seismic waves: a) in the horizontal direction b) in the vertical direction

By means of the FFT analysis the levels of seismic acceleration (explosive) are determined in the measured locations. Due to the short duration of the seismic blast the highest possible averaging is used in order for the amplitudes of vibration, at the monitored frequencies, reached the correct value as closely as possible. The results of the FFT analysis of the seismic waves shows that the maximal amplitude of vibration is at 8 Hz in the horizontal direction, that is the direction of the seismic wave propagation (direction x – see Fig. 2). This frequency represents the fundamental natural frequency of the analyzed structure (house). Its amplitude represents a vibration acceleration of 15.5 mm/s^2 and a vibration velocity of 0,328 mm/s. Therefore, for the estimation of damping the duration of the dynamic excitation can be determined. On the other hand, with known response duration the modal damping properties of the structure can be determined [3], [12], [19]. At this frequency, vibration amplitudes are significantly lower in the vertical direction which corresponds with the shear stress excitation (greatest in the horizontal direction). In general, the amplitudes of the structures vertical vibration are significantly lower. A more significant amplitude of vibration (vertical direction) was

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recorded at a frequency of 33.4 Hz, which is likely the resonance frequency of the floor.

A comparison of the frequency spectra of the seismic waves and secondary vibrations (background) can be seen in Fig. 3 for the decibel scale and in Fig. 4 for the linear scale. In this comparison a noticeable increase in dynamic loading during the seismic event can be observed at lower frequencies. However this increase is not so significant as to negatively impact the structure of the building. Graphs of the frequency analysis in units of vibration acceleration (velocity) – linear scale shown in Fig. 4, can be a measure of seismic threat to buildings and industrial structures. If the linear scale is used for displaying the amplitude, important frequency components of the seismic wave are emphasized and unimportant components are suppressed. From the frequency spectrum in Fig. 4 it is possible to determine the resonant frequency of the building, or its components directly. It is also possible to assign a value for the acceleration and/or velocity to judge the effects of seismic waves on the analyzed structure.

(a)
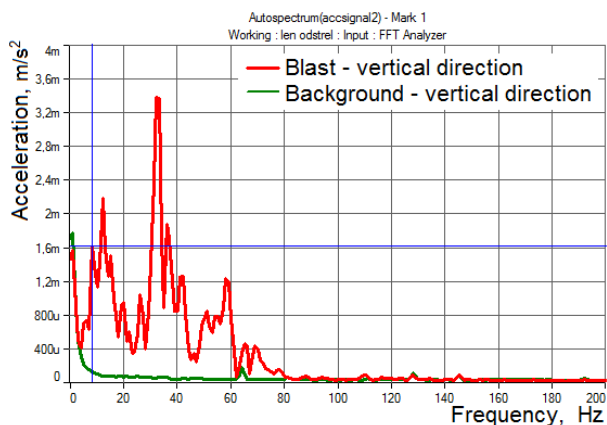
(b)

Fig. 4 Comparison of the frequency spectra for seismic waves generated by a blast in a quarry: a) in the horizontal direction, b) in the vertical direction

B. Analysis of Time History of Seismic Waves Generated by Blast

With the frequency analysis, the time history of secondary dynamic loading in the monitored building was also measured with the time history of the seismic waves. The recorded time history serves further analysis of the dynamic loading in the structure. The time history of the seismic waves for vertical and horizontal directions is seen in Fig. 5. This time record characterizes the seismic wave as a wave package [20], from which first allocates the longitudinal waves (P-waves) with a duration of 3 ms (Fig. 5 bottom). These waves manifest themselves only in the horizontal direction. A delay of 0,4 s results in transverse waves (S-waves), whose duration was particularly longer at 3 s.

Secondary waves (S-waves) are shear waves that are transverse in nature. These waves arrive at sensors after the faster moving P-waves during a seismic event and displace the ground perpendicular to the direction of propagation (Fig. 5 bottom). Depending on the propagation direction, the wave can take on different surface characteristics; for example, in the case of horizontally polarized S-waves, the ground moves alternately to one side and then the other. From the S-waves are created surface waves (Rayleigh waves, Love waves) which they travel slower than S-waves (roughly 90 % of the velocity of S-waves for typical homogeneous elastic media). Because of their low frequency, long duration, and large amplitude, they can be the most destructive type of seismic wave.

The delay of the S-wave, whose phase velocity is approximately 60% of the P-wave, the phase velocity of the longitudinal and transverse seismic wave can be calculated from the position equation, and based on this the type of explosive used. In the given case, the calculated phase velocity is based on a limestone subsurface. The type of subsurface can also be determined from [21]. Comparison of the results for determining the subsurface type of the seismic wave's transfer path coincided.

From the time history, it is possible to accurately determine the peak value of the building segments acceleration (velocity) where the sensor is placed. From Fig. 5 (top) it is possible to state that the peak value in the vertical direction is not significant when compared to the peak value in the horizontal direction (bottom). From Fig. 5 it is possible to determine the peak-to-peak value, whose value impacts the magnitude of shear stress mainly at the contact between terrain and the load bearing elements of the structure [22], [23].

C. Response Analysis of a Seismic Wave on the Given Building

In terms of the standard ISO 4866, the monitored building can be categorized as a modern structure using relatively hard materials, which are connected in all directions and is relatively light with low damping factor. This category consists of the skeletal structure of the building as well as type of materials and load bearing. Buildings can be single level or multi leveled. All roofed types are included. This category

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contains older types of housing who's construction has been made with modern materials, constraints and damping.

ISO 4866 states that the foundation of the monitored building is categorized by A [15], which consist of these types of foundations: bound concrete rebar or steel piles and rigid concrete rebar footing and floor. The analyzed structure is organized into the fluvial sediments, which is combined with dolomite [21]; therefore the transfer path of the seismic wave is through a limestone subsurface (see Fig. 2).
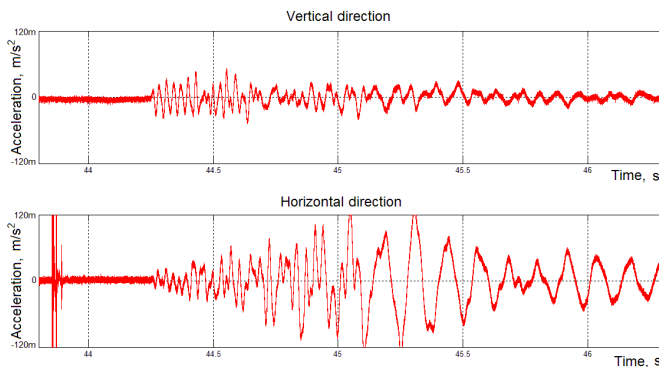

Fig. 5 Time history of a seismic wave generated by blast in stone quarry and background in the vertical direction of measurement (top), and horizontal direction (bottom)

The type of analysis is obvious, if it is identified to which category the structure belongs in [15]. The variables, for this type of dynamic loading, are characterize as deterministic, and thus it is enough to use a simple analysis (effective value, peak value, peak-to-peak value, mean quadratic value).

Greater changes in cyclic stress cause a high risk of fatigue damage. In the given case, fatigue damage is not a factor because, for low levels of vibration which the analyzed source generated, it would require 10^{10} load cycles (blasts) [15]. Fatigue damage can be considered with high levels of response over longer exposition duration. For example, buildings and industrial structures subject to large periodic excitation generated by large rotating machines with oscillating motion. [2]-[5] as well as from transportation sources.

A significant possibility of damage is related to the peak value of the structures segment velocity, whose value, from blasting processes in [15], reaches a few hundred millimeters per second. In the given case, this value is significantly lower. These values are not so great as to negatively affect the monitored building.

IV. CONCLUSION

As was introduced above in the measurement of the seismic waves generated by earthquakes, wind, explosions, random excitation from local transportation, periodic excitation from large rotating and/or machines with reciprocating motion, metal forming processes such as forging, shearing and stamping, chemical reactions, construction and earth moving work, and other strong deterministic and random energy sources caused by human activities it is very important, in the analysis of seismic event on building and industrial structures,

to correctly place the accelerometers such, that the maximum effects on the structure are recorded. Each placement can cause significant deviation from the actual kinematic parameters of excited vibration. In determining the place of measurement it is important to respect also the height of the structure since vibrations tend to increase higher up in the structure. For the given object (house) the measurement point for the horizontal direction were chosen directly below the top of the buildings foundation on the main load bearing wall, which corresponded to the level of terrain outside, and was oriented perpendicular to the direction of high energy wave (toward the source) [16]. The sensor must always be mounted on load bearing elements of the structure or at least as close as possible. Measurement of vertical vibrations was performed near the load bearing wall, since this place better represents the structural integrity of the building than in the middle of the floor. The sensor was placed on a free standing steel cylinder placed horizontally on the floor. In no way should horizontal vibrations be measured in this way, doing such can result in more than 40 % error [11], [12].

Other than object 1, the same measurement was performed using a geophone in three perpendicular directions [14]. A difference of 17% between the two methods was recorded for approximately the same distance whose value is impacted by the path of the seismic wave for the same source, and type of seismic event (see Fig. 1).

The International standard in [15] evaluates the level of damage in buildings by different categories. One of these categories is cosmetic damage, which is characterized by thin hairline cracks on the surface of a wall without finish (stucco), growth of existing cracks in drywall or on the surface of an unfinished wall (without stucco). Such damage, or any other form of damage, was not observed during the measurements.

The resulting 8 Hz resonant frequency of the house corresponds to the frequency interval found through other experiments for such structures (between 4 Hz to 15 Hz for) [15]. In cases where this frequency is known, it is possible to take effective measured to reduce the effects of transmitted seismic waves on buildings and industrial structures.

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