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SITE RESPONSE ANALYSIS BASED ON BOREHOLE ACCELERATION RECORDS FROM LOCATION TOWER, OHRID 3D SEISMIC NETWORK

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Abstract

The Location Tower is one of the three sites from the 3D seismic network originally installed in the 80's which is recently re-established and enabled for real-time monitoring and recording acceleration data. The Location Tower is consisted of one surface and three downhole instruments up to 125 meters down the bedrock; a nine story building with two instruments installed on 6th and 9th storey & 4 instruments installed at the foundation level. In the period of 2021-2022 several small to moderate earthquakes have been recorded with the system. This study presents selected results and comparisons of equivalent linear analysis of the site using real recorded acceleration data. The soil profile is defined based on number of geophysical and geotechnical investigations at the location, both in-situ and laboratory tests. Obtained results are good starting point for further non-linear site response analysis at the location which can be validated with stronger recorded earthquakes in future.

Keywords: site response, amplification, borehole acceleration.

1. Introduction

Local site conditions can significantly influence the characteristics of earthquake ground motion, and hence the degree and extend of damage caused by an earthquake. The destruction of structures and ground motions recorded in Mexico City from 1985 Michoacan Earthquake and in the San Francisco Bay Area from the 1989 Loma Prieta Earthquake had promoted the need for investigation of the site effects. Furthermore, the effects of local soil conditions are of particular significance in seismic micro zonation, seismic design of important facilities, as well as in seismic safety assessment of existing structures and undertaking preventive measures for reduction of seismic risk of existing facilities and urban areas exposed to destructive ground motions.

The existing empirical methods and new techniques for seismic microzoning based on experience rom damage of the structures in the past earthquakes and consideration of local site conditions determined from the studies of microtremors and small earthquakes are hardly reliable methods for evaluation of the seismic design parameters. Verification is ultimately needed for the possibility of extrapolation of

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small records to predict local soil behavior and site effects in the case of strong earthquake motions as well as to verify laboratory techniques for elaboration of dynamic soil properties under high strain levels. For that purpose registration from different location and different level of excitation sources is important to validate the available empirical and analytical analysis methods.

In order to study the local site effects on modification of strong ground motions and dynamic response of structural systems, a three-dimensional seismic network was established in the Ohrid Lake basin in the 80's [1] with the support of USGS (United States Geological Survey). This 3D strong motion array consisted of three free field sites with one surface and three downhole instruments each, 125 meters down the bedrock; a nine story building site with two instruments installed on the building, 4 instruments installed at the foundation level and one outcropping rock site with one instrument (location Tower). With the extensive recent activities, real time recording and health monitoring processes are enabled at the location [2]. This paper focuses on a site response analysis of the soil profile at the Location Tower in comparison to real acceleration records from different depths at the location.

2. Soil profile & location

2.1 Description of the site location

The Tower location is one of the four instrumented locations within the city of Ohrid. There is evidence on intensive seismic activity along the investigated location, namely the earthquakes with magnitudes greater than six (M>6) that happened in the distant past (1906, Ohrid, M_L=6.00; 1911, Ohrid, M_L=6.70). In 2016, an earthquake with a magnitude of 5 according to the European MCS scale was felt in Ohrid. The earthquake epicenter was 12 km northeast from Ohrid. It caused visible damage particularly to older structures and structures pertaining to cultural heritage, showing the gap between the scientific investigations and engineering practice. Previous studies performed for Ohrid by UKIM-IZIIS, [3] showed that, geological conditions in combination with a certain intensity of seismic exposure in some specific regions, could give rise to some geotechnically associated hazards that have an unfavorable effect upon engineering structures.
Based on the latest seismic hazard map of Macedonia prepared according to the Eurocodes (PGA), [4] the city of Ohrid is situated in a zone of moderate to high seismicity, with PGA of 0,3g at bedrock, for a return period of 475 years. The Ohrid city lies in the Ohrid lake watershed area and is characterized by the following geotechnical conditions:

1. Surface Quaternary and deep Pliocene sediments;
2. Surface Quaternary sediments consisting of fine gravel and sand as well as organic clays and sand down to depth of 20 m;
3. Heterogeneous nature characterized by unfavorable physical-mechanical characteristics. The underground water level is generally high.

2.2 Soil profile

To define the geotechnical characteristics of the site, data from previous investigations as well as data from additionally performed geophysical and geotechnical investigations and georadar measurements were used [5, 6]. The results from the geophysical investigations enabled the obtaining of seismic sections down to maximum depth of 150 m whereat local discontinuities and deformations in the terrain structure were defined. The models obtained by analysis of data from the investigations combined with application of seismic refraction, MASW and HVSR, distinguish 5 lithological media characterized by different physical-mechanical characteristics.

The following lithological media are distinguished:

- A surface layer – dusty, sandy and clayey, with seismic velocity values of Vs=150-200 m/s;
- Subsurface layer of clay, dust and sand with seismic velocity values of Vs=200-400 m/s;
- More compact Quaternary sediments with seismic velocity values in the range of Vs=400-600 m/s;

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- Pliocene sediments with seismic velocity values in the range of Vs=650-800 m/s;
- Terrain bedrock, Paleozoic shales with seismic velocity values of Vs>1000 m/s.

From the performed analysis of data obtained from CPT (cone penetration tests) and SPT (standard penetration tests) as well as from the aspect of the lithological composition of the terrain and strength and deformability characteristics, it can be said that the soil on the investigated location is characterized by variable geomechanical characteristics. The investigation mainly shows a lithological structure with alternating occurrence of silty clays with fine gravel and clayey silt that are moderately plastic and with variable thickness of layers. The penetration resistance of silty parts ranges within the limits of q_c=(0,5-1,2) MPa and the corrected number of SPT blows is N_{60} = 4, whereas those of the sandy and fine gravel parts are within the limits of q_c=(6,0-10,0) MPa with N_{60} = 14. Based on the extensive soil investigation, the Vs soil profile was defined presented in Fig. 1.

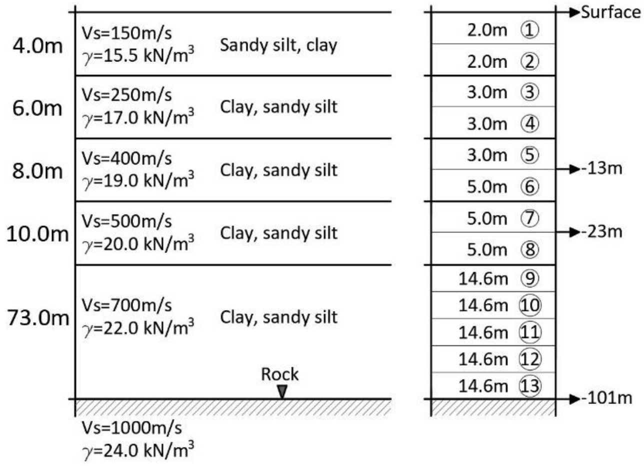
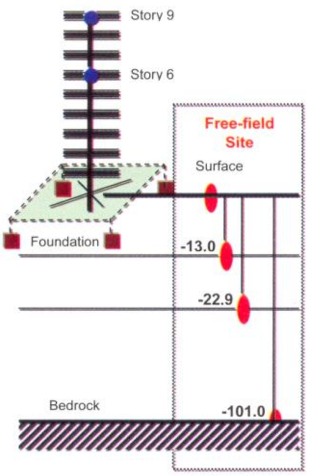


Figure 1. Shear wave velocity Vs [m/sec] profile for analysis of the local site effects.

3. Seismic instrumentation

3.1 Instrumentation at the site

The Location Tower from the 3D strong motion array is consisted of one surface and three downhole instruments each, 125 meters down the bedrock; a nine story building with two instruments installed on the building, 6th and 9th Storey and 4 instruments installed at the foundation level. The number and the depth of the instruments at the locations are presented in Fig. 2.



Instrumentation	Location – 1- Tower In situ laboratory
Site type	Instrumented building
Instruments on the building structure	2 (6th and 9th story)
Instruments at the level of the foundation structure	4
Instruments on soil surface	1
Instruments in soil profile	2 (13.0m, 22.9m)
Instruments at bedrock	1 (101m)
Total number of instruments	10

Figure 2. Instruments setup and depth at the Location Tower

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3.2 Obtained records from small to moderate earthquakes

During planning and installation of the Ohrid Lake Seismic Network in the late 70's, the entire network was composed of the most advanced instruments produced by Kinemetrics Inc., Pasadena, California. However, the analogue recording system could not be maintained in the last decade and there was no possibility for recording real time earthquake events. The time period between 2020-2021 was the beginning of extensive revitalization of the network. Replacement of the recording system by an analogue-digital conversion device, which enables real time recording of earthquake events and thus structural and health monitoring at the Location Tower was realized. Since March 2021, several small to moderate earthquake events have proven the functionality of the installed instruments and have provided important data for further investigation at the location. Selected recorded earthquakes are analyzed in this paper which are given in Table 1. With the presented registrations simple 1-dimensional linear equivalent site response analysis was performed at the site which are presented in further chapter. It is worth noting that three directions are recorded with three channels, and for the analysis one horizontal acceleration per earthquake was used.

Table 1. Selected registered earthquakes with the monitoring system at the Location Tower

	DATE OF REGISTERED EARTHQUAKES	RICHTER MAGNITUDE	EPICENTER
EQ1	09 January 23:38 Pm (UTC) 2022	**4.0**	**Bitola, Macedonia, 8 km southeast of Bistrica, Macedonia***
EQ2	11 January 17:01 Pm (UTC) 2022	**3.5**	**Florina, West Macedonia, Greece***
EQ3	11 January 17:44 Pm (UTC) 2022	**4.5**	**Florina, West Macedonia, Greece***
EQ4	12 January 03:01 Am (UTC) 2022	**3.6**	**Florina, West Macedonia, Greece***
EQ5	22 April 21:07 (UTC) 2022	**5.7**	**42 km SE of Mostar, Bosnia and Herzegovina**

** these quakes were likely an aftershock of the 5.3 quake West Macedonia, Greece, Jan 9, 2022 11:43 pm (GMT +2)*

4. Site response analysis

The local geotechnical media have a specific effect upon the characteristics of motion through the soil surface during earthquakes. Depending on the characteristics of the local geotechnical media and the characteristics of excitation at the level of seismic bedrock, these effects can be greater or lesser. The effect of the local soil conditions is expressed through variation of the amplitude-frequency characteristics of ground motion upon the surface in respect to the corresponding excitation at the level of the seismic bedrock. The analyses were performed by application of the method of vertical propagation of shear seismic waves through a linear viscoelastic system based on the solution of the Kanai wave equation. The procedure of definition of the nonlinear effects in soil resulting from seismic effects includes an approach that uses the equivalent linear characteristics of soil developed by Seed and Idriss, [7]. The analyses were performed by use of the SHAKE2000 software. The model presented on Fig. 1, was analyzed with the selected recorded acceleration records given in Table 1.
The effect of the local medium was evaluated based on the analysis of the dynamic response of the mathematical model. This analysis enabled definition of the peak accelerations along depth of the model as well as the response spectra of the models for the surface level. With the analyses of the local soil effects, there were obtained the mean periods of natural vibration of 0.63-0.65 s, for the real recorded acceleration level (without scaling) corresponding to low level of deformations. Fig. 3 and Table 2, show the variation of peak accelerations along depth of the models obtained by convolution of selected accelerograms, for real recorded input acceleration of a_{max} between 0.0027 and 0.0069g.

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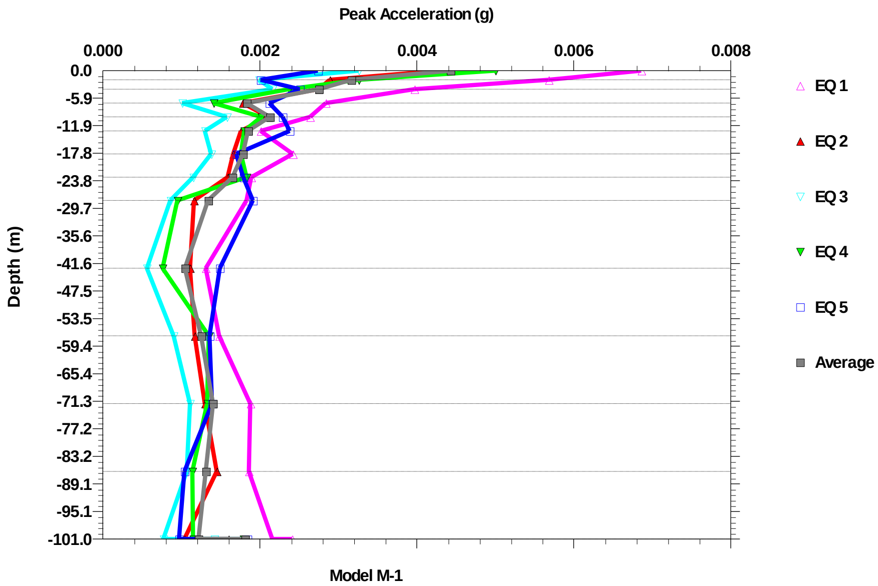

Figure 3. Peak accelerations along Depth for real recorded acceleration– response of the soil column.

Table 2. Calculated peak accelerations along depth, periods of the soil column and DAF_{mean}

DEPTH	MAXIMUM ACCELERATION					
	EQ 1: Florina 11.01.2022 (M4.0)	**EQ 2: Bitola 09.01.2022 (M4.0)**	**EQ 3: Florina 12.01.2022 (M3.6)**	**EQ 4: Florina 11.01.2022 (M3.5)**	**EQ 2: B&H 22.04.2022 (M5.7)**	**Average acc. a_{max} (g)**
0	**0.0069**	**0.0043**	**0.0033**	**0.0050**	**0.0027**	**0.0045**
-4.0	0.0040	0.0027	0.0021	0.0023	0.0025	0.0027
-10.0	0.00264	**0.0021**	0.0016	0.0020	0.0023	0.0021
-13.0	**0.0020**	**0.0018**	**0.0013**	**0.0018**	**0.0024**	**0.0019**
-18.0	0.0024	0.0017	0.0014	0.0017	0.0017	0.0018
-23.0	**0.0019**	**0.0016**	**0.0011**	**0.0018**	**0.0018**	**0.0016**
-57.20	0.0015	0.0012	0.0014	0.0013	0.0013	0.0013
-101.0	0.0024	0.0017	0.0015	0.0019	0.0018	0.0019
DAF (0/-101)	**2.88**	**2.53**	**2.20**	**2.63**	**1.56**	**2.36**
DAF (-4/-101)	**1.67**	**1.59**	**1.40**	**1.21**	**1.39**	**1.42**
PERIOD (S)	0.66	0.64	0.63	0.64	0.66	**Average period:** 0.65 s

Fig. 4 and 5 represent the average computed acceleration time history on the left and the real recorded acceleration time history from instruments on the right for the level of 101m and the surface level 0.0m. The graphs are compatible, and it can be concluded that the modelled soil profile represents the real amplification characteristics of the location.

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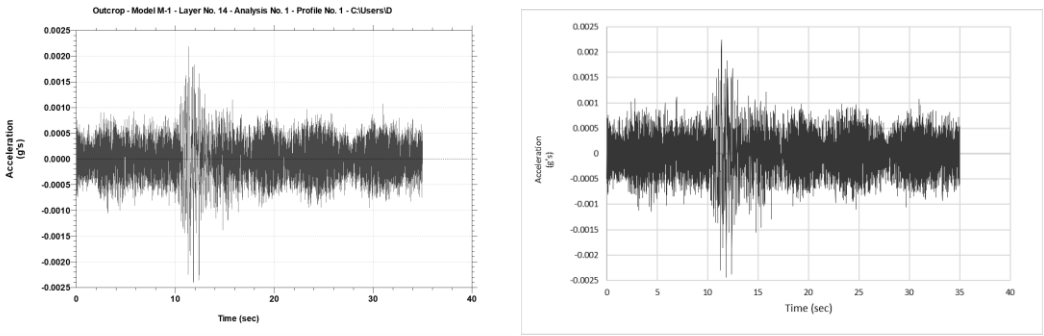

Figure 4. Computed acceleration time history (left) and the recorded acceleration time history (right) for the depth of -101.0 m

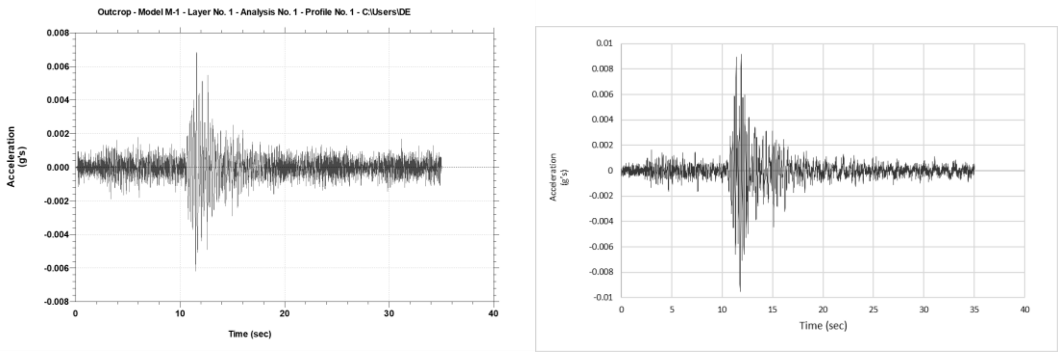

Figure 5. Computed acceleration time history (left) and the recorded acceleration time history (right) for the surface 0.0m.

Calculated acceleration records at the same depths where recorded acceleration records were available were compared and results presented in Table 3. The obtained dynamic amplification factor is presented in Table 4. Results show good correlation to the recorded values on the surface. Additionally, more detailed modelling of the materials model of the soil profile are needed to fit the records for the deeper soil layers at level of 23 meters.

Table 3. Difference in percentage of the recorded acceleration versus the calculated for each depth

	RECORDED ACCELERATION [G]						
DEPTH	**EQ 1: Florina 11.01.2022 (M4.0)**	**EQ 2: Bitola 09.01.2022 (M4.0)**	**EQ 3: Florina 12.01.2022 (M3.6)**	**EQ 4: Florina 11.01.2022 (M3.5)**	**EQ 2: B&H 22.04.2022 (M5.7)**	**Average acc. a_{max} [g]**	**Difference with calculation (%)**
0	**0.0095**	**0.0055**	**0.0024**	**0.0035**	**0.0036**	**0.0049**	**8.9**
-13.0	**0.0021**	**0.0021**	**0.0012**	**0.0022**	**0.0030**	**0.0021**	**10.5**
-23.0	**0.0039**	**0.0016**	**0.0011**	**0.0015**	**0.0027**	**0.0022**	**37.5**
-101.0	**0.0024**	**0.0017**	**0.0015**	**0.0019**	**0.0018**	**0.0019**	/

Table 4. Dynamic amplification factor for each depth in respect to the seismic bedrock, calculated versus recorded

Depth [m]	DAF (calculated)	DAF (recorded acc.)
0.0	**2.37**	**2.58**
-13.0	**1.0**	**1.1**
-22.9	**0.9**	**1.16**
-101.0		

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5. Discussion, conclusions and further work

Obtained results are good starting point for further non-linear site response analysis at the location which can be validated with stronger recorded earthquakes in future. The diagrams show that the surface layers considerably amplify the earthquake effect, which is the result of the low strength characteristics of the soil in these layers. The values of the DAF from the analyzed recorded acceleration match well with the DAF obtained from the site response analysis. Still, to get a more accurate insight, one of the next recommended research steps will be to analyze the local soil conditions by higher number of acceleration records from the site with different magnitudes, comparison of the obtained acceleration records with acceleration records from nearby seismic stations as well as more detailed modelling of the dynamic soil properties (shear modulus and damping) obtained from laboratory experiments on soil samples of the location.

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