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ASSESSMENT OF SEISMIC SITE AMPLIFICATION BASED ON BOREHOLE ACCELERATION RECORDS FROM DIFFERENT DEPTHS

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Abstract: *The Location Tower is one of the instrumented sites from the 3-dimensional seismic network in Ohrid, R. N. Macedonia originally installed in the 80's. The site is consisted of one surface, at 0.0m, three downhole instruments up to 101 meters down the bedrock, at -13.00 metres and -23.0 metres. The seismic network is recently re-established and enabled for real-time monitoring and recording acceleration data. In the period of 2021-2022 several small to moderate earthquakes have been recorded with the system. This study presents assessment of the seismic site amplification of the site analyzing real recorded acceleration data from different depths and comparison to equivalent linear analysis of the soil profile. The soil profile is defined based on number of geophysical and geotechnical investigations at the location, both in-situ and laboratory tests. Obtained results from the equivalent linear analysis correlate with the acceleration records in terms of the dynamic amplification factor (DAF). Comparison of the DAF through the depth of the soil profile give valuable insights towards validation of the soil parameters in the modelling. Performed assessment is good starting point for further non-linear site response analysis at the location which can be validated with stronger recorded earthquakes in future.*

Introduction

Local site conditions can influence significantly 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 amplification 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.

Verification using real acceleration records of small, moderate and strong earthquakes records is crucial to verify modelling of the soil behavior and site effects as well laboratory techniques for definition of dynamic soil properties under low and high strain levels.

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 with the support of USGS (United States Geological Survey) (Petrovski et al., 1995). This 3d strong motion array consisted of three free field sites with one surface and

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three downhole instruments each, 101 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, Bojadjieva et al., 2021. 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 site, not considering the structure at the site.

Soil profile & instrumentation at the site

Soil profile

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, ML=6.00; 1911, Ohrid, ML=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, (Bojadjieva et al., 2019), 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 R. N. Macedonia prepared according to the Eurocodes (PGA), (Milutinovikj et al., 2016), 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 heterogeneous geotechnical conditions with high water level consisted of:

- Surface Quaternary and deep Pliocene sediments;
- Surface Quaternary sediments consisting of fine gravel and sand as well as organic clays and sand down to depth of 20 m;

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, Bojadjieva et al., 2022, Petrovski et al.,1985. 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, Multi channel analysis of surface waves (MASW) and Horizontal to Vertical Spectral ratio (HVSR), distinguished 5 lithological media characterized by different physical-mechanical characteristics.

The following lithological media are distinguished:

- A surface layer – silty, sandy and clayey, with shear wave velocity values of Vs=150-200 m/s;
- Subsurface layer of clay, silt and sand with shear wave velocity values of Vs=200-400 m/s;
- Quaternary sediments with shear wave velocity values in the range of Vs=400-600 m/s;
- Pliocene sediments with shear wave velocity values in the range of Vs=650-800 m/s;
- Terrain bedrock, Paleozoic shales with shear wave 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 show 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. Selected results from geotechnical and geophysical investigations are shown in Figure 1(layout) and Figure 2. It is important to clarify that for the purpose of this research the available geotechnical investigations for regular construction at the location are used, and are not performed for research purposes, which explains the limit of the depth of the investigation. However extensive research and analysis is performed for the geophysical measurements using different methods, previous research at the Ohrid seismic network (Petrovski et., al, 1995) to define the Vs profile to the depth of 101m. The definition of the Vs profile for the analysis is separate field of interest using combined seismic methods, and it is not presented in this work.

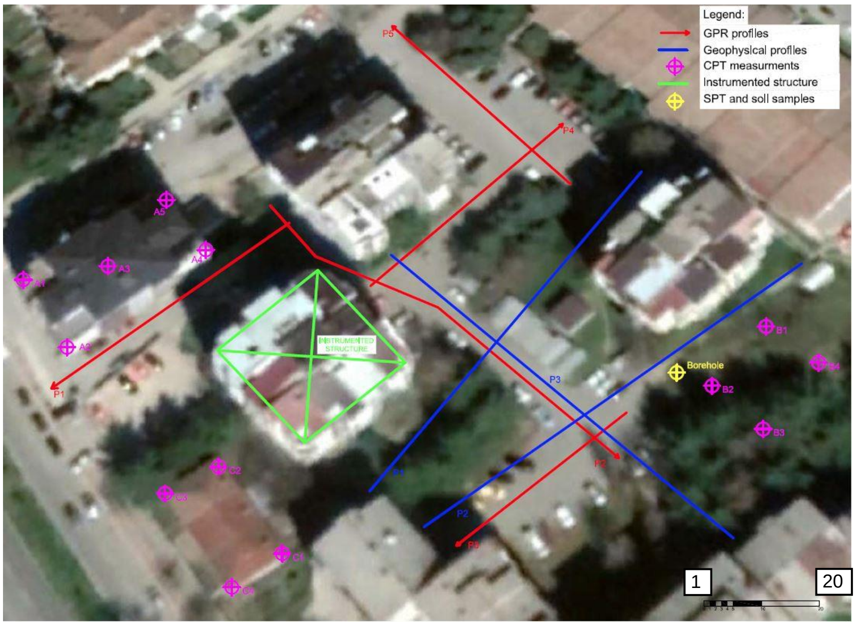


Figure 1. Layout of the performed investigations near the instrumented building - Location - Tower.

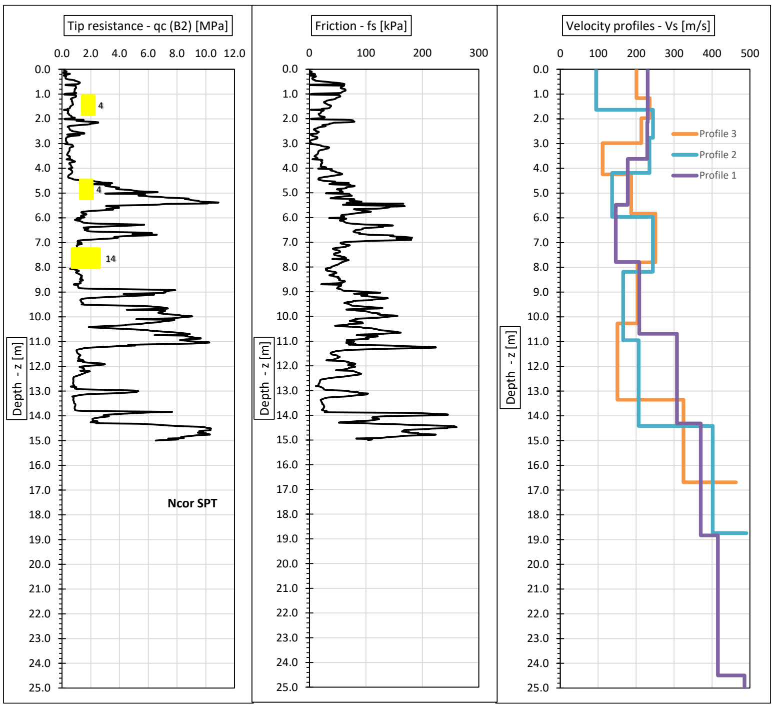


Figure 2. Extensive in-situ performed investigations versus depth at the location.

Based on the extensive geotechnical and geophysical soil investigation the Vs soil profile was defined presented in Figure 3.

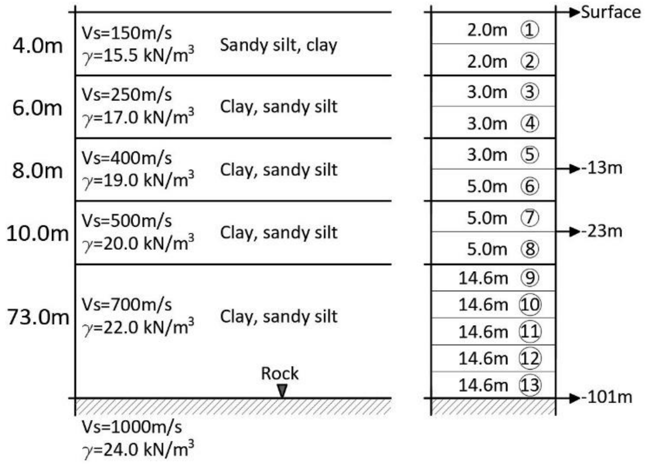
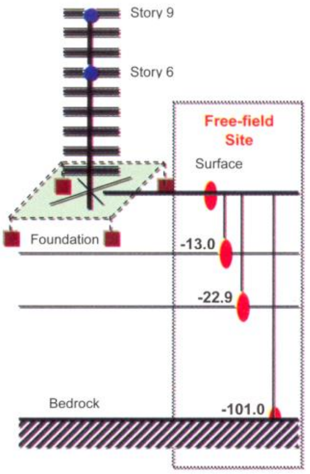


Figure 3. Shear wave velocity Vs [m/sec] profile for analysis of the local site effects.

Instrumentation at the site

The Location Tower from the 3d strong motion array is consisted of one surface and three downhole instruments each, 101 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 Figure 4.



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 4. Instruments setup and depth at the Location Tower.

Selected acceleration records from the site

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 maintain 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 parallel to the y direction of the building was used. Before used in the site amplification analysis, the signals were baseline corrected and filtered.

	Date of registered earthquakes	**Richter Magnitude**	**Epicenter**
EQ1	09 january 23:38 Pm (UTC) 2022	4.0	Bitola, R. N. Macedonia, 8 km southeast of Bistrica, R. N. Macedonia, N-S *
EQ2	11 january 17:01 Pm (UTC) 2022	3.5	Florina, West Macedonia, Greece, N-S *
EQ3	11 january 17:44 Pm (UTC) 2022	4.5	Florina, West Macedonia, Greece, N-S *
EQ4	12 january 03:01 Am (UTC) 2022	3.6	Florina, West Macedonia, Greece, N-S *
EQ5	22 April 21:07 (UTC) 2022	5.7	42 km SE of Mostar, Bosnia and Herzegovina, N-S

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

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

Site amplification 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 (1969). The analyses were performed by use of the SHAKE2000 software and material curves, (modulus reduction and damping ratio curves for sand and clay) given in Seed and Idriss (1970) were used to model the soil properties. The effective strain ratio used in the analysis was defined to be 0.65, and damping of 0.05 % was defined, having in mind the small strain range of interest.

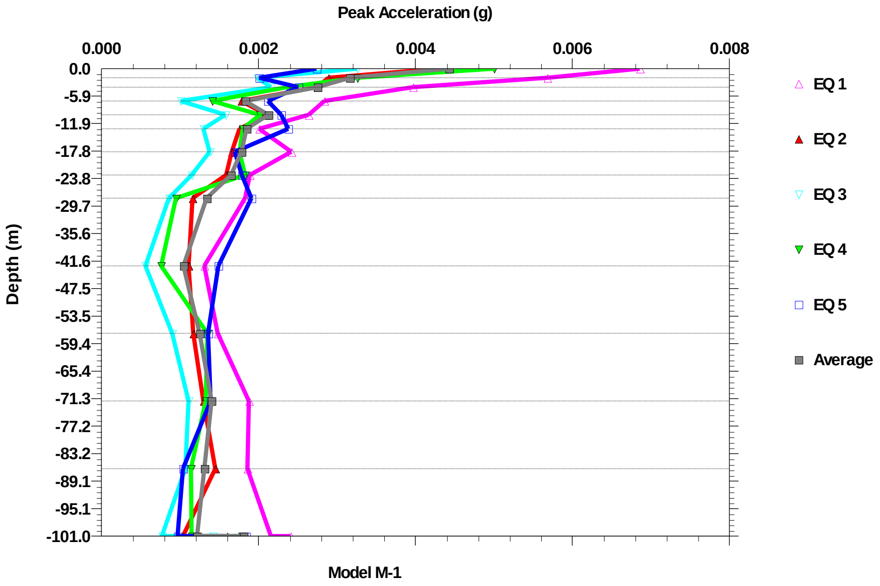


Figure 5. Peak accelerations along Depth for real recorded acceleration– response of the soil column.

The model presented on Figure 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. Figure 5 and Table 2, show the variation of peak accelerations along depth of the models obtained by deconvolution of selected accelerograms, for real recorded input acceleration of a_{max} between 0.0015 and 0.0024g.

Depth	**Maximum acceleration**					
	EQ 1: Florina 11.01.2022 (M_L4.0)	EQ 2: Bitola 09.01.2022 (M_L4.0)	EQ 3: Florina 12.01.2022 (M_L3.6)	EQ 4: Florina 11.01.2022 (M_L3.5)	EQ 5: B&H 22.04.2022 (M_L5.7)	Average acc. a_{max} (g)
0	0.0069	0.0043	0.0033	0.0050	0.0027	0.0045
-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
Period (s)	0.66	0.64	0.63	0.64	0.66	Average period: 0.65 s

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

Figure 6 shows the spectra for each of the selected time histories of acceleration, for damping of D=5%, for both the level of bedrock -101m (left) and the surface level 0.0m (right), along with the mean value from all the analyses. From the obtained spectra, it is clear that the dominant amplitudes occur in the period range of 0.4-1.0 s. 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.

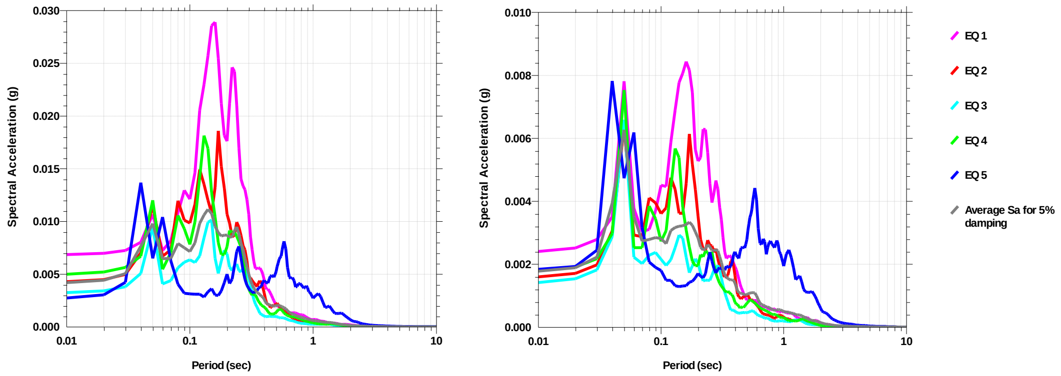


Figure 6. Spectral acceleration for 5% damping at level -101.0m (left) and at Surface 0.0m (right).

Figure 7 represents the recorded acceleration time history inserted as input for the analysis for the level of 101m. Figure 8 represents the average computed acceleration time history on the left and the real recorded acceleration time history from instruments on the right for the surface level at 0.0m. The graphs are compatible, and it can be concluded that the modelled soil profile represents the real amplification characteristics of the location.

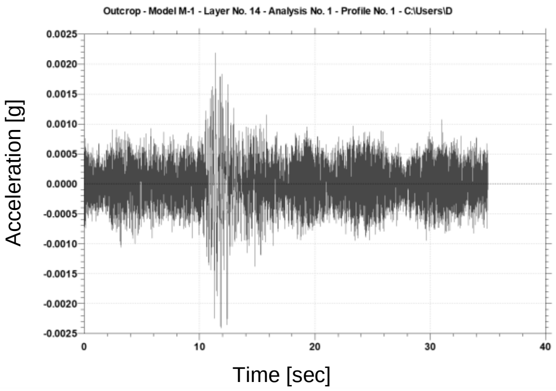


Figure 7. Recorded acceleration time history at depth of -101.0 m inserted as input acceleration time history for the analysis.

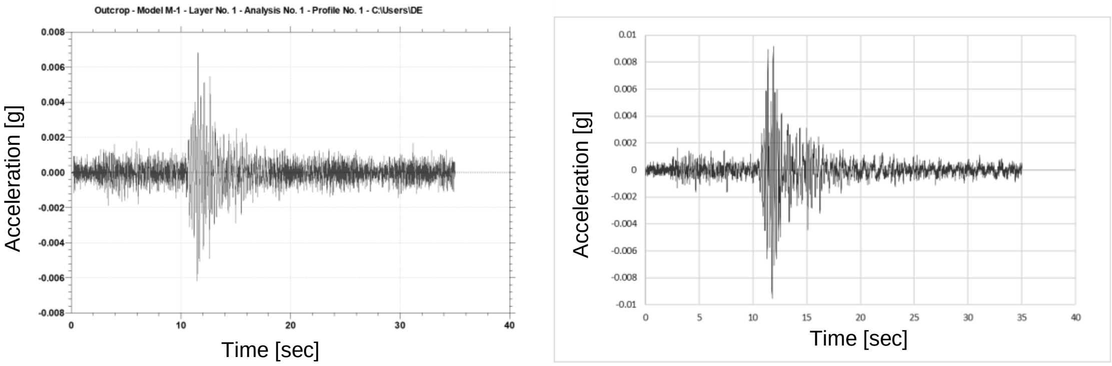


Figure 8. Computed acceleration time history (left) and the recorded acceleration time history (right) for the surface 0.0m.

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. It is expressed as a ratio between the mean peak acceleration a_{max} at the surface level and the corresponding input acceleration and represents, in a simple way, the amplification characteristics of the site. Results are given in terms of average values of the analysed record motions, since generally site response analysis is performed including larger number of accelerograms in order to understand the site response, rather than to try to match only one earthquake. Still, to get a more accurate insight and improved matching of the soil model response with the recorded accelerations, one of the next recommended research steps will be to study 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 realistic modelling of the dynamic soil properties (shear modulus and damping) obtained from laboratory experiments on soil samples of the location.

The values of DAF were also compared to DAF values given in Petrovski et al, 1995 from the seismic source zones in Albania, Greece and R. N. Macedonia recorded during 1992 (Table 5). Four moderate earthquakes with magnitudes in the range of 3.8 to 4.9 (similar magnitudes to the one analyzed in this study) have been recorded on the three-dimensional instruments array with the maximum acceleration amplitudes from 0.0010g to 0.00637g. Maximum acceleration at the bedrock was PGA=0.00121g, foundation level F4 with PGA=0.00322g, and 9th floor PGA=0.00627g all for N-S (transverse) component. Dynamic amplification factor at this site for relatively low excitation is in the soil media DAF = 2.66 in respect to the bedrock and 1.95 for the building in respect to the foundation level.

DEPTH	Maximum acceleration [pga] from the recorded accelerations						
	EQ 1: Florina 11.01.2022 (M_L4.0)	EQ 2: Bitola 09.01.2022 (M_L4.0)	EQ 3: Florina 12.01.2022 (M_L3.6)	EQ 4: Florina 11.01.2022 (M_L3.5)	EQ 5: B&H 22.04.2022 (M_L5.7)	**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 3. Difference in percentage of the recorded acceleration versus the calculated for each Depth

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		

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

Depth	**PGA [g]**	**DAF**
9th floor (building structure)	0.00627	1.95 (in respect to the foundation of the building)
Foundation level (0.0m)	0.00322	2.66 (in respect to the bedrock)
Bedrock (-101m)	0.00121	1

Table 5. Peak ground acceleration values and DAF from the 1992, 13th of August Resen earthquake as given in Petrovski et al., 1995.

Discussion, conclusions and further work

Obtained results are baseline 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 and analyzed from previous small to moderate earthquakes at the site from 1992.

This is initial study focused on the amplification after the re-estabilshment of the seismic network which occurred 30 years later, using the same instruments. It is of tremendous importance to validate the use of the system, and to obtain similar values of the dynamic amplification factor which is focus oof this initial study. However further improvement of matching the numerical modeling of the soil site is planned as further study.

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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