The Role of Local Site Conditions in The Seismic Assessment of Historical Monuments

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SUMMARY:
Presented in this paper are the investigations related to the local site conditions in the seismic assessment of two historical structures in Macedonia: the church of The Holy Mother of God Peribleptos, from the 13th century, located in the old town of Ohrid and the Mustafa Pasha mosque in Skopje, from the 15th century. The objective of the described procedure is to take into consideration the regional and microlocation geological and seismological parameters in order to define the input seismic parameters for dynamic analysis of the historical structures. The obtained results point out the significance of involving local site conditions into the seismic assessment and retrofit of historical structures in general. The procedure has been applied on many buildings of historical importance which require strengthening and rehabilitation with great success and efficiency.

Keywords: Local soil condition, seismic site response, historical monuments

1. INTRODUCTION

Located in the Central Balkan region, the Republic of Macedonia is characterized by a significant cultural and historical heritage, which has experienced many earthquakes during its life time, causing a lot of damages. Historical monuments either collapsed or retained their stability with damages. In this context, it is very important to assess the seismic resistance of the historical monuments in order to retain their existence as future cultural heritage. A comprehensive methodology for seismic risk assessment of historical masonry buildings has been developed and used in Institute for Earthquake Engineering and Engineering Seismology - IZIIS for over 40 years (Sendova and Gavrilovic, 2010). The procedure involves field, laboratory and numerical studies performed in compliance with the latest achievements in the field of earthquake engineering.
The main focus of this paper is related to the part concerning the local soil conditions and their influence on definition of the seismic input. The concept involves: seismic hazard analysis-regional approach, in-situ and laboratory investigations - microlocation approach, modelling of the local soil conditions and performing site response analysis of representative geodynamic models – evaluation of seismic input and definition of the seismic risk. These aspects are presented in details in this paper through two chosen case studies of very unique and specific type of historical monuments: : the Mustafa Pasha mosque in Skopje, from the 15th century and the church of The Holy Mother of God Peribleptos, from the 13th century, located in the old town of Ohrid.

2. DESCRIPTION OF THE APPLIED METHODOLOGY

Earthquake hazard definition for urban areas is the first and the most important step towards a seismic risk analysis and mitigation strategy (Berilngen, 2007). In seismic parameters definition, one would like to quantify the variation of the subsurface response to a specific design earthquake that can be expected in an area (e.g. the earthquake with a return period of 475 years in the European Seismic Code EC-8). Seismic assessment of historical structures requires multidisciplinary approach with

major contributions from geology, seismology and geotechnical engineering. Earthquake ground motions are affected by several factors such as source, path and site effects. An assessment of ground motion therefore depends on the regional seismicity, attenuation of ground motion intensity and local site effects on ground motion.
The applied methodology for definition of the seismic input parameters in the case studies presented in this paper follows the following steps:

- As shown in Figure 1, the first step includes characterization of the design seismic motion based on existing earthquake catalog and seismotectonic data and the seismic hazard through attenuation of ground motion intensity.
- The second step is definition of the subsurface profile of the studied area based on geological geotechnical, geophysical and topographic data. Site characterization is mainly done by geotechnical boreholes, Standard Penetration Test (SPT), Cone Penetration Test (CPT), PS-Logging, Refraction Microtremor (ReMi), seismic reflection and refraction measurements and laboratory index test results to provide engineering bedrock (Vs > 750m/s) depths.
- The next step is selection of earthquake input motions which are applied on the bedrock level and PGA acceleration to which the earthquake motions are scaled based on the results from the seismic hazard analysis
- The third step is to evaluate, for each location within the studied area, all the aspects of the seismic ground response, namely, the elastic response spectra. The local site effects are assessed by carrying out one-dimensional (1-D) ground response analysis) using borehole data and shear wave velocity profiles within the investigated area (Ordonez, 2011).
- Seismic risk analysis;
- Definition of seismic design parameters at different levels (PGA, site design spectra, time histories of accelerations) to be used in the evaluation of the existing seismic stability of the structures.

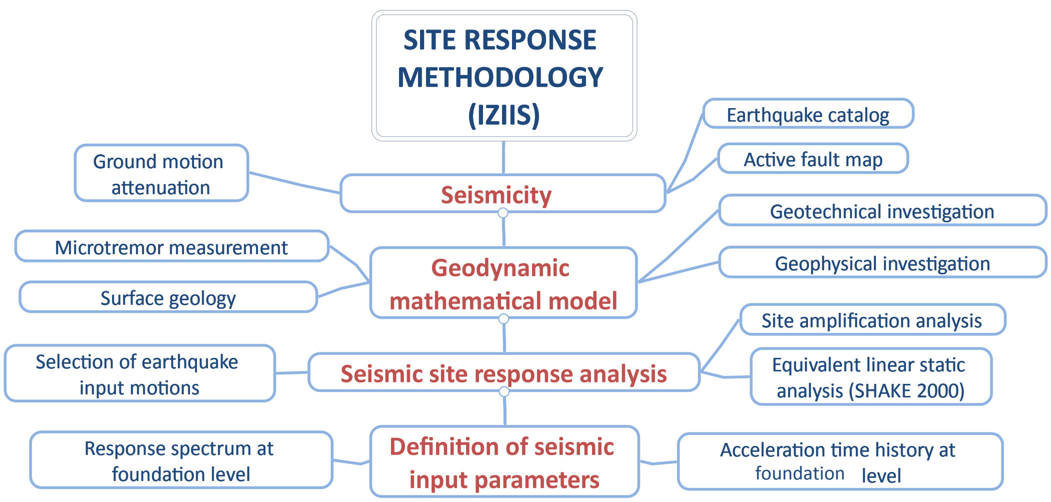

Figure 1. Flow chart of the applied methodology

The ground conditions in the seismic design process are usually taken into account through determination of the base seismic shear force, where the coefficient, which represents the ground conditions, is multiplied by other coefficients to calculate the seismic force. Then quasi-static analysis can be performed in order to design the structural elements and check the seismic performance of the structure. In cases where the design engineer has the task to design buildings of higher importance such as historic monuments, there should be no doubt that the engineer has to perform a time history analysis of the stress - strain state of the structure subjected to seismic loading (Sesov et al., 2012).

This analysis has to be based on the seismic parameters which are defined by the results from the in-situ and laboratory investigations performed for the site.
This paper is primarily focused on application of this methodology in historical structures, which are by themselves and in most of the cases, unique structures of significant cultural importance and as such deserve a multidisciplinary approach to their strengthening and preservation. No matter how sophisticated the structural analysis may be (starting from linear-elastic, pushover and nonlinear time history analysis), yet the variation and the uncertainty associated with the local soil conditions, the design seismic input parameters, determine considerably the response of the structure.

3. CASE STUDY 1 - MUSTAFA PASHA MOSQUE, SKOPJE

As the first case study, presented are the investigations related to the local site conditions in the seismic assessment of a historical structure in Macedonia: the Mustafa Pasha mosque in Skopje, dating back to the 15th century, as shown in Figure 2.

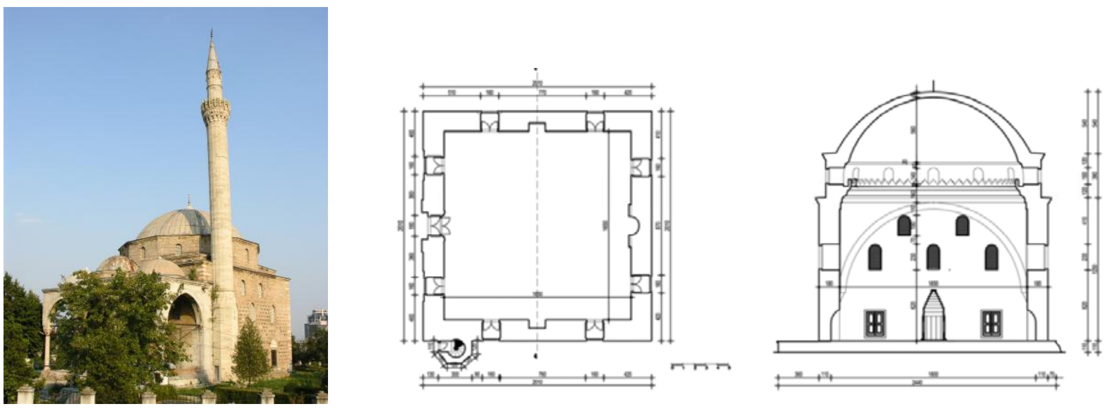

Figure 2. Mustafa pasha Mosque, view, plan and section

The Mustafa Pasha mosque in Skopje is located in the Skopje valley, which was created as a result of neotectonic movements of the surrounding structures. The geological characteristics of the location play an important role as to the amplitude and frequency content of the seismic action. Soils in the region of Skopje in Macedonia are relatively uniform according to stiffness so that the variations along soil depth lead to different levels of damage to structures.
Based on data from the geological investigations of the terrain in the wider urban area of Skopje performed after the Skopje earthquake of 1963 and the data from the geomechanical investigations done for the repair of the mosque in 2007, the terrain of the site is composed from:

- An embankment composed of construction debris, sand and dust (N), with a thickness of 3 to 4 plus metres;
- Miopliocene sediments (MPl) – composed from:
  - Sandstone, semi-compacted, compacted (SFc);
  - Marls, marly sandstone, marlstone and alike (L) that occur alternately;

From tectonic aspect, the region of the site is part of the Skopje valley situated in the Vardar geotectonic and seismogene zone, which is characterized by seismogene faults in three main directions: NNW-SSE, ENE-WSW and E-W. No fault has been recorded to exist on the site.
The geomechanical characteristics of the site are defined in the Report on Geomechanical Research Works and Laboratory Tests on the Site of Mustafa Pasha Mosque from which it is evident that the foundation layer of the site, below the filled layer is composed of semi-compacted sandstone with natural bulk density of 17.4 KN/m^3, internal friction angle of $\phi=27^o$, cohesion of $c=4.0\ KN/m^2$. Presence of underground water has not been recorded.
Geophysical investigations have been carried out to define the parameters of the geological media that have local influence upon the modification of the regional seismic motions as are thickness H, values

of seismic Vp and Vs velocities, densities ρ and predominant periods T of surface layers as well as check and define the position of the mentioned seismogene faults in this area. The investigations have been realized by use of the following methods:

- Seismic refraction; and,
- Shallow seismic reflection;

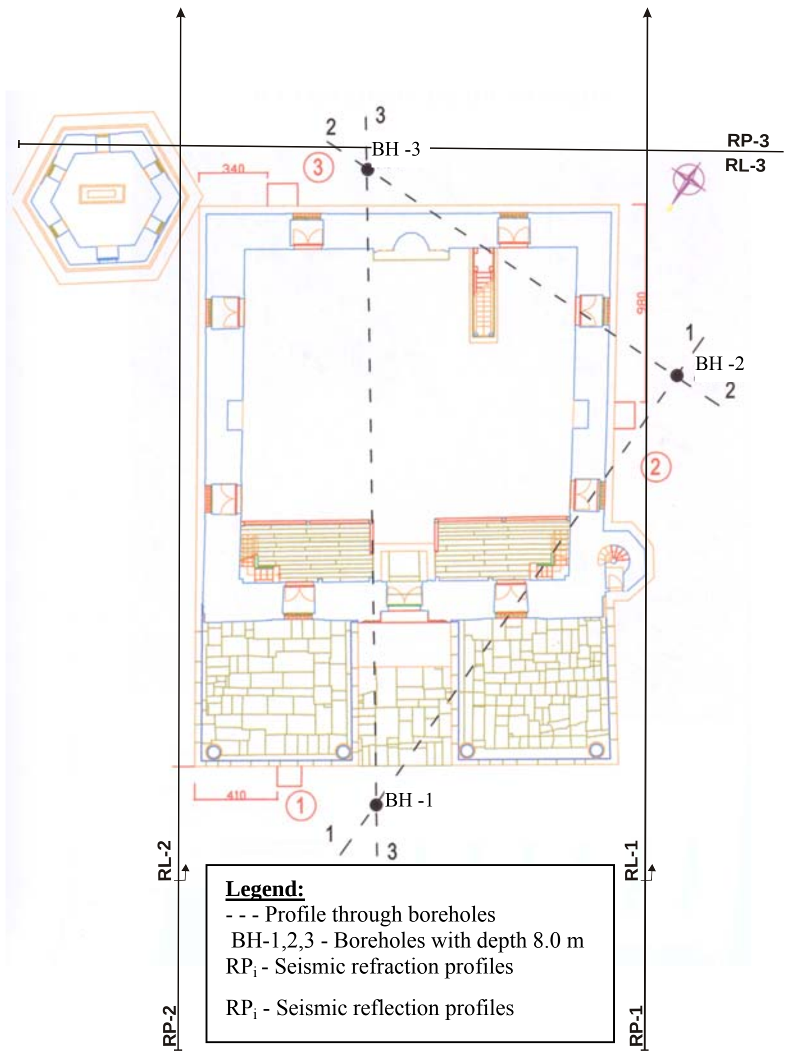

Figure 3. Site plan of performed geophysical and geotechnical investigation

The results from the geophysical investigations provide a good overview of the variation in site quality and detailed information on the engineering geological characteristics and genesis of the soil layers. From the analysis, the following values of wave velocities have been obtained:

- Surface fill layer – composed of construction debris and walls of old structures (N) with overlying depth of 3- 6 m and values of seismic velocities of Vp=270-515 m/s and Vs=120-245 m/s;
- Sandstone, semi-compacted (SFc), compacted with a depth of 3-10 m and values of seismic velocities: Vp=600-750 m/s and Vs=245-340 m/s;
- Marls, marlstone, marly sandstone etc. with a depth of 5 -20 m and Vp=1000-2100 m/s and Vs=400-935 m/s;

The representative soil models have been defined based on the previously mentioned geotechnical and geophysical investigations carried out at the location of the mosque. The soil profile mainly consists of sand, clay as well as marl below depth of 12m. Two representative geodynamic models are presented in figure 4.

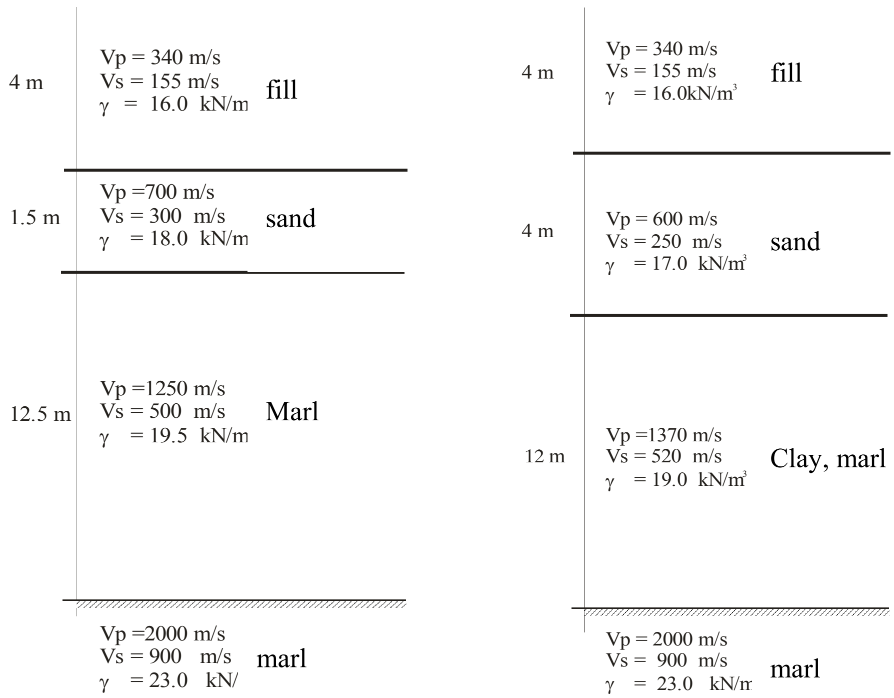

Figure 4. Representative soil models

For the needs of this project, the effect of the local geotechnical media has been defined by analyses of the dynamic response of representative mathematical models of the foundation soil.
The input motions at bedrock have been selected as a result of the hazard investigations and taking into consideration the regional seismogeological characteristics.

- ACC1 accelerogramme: El Centro N-S, USA, 1940, with a magnitude of M=6.7. It has been selected as a representative excitation of earthquakes from near foci, with M=6.5-7.
- ACC2 accelerogramme: Albatros N-S, recorded at rock during the Montenegro earthquake of 15.04.1979 with magnitude M=7.0.
- ACC3 accelerogramme: Petrovac, Oliva N-S, recorded at a deposit of a similar thickness during the Montenegro earthquake of 15.04.1979 with a magnitude of M=7.0. It has been selected as a representative excitation due to an earthquake with a larger magnitude and maximum amplitudes in the period range of 0.25-0.5 s.
- ACC4 accelerogramme: Robic N-S, recorded during the Friuli (Italy) earthquake of 15.09.1976 with a magnitude of M=6.1. It has been selected as the main shock type of an earthquake from a local focus with a large magnitude.
- ACC5 accelerogramme: Parkfild, 1966, selected as the main shock type of an earthquake.

The maximum accelerations have been selected as a_{max}=0.20(g) and a_{max} =0.30(g) which are the expected maximum accelerations at the selected location. The acceleration spectra are given in the following figure.

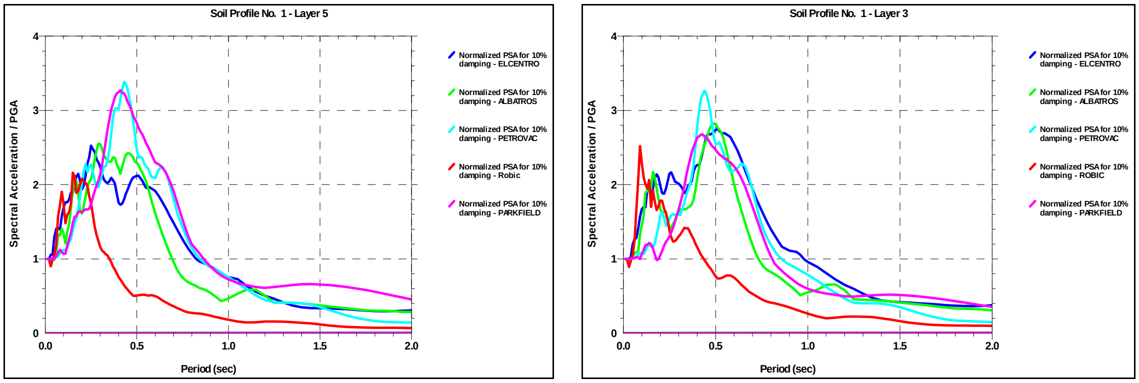

Figure 5. Mean normalized response spectrum for Model 1 (left) and Model 2 (right) for 10% damping

The response spectra for the analyzed mathematical models – MODEL1 and MODEL2 have been computed for the adopted input excitations at depth corresponding to the foundation level Df=-4.00 m, for input acceleration of 0.20 g and damping D=10%. These are presented in Figure 5 for Model 1 and Model2. Presented on the diagrams are the normalized response spectra.

From the obtained spectra, it is seen that, for the analyzed MODEL1, the dominant amplitudes occur in the period range of 0.15 - 0.25 s, i.e., the period of 0.4 s for the input excitations Petrovac and Parkfield. In the case of MODEL2, the maximum amplitudes of response occur for periods of 0.40-0.50 s, except for the input excitation Robic for which the maximum spectral amplitudes occur for the period of 0.1 s. The obtained results on the response spectra of the soil models have carefully been analyzed and taken into account in modelling and analysing the seismic resistance of the mosque.

The main parameters of seismic design, the maximum accelerations have been defined based on the results from the seismic hazard and risk analysis under the following assumptions:

- The serviceability period of the structure is 100 plus years;
- For the design earthquake, the acceptable level of seismic risk is 30-40%
- For the maximum earthquake, the acceptable level of seismic risk is 10-20%

In table 1, acceleration on bedrock (obtained from the seismic hazard analysis) are compared with the acceleration on the foundation level (obtained from the equivalent linear dynamic site response analysis) for different return periods. They are obtained by multiplication of the bedrock acceleration values with the dynamic amplification factor on the foundation level.

Additionally, the spectral amplification factors presented herein can be used in probabilistic seismic hazard assessments, because, unlike the code site factors, the proposed site amplification factors include quantification of the underlying uncertainty in the site-dependent ground motion estimate. For the analyzed structure, an average amplification factor DAF of 1.35 has been adopted.

Table 1. Max. Acceleration at foundation level for different return periods

Acceleration a (g)	**DAF**	**Return period T (years)**				
		50	100	200	500	1000
Bedrock	1.00	0.13	0.19	0.25	0.27	0.36
Foundation level	1.35	0.176	0.257	0.338	0.365	0.48

For dynamic analysis, it is also necessary to know the time histories of accelerations that reflect the characteristics of earthquakes and the time duration of intensive excitation. Having no records on strong motion accelerations in the region of the investigated site, the time histories have been defined by selection of the characteristic previously mentioned records, whose frequency content covers the frequency range of interest for dynamic analysis (Sesov et al., 2007).

4. CASE STUDY 2 – ST. MARY PERIBLEPTOS CHURCH, OHRID

As the second case study, presented are the investigations related to the local site conditions in the seismic assessment of a historical structure in Macedonia: the St. Mary Peribleptos church in Ohrid (figure 6) , dating back to the 13tn century.

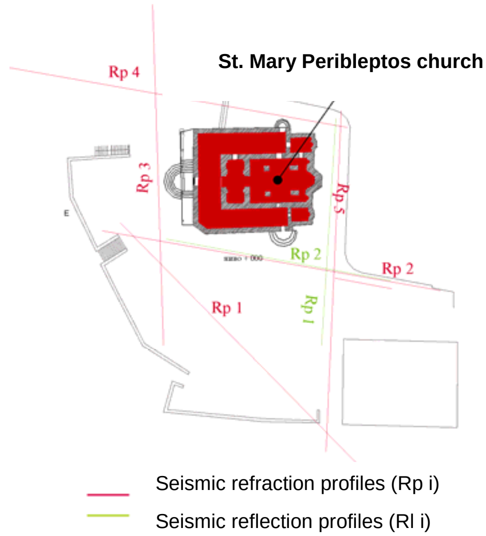

Figure 6. St. Mary Peribleptos church, Ohrid (view and plan of investigations)

The parameters for analysis of the structure of St. Mary Peribleptos church in Ohrid for the effect of seismic excitations expected at the site, have been defined on the basis of the results obtained from the performed investigations that are described in details in the previous case study.
Based on the realized investigations and the obtained results on the seismic potential of the site of the St. Mary Peribleptos church in Ohrid, the following conclusions are drawn:
The data on the seismic activity of the wider area of the site point to moderate exposure to earthquake effects with expected maximum magnitudes of од M=6.9.
The maximum expected accelerations at bedrock have been obtained by seismic hazard analysis. The results for the representative return periods (Table 2) range between 0.20 and 0.25 g , in accordance with the recommendations given in Eurocode 8: Design of Structures for Earthquake Resistance - Part 1: General Rules, Seismic Actions and Rules for Buildings for Damage Limitation Requirements – TDLR=95 years and Non-Collapse Requirements TNCR =475 years

Table 2. Proposed return period

Return period (years)	25	50	95*	100	200	475*	1000
Acceleration at bedrock (g)	0.133	0.164	0.201	0.204	0.232	0.252	0.260

The geotechnical boreholes and geophysical measurements confirmed the existence of a dominant geological formation at the site: below surface - plate-like limestone with presence of superficial alluvial zone with humus cover. The measured velocities of seismic waves show the existence of ground type “B” in accordance with the Eurocode 8 classification.

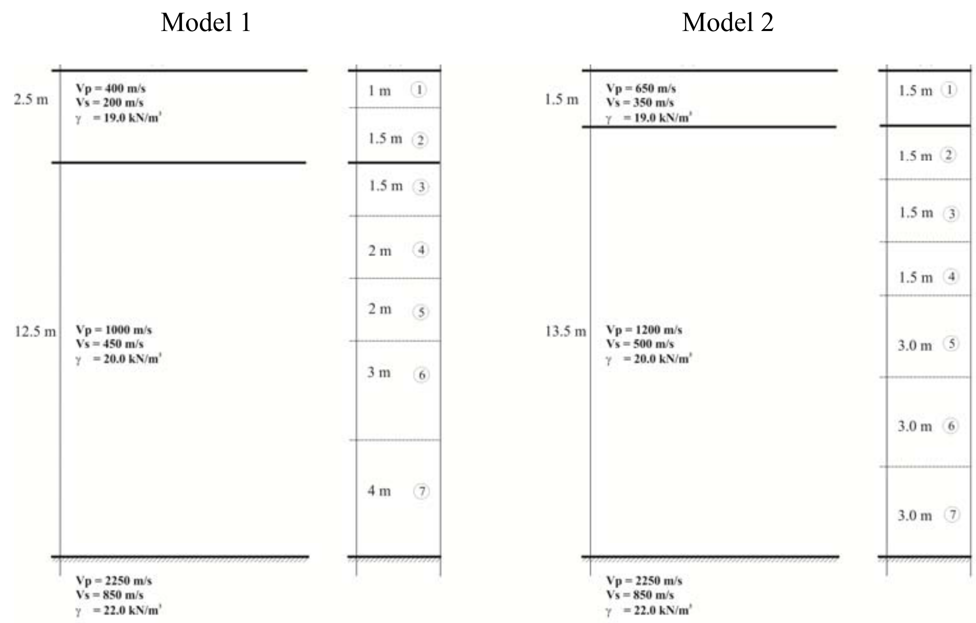

Figure 7. Representative geodynamic models

The performed analyses of seismic response of the site point to several important issues, namely that the predominant periods of the site are in the range of T=0.13-0.15 s . According to the data received from the design engineers, the predominant periods of the structures range between Tchurch =0.2 s, Tbellfry= 0.29 s and Tlodging=0.17s. If a comparison is made with the predominant periods of the site, it can be concluded that there is no danger as to occurrence of resonance effects.

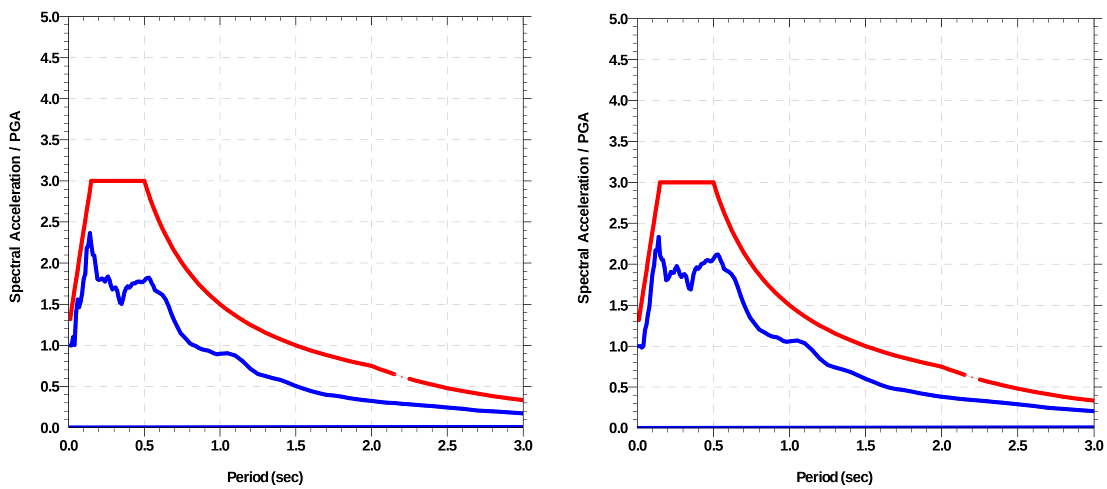

Figure 8. Mean normalized response spectrum for Model 1 (left) and Model 2 (right) and normalized spectrum in accordance with EC8 – ground type B, for 5% damping

The results from the analysis of the seismic response of the site show that the effects of amplification of the local soil are not much expressed (Sesov et al., 2011). The dynamic amplification factor ranges within 1.15 – 1.20.

The amplitudes of the average acceleration spectrum of the site (site specific spectrum) are within the frames, i.e., are lower than the proposed response spectra for ground type "B" in Eurocode 8 (figure 8).

Based on the analyses of the seismic risk, the maximum acceleration as one of the main seismic parameters for seismic analysis is given in function of the return period (Table 3) and the design engineer also has the possibility to adopt a maximum acceleration level based on the adopted level of acceptable risk and serviceability period of the structure which will indirectly provide the return period.

Table 3. Maximum expected acceleration for different return periods

Acceleration (g)	Return period T (years)						
	25	**50**	**95**	**100**	**200**	**475**	**1000**
Bedrock (input)	0.133	0.164	0.201	0.204	0.232	0.252	0.260
Level (foundation depth)	0.16	0.19	0.24	0.24	0.27	0.30	0.31

Table 4. Seismic parameters for analysis of the structure

Serviceability period of the structure	Seismic risk level %	Maximum acceleration a_{max} (g)
100	30	0.28
	10	0.31

The response of the soil layers in the form of time histories of acceleration has been computed and given for individual depths of the soil column (figure 9). These results can be used for seismic analysis of the structures in time domain.

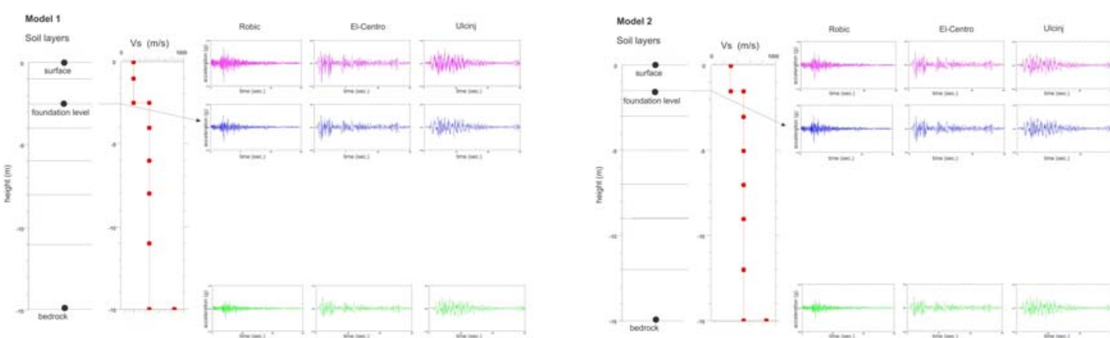

Figure 9. Seismic response of Model 1 (left) and Model 2 (right)-Time histories of acceleration for selected earthquake input

5. CONCLUSIONS

Large scale restoration and retrofitting projects were under concern at two of the important historical monuments in Macedonia, Mustafa Pasha Mosque and the St. Mary Peribleptos church, which have suffered considerable damages during their life time. Within the scope of these projects, detailed soil investigations and site response analyses have been carried out in order to understand the causes of structural damage during the past earthquakes and determine the dynamic parameters needed for structural analysis and retrofitting design for a probable future earthquake. In this paper, the findings from the investigation of the effects of the local soil conditions on the soil amplification in the mentioned case studies are presented. The objective of the described procedure is to take into consideration the regional and microlocation geological and seismological parameters as correctly as possible in order to define the input seismic parameters for dynamic analysis of important structures. The obtained results point out the significance of involving the local site conditions into seismic assessment of historical structures.

The site specific earthquake parameters are used in dynamic analysis of structures and to develop retrofitting techniques to increase the level of safety against future earthquake damages. As a result of this investigation, it is concluded that the local soil conditions which led to amplification of the ground motions in the case of the Mustafa Pasha Mosque during the past earthquakes had played a major role as to the structural damage experienced by the mosque. For the future safety of this valuable monument, the structural system and the elements are strengthened to withstand the inertial forces compatible with the dynamic behavior of the foundation layers during a probable earthquake. In the case of the St. Mary Peribleptos church in which the soil conditions are mainly represented by stiff soils and rock, the amplification does not play a significant role regarding the response of the structure. The presented methodology has been proved to be successful in preservation of the safety level in historical monuments which require strengthening and rehabilitation. This approach is recommended to be used in future rehabilitation and strengthening of old monuments of significant cultural importance located in seismically prone regions.

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