Geotechnical aspects in sustainable protection of cultural and historical monuments

Les aspects géotechniques de la protection durable des monuments culturels et historiques

Sesov V., Cvetanovska J., Edip K.
University "Ss Cyril and Methodius" - Skopje
Institute of Earthquake Engineering and Engineering Seismology

ABSTRACT: This paper describes the geotechnical aspects of comprehensive methodology that has been developed at Institute for Earthquake Engineering and Engineering Seismology for protection of cultural and historical heritage. The methodology has been applied on numerous domestic and international projects. Primarily focus is given on geotechnical conditions related to seismic actions because the history showed that many of the historical monuments have been heavily damaged due to earthquakes. Multidisciplinary approach was used to have clear insight of key parameters that driven the seismic potential of the sites. Seismic hazard and risk analysis defined the level of the seismic potential of the sites. Practical implementation of the methodology is described through three case studies for protection of cultural and historical monuments in Macedonia: the St. Mary Peribleptos Church, from the 13th century, located in old town of Ohrid; the mosque Mustafa Pasha in Skopje, from the 15th century and the 19th century Clock Tower located in the city of Prilep. The obtained results point out the significance of involving local site conditions into the seismic assessment and retrofit of historical structures in general.

RÉSUMÉ : Dans cet exposé sont présentés les aspects géotechniques d'une méthodologie complète qui a été développée à l'Institut de génie sismique et d'ingénierie parasismique pour la protection des monuments historiques et culturels. La méthodologie est appliquée à plusieurs projets domestiques et internationaux. L'attention est particulièrement portée sur les conditions géotechniques liées au chargement sismique, puisque l'histoire a démontré que beaucoup de monuments historiques avaient très endommagés pendant le séisme. Pour obtenir une idée claire des paramètres clés du potentiel sismique des localités, on a utilisé une approche multidisciplinaire. A partir de l'analyse du danger et du risque sismique, on a défini le niveau du séisme potentiel sur les localités. L'implémentation pratique de la méthodologie est décrite sur trois exemples d'étude pour la protection des monuments historiques et culturels en Macédoine: l'église Sainte Marie Peribleptos du 13 siècle, dans le vieille ville d'Ohride, la mosquée Mustafa Pasha de Skopje datant du 15 siècle et la tour de horloge de Prilep construite au 19 siècle. Les résultats obtenus montrent l'importance de la prise en compte des conditions locales dans l'estimation des paramètres sismiques et plus généralement, des informations en retour sur les constructions historiques à partir de leur état initial.

KEYWORDS: geotechnical aspects, sustainable protection, historical monuments

1 INTRODUCTION

Located in the south east part of Europe, having central position in Balkan region, Republic of Macedonia is characterized with significant cultural and historical heritage, which originated from early ancient until recent modern periods. For such long life times these monuments have experienced many unexpected loading actions which produced different consequences, from minor cracks to heavily damages and collapses. Common thing for these 'destructive' situations is when the monument is heavily damaged or collapsed the new monument is built on the foundation of previous-older monument so the location of the monuments remains the same. This is very common situation in Macedonia where several civilization and empires passed through this territory and everyone leaves monuments from their own period. This emphasis the importance of the information and data for the site conditions where these monuments are located toward sustainable preservation and protection of cultural and historical heritage. Comprehensive approach for sustainable protection involving geotechnical aspects is presented through three chosen case studies of very unique and specific type of historical monuments: the Mustafa Pasha mosque in Skopje, from the 15th century, the church of The Holy Mother of God Peribleptos, from the 13th century, located in the old town of Ohrid and the Clock Tower, from the 19th century, located in the city of Prilep.

2 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 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 on 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.

The applied methodology for definition of the seismic input parameters in the case studies presented in this paper follows the following steps:

- The first step, Figure1 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.

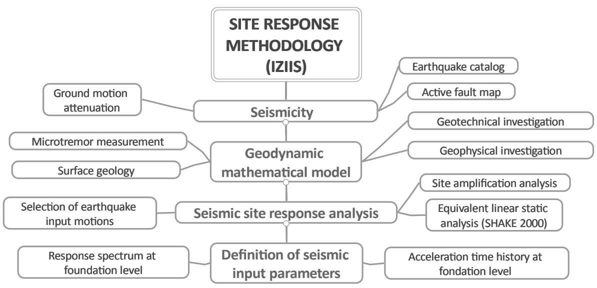

Figure 1. Flow chart of the applied methodology

1 CASE STUDY 1 - MUSTAFA PASHA MOSQUE

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.

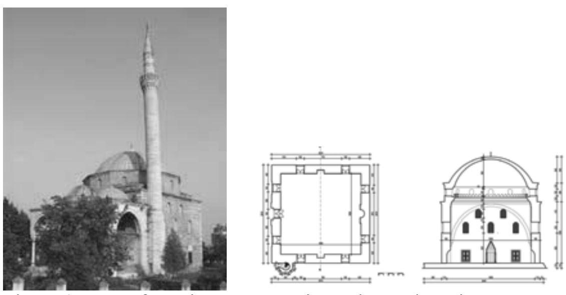

Figure 2. Mustafa pasha Mosque, view, plan and section

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.

The representative soil models have been defined based on comprehensive geotechnical and geophysical investigations arried out at the location of the mosque. The soil profile mainly consists of sand, clay as well as marl below depth of 12m. 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. The maximum accelerations have been selected as amax=0.20(g) and amax =0.30(g) which are the expected maximum accelerations at the selected location. The acceleration spectra are given in the following figure 3.

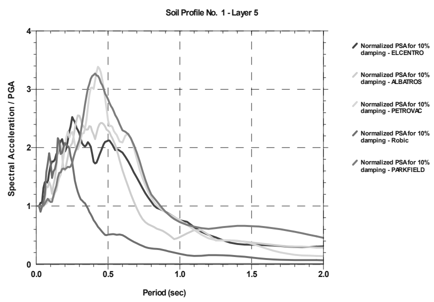

Figure 3. Normalized response spectrum for 10% damping

From the obtained spectra, it is seen that, for the presented MODEL1, the amplitudes occur in the period range of 0.15 - 0.25 s, and in the period of 0.4 s (more dominant) for the analysed input excitations. The obtained results on the response spectra of the soil models have carefully been analysed 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%

The obtained spectral amplification factors 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 analysed structure, an average amplification factor DAF of 1.35 has been adopted.

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).

2 CASE STUDY 2 - ST. MARY PERIBLEPTOS CHURCH

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.

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 M=6.9.

Figure 4. St. Mary Peribleptos church, Ohrid

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

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.

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.

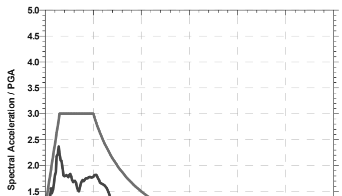

Figure 5. Mean normalized response spectrum and normalized spectrum in accordance with EC8 – ground type B, for 5% damping

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.

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 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**.** 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.

3 CASE STUDY 3 - CLOCK TOWER

The Clock Tower in Prilep (Figure 5) was built in 1858, on the location of an older wooden Clock Tower, which was burnt to the ground. It is an particularly important structure in Republic of Macedonia and beyond, in the Balkan region. It is a unique structure of this kind that has been preserved until present in its authentic architectonic and structural form.

A problem which is to be solved as soon as possible is the evident inclination of the tower, i.e., the displacement of the vertical axis in respect to the vertical line in west and southwest direction by which the existing stability of the tower is disturbed in static, and particularly dynamic conditions. Since 1998, there have been different kinds of research works for the purpose of precise measurement of the extent and the direction of the inclination and defining the reasons for this problem.

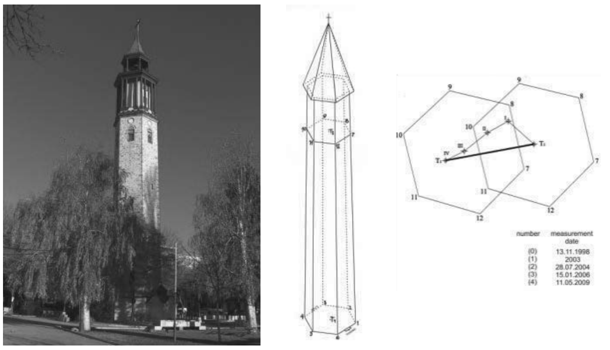

Figure 5. The Clock Tower in Prilep, Macedonia

For the purpose to analyze the existing structure together with the soil condition, a superstructure principle more detailed explained by Wolf, 1985 is applied. The application of the superposition principle, in case of linear i.e. equivalent linear methods, enables the dynamic soil-structure interaction problem to be analyzed in phases so that each phase is solved independently. As first step the structural components of the tower are analyzed where the soil is simulated by springs stiffness, and as second step the stress strain conditions in the soil are analyzed together with the foundation structure where the tower is added as continuous load.

The main model has been analyzed for the effects of dead weight of the tower and seismic forces according to the national regulations. The effects of the seismic forces increase the inclination in the direction as well as reduce the global safety coefficient. The inclination angle of the tower in this case of effects has increased for 40% in respect to the situation with the effects only due to the dead weight. This situation clearly points out that the capacity of the existing state is limited and that the deformation capacity of the tower along with the foundation soil is exhausted regarding maintenance of a satisfying level of safety. Therefore decision for strengthening the Tower has been made.

The main concept of this technical solution for strengthening is to reduce and prevent further uncontrolled inclination of the tower by means of additional structural elements (RC jackets, pile slab and piles) that are connected and make an integral structure (figure 7). This structural unit enables that additional effects contributing to further inclination be sustained and transferred to the soil layers with good strength-deformability characteristics and provides, at the same time, the required stability and safety of the Tower under seismic loads that, in the case of the present inclined position, may cause catastrophic consequences.

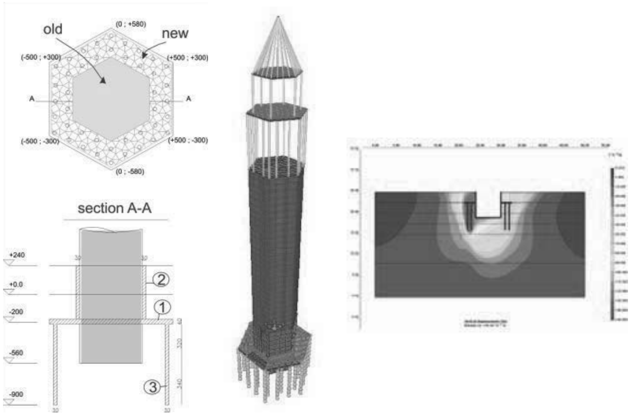

Figure 7. Tehnical solution for strengthening, numerical model of the structure and soil

Based on the obtained results (presented in figure 8) it can be noted that the deformations and the stresses in the soil significantly decrease compared to the existing conditions.

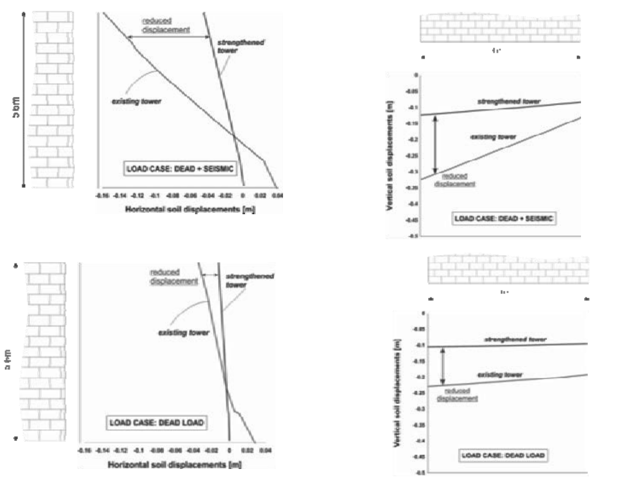

Figure 8. Horizontal and vertical displacements in soil due to dead load and dead + seismic forces

A particularly indicative element is the global coefficient of safety obtained through the incremental "phi-c" analysis which shows the ultimate state of the soil. The results are presented in table 1 for cases of effects due to dead weight and dead weight along with the effect of seismic forces. The increase of the global coefficient points to the fact that the newly designed solution enables a more uniform distribution of the effects of additional loads and their transfer to deeper soil layers with better strength-deformability characteristics.

Table 1. Coefficient of global safety through incremental "phi-c" analysis

Conditions	Load case	Safety coefficient
Existing conditions	Dead weight	2.44
	Dead weight + seismic load	1.91
Conditions of a strengthened structure	Dead weight	4.90
	Dead weight + seismic load	4.02

4 CONCLUSIONS AND RECOMENDATIONS

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.

Based on the analyses of the existing conditions of the Clock Tower and considering the state in which this important cultural historic structure is, a technical solution for consolidation elaborated to a level of a main project has been proposed.

The main concept of the proposed technical solution involves design of new additional structural elements to prevent further inclination of the Clock Tower and raise, at the same time, the safety of this structure to a satisfying level of functioning in the next period. It should be pointed out that most of these new structural elements are anticipated to be constructed below the terrain level, meaning that the anticipated solution will have a minimal impact upon the external façade of the structure.

5 REFERENCES

Berilgen M. M. (2007) Evaluation of Local Site Effects on Earthquake Damages of Fatih Mosque. Engineering Geology 91. 240–253

Marchi M et al. [2011]. "Stability and strength analysis of leaning towers". Geotechnique, 61(12), 1069-1079

SAP 2000. Computers and structures inc.

Sesov, V. et al. (2007) Definition of Seismic Input Parameters for Evaluation of the Seismic Stability of Mustafa Pasha Mosque (in Macedonian). IZIIS Report 2007047

Plaxis V9.0 [2011]. Tutorial Manual, Balkema / Rotterdam / Brookfield publications

Wolf [1985] "Dynamic soil structure interaction" Prentice Hall Inc