COMPREHENSIVE SEISMIC RISK ASSESSMENT OF UNIVERSITY, MOTHER TERESA, SKOPJE, REPUBLIC OF NORTH MACEDONIA

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ABSTRACT

This work presents a comprehensive investigation of the seismic risk at the site of University, Mother Teresa, Skopje, Republic of North Macedonia. The study applies contemporary earthquake engineering methodologies, including geophysical investigations, probabilistic analyses of earthquake effects, nonlinear dynamic simulations of representative geotechnical models, and evaluation of key seismic parameters. The seismic risk assessment accounts for the significant the seismic activity of the region, driven by ongoing tectonic movements associated with early Miocene extensional processes. The Skopje epicentral zone is among the most seismically active regions of the country, with historically destructive earthquakes exceeding ML>6 in 518, 1955, and 1963 (all with intensity I_0=IX). Identified risk factors include local seismic hazards originating within Skopje Valley sources, as well as the potential influence of more distant seismogenic sources.

Keywords: seismic risk, Mother Theresa University, earthquake engineering methodologies

1. INTRODUCTION

This work incorporates several essential components related to the definition and characterization of seismicity at the site of the University, Mother Theresa, Skopje, Republic of North Macedonia (Edip *et al*. 2021). It begins with an analysis of the seismotectonic characteristics of the region, providing the geological framework necessary for understanding the broader tectonic context (Edip *et al*. 2012). Building on this foundation, the study proceeds with a probabilistic assessment of seismic risk parameters, including calculation of maximum ground acceleration values for various return periods (Salic *et al.* 2020) . To enhance the understanding of site-specific conditions, the work presents a detailed description of the geological and geophysical characteristics of the location, derived from direct field investigations. These elements are integrated in the final section, where the influence of local ground conditions is analyzed, with particular attention to the amplitude and frequency characteristics of possible seismic motions (Woessner *et al.* 2015).

In conclusion, the study provides a detailed specification of seismic design parameters for different earthquakes design levels, along with final findings and recommendations relevant to the structural design of university facilities. Thorough assessment of seismic risk remains essential for ensuring safe and resilient construction.

2. REGIONAL SEISMOGEOLOGICAL CHARACTERISTICS

Over its long geological history, the territory of present-day North Macedonia and the wider region has undergone polyphase tectonic processes, sedimentation and magmatic-metamorphic processes, resulting in the formation of six fundamental geotectonic units: (i) the Vardar Zone, (ii) the Pelagonian Massif or Pelagonian Horst-Anticlinorium, (iii) the Western Macedonian Zone, (iv) the Cukali-Krasta Zone, (v) the Serbo-Macedonian Massif and (vi) the Kraishte Zone. The narrowly defined area of Çair Municipality lies within the transitional boundary between the Vardar Zone and the Pelagonian Horst-Anticlinorium. The Vardar Zone, located between the Serbo-Macedonian Massif to the east and the Pelagonian Horst-Anticlinorium to the west, originated as a Paleozoic geotectonic unit during the early Paleozoic. In the Jurassic, however, it evolved into a rift system characterized by the development of an oceanic-type of crust. Today, this geotectonic unit is regarded as the most tectonically active structure in the paraneotectonic period. According to geological maps, the study site is positioned within a belt of Miocene sands, clays and marls, as well as middle river terraces from the Pleistocene age. A clearly defined fault is mapped to the south of the location, extending westward for more than 10 km along mount Vodno in Skopje.

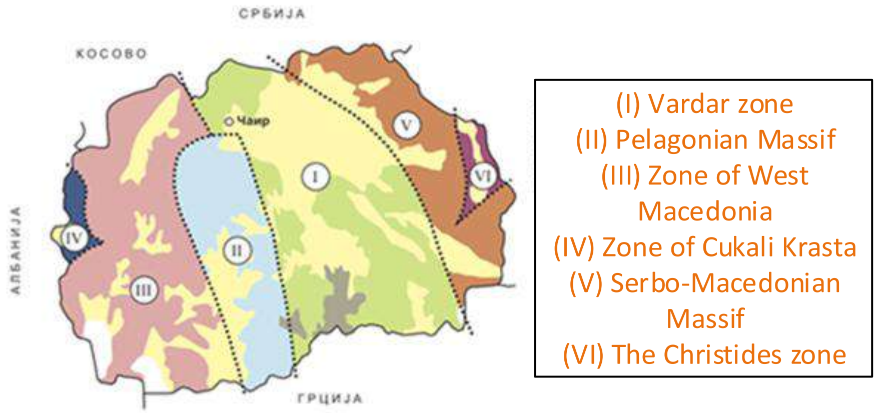

Fig.1: Schematic representation of the main geotectonic units in North Macedonia

The Vardar Zone, located between the Serbo-Macedonian Massif to the east and the Pelagonian Horst-Anticlinorium to the west, originated in the early Paleozoic but was transformed during the Jurassic into a rift system characterized by the development of an oceanic-type crustal crust. Today, it is regarded as the most tectonically active structure in the para-neotectonic period, comprising tectonic blocks ranging in age from the Proterozoic to Quaternary. The Pelagonian Horst-Anticlinorium represents a central massif composed of high-grade Proterozoic metamorphic complexes, bordered by marginal belts of low-grade Riphean-Cambrian metamorphic rocks. The core of the massif consists of gneiss-mica schist assemblages and amphibolites, overlain by mixed sequences of gneisses, mica schists and thick beds of Proterozoic marbles in the upper structural levels. The Skopje epicentral area is widely recognized as one of the most seismically active areas in the Republic of North Macedonia. Historical records document several strong earthquakes with ML>6, notably the events of AD 518 (ML=6.05, MW=6.08, I0=IX), 1955 (ML=6.05, MW=6.08, I0=IX) and 1963 (ML=6.1, MW=6.13, I0=IX), (Figure 2).

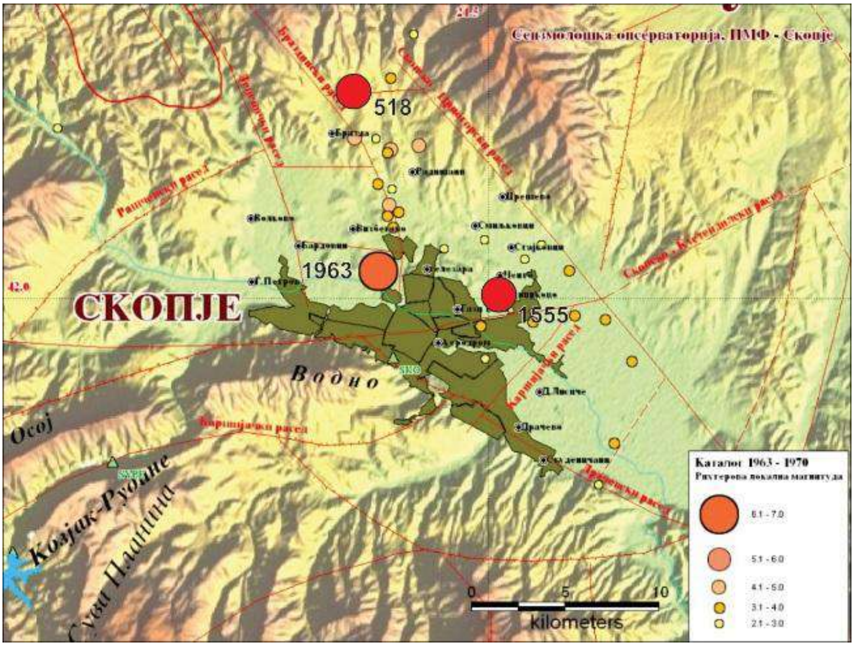

Fig.2: Epicentral map of historical earthquakes (518 and 1555) and earthquakes from the territory of the Skopje epicentral area occurring in the period 1963 – 1970. (Data source: Seismological Observatory at UKIM-PMF, Skopje).

3. SEISMIC HAZARD

In determining the seismic hazard for the planned location of Mother Teresa University in Skopje, the most-up-to-date knowledge of the region’s the seismotectonic characteristics of the region’s seismotectonic characteristics has been incorporated, with particular emphasis on the geological and tectonic framework, neotectonic features, seismogenic zones, and the latest available seismological data. The seismic hazard at the site was assessed using the probabilistic seismic hazard assessment (PSHA) method, which is based on the spatial and typological characterization of seismic zones, where seismicity is assumed to follow Poisson distribution. Two different mathematical models of seismic hazard were applied. The results are presented cumulatively for several return periods of interest (50, 100, 200, 500 and 1000 years), calculated for ground type A according to Euro Code (EC) classification, and expressed as peak ground acceleration (PGA) in units of gravitational acceleration.

Table 1 provides the expected average maximum acceleration on bedrock (PGA) for return periods of seismic action of 50, 100, 200, 500 and 1000 years.

Table 1. Expected average maximum accelerations on bedrock PGA

Return period in **years**	50	100	200	500	1000
Acceleration in **g**	0.114	0.153	0.201	0.283	0.335

4. SEISMO GEOLOGICAL INVESTIGATIONS

The geophysical investigations within the framework of this work were conducted with the purpose of determining the parameters of the lithological environments of the investigated location, which have local influence on the changes of regional seismic force.

Fig.3: Investigated location

The geophysical investigations conducted in this study aimed to dertermine the lithological parameters of the site, which exert a local influence on variations in regional seismic forces results of the investigations are presented as 2D seismic sections that clearly illustrate both vertical and lateral variations in seismic wave velocities. According to existing engineering-geological data, the broader Skopje area is composed of alluvial-proluvial sediments (gravel, sand, and clay) and Mio-Pliocene sediments consisting of gravel, sand, clay, marl, marlstone, and conglomerates. The Neogene sediments and Quaternary deposits on the surface that form the Skopje Depression attain a maximum thickness of approximately 2500 meters, underlain by older Paleozoic crystalline rocks, quartzites and marbles. At the study site, existing geological information indicates that the surface layers consist of sandy clayey silt, clay, and marly silt, underlain by more compact Mio-Pliocene sediments, including dense clay, marls, sands, and marlstone. The geophysical investigations enabled the delineation of subsurface layers based on contrasts in seismic wave propagation velocities (Bojadjieva *et al*. 2022).

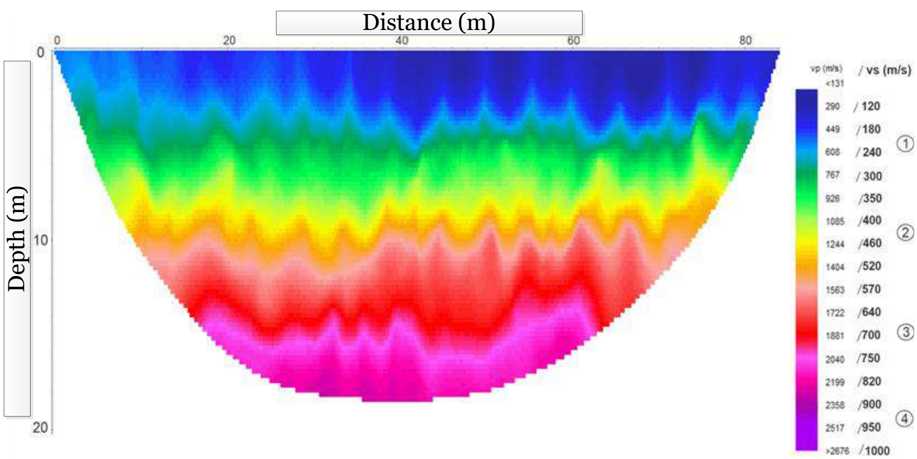

Fig.4: Seismic refraction profile.

5. EFFECTS OF LOCAL SOIL PARAMETERS

The local geotechnical environment has a significant influence on the characteristics of ground- surface motion during earthquakes. This influence is manifested through modifications in the amplitude-frequency characteristics of surface ground motion relative to the corresponding seismic excitation at bedrock level. For the purpose of mathematical analyses of local ground effects, the geological environment at the site is represented by an appropriate mathematical model. This model incorporates, both qualitatively and quantitatively, the key mechanical parameters of the near-surface geological layers that predominantly control the modification of seismic amplitude and frequency. Based on the results of the geophysical and geotechnical investigations, the mathematical model-M1 for the site has been defined, as presented in Figure 5 (Bojadjieva *et al*. 2022).

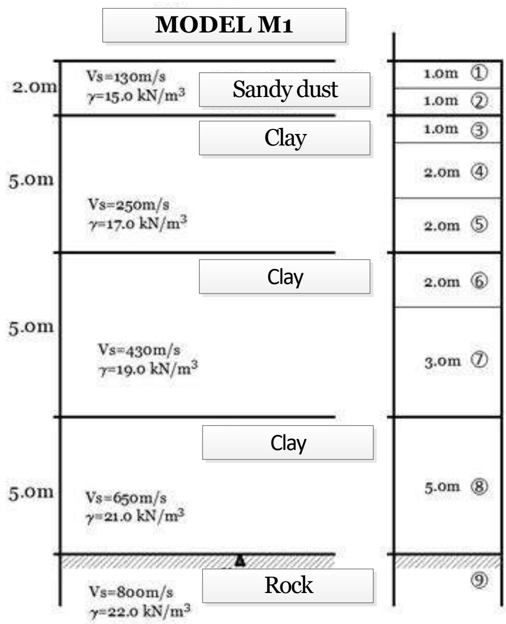

Fig.5: Matematical model of the location.

For the seismic base of the models, a transverse wave velocity of Vs≥800m/s has been adopted (Bojadjieva *et al*. 2022). As input excitations for the analyses, recorded earthquake acceleration time histories were used, selected to be critical with respect to the dominant periods of the location. The following accelerograms were employed: ACC1 - El Centro N-S, USA, 1940, (M=6.7), selected as a representative excitation for earthquakes from nearby sources with magnitudes in the range M=6.5-7.0. ACC2- Robič N-S, recorded during the earthquake in Friuli, Italy, on 15.09.1976 (M=6.1), chosen as an impulsive excitation representative of a strong local event. ACC3 -Ulcinj-Albatros N-S, recorded on rock during the Montenegro earthquake of 15.04.1979 (M=7.0). ACC4-Bitola N-S, recorded on 01.09.1994 (M=5.2-5.4). ACC5 -Ulcinj-Olympic N-S, recorded on soil during the Montenegro earthquake of 15.04.1979 (M=7.0), selected as a representative excitation of a large-magnitude earthquake with a relatively broad frequency band of maximum amplitudes.

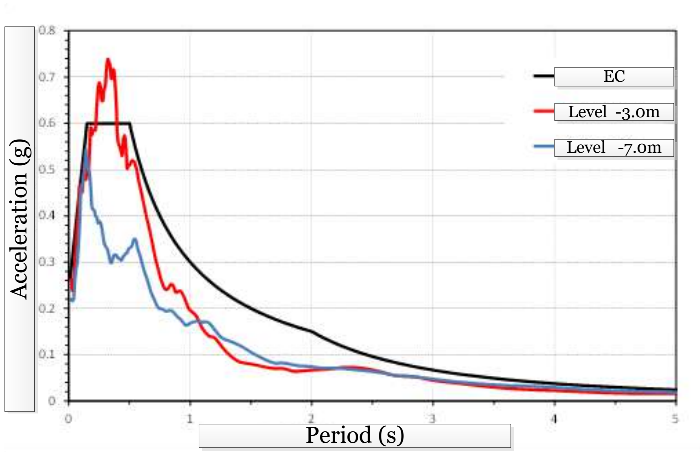

Fig.6: Average acceleration spectra for different depths for 5% damping at assumed foundation levels compared with the Eurocode acceleration spectrum

The seismic design parameters of the structure were determined based on the results of the conducted investigations. Considering the requirements of dynamic analysis and design of structures, the seismic parameters are presented as expected maximum accelerations and acceleration time histories. The determination was been carried out by incorporating the probabilistic seismic hazard of the location—reflecting its seismotectonic hazard methodology that integrates technical methodology that integrates technical, economic, and technological considerations. This comprehensive approach provides an accurate assessment of seismic threat and ensures that construction solutions remain both safe and economically viable. The adopted methodology accounts for all factors influencing structural performance during seismic events, including life-cycle cost considerations and the technologies available in contemporary engineering practice.

The maximum ground accelerations at the cite depend on the bedrock accelerations and on the seismic influence of the local geotechnical environment, expressed through the dynamic amplification factor (DAF). This relation demonstrates that the intensity of ground motion at the surface results from two primary components: the initial seismic excitation generated at the source and its subsequent modification by the overlying soil layers.

Table 2. Maximum acceleration for different time periods of recurrence

Acceleration a(g)	**Return period T (years)**				
	50	100	200	500	1000
Acceleration in rock	0.114	0.153	0.201	0.283	0.335
Level of foundation (-3.0m)	0.171	0.2295	0.3015	0.4245	0.5025
Level of foundation (-7.0m)	0.12768	0.1714	0.2251	0.317	0.3752

The expected accelerations to which building structures may be exposed are defined by seismic hazard parameters, which refer to longer time periods significantly longer than the service life of the structures themselves. This arises the practical question of selecting the occurrence period of a period of earthquakes of a given intensity that should be considered for defining seismic design parameters. The first step in determining seismic risk is the assessment of seismic hazard. The subsequent step incorporates additional parameters of fundamental importance—such as the acceptable level of seismic risk and the service life of structures — into the seismic risk model, using a binominal probability distribution.

For different combinations of structural service life and acceptable seismic risk, corresponding return periods are obtained. The relationship among these variables is presented graphically in the diagrams shown in Figure 7. These diagrams are spatially independent and may be applied to any location within seismic zone, provided that the return-period curves of maximum accelerations for the specific site have been previously determined.

Using these diagrams, seismic design parameters — specifically maximum accelerations — can be defined to match the structures's service life and acceptable risk level. In other words, seismic acceleration can be determined as a function of return period and the probability that the design parameters will not be exceeded during the structure's operational life. The considerations of rationality and risk in seismic design require the application of two criteria:

- **Design earthquake.** Structural analysis is performed for a moderate-intensity earthquake that has a high probability of occurring at least once during the service life. The allowable level of damage is such that it can be anticipated, controlled during design, and repaired relatively easily.
- **Maximum earthquake.** Structural analysis is performed for a strong earthquake that has a low probability of occurring during the structure's service life (Semblat *et al*. 2005).

The fundamental parameters for seismic design—and the maximum accelerations—were determined through seismic hazard and seismic risk analyses using the following assumptions:

- service life of the structure is 100 years and more
- 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%

By applying these assumptions together with the functional relationships between maximum surface accelerations and their recurrence periods (Figure 7a), and between structural service life, risk level, and return period (Figure 7b), the corresponding acceleration values for both the design earthquake and the maximum earthquake have been derived. These values form the basis for safe and reliable seismic design, ensuring an appropriate balance between structural safety, the probability of occurrence of earthquakes of different intensities, and the economic considerations associated with implementing protective measures.

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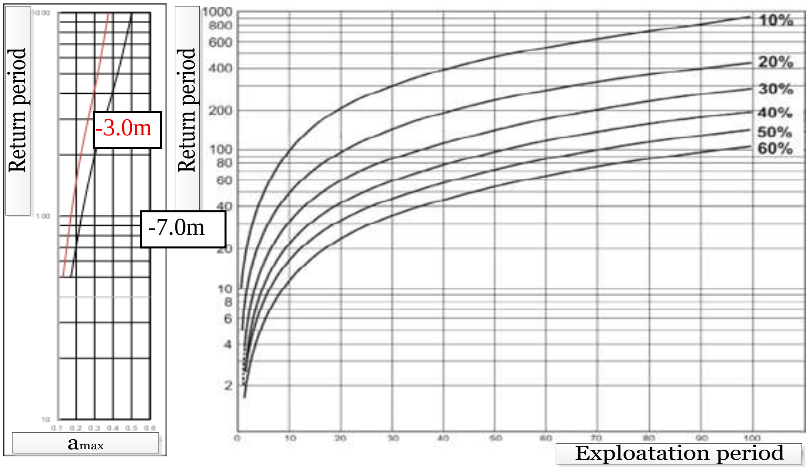

Fig.7: a) Maximum acceleration at foundation level for different return periods b) Relationship between service life of structures, risk level and earthquake return period spectra for different depths for 5% damping at assumed foundation levels.

Based on the comprehensive study conducted for the assessment of local seismic risk and the analysis of dynamic ground response, several important conclusions have been reached that define the fundamental parameters for the seismic design of the planned structure. The analyses clearly demonstrate that the dominant periods of the site represent a key characteristic for understanding the dynamic behaviour of the ground during seismic events. This information is essential for designers, as it indicates how the soil will respond at specific frequencies and allows them to implement appropriate measures to avoid harmful resonance between the structure and the ground.

The results of the site-specific seismic response analysis reveal a critical aspect of local ground behaviour: amplification effects within the surface layers are highly pronounced and significantly influence the intensity of seismic motion. At the planned foundation depth of –3.0 m, the dynamic amplification factor (DAF) reaches 1.5, indicating a 50% increase in seismic motion compared to bedrock. This considerable amplification is attributable to the specific mechanical properties of the near-surface layers and highlights the need for special design measures. In contrast, at the deeper foundation level of –7.0 m, the amplification factor is 1.12, corresponding to a more moderate 12% increase, suggesting that deeper foundations offer more favourable seismic conditions.

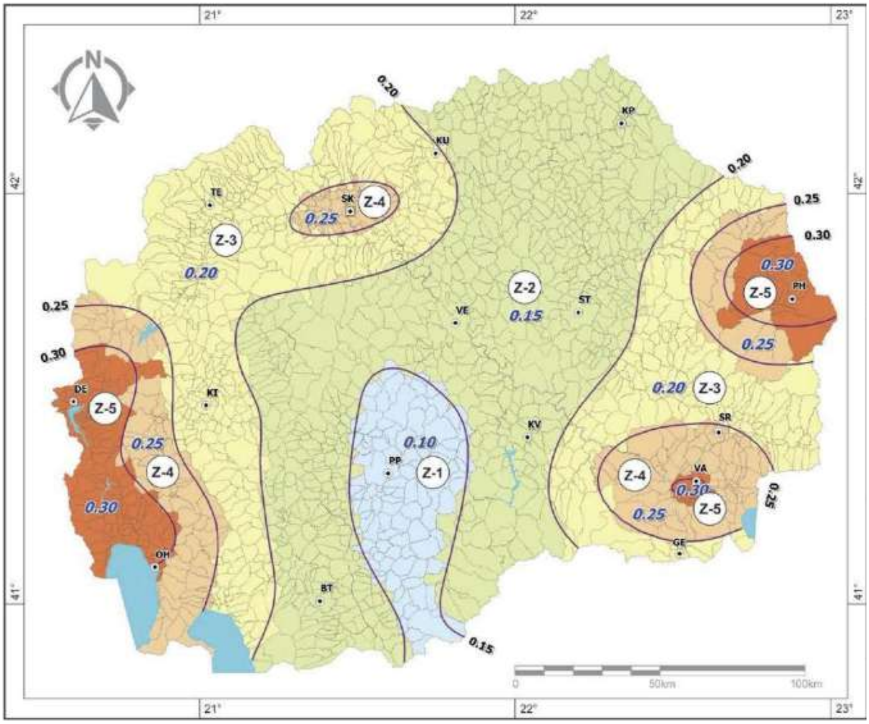

Fig.8: Map of seismic zoning for values of peak ground acceleration scaled with gravity **g** (Standardization Institute of the Republic of North Macedonia (2020) Eurocode 8: Design of Structures for Earthquake Resistance. Part 5: Foundations, retaining structures and geotechnical aspects – National annex. Reference number: MKC EN 1998-1:2012/HA:2020)

These higher acceleration values define the structural safety limits for the most severe credible seismic events, ensuring that the structure will retain its integrity even under the most critical loading conditions. The results are in line with findings from comparable site response studies conducted in similar geological environments across the Balkan region, where amplification factors between 1.4 and 1.6 are commonly reported for shallow alluvial deposits. Studies from other seismically active areas of Southern Europe—particularly Greece and Turkey—have documented comparable amplification characteristics for sites with analogous soil profiles, further validating both the methodology and the results of the present analysis (Semblat *et al*. 2005; Kanli *et al*. 2008; Pitilakis *et al*. 2012).

The adopted design strategy, which integrates site-specific ground response analysis with probabilistic seismic hazard assessment, is consistent with international best practice as recommended by current Eurocode provisions. It also aligns with methodologies successfully implemented in recent large-scale infrastructure projects across seismically active regions of Southern Europe and the broader Mediterranean basin (Tarchini *et al*. 2025).

6. CONCLUSIONS

In conclusion, the clear differences in acceleration values between the two foundation levels highlight the importance of selecting an optimal foundation depth. A deeper foundation provides significantly more favourable seismic conditions by reducing the influence of surface-layer amplification. While the numerical results offer solid guidance for design decisions, it is important to acknowledge that the amplification factors and acceleration values are subject to inherent uncertainties. These arise from variability in soil properties, limitations in defining the precise geometry of subsurface layers, and epistemic uncertainties in the ground-motion prediction models applied in the probabilistic analysis. A comprehensive sensitivity analysis addressing key input parameters—such as variations in shear-wave velocity, soil damping ratios, and the selection of seismic input motions—would enhance confidence in the robustness of the conclusions and help quantify the range of potential outcomes under different assumptions.

These findings provide a sound scientific basis for informed decision-making during the design phase and help ensure that the planned structure meets the highest standards of seismic safety in accordance with the geological and seismotectonic characteristics of the site. Nevertheless, several limitations should be recognized. The analysis relies on a one-dimensional (1D) site response model which, although suitable for horizontally stratified conditions, does not account for potential two-dimensional or three-dimensional basin effects caused by lateral geological variations or irregular bedrock topography. In addition, the equivalent-linear method used, while widely adopted in engineering practice, cannot fully capture the nonlinear soil behaviour expected under very strong ground motions.

Future work could strengthen the analysis by incorporating more detailed investigations of layer orientation and possible basin-geometry effects through advanced geotechnical exploration and two-dimensional or three-dimensional numerical modeling. Further improvements may also include fully nonlinear site response analyses to better represent soil behaviour at high strain levels, parametric studies to assess sensitivity to key soil parameters, and the use of site-specific recorded ground motions, where available, to validate analytical predictions. Moreover, this analysis provides a useful reference framework for geophysical investigations examining the influence of different subsurface layers and can serve as a benchmark for future studies employing more advanced modeling techniques and additional site-characterization data.

Declarations

Data accessibility (websites, platforms): Information is available online: www.iziis.ukim.edu.mk

Declaration of AI use: AI use has not been practiced since there is no big amount of Data

Authors' contributions:

KE- conceptualization, writing; VSh, JB, RS-M, MS, IGj-review and editing.

Authors' approval

All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

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