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Article

Developing design response spectra for Benghazi city including soil magnification effects

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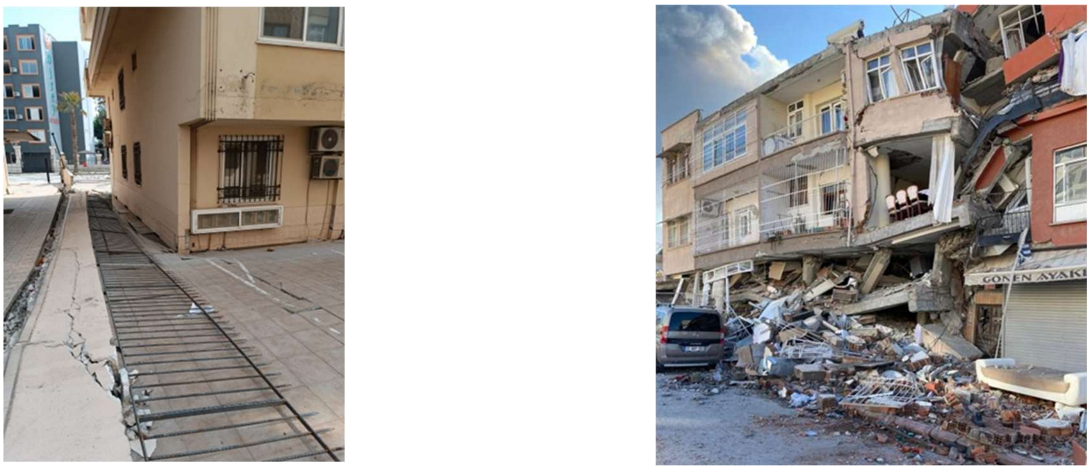
Abstract: Earthquakes in some countries worldwide cause loss of lives and properties. In Libya, the design of structures to resist earthquake forces was based on a paper published by Mallick in 1976. In 1977, and after small changes in the earthquake zoning map of Libya, the ministry of housing, at that time, adopted it as a draft code of practice for the design of structures to resist earthquake forces. With Benghazi city undergoing significant rehabilitation and development programs, including major national projects, there is a pressing need to estimate updated probabilistic seismic hazard maps and design response spectra specific to the city. This study presented updated probabilistic seismic hazard ground motion for Benghazi city, considering different return periods and accounting for peak ground acceleration (PGA) values with various soil conditions. Proposed design response spectra for Benghazi City unveil substantial PGA amplifications in soft soil areas.

Keywords: earthquake; response spectra; soil conditions; amplifications; Benghazi; Libya

1. Introduction

In recent decades, some countries have experienced unexpected earthquakes, resulting in the loss of lives and properties. Among these countries is Turkey, where the code of practice for buildings to resist earthquakes has been developed since 1940 many times. The latest version of this code was drafted in 2018, which mainly adheres to ASCE 7-16 [1]. In light of the preliminary report by Erdik et al. [2] on the February 2023 Turkey earthquake, it was concluded that the latest version of the Turkish earthquake code, based on ASCE 7-16 [1], is considered more reliable compared to previous versions. This is attributed to its comprehensive incorporation of ductility, detailing, and capacity design principles. It was also observed by Karakale et al. [3] that a significant proportion of collapsed buildings, as shown in **Figure 1**, were constructed prior to the year 2000, when the revised earthquake-resistant design code and design-construction controls were implemented. Furthermore, in some areas, soft soil conditions and a high level of underground water table level cause amplifications of the seismic waves and liquefaction problems, as shown in **Figure 1**. Hence, design earthquake loads should take into account local site soil conditions.



(a) **(b)**

Figure 1. Post-Kahramanmaraş earthquakes' impact on Pre-2000 constructed buildings. **(a)** Low quality concrete and poor detailing; **(b)** Soil liquefaction.

Benghazi, as the second-largest city in Libya, holds significant importance in the country's plans for rehabilitation and development. Its strategic location along the coast of the Mediterranean Sea promotes regional growth and economic activities. However, the existing seismic design code used for assessing earthquake forces in Libya, as outlined by Mallick [4], lacks the incorporation of design requirements for the response spectra method in building design. Furthermore, this code has not been updated since it was initially proposed as a local standard by the Ministry of Housing in 1978, leading to a high level of uncertainty when estimating earthquake forces during structural design. This shortfall in the seismic design code is a concern, as it can have significant implications for the safety and resilience of buildings and infrastructure in Libya. To ensure the country's preparedness for seismic events, it is crucial to update the seismic design code to incorporate the latest advancements in earthquake engineering and consider the specific response spectra requirements for building design. The results of the commonly developed, fully harmonized newly released Libyan seismic hazard model published by Lagesse et al. [5] provide a pertinent newly developed reference for seismic hazards at some major cities in Libya, including Benghazi City. The published paper showed the acceleration parameters required to construct the design spectrum curves required to design structures against earthquake forces. These values of horizontal spectra acceleration with 5% damping for peak ground acceleration are presented for 475-year and 2475-year return periods. This study is to address this issue by presenting an updated seismic design code that takes into account local site soil conditions. And developing customized design response spectra curves that engineers can utilize when designing reinforced concrete buildings in Benghazi city. These response spectra curves will be aligned with the more comprehensive ASCE 7-16 [1]. To accomplish this, it is crucial to incorporate up-to-date seismological data specific to the study area. By doing so, the study aims to enhance the seismic resilience and safety of structures in Benghazi city, considering the lessons learned from the Turkey earthquake and the advancements in earthquake-resistant design principles. Furthermore, engineers and designers in Benghazi will have access to more accurate and reliable tools for estimating earthquake forces and designing structures that can withstand seismic events. This will contribute to enhancing the safety and resilience of the city's built environment and supporting its ongoing rehabilitation and development efforts.

Benghazi, the second-largest city in Libya, plays a crucial role in the country's plans for rehabilitation and development, thanks to its strategic location on the Mediterranean coast. However, the current seismic design code used in Libya, as outlined by Mallick, lacks the necessary provisions for incorporating the response spectra method into building design. Moreover, this code has not been updated since its initial proposal as a local standard by the Ministry of Housing in 1978, leading to significant uncertainties when estimating earthquake forces during structural design. This deficiency in the seismic design code poses a considerable risk to the safety and resilience of buildings and infrastructure in Libya [6,7].

1.1. Unveiling the seismic potential of the study area

Comprehensive seismic hazard assessments of Libya, as conducted by Kebeasy [8], Suleiman and Doser [9], Al-Heety [10], Al-Heety and Eshwehdi [11], provide detailed insights into seismicity, seismotectonics, and ground motion. These studies benefited from locally obtained ground motion data from the Libyan Digital Seismological Network (LDSN). It is worth noting that the seismically active Hün Graben may extend further north, raising concerns about the potential occurrence of larger earthquakes near densely populated coastal regions. Shaw and Jackson suggest a strong correlation between seismicity and mapped faults, indicating the possibility of extensions of known or expected faults that are currently unmapped [12].

Northeastern Libya has notable seismic potential due to its location near active fault lines and regional tectonic activity. The area sits on the northern margin of the African Plate, close to the Eurasian Plate boundary, resulting in stress accumulation and release along fault lines. The Hellenic Arc is a significant fault system in the region. Historical records and geological studies indicate past seismic events causing damage [13–15]. Assessing the seismic potential involves considering historical seismicity, active fault lines, and seismological data. Probabilistic seismic hazard analysis estimates the likelihood and intensity of future earthquakes. Ongoing research, monitoring, and updates improve understanding and accuracy to safeguard the population and infrastructure.

1.2. Peak ground motion acceleration in Benghazi city

Lagesse et al. presented a comprehensive earthquake hazard catalog for various locations in Libya, including Benghazi City [5]. Their study aimed to assess the potential risks associated with seismic activity by considering factors such as earthquake frequency, magnitude, and ground motion characteristics. They utilized extensive research, historical data, and geological features to develop probabilistic seismic hazard analysis (PSHA) models, which predict future earthquakes and their impact. The study also incorporated local geotechnical conditions and site-specific factors influencing ground shaking.

To estimate the ground motion levels, the researchers employed Ground Motion Prediction Equations (GMPEs) based on earthquake magnitude, distance from the site, fault type, and ground conditions. Specific GMPEs were selected for each seismic source zone, including shallow-crustal, stable continental, and subduction zone GMPEs. Seismic hazard curves were calculated for different locations in Libya, indicating generally low seismic hazard levels, with slightly higher values near the Jabal al Akhdar Uplift and Hellenic Arc Subduction Zone. Interestingly, the hazard values in northeast Libya, specifically Benghazi and Derna, were found to be higher compared to northwest Libya, contradicting previous findings.

In their published paper, the authors summarized the spectra ordinates of Peak Ground Acceleration (PGA) at 0.2s, 1.0s, and 2.0s for return periods of 475 and 2475 years; this is equivalent to 10% and 2% of exceedance in 50 years, respectively. These values are specifically for sites with bedrock conditions (class B of ASCE 7-16 [1]). **Table 1** provides a summary of these values for Benghazi City.

Table 1. Spectral ordinates for PGA at 0.2 s,1.0s and 2.0s for Benghazi City.

Return period	Period (s) and Spectral Acceleration (g)		
	0.2	**1**	**2**
475 years	0.16	0.03	0.01
2475 years	0.39	0.09	0.04

2. Exploring the soil profile of Benghazi city

A comprehensive data collection process was conducted to assess the soil profile of Benghazi city. This involved gathering information from 65 strategically executed boreholes across the study area. The depths of these boreholes varied from 8 to 20 meters, with a significant portion reaching an approximate depth of 15 meters below ground level. **Figure 2** visually depicts the distribution and locations of the boreholes. Each borehole was utilized to collect soil properties and classifications from both undisturbed and disturbed soil samples, while also determining the groundwater table level at each location.

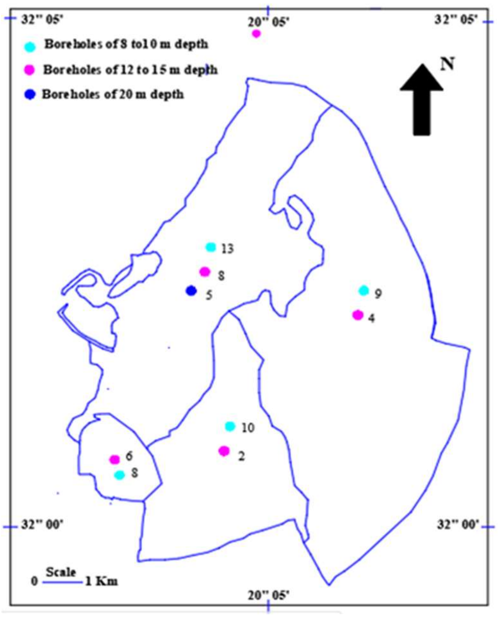


Figure 2. Borehole quantities and associated depths.

The field investigations revealed diverse soil types across the study area; the recorded Standard Penetration Test (SPT) values are corrected for split spoon configuration, borehole diameter, rod length, and energy efficiency factors. The northeast part of Benghazi city exhibited the lowest SPT blow counts, where in some instances, boreholes at a depth of 4 m displayed an overall SPT value less than 10, with certain locations even recording values below 5. However, as the depths increased, the SPT values generally increased, indicating denser soil or rock conditions. It should be noted that SPT testing is most reliable in granular soils, including silt and sand, which are prone to liquefaction and typically have lower SPT readings. At greater depths, SPT values reached 20 or more.

As we move from northeast to southwest of the city, the groundwater level gradually increases, from less than 1 m to exceeding 80 m.

The middle region of Benghazi, stretching from the northwestern and southeastern parts, comprises predominantly silty sand and marland calcarenite. As we move towards the southeast, the soil transitions to strong limestone with some shallow pockets of clay. Based on the soil profile data collected in the study area and referencing the geological information from the Benghazi sheet in Libya, the study area has been divided into different zones according to the site classification conditions specified in Table 20.3-1 of ASCE 7-16 [1].

These zones are classified from A to F, representing varying site conditions and characteristics. **Figure 3** illustrates the segmentation of the Benghazi area into these different segments, aligning with the ASCE 716 [1] site classification conditions. This categorization provides a comprehensive understanding of the site-specific considerations necessary for seismic design and assessment in the study area. By considering the specific site classification conditions, engineers and designers can make informed decisions and implement appropriate design measures to ensure the structural integrity and resilience of buildings and infrastructure in Benghazi city.

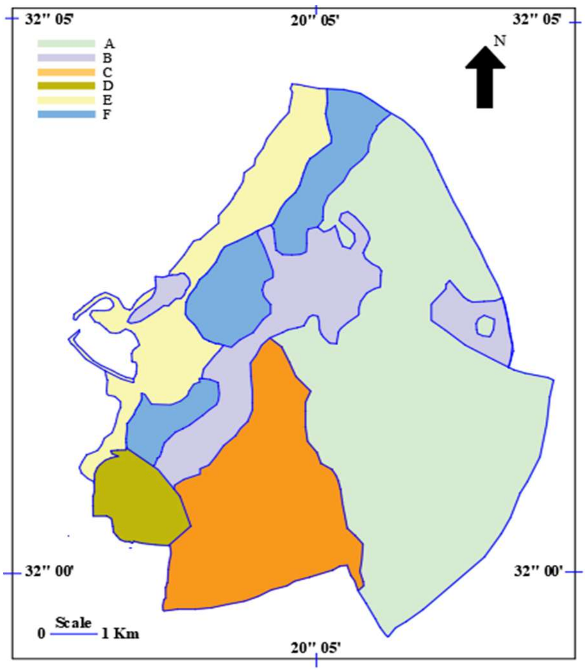


Figure 3. Alignment of Benghazi area with ASCE site classification conditions.

To gain a comprehensive understanding of the response of soil profiles in regions B, C, D, and E under the influence of six distinct earthquake events (Chi Chi, Imperial Valley, Kocaeli, Northridge, Loma Gilroy, and Parkfield earthquakes), the authors of this paper have utilized the DEEPSOIL software program developed at the University of Illinois [16]. This analysis serves the purpose of probing into the nonlinear time domain response exhibited by the soil profiles in these regions.

Additionally, the results obtained from this analysis are compared with the findings derived from the response spectra curves developed in this study, contributing to a more thorough comprehension of the soil behavior in response to seismic events.

The shear wave velocity of the soil profiles was determined using empirical formulas based on Standard Penetration Test (SPT) values, and the calculated values are presented in **Table 2**. These shear wave velocities were utilized in the DEEPSOIL analysis program.

Table 2. Shear velocity values (m/s) in Benghazi city based on SPT values for various researcher's models.

Region	SPT (Average value)	Kanai	Seed and Idriss	Hanumantharao	Uma et al	Hasançebi and Ulusay
A	-	-	-	-	-	-
B	-	-	-	-	-	-
C	45	186.50	409.20	425.51	300.79	291.80
D	25	131.07	305.00	330.48	252.01	243.34
E	12	84.38	211.31	241.03	202.06	193.96
F	5	49.90	136.40	165.42	155.25	147.99

3. Reimagining design response spectra

ASCE 7 uses the two fundamental ground motion parameters: S_S and S_1. S_S represents the "short period" spectra acceleration (T = 0.2 s), while S_1 represents the 1s (T = 1.0 s) spectra acceleration for sites on firm rock (Site Class B). which are based on the maximum considered earthquake (MCER) with a risk-based probability of approximately 10% and 2% of being exceeded within a 50-year period.

The determination of spectra response acceleration parameters for the Risk-Targeted Maximum Considered Earthquake (MCER), considering Site Class effects, is conducted using Equations (1) and (2), as outlined in ASCE 7-16 [1].

$$S_{MS} = F_a S_s \tag{1}$$

$$S_{M1} = F_v S_1 \tag{2}$$

The site coefficients F_a and F_v are obtained through interpolation from values provided in Tables 11.4-1 and 11.4-2 of ASCE 7-16 [1] respectively.

Additionally, a multiplier of 2/3 is applied to convert from the MCER basis to a slightly lower level of shaking known as the design basis earthquake (DBE).

$$S_{DS} = \frac{2}{3} S_{MS} \tag{3}$$

$$S_{D1} = \frac{2}{3} S_{M1} \tag{4}$$

The above design spectra values S_{Ds} and S_{D1} are used to construct the design spectra curves for the different site conditions through the following equations:

$$S_a = S_{DS}\left(0.4 + 0.6\frac{T}{T_o}\right) 0<T<T_0 \quad (5)$$

$$S_a = S_{DS} T_0<T< T_S$$

$$S_a = \frac{S_{D1}}{T} \quad (6)$$

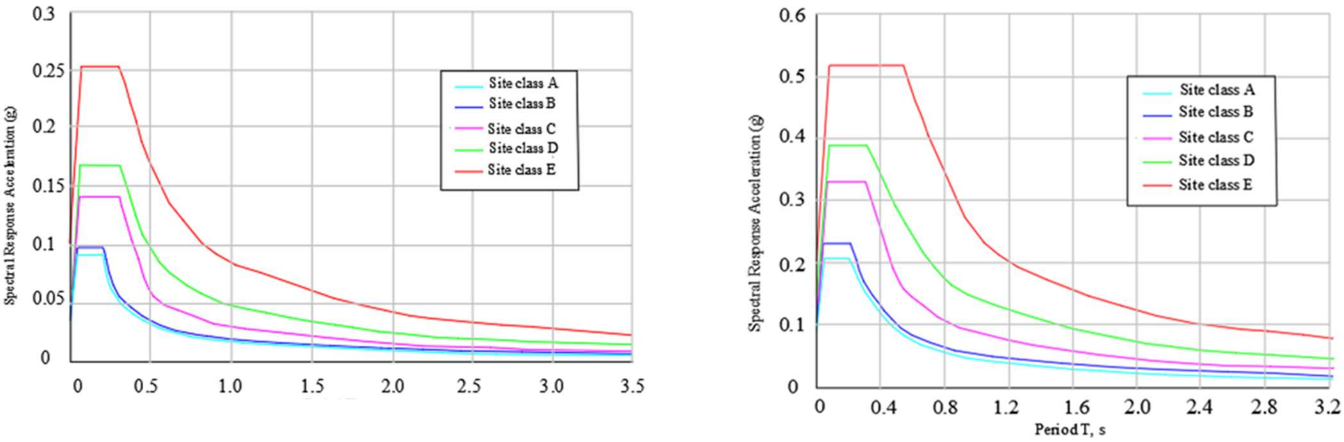
$$S_a = \frac{S_{D1}T_L}{T^2} T>T_L \quad (7)$$

where:

T: the fundamental period of the structure, s$T_o = 0.2\frac{S_{D1}}{S_{Ds}} T_s = \frac{S_{D1}}{S_{Ds}}$,

T_L: long-period transition period (s), Conservatively is taken 2 s.

The following **Figure 4a,b** illustrates the design response spectra curves corresponding to various sites classified according to ASCE 7-16 [1] from A to E. These curves represent the seismic response characteristics of the respective sites. The design response spectra curves were generated considering an importance factor (*I*) of 1 and a response modification coefficient (*R*) of 1.



(a) **(b)**

Figure 4. Design spectra curves for Benghazi city. **(a)** 475-Year Return Period; **(b)** 2745-Year Return Period.

These curves provide valuable information for engineers and designers in estimating the potential ground motion and designing structures that can effectively withstand seismic forces in accordance with ASCE guidelines. The importance factor (*I*) and response modification coefficient (*R*) are significant parameters in determining the structural response and level of seismic resistance required for different site classifications. By referring to these design response spectra curves, appropriate design measures can be implemented to ensure the safety and integrity of structures in various site conditions.

For buildings to be constructed on site type F, as defined in the ASCE 7-16 [1], several soil conditions are considered vulnerable to potential failure or collapse under seismic loading. These conditions include liquefiable soils, quick or highly sensitive clays, and collapsible or weakly cemented soils. Additionally, peat and/or highly organic clays with a depth (H) greater than 3 meters, very high plasticity clays with a depth (H) greater than 8 meters and a plasticity index (PI) greater than 75, and very thick soft to medium stiff clays with a depth (H) greater than 37 meters and an undrained shear strength (su) lower than 50 kPa fall under site type F. In these conditions, it is crucial to consider the interaction between the local site conditions and the earthquake forces. This emphasizes the need for a thorough assessment of the specific characteristics of the site to ensure appropriate design considerations and measures are implemented to mitigate the effects of seismic activity.

4. Solution by DEEPSOIL software and comparison with response spectra curves

To capture the variations in soil shear strength with depth, each soil profile in the regions was divided into multiple layers with consistent shear wave velocity but varying shear strength. This division accounts for the well-known phenomenon of increasing soil shear strength with depth. The thickness of each layer was selected in accordance with the DEEPSOIL program's requirement, Hashash et al. [16], that the natural frequency of each layer should exceed 30 Hz. This criterion was essential for obtaining accurate results. However, specific layer thicknesses were not specified in the given information.

The analysis results for the Chi Chi earthquake time history shown in **Figure 5** are presented in **Figure 6**. The figure illustrates the amplification of peak ground acceleration (PGA) for each soil profile in response to the Chi Chi earthquake.

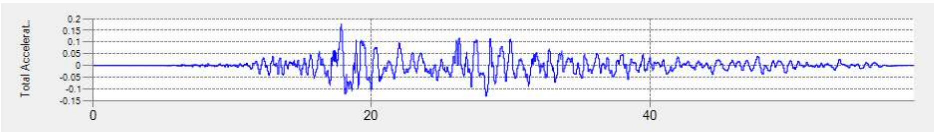


Figure 5. Time history of the chichi earthquake.

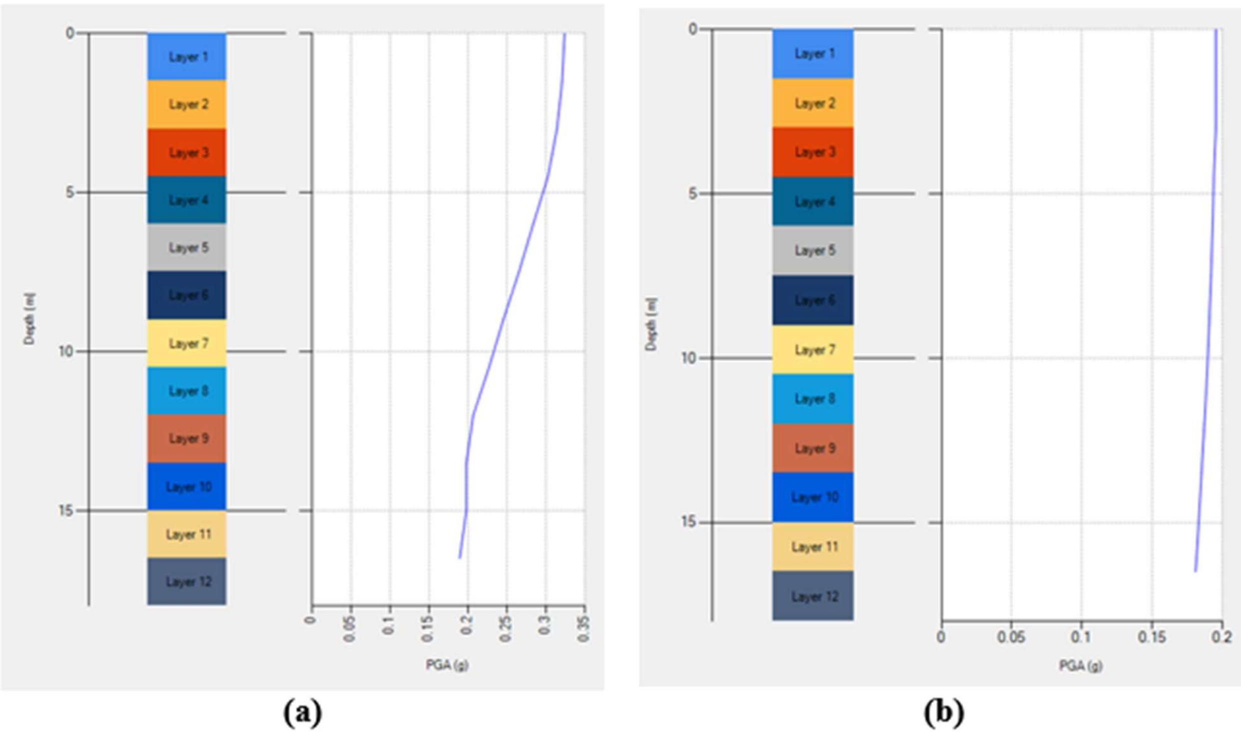
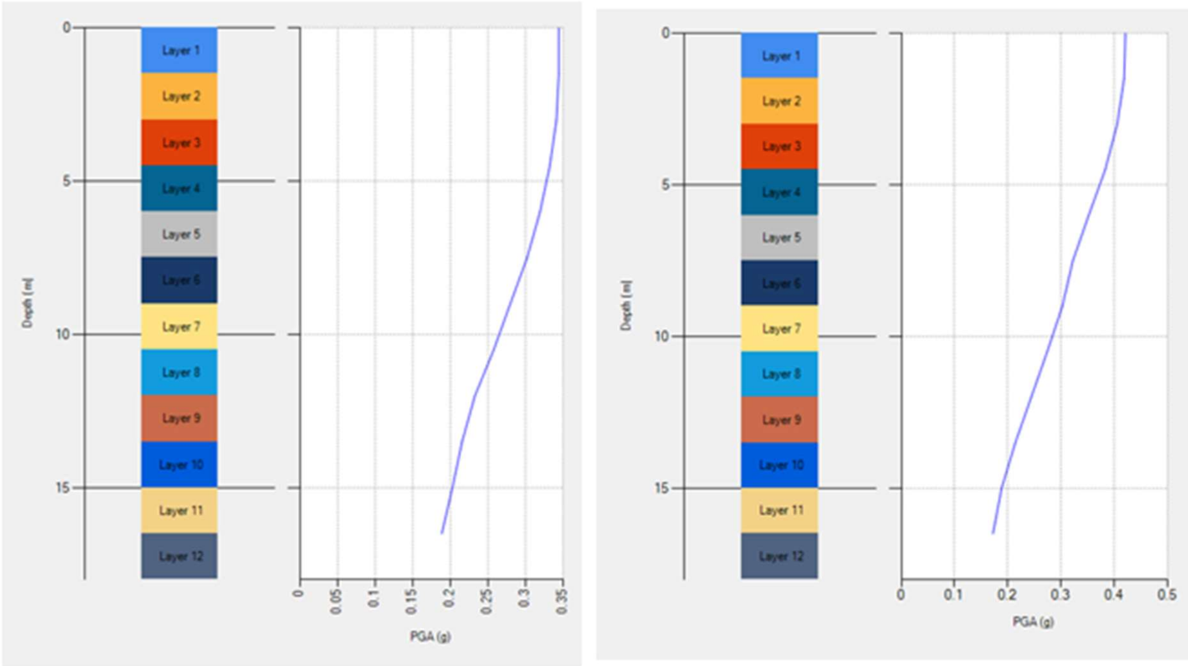


Figure 6. (*Continued*).



(c) (d)

Figure 6. Soil peak ground acceleration (PGA) response during the Chi Chi Earthquake. **(a)** B region response; **(b)** C region response; **(c)** D region response; **(d)** E region response.

Table 3 provides the average PGA amplification factors for all the regions analyzed under the different earthquake events. The results indicate that as the shear wave velocity decreases, the peak ground acceleration (PGA) increases. Notably, regions C, D, and E experienced the most significant amplification, with the PGA increasing by more than two times. This implies that design earthquake loads may need to be more than doubled in regions with soft soil conditions. Therefore, it is crucial to consider soil conditions when designing earthquake loads for the Benghazi area.

Table 3. Amplification factor of all regions under various earthquakes.

Region	Imperial valley	Chi Chi	Kocaeli	Northridge	Loma Gilroy	Parkfield	Amplification factor (root mean square)
A	1.06	1.02	1.05	1.07	1.06	1.03	1.05
B	1.30	1.10	1.24	1.23	1.13	1.18	1.19
C	2.40	1.65	1.62	235	2.26	1.58	2.01
D	2.85	1.75	1.65	2.5	2.32	1.84	2.20
E	3.00	2.10	1.70	2.53	2.37	2.23	2.36

The results obtained from the DEEPSOIL software program align closely with the corresponding values derived from the developed response spectra presented in this study. This good agreement confirms the reliability of these curves for engineers and designers when considering earthquake forces in the structural design of buildings in Benghazi city.

Region F was not analyzed due to its low SPT values, indicating a potential risk of liquefaction. This exclusion highlights the need for further investigation and careful consideration of soil conditions in that particular region.

5. Conclusion

In light of the extensive rehabilitation and development programs taking place in Benghazi city, including major national projects, there is an urgent requirement to generate updated probabilistic seismic hazard maps and design response spectra specifically tailored to the city. This estimation process takes into account recent seismic activity and incorporates an enhanced earthquake design code.

The presence of soft soil conditions in regions D, E, and F within Benghazi city may result in earthquake loads that exceed twice the normal levels.

This study has presented updated probabilistic seismic hazard ground motion assessments for Benghazi city, considering different return periods and accounting for peak ground acceleration (PGA) values associated with various soil conditions. The analysis employed an extensive and current earthquake catalog as well as a customized probabilistic seismic hazard assessment (PSHA) methodology tailored to the study area.

The results obtained from the DEEPSOIL software program and the developed response spectra in this study demonstrate a strong correlation. This robust agreement confirms the reliability of the response spectra curves, providing engineers and designers with dependable information to incorporate earthquake forces into the structural design of buildings in Benghazi city.

To ensure the safety and resilience of large-scale structures and critical facilities, it is essential to conduct detailed investigations into the local site conditions at their respective locations. These investigations should encompass a comprehensive understanding of the geological and geotechnical factors that may influence seismic response.

By integrating the findings of this study into the design and construction processes, engineers and planners in Benghazi city can make well-informed decisions and implement appropriate measures to enhance the seismic performance of structures. This will contribute to the overall safety and resilience of the city's infrastructure, supporting its ongoing rehabilitation and development endeavors.

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