Site-specific seismic hazard levels at the economic zone of Duqm, Oman

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Abstract
A site-specific probabilistic seismic hazard assessment (PSHA) was achieved in the area of special economic zone authority of Duqm, involving hazard evaluation at the bedrock conditions and assurance of potential site influence on seismic ground motion at the bedrock. Appropriate source and ground-motion prediction models were selected and seismic hazards were identified by means of 5% damped Uniform Hazard Spectra (UHS) for three return periods of 475, 975, and 2475 years. A logic-tree algorithm was used to study the influence of the epistemic uncertainties on the source models, earthquake recurrence and maximum magnitude, along with ground-motion prediction equations (GMPEs). The local geology effects were characterized by fundamental resonance frequency (Fo) using the horizontal-to-vertical spectral ratio technique and the soil amplification factors. The effects of soil were assessed using SHAKE91 for soil parameters defined by 55 geotechnical boreholes in conjunction with surveys of 2D multichannel analysis of surface waves (MASW) at 90 sites. Scaling was performed for selected strong-motion applying spectral matching technique to be used at the soil column bottom. Selection of such records is based on scenarios characterized by deaggregation of the PSHA results on the bedrock tops. The Duqm area mostly features low amplifications, below 1.3 for the considered spectrum. Surface ground-motion maps show low hazard values with Peak Ground Accelerations (PGA) vary between about 2 and 5% g for a 475-year return period. Although several sites are assessed to be susceptible to liquefy, liquefaction analyses indicate that surface ground motions for a 475-year return period are insufficient to produce liquefaction.

Keywords: seismic hazard, amplification, liquefaction, Duqm, Oman

1. Introduction

The Duqm area is currently experiencing speedy industrial and social development with ambitious growing plans using existing areas for social, industrial, tourism and marine transport mega-projects. The historical and instrumentally recorded earthquakes around the Duqm area show very low seismicity. However, there are signs of a moderate earthquake incidence (5.3 Ms) in 1939 within 200 km from the Duqm area (Aldama 2009). The important facilities to be built in this space should resist the expected seismic forces and continue to function efficiently after the tremor has occurred. This underlines the necessity of assessing seismic hazards, which is crucial for any earthquake resistant designs of critical assets, risk management, emergency response and insurance guidelines. The hazard evaluation at the Duqm area facilitates planning and developing advanced and proper...
infrastructures, attracting investors and expanding the old Duqm City with intention of increasing its population to 100,000 by 2025.

The Duqm area lies at the most eastern middle part of Oman, within 200 to 500 km of seismically active margins owing to the interaction between the Arabian, Eurasian, Indian and African plates (figure 1). Duqm lies within the hosting Arabian Plate, which is regarded as a stable craton area according to (Fenton et al. 2006). Directly offshore of the Duqm area lies the Arabian Sea, which is characterized by the existence of Owen Fracture Zone and the Murray Ridge to the east. These two tectonic structures mark the Arabia–India plate boundary. Two convergent margins are evident along the Zagros and Makran toward north-northeast, respectively, where the Arabian Plate moves toward the Eurasian Plate. The splitting of the Arabian and African Plates gives rise to the Gulf of Aden, which is a seismically active divergent tectonic boundary to the south. Moreover, some small to medium events occurred in Oman Mountains, which show evidence of recent tectonic movements (Kusky et al. 2005). Details of these seismotectonic elements were discussed in El-Hussain et al. (2018).

The main goal of this analysis was to conduct a site-specific PSHA for the Duqm economic zone using EZ-FRISK8.0b software from Fugro USA Land, Inc. The hazard analysis at the bedrock condition was conducted by the well-established and widely used Cornell–McGuire methodology (Cornell 1968; McGuire 1976). Then site impact due to earthquake excitations was estimated at carefully selected sites for classifying the surface ground-motion levels.

Surface geologic investigations throughout the area, along with information from 55 geotechnical boreholes were used for giving details about the surface geological setting (figures 2 and 3). Additionally, geophysical surveys at 90 selected, well-distributed sites with spatial spacing of about 1–2 km were conducted. The field-surveys included microtremor measurements, P-wave shallow seismic refraction and MASW. Boring observations and geophysical survey results were used to determine the Fo at each studied site and to define their site response using the identified soil
characteristics (e.g. P-wave and shear-wave velocities (Vs), density, thickness etc.).

The Fo of the soft sediments offers an informative indication on the frequency of the largest ground-motion amplification most. Nakamura’s (1989) method was applied to determine Fo within the Duqm area. Nakamura’s (1989) technique described each studied site using the horizontal Fourier spectra to the vertical ratio (HVSR) of microtremors that were recorded by single three-component seismographs. Thus, if sufficient microtremor measurements were available over the Duqm area, the resulting Fo could be mapped.

Vs depicts the superior descriptive parameter for the stiffness of the medium (Aki & Richards 1980), so Vs is usually believed the most essential element in characterizing soil amplification. Sections of shear-wave velocity were obtained using 2-D active MASW technique, which is proved to estimate the Vs reasonably (El-Hussain et al. 2014; Mohamed et al. 2019). Conventional P-wave shallow seismic refraction measurements were accomplished to initiate preliminary depth models to invert the Rayleigh-waves dispersion curves of MASW analyses. The obtained P-wave velocities were transformed to initial Vs using a Poisson’s ratio of 0.4. Afterward, final Vs profiles were introduced into SHAKE91 (Idriss & Sun 1992) algorithm in combination with suitable earthquake time histories for acquiring the soil’s site effect at the chosen 90 sites. Spectral amplification with surface PGA and pseudo spectral ground accelerations (PSA) for three return periods of 475, 975 and 2475 years were mapped.

2. Seismic hazard assessment at the bedrock

Inputs necessary to conduct a PSHA include delineation of contributing seismic zones, characterizing earthquake recurrence for each outlined seismic source, choice of applicable GMPEs and integration of these parameters to get

Figure 2. Locations of the drilled boreholes.
hazard values. The classic ‘Cornell–McGuire’ methodology was implemented to integrate these parameters, comprising proper management of the aleatory and epistemic uncertainties. Aleatory variability was introduced to the formula depicting the hazard by stating the mean of the parameter with standard deviations of the predicted ground motions. Epistemic uncertainties were handled using the logic-tree algorithm, offering various possibilities for the models representing seismic sources, recurrence parameters, maximum possible earthquake and GMPEs.

Two seismic source models were extracted from Deif et al. (2020) in their update of PSHA for Oman (figure 4). The two models consider the delineated seismic zones as seismically homogenous areas, relying on a modernized seismic database (Deif et al. 2017), existing geophysical data, active faults and other major geologic elements, and earlier related studies. The first model is superior to the second as it is of higher resolution and correlated better to the identified distinct active geologic structures. Additionally, the first model splits Makran Subduction Zone into two stand-alone seismic zones (east and west segments), and divides Owen Fracture Zone to Owen and Murray Ridge seismic zones. The second model considers Makran and Owen as one seismic zone each. Therefore, the first model is privileged with a higher weight, 0.8, while a smaller weight 0.2 is assigned to the second one.

Similarly, Cornell & Vanmarcke’s (1969) parameters were extracted from Deif et al. (2020), describing the earthquake recurrence at each zone. For most seismic zones, maximum magnitude (Mmax) values were provided implementing the Kijko (2004) algorithm. For zones lacking earthquake data to execute satisfactory statistical analysis, Mmax values were estimated by adding 0.5 unit of seismic moment magnitude to the largest observed event. The epistemic uncertainties of the earthquake recurrence parameters were considered using their mean values, along with ±1 standard deviation. A weight of 0.6 was given to the mean results, whereas weights of 0.2 were given to the recurrence parameters ±1 standard deviation.

One more uncertainty related to maximum observed earthquake in western Makran segment was introduced into calculations as a consequence of the earthquake of 1483. If this event truly occurred with an M 7.7 in western Makran as according to Ambraseys & Melville (1982), Mmax is estimated to be Mw 8.2. Instead, Musson (2009) located this
event at Hormuz Island with an Ms 6.0, leading to a maximum credible earthquake value of Mw 6.24 in the western Makran segment. A relatively low weight of 0.3 was allocated to the former option owing to its reliance on relatively old studies with high ambiguity in the location of the earthquake. A weight of 0.7 is allocated to the other alternative, considering the frequent foreshocks headed the main shock at Hormuz Island.

Scarcity of acceleration time histories in Oman stimulated using GMPEs already created in other localities, within tectonic areas analogous to these might affect the country. The two applied source models contain three different seismotectonic regimes, namely subduction areas, shallow active areas and stable continental areas. Three GMPEs were selected for each seismotectonic regime based chiefly on the assumptions of Delavaud et al. (2012) and Douglas et al. (2014) in the work on a seismic hazard model in the Middle East. All preferred models are capable of determining the horizontal PGA and five percentage-damped PSA.

The GMPEs of Youngs et al. (1997); Atkinson & Boore (2003) and Zhao et al. (2006) were used to describe how the seismic waves attenuate at the Makran Subduction Zone, while models by Zhao et al. (2006); Chiou & Youngs (2008) and Akkar & Bommer (2010) were applied for exhibiting the ground-motion attenuation behavior in shallow active seismic zones. The two GMPEs of Campbell (2003) and Atkinson & Boore (2006) were used for stable continental areas (the Arabian craton) in combination with the three active shallow GMPEs. This is followed because the Arabian Peninsula cannot purely be characterized by the stable craton (Aldama et al. 2009).

For GMPEs implemented in shallow active zones, the model by Akkar & Bommer (2010) was allocated a 0.5 weight. This was used because these equations are the latest, chosen from the better GMPEs for the Middle East and used several time histories of strong-motion instruments established therein. The equations by Zhao et al. (2006) and Chiou & Youngs (2008) were allocated the same weights of 0.25. The GMPE of Zhao et al. (2006) was prioritized with a 0.5 weight in Makran Subduction area, whereas the remaining weight was like that given to the Youngs et al. (1997) and Atkinson & Boore (2003) GMPEs. For the seemingly stable Arabian craton, models by Campbell (2003) and Atkinson & Boore (2006) were preferred over the shallow active GMPE with weights of 0.3 and 0.25, as they were created for stable regions. The residual weight was portioned among like equations of the shallow active zones at 0.15 each.

To put all GMPEs in one logic tree, all of them had to be compatible concerning the magnitude scale, source-site distance and the classification of horizontal component. All chosen models defined the earthquake size using moment magnitude (Mw). Luckily, the chosen models in EZ-FRISK8.0b could be introduced into calculations as tables, comprising the chosen parameter’s ground-motion value of a specific scenario (magnitude-distance pair). Therefore, various distance styles could be treated independently without additional modifications as the hazard levels herein were characterized by the geometric mean of the PSA horizontal component. Ground motions that calculated using GMPEs that do not define horizontal ground-motion similarly were transformed into this class using the method by Beyer & Bommer (2006).

Figure 4. Seismic source models developed for PSHA studies for the Duqm area. Right panel presents the preferable model with more seismic source zone a, while the left panel illustrates the more regional seismic source model.
2.1. Hazard calculations at bedrock

Seismic hazard analysis was conducted at bedrock layers characterized by $V_{30}$ of 765 m s$^{-1}$, whereas $V_{30}$ represents weighting average $V_s$ for the topmost 30 m of layers. Seismic zones were described as seismically homogenous areas of fixed depth equivalent to the average depth of an earthquake in the catalog used at every single zone. Assumed fixed depths due to location difficulties (e.g. 10 and 33), which were frequently encountered in the seismic dataset, were discarded during the calculations of average depths. The minimum magnitude ($M_{\text{min}}$) was set to 4.0 in all zones, as smaller events are supposed as being incapable of producing serious damage to engineered structures. A single point at the center of the Duqm area was selected to represent the entire area because no significant change was expected in the hazard results at the bedrock for this relatively small area. The hazard products at the bedrock were provided using the seismic hazard curves, deaggregation results and UHS for the three studied return periods.

2.2. Hazard curves

Final hazard curves were evaluated as the weighted average of all yielded hazard curves of the applied logic tree, illustrating how a particular ground-motion intensity is annually exceeded. Figure 5 shows the hazard curves of PGA and five percentage-damped PSA for 0.2 and 1.0 s. Moreover, PGA hazard curves of most influencing seismic zones are shown in figure 6. The figure reveals that the hazard levels for bedrock conditions at Duqm site is low and mainly influenced by the host Arabian background zone for the studied return periods. The calculated low hazard is credited to the location of Duqm site in central Oman, far from the sources of high seismicity and accordingly being more affected by fewer active seismic sources.

2.3. Uniform hazard spectra

The UHS were established by calculating hazard curves at essential spectral periods, for covering the expected heights of engineering structures in Duqm. UHS at the bedrock in the Duqm area are depicted in figure 7 for various return periods studied. The PGA weighted average for a 2475-year return period was 51 cm s$^{-2}$ and the largest weighted average horizontal acceleration was 114 cm s$^{-2}$, which was detected at a 0.1 s spectral period.

2.4. Deaggregation of ground motion

The deaggregation process aims to define the different future earthquake scenarios aftermath on the whole hazard at specific locations for specified return periods. This process is
essential for many design circumstances, especially for high importance facilities, it is more appropriate using ground-motion time history of a particular earthquake scenario for defining probable earthquake action. Deaggregation findings are represented here in an equal magnitude-distance spacing form. The deaggregated PGA and PSA of 0.2, 1.0 and 2.0 seconds as representative of short and long spectral periods are presented in figure 8 for return periods of 475 and 2475 years. Deaggregation findings revealed the domination of the background zone on short spectral period hazards. The mean magnitude and distance of effective scenarios for return periods of 475 years were 5.2 and 21.5 km. Large earthquakes of greater distance affect the hazard most at longer spectral periods, indicating improbable large seismic hazards from the low seismicity Arabian background zone.

Figure 6. Seismic hazard curve reflecting the contribution of the source zones on PGA.

Figure 7. UHS for the 475-, 975- and 2475-year return periods at the bedrock conditions.
3. Site characterization

3.1. Local geology

Carefully collected 146 soil samples from a site walk plus the products of 55 geotechnical boreholes were used for soil description at the Duqm area. A detailed soil survey and sampling of traverse soil profiles were performed along predefined lines, crossing all the detected surface geologic elements in the prevailing geologic map (figure 9). The samples of soil were gathered at prearranged sites or wherever any variation
in soil nature was encountered. A 60 to 80 cm depth pit was excavated at every chosen site and the 146 samples of soil were collected from the native soil after eliminating the topmost transportable soil cover. The 55 geotechnical boreholes were drilled to depths ranging from 6 to 20 m beneath the surface, aiming to reach the geotechnical bedrock. Standard Penetration Tests (SPT) were accomplished at 2-meter intervals or where the soil settings were appropriate. Moreover, coring of the rock was conducted using a T6-101/NQ Wire line core barrel generating a nominal core diameter of 47.5 mm.

The Duqm area is flat at the south and northeast parts and becomes undulated rough ground toward the north and northwest areas. Various materials are encountered throughout the investigated area, ranging from outcropping rocks at the western and northern areas parts to very soft Sabkha deposits, sand and gravels, at the remaining areas. In the south, Duqm is generally covered with evaporites, silt and clay, constituting the Sabkha area. Slightly northward, it is covered by gravelly sand to sandy gravel. In the northeast parts, the silty fine sand Sabkha is bordered by high lands westward covered with gravelly sand and conglomerate. Toward the east, Duqm is covered with a low-lying sandy ridge and silty coastal strip. Sieve analyses reveal that, soils with coarser grains are mostly found toward the north and finer grain soils are localized at the northeast and southern parts regardless of the coarser grain soils at southernmost end of the Duqm area.

The drilling program results demonstrate that the area is mostly covered with a very thin (0.5 to 6 m) layer of loose soils. Minor exceptions appear at the eastern parts where the soil cover reaches exceeds 20 m at very few individual points. The top soil is formed by generally soft to medium stiff fine-grained soils (silts), and loose to medium dense granular soils (sands). Bedrocks were described as conglomerates, weak to very weak calcareous sandy mudstone, siltstone of various thicknesses and weak limestone (marl).

### 3.2. Fundamental resonance frequency (Fo)

The Fo throughout the Duqm area was determined by applying the Nakamura (1989) method. This method applied the Fourier horizontal-to-vertical spectral ratios (HVSR) of seismic records to provide a reliable site effect on upright incident shear-waves. HVSR has proved to provide a
trusted mainly near the western, middle and northern parts (e.g. Theodulidis & Bard 1995; Mohamed et al. 2008).

3.2.1. Field measurements. The recommendations suggested by Koller et al. (2004) were implemented here to assure truthful experimental circumstances. Ambient noise data were collected using two Taurus seismographs of Nanometrics and tri-axial Trillium 20 and 40 s velocity sensors. Continuous noise recordings for no less than 3 hours at a sampling rate of 100 Hz were carried out for the chosen 90 locations, representing each delineated geological entity.

3.2.2. Data processing. Ambient noise measurements were evaluated applying the GEOPSY software created within the SESAME (2004) project. Different windows with a minimum time duration of 25 non-overlapping seconds were selected from the quietest portions of the noise records. This was made using the STA/LTA anti-trigger procedure, with STA/LTA allocated less than a small threshold (1.5–2.5).

For every site, at least 10 simultaneous time widows of the three components were selected. Each windowed signal was base-line corrected, tapered, fast Fourier-transformed and smoothed using the Konno and Omachi (1998) procedure. The geometric mean of the two horizontal spectra for each window was calculated and the produced HVSR curves were averaged to define the final Fo at the site. All peaks on HVSR curves were examined for their reliability and clarity. Moreover, they were checked to see whether they were of natural or artificial origin. HVSR curves of artificial origin or that could not meet the criteria for reliable and clear curves were discarded as they were not formed due to site characterization.

3.2.3. HVSR results. HVSR curves were eventually used to facilitate mapping the Fo on account of the topmost soft deposit layers in the Duqm study area. This map demonstrates that Fo can change even within short distances, mostly on the grounds of the changes in the thickness of soft soil. Moreover, the type of soil varies throughout the area as the marl and limestone outcrop in the western and northern parts, while recent deposits of sand, clay and silt occupy the eastern and middle parts.

The resonance frequency distribution map shows 30 HVSR curves without a significant peak (Flat curves) over the entire range of frequency applied in the current analysis (0.25–20 Hz), proposing rocky locations (figure 10). These locations are mainly clustered in northeastern and western areas where the formations of shale, marl, siltstone and limestone outcrop. Locations of these flat HVSR curves are represented on the Fo map by a letter ‘F’ (figure 11).

High Fo (>10 Hz) dominate most of the Duqm area, consistent with the general geology of Duqm. They are clustered mainly near the western, middle and northern parts (figure 11). This confirms the existence of thin weathered rocks covering the bedrock, implying that despite these areas being classified geologically as rocks, site conditions may be reclassified, relying on existence or absence of weathered rocks or soils and their thicknesses.

Smaller Fo are seen at the eastern coast strip of the Duqm area, indicating considerable soil thickness. The lowermost Fo is 0.85 Hz at the northeastern corner where the soft layer thickness exceeds 25 m as the boreholes show.

The map of Fo could be understood considering both the number of stories and the fundamental frequencies. Resonance cannot affect most of the Duqm area, where high Fo (≥10 Hz) dominates. Structures that might be influenced through soil effect are located at minor areas in the eastern and middle parts, where the Fo varies between 1.8 and 8 Hz. These would be buildings of about 1–5 stories high.

3.3. Soil effect analysis

Amplification of ground motion instigated by soft soils is largely influenced by their shear-wave velocity, which is usually considered the best elastic parameter to define stiffness (Aki & Richard 1980). A 1D ground response study using SHAKE91 was implemented for soil effect assessment on the anticipated ground motion in the Duqm area.

3.3.1. Inputs for the ground response analysis. Vital input data necessary for effective soil response evaluation formed the subsurface model that presented the shear-wave velocity, density, thickness and lithology. These data can be obtained from the conducted geophysical surveys and available borehole data.

Nonlinear behavior of soil was introduced into SHAKE 91 using shear modulus reduction (G/Gmax) and damping curves (ξ), which highly depend on changes in shear strain. Hence, ground-motion records at the soil base are also crucial for soil response analysis. The modulus reduction (G Gmax) and the damping curves developed by Seed & Idriss (1970), Seed et al. (1986) and Schnabel et al. (1972) are used for the sand, gravel and rock in the Duqm region, respectively.

3.3.1.1. Shear-wave velocity determination

The MASW technique (Miller et al. 1999; Park et al. 1999) was used to calculate Vs at the chosen 90 sites using the SURFSEIS 5 software of the Kansas Geologic Survey. MASW has proved a robust procedure that can present consistent shear-wave velocity for the topmost 30 m (e.g. Park et al. 1999; Mahajan et al. 2007). It uses a profile of geophones to record surface waves using active controlled seismic sources, or inactive ones (man-made and natural noise). Each geophone gather creates a 1D shear-wave velocity profile of the subsurface applying an inversion process for Raleigh wave dispersion curves of a multichannel...
Figure 10. HVSR calculations in a rocky site, showing almost a flat curve at site GS-c08. Panel 1 demonstrates the amplitude spectrum of the three components, Panel 2 illustrates the HVSR curve, Panel 3 shows the horizontal spectrum rotation with azimuth degrees, and Panel 4 shows the HVSR rotation with azimuth degrees.

record. The resulting 1D velocity profiles were combined for the constructions of 2D ones.

3.3.1.1. MASW data acquisition. Active MASW surveys were conducted using a 24-channel seismograph ‘SmartSeis ST’ by Geometrics Inc., USA. Surface-wave information was gathered along 90 carefully chosen profiles (figure 2). The Vs was intended to be estimated from the surface down to the maximum depth possible. Thus, 4.5 Hz vertical geophones were arrayed at 1-m spacing along a multichannel linear arrangement to detect the smaller frequency components efficiently. A sampling rate of 1.0 ms and recording time-span of 1.0 s were used.

Seismic waves were generated using an 8-kg sledge hammer with a 5 m offset. The target signals (surface waves) were acquired and logged in SmartSeis ST in SEG-2 format. A shooting interval of 4 m was used and a typical roll-along procedure was performed across a 52 m profile. For records with low levels of signal-to-noise ratio, the signals were enhanced by stacking several hammer strikes.

3.3.1.2. MASW data processing. Raw data in SEG-2 format were transformed into Kansas Geological Survey format, merging the entire shot gathers of each line to one multi-record. Body-waves were then recognized and discarded using filtering and muting processes. Dispersion curves for each shot gather in the multi-record file were acquired from the fundamental mode of the dispersion image (e.g. figure 12). The extracted dispersion curves were individually inverted to generate a 1D shear-wave velocity profile, representing the
mid-point of the geophone gather (figure 13). Multiples of these 1D shear velocity results were interpolated to get 2D profiles (figure 14).

MASW results were consistent with the subsurface data acquired from the geotechnical boreholes. Mostly, a satisfactory agreement was noticed among soil thickness, blow number ($N$ value) and consequently $V_s$ in both geophysical results and geotechnical borehole data, indicating the efficacy of MASW for obtaining the near-surface characteristics (figure 15). The obtained shear-wave velocity was used to define the soil thickness, $V_{S30}$ and soil response.

3.3.1.1.3. MASW results. Three layers characterize the shallow deposits in the Duqm area. Characteristics of every single layer change from site to another as fairly large gaps among the examined sites (1–2 km) exist and the near-surface geology diverse substantially within the area. $V_s$ in the initial layer ranges from 180 to 480 m s$^{-1}$, while the second layer exhibits shear-wave velocities vary between 480 and 900 m s$^{-1}$. The third layer represents the bedrock as it has shear-wave velocity varying from 780 to 1600 m s$^{-1}$ in most sites.

The $V_{S30}$ at the Duqm area varies from 306 to 1197 m s$^{-1}$ (figure 16). Rocky sites toward west, south, and northeast are distinguished by higher $V_{S30}$ values (798 to 1102 m s$^{-1}$), which are B class on NEHRP site classification. Moving eastward, the $V_{S30}$ gets lower as recent deposits of variable thickness do exist. The lowest $V_{S30}$ sits at the borehole BH-16 site at 306 m s$^{-1}$ (near the upper boundary of D category as per NEHRP standard). This site is
associated with relatively considerable thickness of soft cover (12.37 m depth) as identified using boreholes, comprising very soft dark gray distinctly weathered marl with low $N$ values. The remaining sites belong to the C category on the NEHRP standard with $V_{S30}$ ranging from 379 to 736 m s$^{-1}$.

A soil thickness map was produced from the integrated database produced by MASW results ($V_s \leq 765$ m s$^{-1}$), HVSR and the available borehole data (figure 17). The bedrock can be encountered as shallow as 0 m to as deep as 29 m. The soil thickness map illustrates the thin soil layer ($\leq 2.5$ m) toward the north, west and the largest part of the southern areas. The soil thickness tends to increase toward the east, reaching about 14 m at the middle area. The largest soil thickness can be seen in the utmost northeastern corner at 29 m.

### 3.3.1.2. Bedrock ground motion

A basic input parameter for 1D site response is seismic ground-motion records. The best procedure is to use local wide spectrum of scenarios (magnitude-distance) of real recorded strong motions. Caused by the shortage of such strong-motion records in Oman, real strong ground-motion records were obtained from comparable tectonic environments through searching the PEER NGA7.3 database. Appropriate records that fulfilled the searching criteria provided by the deaggregation process at the bedrock (magnitude, distance) were downloaded. These initial time histories were amended applying the spectral matching approach of Al Atik & Abrahamson (2010) with the purpose of lowering the influence of unavoidable inconsistency between their characteristics and the resultant hazard.
3.3.2. 1-D soil response using SHAKE-91. Surface PGA and five percentage PSA for the three studied return periods were estimated by 1D soil response analysis using SHAKE91. The modified time histories, Vs profiles, thickness, density and corresponding shear and damping curves were supplied to SHAKE91 in EZ-FRISK8.0b as input. The amplification curves and the average ground-motion intensities were assessed for getting the site-specific seismic hazard at the relevant 90 sites.

Amplification values for various spectral periods were mapped for the three studied return periods. Figure 18 shows the amplification map of PSA of 0.2 s for a 475-year return period. The Duqm area shows an amplification factor less than 1.3 for the whole spectrum for all analyzed return periods.

Figure 14. 2D velocity model for site No. 20.

Figure 15. Correlation between 1D MASW and geotechnical observations at borehole 03.
Although these low amplification values were dominant, the amplification factor reached 2.5 and 3.0 for PGA and a 0.2 s spectral period, respectively, at minor spots at the northeastern parts attributable to the deposition of relatively large thickness of soils.

3.3.3. Surface hazard maps. The PGA and five percentage-damped PSA for the three studied return periods were mapped. Hence, the PSA of important periods for common engineered structures are fairly well covered. Figures 19 and 20 show PGA variation and five percentage PSA at 0.2 s at the ground surface for a 475-year return period.

The maximum hazard levels were noticed at the northeastern areas because of the relatively thick soft soil layers of recent beach sands with PGA of about 46 and 93 cm s$^{-2}$ for the return periods of 475 and 2475 years, respectively. The ground motion values decline toward west. A maximum hazard value of five percentage-damped horizontal PSA was found at a PSA of 0.2 s, ranging from 57 to 174 cm s$^{-2}$ for a return period of 475 years and between 87 and 302 cm s$^{-2}$ for a return period of 2475 years. Five percentage-damped ground motion of 1.0 s time periods are naturally smaller than those of high frequencies (0.1 and 0.2 spectral periods) with maximum surface hazard values of about 18 and 28 cm s$^{-2}$ at most studied localities for return periods of 475 and 2475 years. These surface spectral accelerations are almost equivalent to the bedrock values with almost no amplification.

4. Seismic liquefaction in the Duqm area

Seismic liquefaction is a damaging engineering phenomenon that mostly has an effect within saturated loose, granular soils during violent ground shaking. Liquefaction occurs when
Figure 17. Soil thickness map at the Duqm area.

substantial reduction takes place in soils’ shear-strength as a consequence of a rapid buildup in pore liquid pressure. Thus, the soil behaves like a liquid, causing buildings to experience subsidence or tilt over.

The seismic liquefaction initiates from the association of two constituents, namely susceptibility and opportunity, which define the capability of a site to liquefy and describe the ability of earthquake to cause soil liquefaction, respectively. The loading action of earthquakes along with the soil strength (liquefaction resistance) represent the opportunity. The seismic load action is identified as the measure of cyclic stress ratio (CSR), whereas the soil ability for resisting the load imposed by seismic events is represented by cyclic resistance ratio (CRR). Soil susceptibility evaluation is the starting point in liquefaction analysis to exclude sites with unlikely liquefaction potential. When soils are known to be susceptible, the analysis process shifts to liquefaction initiation. Liquefaction potential is calculated at a particular depth using the concept of factor of safety (FS), comparing loading levels induced via the seismic event (CSR) to the soil resistance to liquefy (CRR). Once soil resistance is lower than the seismic loading, liquefaction will be initiated.

Fifty-five boreholes were carefully examined for site susceptibility to liquefaction. The water table was encountered at 20 boreholes only, at depths varying from 0.94 to 6.5 m below the ground surface. Seven boreholes out of 20 were referred to be susceptible to liquefaction owing to their appropriate local soil characteristics and were thus analyzed for quantification of their liquefaction potential. The susceptible seven boreholes showed that soil columns consist mainly of (from top to bottom) very sandy silt, fine to medium sand, very sandy gravel and silty clayey gravelly sand.
Figure 18. Estimated ground-motion amplification of PSA 0.2 s for 475-year return period.

CSR is defined by surface PGA and depth reduction parameter ($r_d$) using the Seed & Idriss (1971) procedure (simplified procedure). NCEER (1997) revised their initial formula to be:

$$\text{CSR} = 0.65 \left( \frac{a_{\text{max}}}{g} \right) \left( \frac{\sigma_{v0}}{\sigma'_{v0}} \right) r_d$$  \hspace{1cm} (1)

where $\sigma_{v0}$ and $\sigma'_{v0}$ are the total and effective overburden stresses, $a_{\text{max}}$ is the horizontal site-specific PGA and $r_d$ is peak shear stress reduction rate with depth and is estimated herein using NCEER (1997) equations. Site-specific probabilistic PGA values for a 475-year return period along with corresponding earthquake magnitude were used. This return period was chosen to be equal to the return period intended for the Omani seismic building code.

CRR evaluation for the seven susceptible boreholes sites was achieved using the blow counts of SPT ($N$ values). These raw $N$ values were subjected to many corrections to find the standardized ($N_1$)60 (equivalent SPT blow counts for clean sand). Clean sands are those with a fine content less than 5%. These corrections included depth correction (effective overburden pressure), efficiency of hammer energy, borehole diameter, rod length and sampling procedure. For sands with fine contents greater than 5%, additional corrections were implemented for obtaining a clean sand equivalent; as such sands being anticipated to have increased resistance to liquefaction.

4.1. Factor of safety against liquefaction

FS is mathematically expressed as:

$$\text{FS} = \left( \frac{\text{CRR}_{7.5}}{\text{CSR}} \right) \text{MSF}.$$  \hspace{1cm} (2)

Curves of liquefaction against CRR are built for an earthquake with Mw 7.5. The purpose behind the magnitude-scaling factor (MSF) is to amend CRR$_{7.5}$ values for seismic events with magnitudes different from 7.5, accounting for the duration effect on the calculated ground motion. MSF proposed by the revised Idriss formulation in NCEER (1997) is applied herein:

$$\text{MSF} = \left[ \frac{10^{2.24}}{\text{Mw}^{2.56}} \right].$$  \hspace{1cm} (3)
Generally, the soil layers are deemed liquefiable when $FS$ is less than 1.0. Sometimes, soils may be liquefiable at an $FS$ greater than 1.0, so, an $FS$ of 1.2 is selected to be the limit at which the soil layers are rendered non-liquefiable. Figure 21 shows the principal results obtained at a borehole (34). The surface soil was (beige to yellowish brown), gravelly, very silty, slightly gypsiferous and calcareous sand down to a 1.0 m depth with 8.0 blow counts. The lithology became medium dense, (beige to yellowish brown), silty/clayey and very sandy gravel with much higher blow counts ($N > 50$) down to a depth of 2.0 m depth. Next, a yellowish brown, very silty/clayey, gravelly, sand with a $31 N$ value extended to the bottom at depth of 20 m. The water table was encountered at 3.49 m. The $FS$ value at borehole number 34 was very much higher than 1.2 for a 475-year return period, indicating non-liquefiable soils. Similarly, all the sites within the area were non-liquefiable, attributable to low ground motion and small soil thickness.

5. Discussion

Accurate seismic zones geometry, fault rupture scenarios and GMPEs for strong-motion parameters are lacking for Oman. Thus, several widely different and competing alternatives were introduced into a logic-tree algorithm to reasonably provide the seismic hazard truthfully at the top of bedrock. Results were highly reliant on the supposition that future seismic events will essentially continue to occur within the restrictedly defined seismic zones.

The $F_0$ map could identify the boundaries between the rock outcrops toward west and north, and the soil zones in remaining areas. This map helped to recognize sites that could suffer more damage by reason of the agreement of soils $F_0$ and the natural period of the buildings. Accordingly, short buildings (1–5 stories) at the middle and eastern parts may suffer more if a destructive earthquake occurs.

$V_{S30}$ and NEHRP (2001) site classifications were determined from the calculated velocity data. Estimated soil thickness was strengthened by the outcomes of shallow seismic refraction, MASW and HVSR surveys. Combined results of the three geophysical methods enhanced the output and restricts soil physical parameters. Comparing the soil thickness map with the $F_0$ and the $V_{S30}$ maps showed a good match between them. High and medium $V_{S30}$ and $F_0$ values corresponded to areas of no or small soil thickness toward the
Variation of surface ground-motion values introduced the seismic hazard as a crucial factor in anticipating the earthquake actions for design engineers, liquefaction potential, developing risk mitigation strategies, land use management and urban planning. This paper gave the site-specific seismic hazard findings at the Duqm area for the three studied return periods. In light of the outcomes of 55 boreholes with N values and three geophysical surveys, site characterization was evaluated. This study provided knowledge on soil elastic properties, delineating the acoustic impedance boundaries between the surface and bedrock. The study ended up with a soil thickness map, Fo map, $V_{S30}$ map, amplification maps and surface ground-motion maps. The economic zone of Duqm was distinguished by very low hazard values with relatively large PGA values at the northeastern Duqm area with 46 and 93 cm s$^{-2}$ for return periods of 475 and 2475 years.

Site-specific hazard map reliability depended vastly on the interpolation of the available boreholes and the geophysical surveys. Site-specific ground motions were calculated at
Figure 21. Liquefaction potential at borehole No 34 in the Duqm area.

particular 90 sites with spatial spacing of about 1–2 km. As the site characterization can change over small distances, site-specific investigation for spaces between the investigated 90 sites should be performed to design against the earthquake force on the critical structures.

The performed liquefaction analysis showed the safety of the economic zone of the Duqm area against liquefaction for site-specific ground motion of a 475-year return period.

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References

Aki, K. & Richards, P.G., 1980. Quantitative Seismology, Freeman and Co., New York.

Akkar, S. & Bommer, J.J., 2010. Empirical equations for the prediction of PGA, PGV and spectral accelerations in Europe, the Mediterranean region and the Middle East, Seismological Research Letters, 81, 195–206.

Al Atik, L. & Abrahamson, N., 2010. An improved method for non-stationary spectral matching, Earthquake Spectra, 26, 601–617.

Aldama, B., 2009. An exploratory study of parameter sensitivity, representation of results and extension of PSHA: case study-United Arab Emirates, PhD Thesis, Imperial College, London.

Aldama, B., Bommer, J.J., Fenton, C.H. & Staford, P.J., 2009. Probabilistic seismic hazard analysis for rock sites in the cities of Abu Dhabi, Dubai and Ra’s Al Khymah, United Arab Emirates, Georisk, 3, 1–29.

Ambraseys, N.N. & Melville, C.P., 1982. A History of Persian Earthquakes. Cambridge University Press, Cambridge.

Atkinson, G.M. & Boore, D.M., 2003. Empirical ground-motion relations for subduction-zone earthquakes and their application to Cascadia and other regions, Bulletin of Seismological Society of America, 93, 1703–1729.

Atkinson, G.M. & Boore, D.M., 2006. Earthquake ground-motion prediction equations for Eastern North America, Bulletin of Seismological Society of America, 96, 2181–2205.

Beyer, K. & Bommer, J.J., 2006. Relationships between median values and between aleatory variabilities for different definitions of the horizontal component of motion, Bulletin of Seismological Society of America, 96, 1512–1522, Erratum (2007) 97, 1769.

Campbell, K., 2003. Prediction of strong ground-motion using the hybrid empirical method and its use in the development of ground-motion (attenuation) relations in Eastern North America, Bulletin of Seismological Society of America, 93, 1012–1033.

Chiou, B.S. & Youngs, R.R., 2008. An NGA model for the average horizontal component of peak ground motion and response spectra, Earthquake Spectra, 24, 173–215.

Cornell, C.A., 1968. Engineering seismic risk analysis, Bulletin of Seismological Society of America, 18, 1583–1606.
Cornell, C.A. & Vanmarcke, E.H., 1969. The major influences on seismic risk, in Proceedings of the Fourth World Conference of Earthquake Engineering, 1, Santiago, Chile, 69–83.

Deif, A., Al-Shijbi, Y., El-Hussain, I., Ezzelarab, M. & Mohamed, A.M.E., 2017. Compiling an earthquake catalogue for the Arabian Plate, Western Asia, Journal of Asian Earth Sciences, 147, 345–375.

Deif, A., El-Hussain, I., Al-Shijbi, Y. & Mohamed, A.M.E., 2020. Updating a Probabilistic Seismic Hazard Model for Sultanate of Oman, Arabian Journal of Geosciences, 13, 502.

Delavaud, E. et al., 2012. Towards a ground-motion logic tree for probabilistic seismic hazard assessment in Europe, Journal of Seismology, 16, 451–473.

Douglas, J. et al., 2014. Comparisons among the five ground-motion models developed using RESORCE for the prediction of response spectral accelerations due to earthquakes in Europe and the Middle East, Bulletin of Earthquake Engineering, 12, 341–358.

El-Hussain, I., Al-Shijbi, Y., Deif, A., Mohamed, A.M.E. & Ezzelarab, M., 2018. Developing a seismic source model for the Arabian Plate, Arabian Journal of Geosciences, 11, 435.

El-Hussain, I., Deif, A., Al-Jabri, K., Mohamed, A.M.E., El-Hady, S. & El-Habsi, Z., 2014. Efficiency of horizontal-to-vertical spectral ratio (HVS ratio) in defining the fundamental frequency in Muscat Region, Sultanate of Oman: a comparative study, Arabian Journal of Geosciences, 7, 2423–2436.

Fenton, C.H., Adams, J. & Halchuk, S., 2006. Seismic hazards assessment for radioactive waste disposal sites in regions of low seismic activity, Geotechnical and Geological Engineering, 24, 579–592.

Idriss, I.M. & Sun, J.L., 1992. User’s manual for SHAKE91, Computer program for conducting equivalent linear seismic response analyses of horizontally layered soil deposits. University of California, Davis.

Kijko, A., 2004. Estimation of the maximum earthquake magnitude Mmax, Pure and Applied Geophysics, 161, 1655–1681.

Koller, M.G., Chatelain, J.L., Guiller, B., Duval, A.M., Atakan, K., Lacave, C. & Bard, P.Y., & SESAME participants, 2004. Practical user guideline and software for the implementation of the H/V ratio technique on ambient vibrations: measuring conditions, processing method and results interpretation, in Proceedings of the 13th World Conference on Earthquake Engineering, August 1–6, Vancouver, BC, Canada, Paper No 3132.

Konno, K. & Ohmachi, T., 1998. Ground motion characteristics estimated from spectral ratio between horizontal and vertical components of microtremors, Bulletin of Seismological Society of America, 88, 228–241.

Kusky, T., Robinson, C. & El-Baz, F., 2005. Tertiary-Quaternary faulting and uplift in the northern Oman Hajar Mountains, Journal of the Geological Society, 162, 871–888.

Mahajan, S.S., Ranjan, R., Sporry, R., Champati Ray, P.K. & van Westen, C. J., 2007. Seismic microzonation of Dehradun City using geophysical and geotechnical characteristics in the upper 30 m of soil column, Journal of Seismology, 11, 355–370.

McGuire, R.K., 1976. FORTRAN computer programs for seismic risk analysis, U.S. Geological Survey Open-File Report No 76-67.

Miller, R.D., Xia, J., Park, C.P. & Ivanov, J., 1999. Multichannel analysis of surface waves to map the bedrock, the leading edge, 18, 1392–1396.

Mohamed, A.M.E., Deif, A., El-Hadidy, S., Moustafa Sayed, S.R. & El Werr, A., 2008. Definition of soil characteristics and ground response at the northwestern part of the Gulf of Suez, Egypt, Journal of Geophysics and Engineering, 5, 420–437.

Mohamed, A.M.E., El-Hussain, I., Deif, A., Arafà, A.A.S., Mansour, Kh. & Al-Rawas, G., 2019. Integrated GPR, ERT and MASW techniques for near-surface caverns detection at Duqm area, Sultanate of Oman, J. Near Surface Geophysics, 17, 379–401.

Mussan, R.M.W., 2009. Subduction in the Western Makran: the historian’s contribution, Journal of Geology and Society, London, 166, 387–391.

Nakamura, Y., 1989. A method for dynamic characteristics estimation of subsurface using microtremors of the ground surface, QR of RTRI, 30, No. 1, 89, Feb.

NCEER, 1997. Technical report NCEER-97-0022, edited by: National Center for Earthquake Engineering Research, Buffalo, New York, USA.

NEHRP, 2001. NEHRP recommended provisions for seismic regulations for new buildings and other structures (FEMA 368 and 369). 2000 ed. Washington, DC: Building Safety Council, National Institute of Building Sites.

Park, C.B., Miller, R.D. & Xia, J., 1999. Multi-channel analysis of surface waves, Geophysics, 64, 800–808.

Schnabel, P.B., Lysmer, J. & Seed, H.B., 1972. SHAKE: a computer program for earthquake response analysis of horizontally layered sites. Report No. UCB/EERC-72/12. Earthquake Engineering Research Center, University of California, Berkeley.

Seed, H.B. & Idriss, I.M., 1970. Soil moduli and damping factors for dynamic response analyses, Earthquake Engineering Research Center. University of California, Berkeley, California, Rep. No. EERC-70/10.

Seed, H.B. & Idriss, I.M., 1971. Simplified procedure for evaluating soil liquefaction potential, Journal of Soil Mechanics and Foundation Engineering, 97, 1249–1273.

Seed, H.B., Wong, R.T., Idriss, I.M. & Tokimatsu, K., 1986. Moduli and damping factors for dynamic analyses of cohesionless soils, Journal of Geotechnical Engineering, 112, 1016–1032.

SESAME, 2004. Site effects assessment using ambient excitations Euro- pean research project, http://sesamefp5.obs.ujf-grenoble.fr.

Theodulidis, N. & Bard, P.Y., 1995. Horizontal to vertical spectral ratio and geological conditions, an analysis of strong motion data from Greece and Taiwan (SMART-1), Soil Dynamics and Earthquake Engineering, 14, 177–197.

Youngs, R.R., Chiou, S.J., Silva, W.J. & Humphrey, J.R., 1997. Strong ground motion attenuation relationships for subduction zone earthquakes, Seismological Research Letters, 68, 58–73.

Zhao, J., Zhang, J., Asano, A., Ohno, Y., Oouchi, T., Takahashi, T., Ogawa, H., Irikura, K., Thio, H.K., Somerville, P.G., Fukushima, Y. & Fukushima, Y., 2006. Attenuation relations of strong ground motion in Japan using site classification based on predominant period, Bulletin of the Seismological Society of America, 96, 898–913.