PROBABILISTIC SEISMIC HAZARD ASSESSMENT FOR LIBYA

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Abstract

This paper presents the results of a regional seismic hazard assessment undertaken for Libya and the offshore region. This area includes a number of major regional tectonic features including the Hellenic Arc and Calabrian Arc subduction zones, the stable continental Saharan Metacraton, forming part of the African Plate, and the Hün Graben in Libya where a magnitude 7.1M_w earthquake and a series of large aftershocks occurred in 1935. An earthquake catalogue has been compiled and critically reviewed for the region and seismic source zones and their associated magnitude recurrence parameters have been defined. Ground motion prediction equations have been selected based on the tectonic character of the source zones. The uncertainty in each element of the hazard assessment has been included using logic tree methodology. The seismic hazard results are presented in the form of geometric mean peak ground acceleration for selected cities and major oil and gas facilities in the region. The paper also discusses how these results compare with design values typically used for seismic design purposes in the region.

Keywords: Libya, North Africa, seismotectonics, probabilistic seismic hazard, peak ground acceleration

1. Introduction

The seismic hazard of the African continent has been researched with the focus largely confined to the East African Rift System (EARS), the Ibero-Maghreb region, and the Red Sea. While there have been several regional and global studies that have incorporated Libya, the models used have often been based on a small number of outdated studies that have made relatively crude assumptions with Libya typically forming the periphery of those regional models. This study attempts to fill that gap by deriving estimates of the hazard levels based on a Libya, and surrounding region, -specific seismic source model. In addition, given that Libya has the largest oil reserves in Africa, it is also intended to have industry applications in the development of oil and gas and other critical national infrastructure.

North Africa and the Mediterranean region have been covered as part of various international seismic hazard mapping programmes including GSHAP and SESAME. Recently, Mourabit et al. (2013) published a seismic hazard map for North Africa based on neo-deterministic seismic hazard analysis methodology. The seismic hazard maps generated as part of the above studies were understandably developed with more of a focus on seismically active areas of the Euro-Mediterranean area, such as Turkey and Italy. While the maps produced for Libya are an indicator of broad seismic hazard levels across the country, they may not be suitable for deriving region specific hazard values for design.

While no definitive probabilistic seismic hazard assessments (PSHAs) have been undertaken for Libya, a number of studies investigating the seismicity and the seismotectonics do exist. Early seismic zonation maps were presented by Mallick & Morghem (1977) and Kebeasy (1981). These studies neglected the underlying geological and seismotectonic drivers of seismicity and considered a very narrow temporal window for the derivation of magnitude-recurrence relations. More recent studies by Suleiman & Doser (1995), Al-Heety & Eshwehdi (2006) and Al-Heety (2013) provide a more comprehensive account of the seismicity and seismotectonics and benefit from locally obtained strong-ground motion data from the Libyan Digital Seismological Network (LDSN).

2. Geological and Tectonic Setting

North Africa and the Mediterranean region are situated in a complex tectonic environment on the plate margin where the African and Arabian plates are migrating north and north-westward towards the Eurasian Plate respectively. In addition, the Aegean Sea Plate has a south western motion relative to the Eurasian Plate yielding a more rapid convergence in the Hellenic Arc Subduction Zone (Fig. 1) than is accommodated purely by convergence of the African and Eurasian plates. In general terms the complex tectonic situation has given rise to two principal relative motions along the plate margin (Udías, 1985). Firstly, right-lateral strike slip movement along the Azores-Gibraltar Fault in the Atlantic and the Anatolian Fault in Turkey. It is considered that this may also regulate the motion in the Calabrian Arc Subduction Zone (Fig. 1). Secondly, convergence of the plates has caused compression zones along the eastern end of the Azores-Gibraltar Fault, Northwest African margin, north-eastern coast of the Adriatic Sea and the subduction zones of the Calabrian and Hellenic arcs. Fig. 1 presents the present day tectonic setting in the Mediterranean and North Africa.

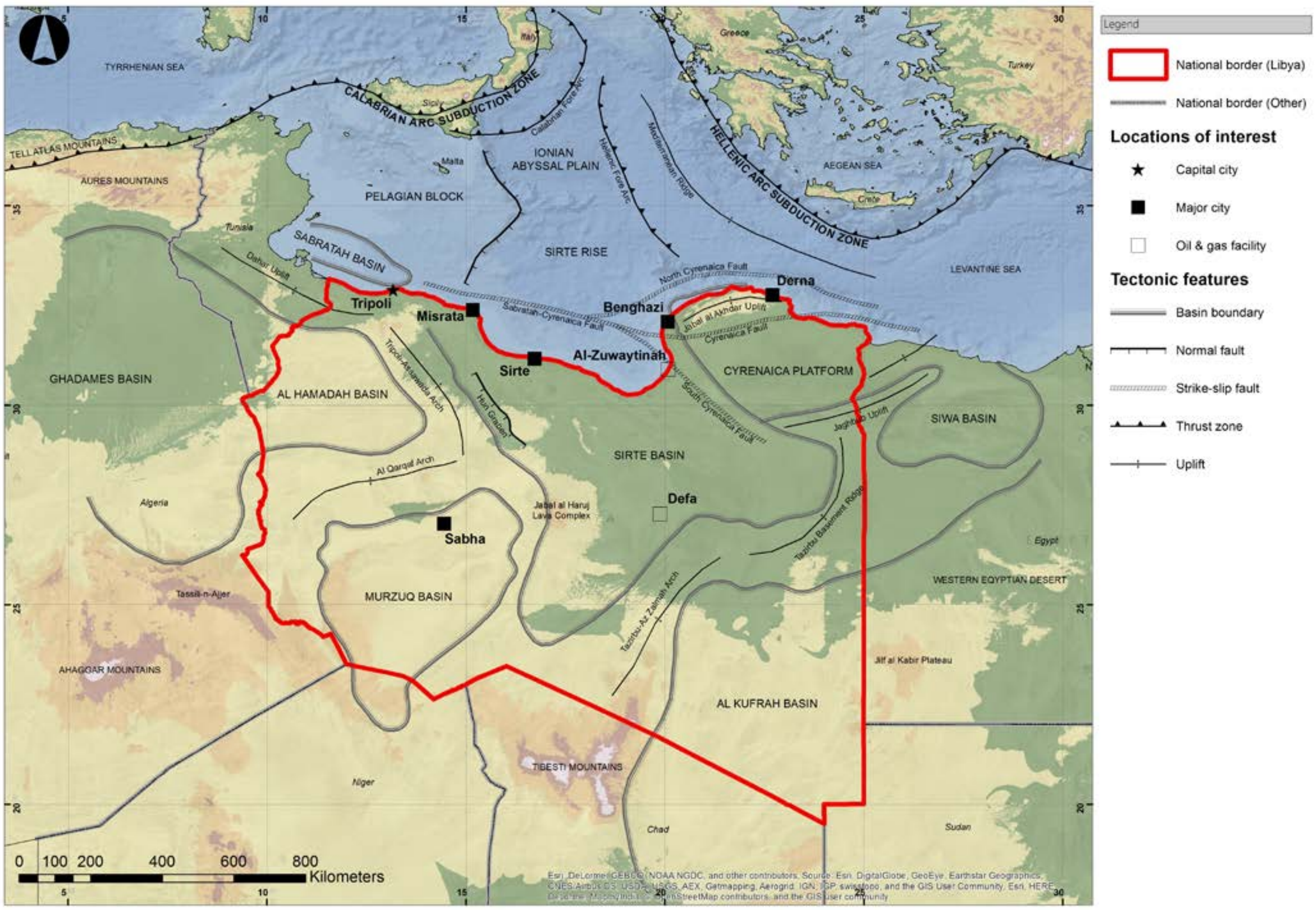

Fig. 1 - Present day tectonic setting in Libya and the Mediterranean offshore area to the north.

The geological structure of Libya has been largely defined by Pan-African and Hercynian orogenic events and more recently the evolution of the Tethys/Mediterranean basin and Alpine tectonism. The Precambrian and early-Palaeozoic age cratonic basement is overlain by a thick sedimentary succession covering much of the country with the tectonics and subsequent structure having controlled the sedimentation. Volcanic intrusions and extensive surface lava flows occurred throughout the Tertiary (Hallet, 2002).

The Libyan offshore area is divided into structural provinces that exhibit tectonic influences from the Calabrian and Hellenic subduction zones to the north of Libya (Hallet, 2002). Interestingly, although the Calabrian Arc is geographically further away than the Hellenic Arc to the Libyan foreland, the tectonic effects appear to be more profound. It is interpreted that this is due to the east-west motion of the Calabrian Arc inducing significant wrenching motions over the region, which has led to the development of the Sabratah-

Cyrenaica Fault system (Fig.1), while the compressional north-south motion of the Hellenic Arc appear to have less influence. In terms of seismicity, the Calabrian Arc subduction zone is considered too far away to influence the seismic hazard and ground motion in Libya.

3. Seismicity and Seismotectonics

Due to the location of Libya on the Mediterranean foreland of the Saharan Metacraton, the onshore region can be considered an intraplate environment. The causative mechanisms of intraplate seismicity can generally be attributed to the reactivation of pre-existing fault structures (Sykes, 1978) and variations in local stress concentrations (Campbell, 1968). The seismotectonics in North Africa represent the interaction between the active plate margin and the imparted fault systems (Mourabit et al., 2013). Faulting is dominated by northwest-southeast and NNW-SSE trending normal faults in eastern Libya, with a significant number of strike-slip earthquakes in western Libya indicating that the existing structures are being reactivated in a stress regime concordant with the convergence of the African and the Eurasian plates (Suleiman & Doser ,1995). The style and orientation of faulting in eastern Libya and the Sirte Basin (Fig. 1) could suggest reactivation of basement structures (Goudarzi, 1980). Campbell (1968) suggests earthquakes in Libya are caused by the relief of stresses that have built up between the stable metacraton and the mobile zone to the north.

Both Suleiman & Doser (1995) and Al-Heety & Eshwehdi (2006) suggest that the correlation between seismicity and mapped faults is generally strong and thus there is the possibility for extensions of some unmapped but known or expected faults. In particular Suleiman & Doser (1995) suggest that the seismically active Hün Graben (Fig. 1) may extend further north and thus there is the potential for larger earthquakes to occur closer to the major population centres of Tripoli and Misrata.

Ganas et al. (2009) suggests the Hellenic Arc subduction zone, which is occurring along the boundary region of the African, Eurasian and Aegean Sea plates, is the most seismically active part of Europe. Strike-slip and reverse with some normal fault motions are responsible for much of the seismicity from Crete north-westwards along the arc. To the east of Crete, normal fault and strike-slip earthquakes are predominant with Crete forming the transition zone between these seismotectonic domains. There is historical evidence of large magnitude earthquakes in this transition zone around Crete. As such, it is important to encapsulate this zone into the Study Area such that they are accounted for in the hazard calculations.

4. Earthquake Catalogue

The earthquake catalogue has been compiled for the Study Area bounded by Latitudes 18.5°N to 35°N and Longitudes 8°E to 26.5°E. Due to the relative difference in seismicity and level of existing information between the Hellenic Arc and the Libyan mainland and offshore area, separate catalogues have been compiled and amalgamated to form a final catalogue. The catalogue for Greece presented by Makropoulos et al. (2012) has been used to compile a catalogue for the Hellenic Arc for magnitudes $\geq 4.0 M_w$ between 1900 and 2009. For the time period between 2010 and 2013 the catalogue has been supplemented by data from the European Mediterranean Seismological Centre (EMSC).

For the Libyan mainland and offshore area, an earthquake catalogue has been compiled from a range of data sources summarised in Table 1. While there is an established seismological network in Libya (Libyan Digital Seismological Network, LDSN), no data was directly available and thus the data sources comprise global and regional catalogues. Historical records and catalogues have also been reviewed and incorporated into the catalogue but it is widely reported in the literature that the historical seismicity of Libya remains poorly known (Ambraseys et al., 1994; Suleiman & Doser, 1995; Suleiman et al., 2004).

Prior to processing the earthquake catalogue, duplicates between data sources were removed based on location and magnitude parameters. Priority has been given to more reputable international data sources and duplicates have been removed from subsequent catalogues. Catalogue processing has subsequently been undertaken to provide a consistent set of historical and recent earthquake events considered representative as possible of the actual seismicity in the Study Area.

Table 1 - Earthquake data sources used in the compilation of the earthquake catalogue.

Period	Catalogue / Reference	Region	Date range	Magnitude range
Historical	National Geophysical Data Centre (NOAA-NGDC)	Global	2150 B.C. to 1903	≥4.0
	Ambraseys et al. (1994)	Egypt / Arabia / Red Sea	184 A.D. to 1992	≥4.0
	Suleiman et al. (2004)	Libya	262 A.D. to 1935	≥5.0
	Ambraseys (1994)	Libya	262 A.D. to 1990	≥4.0
Instrumental	International Seismological Centre (ISC-GEM)	Global	1900 to 2014	≥5.5
	Engdahl, van der Hilst, and Buland (EHB)	Global	1960 to 2008	≥4.0
	International Seismological Centre (ISC Bulletin)	Global	1904 to 2015	≥5.5
	National Earthquake Information Centre (NEIC)	Global	1973 to 2014	≥4.0
	European Mediterranean Seismological Centre (EMSC)	Europe / Mediterranean	2004 to 2014	≥2.0
	European Mediterranean Seismological Centre (EMSC) Bulletin	Europe / Mediterranean	2004 to 2014	≥2.0

4.1 Magnitude Conversion

A consistent magnitude scale is required for the PSHA calculations, therefore all earthquake magnitudes have been converted to moment magnitude (M_w). The relationships selected for conversion to M_w from M_s (surface wave magnitude), m_b (body wave magnitude), M_L (local magnitude) and M_D (duration magnitude) are outlined below. The conversions are based on regression analysis comparing the study data to published correlations.

For conversion from M_s to M_w the relationship by Grünthal et al. (2009) was selected:

$$M_W = 10.85 - (73.74 - 8.38M_S)^{0.5}$$

…for magnitudes ≤ $7.0M_s$ (1)

For conversion from m_b to M_w the relationship by Grünthal et al. (2009) was selected:

$$M_W = 8.17 - (42.04 - 86.42m_b)^{0.5}$$

…for magnitudes ≤ $6.5m_b$ (2)

For conversion from M_L to M_w the relationship by Akkar et al. (2008) was selected:

$$M_W = 0.953M_L + 0.422$$

…for magnitudes ≤ $6.5M_L$ (3)

There was a very limited set of data where both M_D and M_w were reported. As such, a 1:1 relationship was considered appropriate for the conversion of the study data from M_D to M_w.

4.2 Aftershock / Foreshock Removal

The software package Oasys EQCAT, an in-house catalogue processing programme, has been used to process the earthquake catalogue for the removal of aftershocks and foreshocks adopting the method proposed by Gardner and Knopoff (1974).

4.3 Catalogue Completeness

Completeness thresholds were determined based on the method proposed by Stepp (1972), where the activity rate is assessed for various time intervals of the catalogue. While seismic events in Libya have been recorded as early as 262 A.D., the reliability of records prior to 1900 is questionable and the data is not considered complete, even for large magnitude events. It is acknowledged that the completeness window is very short and a thorough assessment of historical seismic data is needed.

The completeness of the catalogue for the Hellenic Arc was assessed as part of the study conducted by Makropoulous et al. (2012) also based on Stepp's method. The completeness thresholds for a range of magnitude values for the Study Area catalogue are listed in Table 2.

4.4 Final Catalogue

The final earthquake catalogue comprises a single catalogue compiled for the whole Study Area. The Libya and offshore area comprises earthquakes with a magnitude equal to, or greater than, 2.0M_w in the full catalogue and 3.0M_w in the complete catalogue. The Hellenic Arc comprises earthquakes with a magnitude equal to or greater than 4.0M_w in the full and complete catalogues. The full catalogue comprises 1,417 earthquakes and the complete catalogue comprises 1,125 earthquakes. The distribution of statistically complete seismicity within the Study Area is shown in Fig. 2. On this drawing the symbol size for earthquake epicentre location is proportional to the moment magnitude (M_w).

The onshore distribution of seismicity is represented by two principal areas of high seismicity in north-western and north-eastern Libya. There is potentially another minor area of concentrated seismicity in the Sirte Basin but in general the seismicity is sparsely distributed. Onshore focal depths in Libya are invariably shallow (<50km). Several large earthquakes were recorded in Libya in 1935, the largest recorded was a magnitude 7.1M_w with two large aftershocks of magnitudes 6.0M_w and 6.5M_w. These earthquakes were located in close proximity to the Hün Graben. Since 1935, several other moderate shocks have occurred in broadly the same area (Suleiman & Doser, 1995). A magnitude 5.8M_w was recorded in the coastal region of the Jabal al Akhdar Uplift, in north-eastern Libya, in 1963 causing severe damage to the town of Al-Marj (Campbell, 1968; Kebeasy, 1980).

The largest magnitude earthquake to have occurred in the Hellenic Arc since 1900 was a magnitude 7.3M_w (Ganas et al., 2009). However, within the Study Area the largest is a magnitude 6.4M_w. Historical records indicate that there is evidence of earthquakes with magnitudes greater than 8.0M_w in ancient history, for example in 365A.D. and 1303A.D. (Guidoboni & Comastri, 1997; Papazachos & Papaioannou, 1997; Stiros, 2001), which have occurred within the seismotectonic transition zone around Crete. Stiros (2001) suggests that the 365A.D. event may have had a magnitude between 8.3 to 8.5M_w. Shaw & Jackson (2010) suggest these large earthquakes occur on steeply dipping thrust splays in the overriding Aegean Sea Plate rather than the subduction zone interface. Ambraseys et al. (1994) commented that earthquakes originating in the Hellenic Arc have the potential to generate slow and sustained large amplitude ground motions in Libya.

5. PSHA Input Parameters

The seismic hazard assessment has been carried out following probabilistic methodology (Cornell, 1968; Reiter, 1990) using the software Oasys SISMIC, an in-house seismic hazard calculation software package. This methodology combines seismic source zoning, earthquake magnitude-recurrence and ground motion prediction equations (GMPEs), with the epistemic uncertainty explored with a logic tree approach, to produce hazard curves in terms of ground motion and an associated annual frequency of exceedance.

Table 2 - Table summarising earthquake catalogue completeness thresholds.

Libya and offshore area		Hellenic Arc (after Makropoulos et al. (2012)	
Magnitude	**Year of completeness**	**Magnitude**	**Year of completeness**
≥2.0M_w	Not complete	-	-
≥2.5M_w	Not complete	-	-
≥3.0M_w	2006	-	-
≥3.5M_w	2000	-	-
≥4.0M_w	1963	≥4.0M_w	1976
≥4.5M_w	1963	≥4.5M_w	1950
≥5.0M_w	1963	≥5.0M_w	1940
≥5.5M_w	1900	≥5.4M_w	1911
		≥5.9M_w	1900

4.1 Seismic Source Model

The source model was developed with detailed consideration of the potential controls of the regional geology and tectonics on the distribution of observed seismicity in Libya. The aim of the model was to evolve and refine previous source models, in particular Kebeasy (1981), with an enhanced understanding of the kinematic interactions between tectonic elements based on a model presented by Anketell (1996).

The key fault systems and tectonic components as well as the associated observed seismicity and focal mechanisms were used as the basis for developing area source zones. Although it may be possible to spatially correlate activity with faults, without detailed investigation (i.e. fault trenching, intrusive ground investigation) and in the absence of fault source parameters in the literature, it is impractical to determine the activity and subsequently derive seismic parameters for a fault model to be generated. As such, fault sources were not used in the analysis. The Hellenic Arc subduction zone is modelled predominantly based on, Shaw & Jackson (2010), Shaw et al. (2008), Ganas et al. (2009), Snopek et al. (2007), and Papazachos & Papaioannou (1997) supported by the model presented by SHARE. The seismic source model for the Study Area is presented in Fig. 2.

4.2 Magnitude-recurrence

Magnitude-recurrence parameters were calculated based on the truncated Gutenberg and Richter (1956) power law model; this requires the definition of minimum and maximum magnitude bounds. The minimum magnitude (M_{min}) was taken as 4.0M_w for all sources zones. With the exception of the Hellenic Arc, the maximum magnitude (M_{max}) was taken as the observed maximum magnitude plus 0.5M_w units (M_{maxOBS} + 0.5M_w), with a minimum M_{max} of 6.5M_w for any source zone, even if the observed maximum magnitude was lower. The observed maximum magnitude in the earthquake catalogue for the Hellenic Arc was a magnitude 6.4M_w. However, there is precedent in ancient history for earthquakes with magnitudes potentially up to 8.5M_w (Stiros et al., 2001). Laigle et al. (2004) suggests the Hellenic Arc is capable of generating >8.0M_w based on the geometry of the seismogenic part of the subduction zone interface. Based on the above, a M_{max} of 8.0M_w has been used.

The regression of the seismicity rates was performed using the maximum likelihood approach based of Weichert (1980) for catalogues with differing levels of completeness. The magnitude recurrence parameters for each seismic source zone were estimated using the software ECIS+ and are presented in Table 3.

4.3 Ground Motion Prediction Equations (GMPEs)

Ground motion prediction equations are used to predict the level of ground motion based on the magnitude of the earthquake, the distance of the earthquake from the site, the type of faulting, the ground conditions, etc. and represent the level of attenuation from source to site. For this study, the GMPEs were chosen based on the tectonic environment for each seismic source zone, and can be grouped to shallow-crustal, stable continental and subduction zone GMPEs. Table 4 summarizes the GMPEs assigned to each source zone for this study, including the tectonic regime and style of faulting. The GMPEs were not modified to account for local attenuation characteristics.

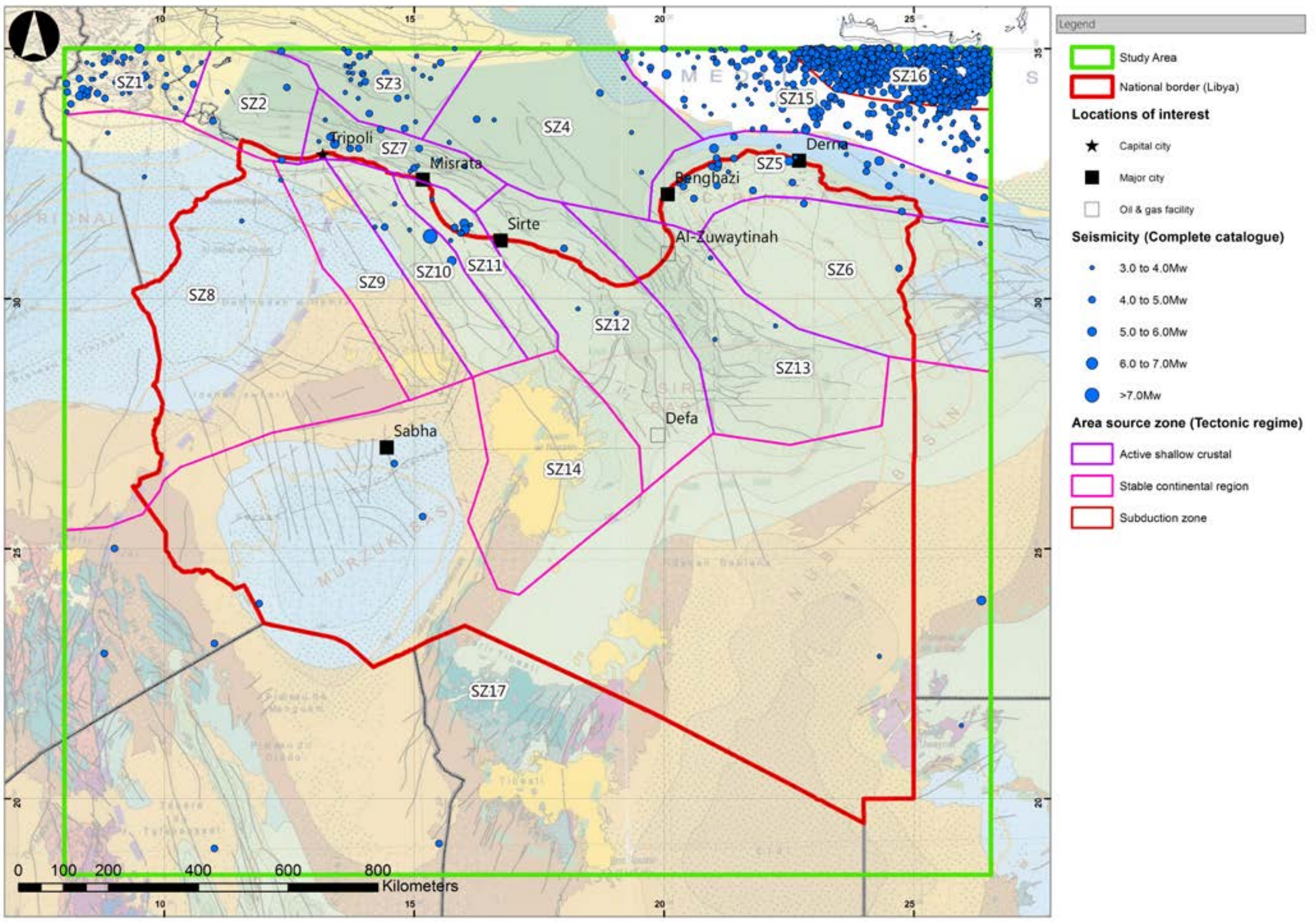

Fig. 2 – Final earthquake catalogue (graduated circles) and seismic source model (coloured polygons) developed for the Study Area.

4.4 Logic Tree

Epistemic uncertainty has been addressed by using a logic tree approach. This approach uses a series of nodes and branches to weight uncertain parameters, models or assumptions and produce 'weighted' hazard curves by exploring all plausible discrete alternative outcomes. Fig. 3 illustrates the logic tree developed for this study, including the weights assigned to each branch (W).

The logic tree was developed to capture the effect of epistemic uncertainty on the a-value, b-value, M_{max}, and the GMPEs. Variation in the a-value was incorporated into the model by assigning weights of 50% to the mean, and 30% and 20% mean ±1.6σa respectively. Variation in the b-value was incorporated by assigning weights of 60%, 20% and 20% to the mean and mean ±1.6σb respectively. Varying the a- and b- value did not apply to the Hellenic Arc source zones. Variation in the M_{max} was incorporated by assigning 60% of the weight to the mean and 20% to each of the mean ±σM pair.

Equal weightings were assigned to the GMPE's and source zones in shallow crustal regions were separated based on the dominant fault focal mechanisms. For the ground motion models, uncertainty in the truncation of the standard error was not included, choosing a truncated distribution at 5 standard deviations above the median predictions.

Table 3 - Table summarising magnitude-recurrence parameters.

Source ID	Source zone name	b-value		Activity rate (a-value)		Maximum magnitude	
		Mean	Sigma	N≥4.0M_w / yr	Sigma	Observed	Mmax
All (excl. SZ16)	All (excl. Hellenic Arc Subduction Zone)	0.82	0.029	3.485	0.179	7.1M_w	7.6M_w
SZ1	South Atlas Flexure	0.92	0.080	0.479	0.062	5.6M_w	6.5M_w
SZ2	Sabratah Basin	0.68	0.187	0.074	0.028	5.0M_w	6.5M_w
SZ3	Pelagian Block	0.98	0.105	0.282	0.046	4.7M_w	6.5M_w
SZ4	Sirte Rise	0.93	0.235	0.056	0.021	4.7M_w	6.5M_w
SZ5	Jabal al Akhdar Uplift	0.67	0.084	0.365	0.063	5.8M_w	6.5M_w
SZ6	Cyrenaica Platform	0.67	0.081	0.030	0.017	4.3M_w	6.5M_w
SZ7	Misrata Basin	0.87	0.147	0.139	0.035	5.2M_w	6.5M_w
SZ8	Ghadames Basin	0.72	0.132	0.066	0.008	3.9M_w	6.5M_w
SZ9	Tripoli-Tibisti Arch	0.78	0.118	0.009	0.062	2.8M_w	6.5M_w
SZ10	Hün Graben	0.78	0.118	0.079	0.030	7.1M_w	7.6M_w
SZ11	Sirte Basin Northwest	0.78	0.118	0.085	0.030	5.6M_w	6.5M_w
SZ12	Sirte Basin Central	0.78	0.118	0.020	0.011	4.7M_w	6.5M_w
SZ13	Sirte Basin East	0.78	0.118	0.002	0.001	3.6M_w	6.5M_w
SZ14	Sirte Basin Southwest	0.72	0.132	0.009	0.062	2.9M_w	6.5M_w
SZ15	Hellenic Arc Accretionary Complex	0.80	0.041	1.673	0.125	6.3M_w	7.5M_w
SZ16	Hellenic Arc Subduction Zone	1.08	0.029	24.627	0.794	6.4M_w	8.0M_w
SZ17	Intraplate background seismicity	0.72	0.132	0.126	0.038	5.2M_w	6.5M_w

Table 4 - Table summarising ground motion prediction equations (GMPEs).

Tectonic regime	Source Zones	Style of faulting	GMPE
Active shallow crustal	South Atlas Flexure, Sabratah Basin, Pelagian Block, Sirte Rise, Misrata Basin, Tripoli-Tibisti Arch, Hün Graben, Sirte Basin Northwest, Sirte Basin Central, Sirte Basin East	Normal and strike-slip	Akkar et al. (2014) Chiou & Youngs (2014) Zhao et al. (2006)
	Hellenic Arc Accretionary Complex	Reverse/thrust	
Stable continental region	Cyrenaica Platform, Ghadames Basin, Sirte Basin Southwest, Intraplate background seismicity	All	Atkinson & Boore (2011) Pezeshk et al. (2011)
Subduction zone	Hellenic Arc Subduction Zone	Reverse/thrust and interface	Zhao at al. (2006)

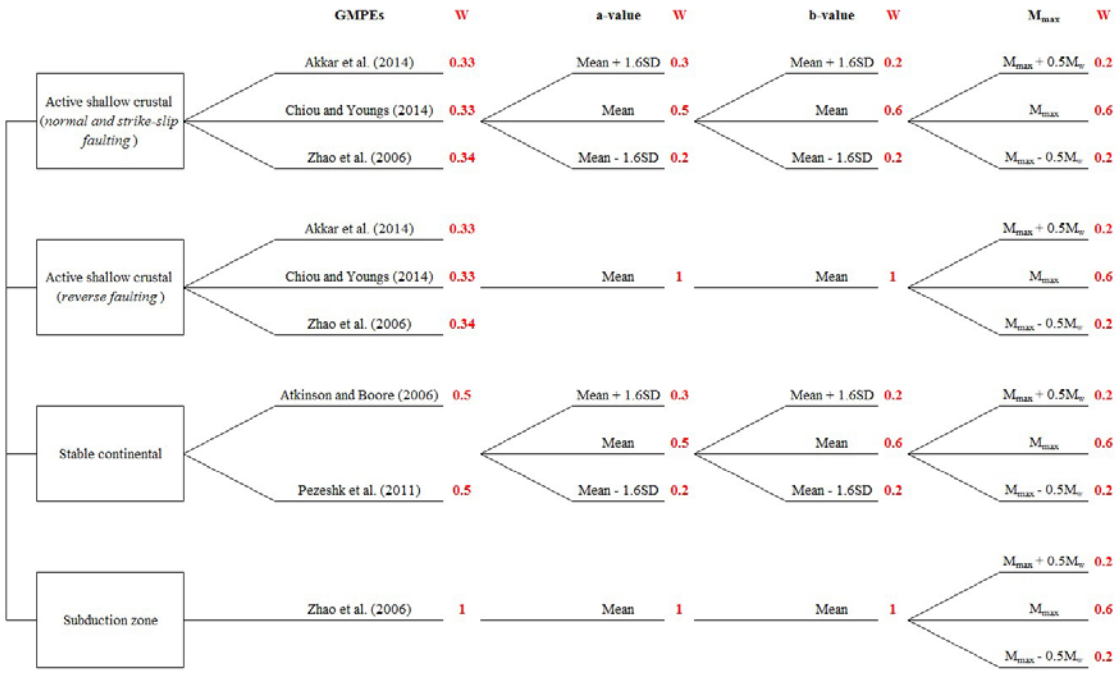

Fig. 3 – Logic tree adopted in the analysis.

5. Results of PSHA

4.4 Seismic Hazard Curves

Mean seismic hazard curves (SHCs) illustrating spectral acceleration (SA) versus annual probability of exceedance have been calculated for geometric mean horizontal peak ground accelerations (PGA) for stiff soil (V_{S30} ≥360m/s) and bedrock (V_{S30} ≥760m/s) sites (Fig. 4). This has been done for various locations in Libya comprising six major cities and two major oil and gas sites: the Al Zuwaytinah refinery and export terminal in northeast Libya, and the Defa oil and gas field in the southern Sirte Basin.

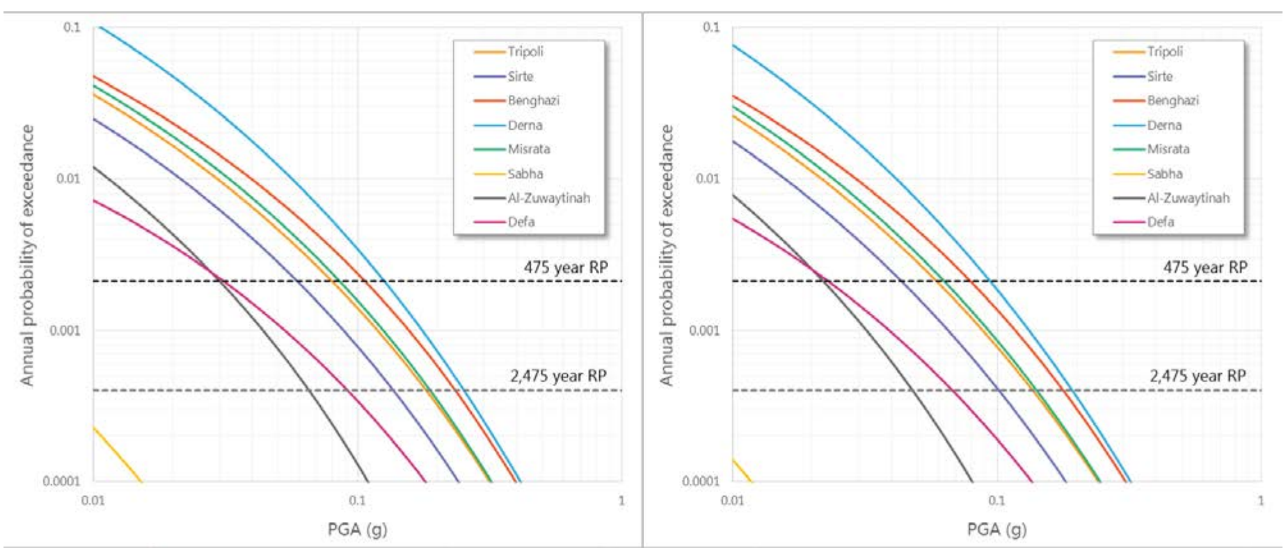

Fig. 4 – Seismic hazard curves at PGA for stiff soil (V_{S30} ≥360m/s) (*left*) and bedrock (V_{S30} ≥760m/s) (*right*) site conditions for various locations in Libya.

The seismic hazard curves generally indicate overall relatively low seismic hazard in Libya with slightly higher hazard values for locations in closer proximity to the Jabal al Akhdar Uplift and the Hellenic Arc Subduction Zone in the northeast of the country. Interestingly, the seismic hazard levels in northwest Libya are dominated by contributions from offshore events, in the Misrata Basin, rather than the Hün Graben. For bedrock site conditions, values of horizontal spectral acceleration with 5% damping for PGA, 0.2s (short period), 1.0s and 2.0s (long period) are presented in Table 5 for 475 year and 2,475 year return periods.

Table 5 - Table summarising spectral ordinates at PGA, 0.2s, 1.0s and 2.0s for return periods of 475 and 2,475 years for a site with bedrock site conditions (V_{S30} ≥760m/s).

Location	Period (s) and spectral acceleration (g)							
	PGA		0.2		1.0		2.0	
	475 year	2,475 year	475 year	2,475 year	475 year	2,475 year	475 year	2,475 year
Tripoli	0.06	0.14	0.12	0.29	0.02	0.05	0.01	0.02
Misrata	0.06	0.14	0.13	0.30	0.02	0.06	0.01	0.03
Sirte	0.04	0.10	0.09	0.21	0.02	0.05	0.01	0.02
Benghazi	0.08	0.18	0.16	0.39	0.03	0.09	0.01	0.04
Derna	0.09	0.19	0.20	0.43	0.05	0.12	0.03	0.06
Sabha	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00
Al Zuwaytinah	0.02	0.05	0.04	0.10	0.01	0.03	0.01	0.01
Defa	0.02	0.07	0.04	0.13	0.01	0.02	0.01	0.01

4.4 Comparison of PSHA Results with the Literature

The spectral accelerations follow the expected trend that the values are higher in the coastal regions, however, the relatively greater hazard values in northeast Libya (Benghazi/Derna) compared to northwest Libya (Tripoli/Misrata) have not been reflected in the literature. The spectral accelerations values in the intraplate zone are low as expected, particularly in Sabha where the response is negligible. Table 6 presents a summary of the hazard values calculated in this study compared to values from the literature.

Table 6 - Table summarising calculated hazard values for stiff soil (V_{S30} ≥360m/s) and bedrock (V_{S30} ≥760m/s) site conditions for a return period of 475 years compared to related values from the literature.

Location	Peak ground acceleration, PGA (g)					
	GSHAP (bedrock)	**IGCP-382 SESAME** (stiff soil)	**ESC-SESAME** (stiff soil)	**Mourabit et al. (2013)** (bedrock)	**This study**	
					Stiff soil (V_{S30}≥360m/s)	**Bedrock** (V_{S30}≥760m/s)
Tripoli	0.13	0.09	0.1	0.04	**0.08**	**0.06**
Misrata	0.13	0.1	0.1	0.3	**0.09**	**0.06**
Sirte	0.13	0.1	0.1	0.3	**0.06**	**0.04**
Benghazi	0.13	0.08	0.1	0.01	**0.11**	**0.08**
Derna	0.13	0.1	0.1	0.08	**0.13**	**0.09**
Sabha	-	0.04	-	-	**0.002**	**0.001**
Al-Zuwaytinah	0.1	0.04	0.06	0.005	**0.03**	**0.02**
Defa	-	0.00	-	0.01	**0.03**	**0.02**

In general, when compared to regional studies using PSHA methodology (IGCP-382 and ESC SESAME), the results from this study are similar but lower. However, where the seismic hazard is greater, in the northeast of Libya (Derna, Benghazi), the calculated hazard values are in reasonable agreement with these studies. It has been noted in previous studies (Allen et al., 2009; Stein et al., 2013; Nekrasova et al., 2013) that these global and regional hazard maps tend to overestimate the hazard due to the GMPEs used.

When comparing the results using DSHA methodology (Mourabit et al.), the results from this study are generally slightly greater. This is with the exception of Misrata and Sirte, where the alternative methodology outputs significantly greater hazard values. DSHA methodology relies on a 'maximum credible event' scenario using a characteristic earthquake magnitude-recurrence model. As such, it is likely that the proximity of these locations to the Hün Graben, where the 1935 7.1M_w event occurred, has resulted in significantly greater deterministically derived hazard levels in this area.

5.0 Conclusions

This study has presented a new seismic hazard model for Libya with a detailed review of the seismotectonics. The results of the PSHA are presented in terms of ground motions in rock and stiff soil with spectral accelerations at short and long periods for various key locations in Libya. Epistemic uncertainty in the source model and the ground motion models have been addressed using a logic tree approach.

While the model would benefit from development, particularly with respect to detailed fault modelling, GMPE modelling and a thorough assessment of historical seismic data, the results suggest that existing regional and global models broadly overestimate the seismic hazard in the country. However, to err on the side of conservatism, it may be more appropriate to use the hazard values derived in this study for a 2,475 year return period for design.

6.0 Discussion

Suleiman et al. (2004) suggests some historical sources for further research that may provide additional information on historical seismicity in Libya but the uncertainties surrounding historical data have to be accepted. Since it is not expected that any further data on any historical earthquakes will emerge that materially changes our state of knowledge, the emphasis therefore needs to be on what procedures to adopt in the PSHA analysis to represent this uncertainty.

Macroseismic intensity recordings can be used to estimate historical ground motion. However, macroseismic study relies on earthquakes to be felt and recorded by human presence. While this may be appropriate for populated regions with a relative long anthropic presence, large sparsely populated regions, such as Libya, may prevent effective macroseismic study.

Ground-motion modelling in areas of low to moderate seismicity can also be problematic due to the absence of available strong ground-motion data for the region. Empirical ground motion prediction equations derived from well-studied areas, elsewhere in the world are used. While the GMPEs used in this study are considered to be appropriate, locally obtained strong ground motion records from the LDSN are required to calibrate and verify them.

7.0 References

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