The paper was published in the proceedings of the 7th International Conference on Earthquake Geotechnical Engineering and was edited by Francesco Silvestri, Nicola Moraci and Susanna Antonielli. The conference was held in Rome, Italy, 17 – 20 June 2019.

Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions – Silvestri & Moraci (Eds)
© 2019 Associazione Geotecnica Italiana, Rome, Italy, ISBN 978-0-367-14328-2

Assessment of liquefaction potential index of Benghazi sabkha deposits

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ABSTRACT: This study evaluates the liquefaction potential based on in situ geotechnical data available in technical and academic reports on Benghazi sabkha, which consists of poorly graded fine to medium sand with some silts and traces of gravels in very loose to medium dense state. Liquefaction potential index (LPI) of sabkha soils are computed from factor of safety values based on Luna and Frost (1998), which indicate different levels of liquefaction severity for earthquake magnitudes of 5.3, 6 and 7.1. A very high liquefaction severity level was obtained for the potential earthquake of 7.1, based on Iwasaki et al. (1978) criterion. Furthermore, the liquefaction potential of layers was quantified and utilized to predict post-liquefaction settlements resulting from pore water pressure dissipation. The recommendations suggested by Ishihara and Yoshimine (1992) were used, the results of which indicated high values for sabkha layer within the top 2-6 meters from the ground surface, which varied from 50 –250 mm in average.

1 INTRODUCTION

Rapid expansion of the economic growth in Libya in the past fifteen years has led to serious consideration of sabkha lands as potential construction sites. A vast proportion of building activities in Benghazi area is founded on sabkha soils, and about 75% of new construction projects are ongoing in this region, including high-rise buildings. The sabkha deposits are often exposed to seawater flooding and subsequent evaporation leaves thick crust of salt. Sabkhas are deposits possessing variable properties in terms of sedimentation layering, grain size and shape, the degree of salinity, cementation, density, etc. An extensive review of the current literature has shown that no definitive liquefaction studies have been undertaken for Libya yet, although sandy deposits exist in various areas along Libyan coast under water table.

A number of studies have examined the liquefaction potential of sabkha soils (Al-Karni 2007; Bilsel et al., 2010; Ahmed and Al Shayea, 2017). Ahmed and Shayea (2017) evaluated the liquefaction potential of sabkha soils in Jubail industrial city, Saudi Arabia; the results revealed that there is a significant probability for liquefaction of sabkha at higher peak ground acceleration (PGA) values.

The liquefaction potential index (LPI) is the most significant indicator to characterize liquefaction hazard, originally suggested by Iwasaki et al. (1978). The prediction by LPI is dissimilar to that provided by the simplified method of Seed and Idriss (1971). The simplified method predicts liquefaction that can happen to a soil element whereas the LPI predicts the response of the whole soil column and the liquefaction effects on the ground surface.

The liquefaction potential index (LPI) is evaluated in this paper with field data collected from Benghazi sabkha. The data are standard penetration test (SPT) soundings conducted along the coastline of Benghazi city. The principal objective of the present study is to evaluate the liquefaction potential index for Benghazi sabkha, which has not been previously studied specifically for this area.

2 GEOMORPHOLOGY AND GEOLOGY

Benghazi is the second biggest city in Libya. It is located at the north-western part of Cyrenaica in the eastern part of the country, between latitudes of 32° 00′N to 32° 15′N and between longitudes of 20° 00′E to 20° 15′E. The Benghazi plain is triangular shaped, bounded on the northwest by the Mediterranean Sea, and on the east by the escarpment of Jabal Akhdar. The city covers an area of 314 km^2 having a population of around 1 million as the second most populated city in Libya. The average elevation in Benghazi is about 15 m above sea level. The surface geology of Benghazi city is mainly Tertiary and Quaternary in age. The city may be divided into six geological units based on geomorphology, stratigraphy, geology and geotechnical properties (Khan and Hasnain 1981). These units are alluvial sediments (Qa), beach sand (Qb), sabkha sediments (Qs), calcarenite (Qc), Al Rajmah formation (TmRQ). Figure 1 depicts the geological map of Benghazi basin.

The Sabkha deposits extend along the coastline of southern Benghazi. The deposits contain red silty or sandy clay with accumulated minute gypsum and salt crystals. The clay is fine-grained beach sand and brownish-red silt brought in by northwestern and southern winds respectively (Khan and Hasnain, 1981). Sabkhas are usually separated from the sea by sand dune strips, formed by the winds blowing from the sea, which allow sea water to go through and supply salt to sabkha. Figure 1 shows the location of sabkha on Benghazi plain. The beach sand extends hundreds of meters wide and all along the coastline surrounding Benghazi in the north, and is classified as a calcareous deposit containing shell fragments and limestone, with an admixture of red aeolian silt formed by southern winds.

3 SEISMOTECTONIC SETTING AND SEISMICITY

Libya is located between the Mediterranean foreland of the Saharan Metacraton and the marine region. Particularly its northern coastal regions can be classified as an intraplate seismic zone. Lagesse et al. (2017) reported that Northeastern part of Libya (Benghazi-Derna) has greater hazard values compared to northwestern part of the country (Tripoli-Misrata). In particular, hazard levels are higher for locations close to the al Jabal al Akhdar uplift and the subduction zone of the Hellenic arc in the north of Cyrenaica (Hassen 1983).

Libya has been affected by several earthquakes of varying magnitudes (4-7.1) on Richter scale. Mallick and Morghem (1977) has divided Libya map into seismic zones based on tectonic and geological structure, seismic history and importance of the region, as given in Figure 2. It can be observed that Benghazi City is situated in seismic zone III.

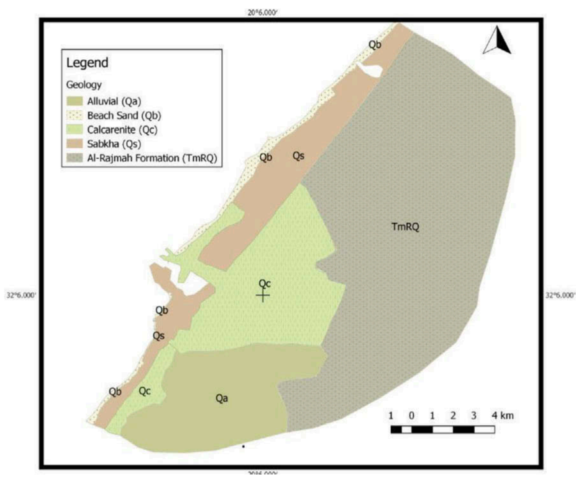

Figure 1. Geological map of Benghazi basin (modified from Khan and Hasnain 1981).

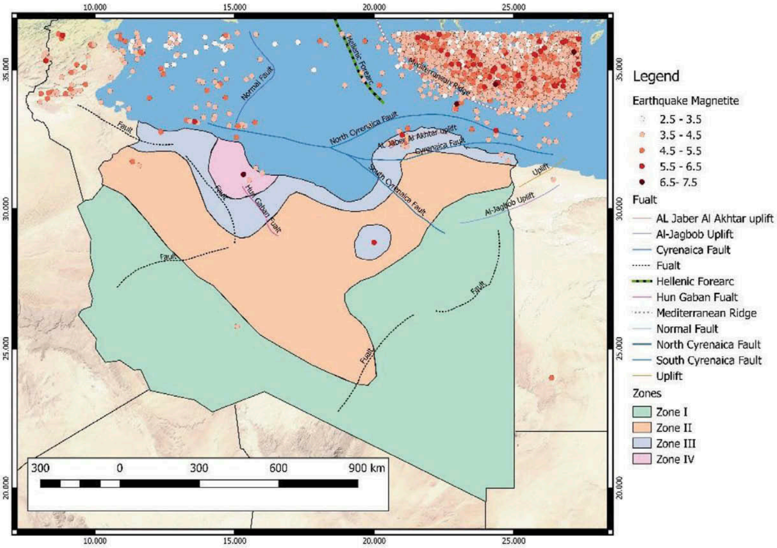

Figure 2. Present seismic zoning map of Libya (modified from Mallick and Morghem 1977).

Due to the absence of strong ground motion database for the studied area, the previous seismic hazard studies in Libya, Mallick and Barony (1980), Mourabit et al. (2013) and Lagesse et al. (2017) have suggested models to estimate the ground motion parameters of Libya, the calculated peak ground acceleration (PGA) values ranging between 0.08 and 0.18g for Benghazi region.

4 GEOTECHNICAL CHARACTERISTICS OF BENGHAZI SABKHA

The sabkha deposits extend along the coastline of southern Benghazi. sabkha layer exists with a thickness of about 5.0-10.0 meters from the ground surface. The soil in the study area is mainly sand to silty sand, with N-SPT values around 0-25 blows at different depths. The major soil categories constituting sabkha deposits are poorly graded fine to medium sand with some silts and traces of gravels. They are classified as SP, SM, and SP-SM according to the unified soil classification system.

The natural moisture content of sabkha soil for samples obtained from a depth of 1 m generally varies from 9.2% to 25.2%. The laboratory results are compatible with Benghazi sabkha, which does not possess any plasticity and the soil thus was classified as non-plastic. Samples were found to be silty sand (SM) and clayey sand (SC) which yield liquid limit (LL) values varying from 18.2% to 22%. The most common chemical elements in sabkha deposits are sodium chloride and gypsum. Geotechnically, sabkha can be considered as a deposit possessing variable properties in terms of sedimentation, layering, grain size and shape, density, the degree of salinity and cementation.

5 METHODOLOGY AND DATA

5.1 *Data collection*

In this work, N-SPT data were used to categorize sabkha soils and to estimate the factor of safety against liquefaction. More than 95 bore log data have been collected from borehole locations shown in Figure 3.

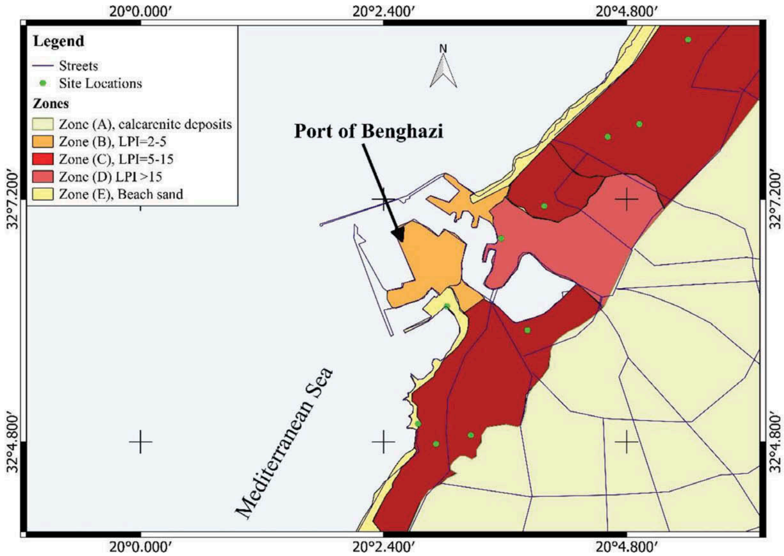

Figure 3. Liquefaction zonation map of Benghazi sabkha based on 7 earthquakes.

5.2 *Liquefaction potential index*

The most common method used to predict factor of safety against liquefaction (FS) was originally proposed by Seed and Idriss (1971). FS is defined as the cyclic resistance to cyclic stress ratio for a layer of soil at depth z (m). Liquefaction is estimated to occur when FS ≤ 1 and not to occur when FS > 1. The FS values can be estimated by Equation 1.

$$FS = \frac{CRR}{CSR_{Mw=7.5}} \tag{1}$$

The cyclic stress ratio (CSR) can be expressed by Equation 2, where α_{max} is the peak horizontal acceleration, g is the nominal gravitational acceleration, σ_{v0} and σ'_{v0} are total vertical overburden stress and the effective vertical overburden stress respectively, at a depth of interest, MSF is the magnitude scaling factor and r_d is shear stress reduction factor that accounts for the dynamic response of the soil profile.

$$CSR = 0.65 \frac{\alpha_{\max}}{g} \frac{\sigma_{vo}}{\sigma'_{v0}} r_d \frac{1}{MSF} \tag{2}$$

Idriss and Boulanger (2006) proposed Equation 3 to determine the stress reduction factor (r_d).

$$r_d = exp[\alpha(z) + \beta(z).M] \tag{3}$$

$$\alpha(z) = -1.012 - 1.126\ sin\left(\frac{z}{11.73} + 5.133\right) \tag{3.a}$$

$$\beta(z) = 0.106 + 0.118\ sin\left(\frac{z}{11.28} + 5.142\right) \tag{3.b}$$

where z is depth below the ground surface in meters, and M is moment magnitude. The magnitude scaling factor (MSF) is provided to an equivalent CSR for an earthquake magnitude of M_w=7.5, which is given by Equation 4, where M_w is the moment magnitude of the earthquake.

$$MSF = 6.9\exp\left(\frac{-M_w}{4}\right) - 0.058 \leq 1.8. \tag{4}$$

The cyclic resistance ratio (CRR) is calculated based on the standard penetration test data (N-SPT). Idriss and Boulanger (2008) calculate CRR value in terms of $(N_1)_{60cs}$ value as given in Equation 5.

$$CRR = exp\left(\frac{(N_1)_{60cs}}{14.1} + \left(\frac{(N_1)_{60cs}}{126}\right)^2 - \left(\frac{(N_1)_{60cs}}{23.6}\right)^3 + \left(\frac{(N_1)_{60cs}}{25.4}\right)^4 - 2.8\right) \tag{5}$$

where $(N_1)_{60cs}$ is equivalent clean sand adjustment for fines content estimated by Equation 6, and is limited to values ≤ 46 for use in Equation 5.

$$(N_1)_{60cs} = (N_1)_{60} + \Delta(N_1)_{60} \tag{6}$$

$\Delta(N_1)_{60}$ is the correction for fines content (%FC) in the soil and is calculated using Equation 7.

$$\Delta(N_1)_{60} = exp\left(1.63 + \frac{6.7}{FC + 0.01} - \left(\frac{15.7}{FC + 0.01}\right)^2\right) \tag{7}$$

FS is an indicator of the liquefaction potential at a particular depth. Iwasaki et al. (1978) recognized that the damage of structures due to liquefaction are affected by the severity of liquefaction at surface level. For this reason, liquefaction potential index (LPI) has been proposed to estimate the severity of liquefaction and to predict the potential of liquefaction to cause structural damage or failure of potential liquefiable areas, using Equation 8. LPI can be calculated at the site by integrating the factors of safety (FS) along the soil column at a specific location up to a depth of 20 m.

$$LPI = \int_{o}^{20} F(z)\ W(z)\ dz \tag{8}$$

With:

$$W(Z) = 10 - 0.5z \; for \; z < 1.0m. \tag{8.a}$$

$$W(Z) = 0 \; for \; z > 20m. \tag{8.b}$$

$$F(Z) = 1 - FS \; for \; FS < 1 \tag{8.c}$$

$$F(Z) = 0 \; forFS > 1 \tag{8.d}$$

where z is the depth under the water table level (0 to 20 m), and dz is the differential increment of depth. F(z) and W(z) are weighting functions added to give more weight to the layers nearer to the ground surface. LPI estimated for the soil column can be compared with the ranges proposed in Table 1 for different levels of liquefaction.

5.3 *Evaluation of liquefaction-induced settlement based on SPT data*

Idriss and Boulanger (2008, 2010) suggested an empirical method to forecast liquefaction induced settlement based on standard penetration test values. The calculation procedure involves estimation of the factor of safety (Equation 1) and post-liquefaction reconsolidation

Table 1. LPl levels for liquefaction severity (Iwasaki et al., 1978).

LPI	Liquefaction Severity
LPI=0	Very low
2<LPI<5	Low
5<LPI<15	High
15<LPI	Very high

strain(ε_v), which is based on the approach developed by Ishihara and Yoshimine (1992), expressed in terms of SPT penetration resistance in Equation 9.

$$\varepsilon_v = 1.5\ exp\left(-0.369\sqrt{(N_1)_{60cs}}\right).\ min(0.8, \gamma_{max}) \tag{9}$$

where γ_{max} is the maximum shear strain, which can be estimated by Equations 9.a to 9.e, proposed by Yoshimine et al. (2006).

$$\gamma_{\max=0} \quad If\ FS \geq 2 \tag{9.a}$$

$$\gamma_{max=}min\left(\gamma_{\lim\prime}\frac{0.035(2-FS)(1-Fa)}{FS-Fa}\right)If 2>FS>F_\alpha \tag{9.b}$$

$$\gamma_{\max=}\gamma_{\lim} \quad If\ FS \leq F_a \tag{9.c}$$

where γ_{lim} = the limiting shear strain expressed as:

$$\gamma_{\lim} = 1.859\left(1.1-\sqrt{\frac{(N_1)_{60cs}}{46}}\right)^3 \geq 0 \tag{9.d}$$

and, F_α = the limiting value given as:

$$F\alpha = 0.032 + 0.69\sqrt{(N_1)_{60cs}} - 0.13(N_1)_{60cs}; (N_1)_{60cs} \geq 7 \tag{9.e}$$

Post-liquefaction reconsolidation settlement is also estimated according to Idriss and Boulanger (2008) as a function of the post-liquefaction reconsolidation strain.

$$S_{v-D1} = \int_0^{z_{\max}} \varepsilon_v d_z \tag{10}$$

or it can be simplified as in Equation 11, where t is thickness of layer.

$$S_{v-D1} = t.\varepsilon_v \tag{11}$$

6 RESULTS AND DISCUSSIONS

The study area found on large thickness of loess soil deposits and shallow ground water levels are observed to be more susceptible to liquefaction. The factor of safety values indicate that the sabkha deposit will not liquefy unless the earthquake magnitude exceeds 6. A significant result to emerge from the data is that the factor of safeties within 2-10 meters indicate that this layer is critical and susceptible to liquefaction during an earthquake of M_w=6 and higher. Liquefaction potential index (LPI) is estimated based on the method proposed by Iwasaki et al. (1978). Tables 2 and 3 present the calculations of liquefaction potential index (LPI) corresponding to M_w =6.5, and 7. The results indicated that the LPI of sabkha soils is classified as low to very high as most of LPI results are between 2- 24.85.

Table 2. Computation of Liquefaction Potential Index (LPI) for Mw=6.5 and PGA=0.18g.

Depth	(N1)60	FS	Z	H	W(z)	F	W(z).(F).H
2	5	1.24	1	2	9.5	–	–
3	3	0.86	1.5	1	9.25	0.14	1.29
4.5	3	0.75	2.25	1.5	8.88	0.25	3.33
6	14	2.09	3	1.5	8.5	–	–
12	4	0.91	6	6	7	0.09	3.78
13.5	2	0.81	6.75	1.5	6.63	0.19	1.89
15	7	1.09	7.5	1.5	6.25	0.004	0.035
							10.32

Table 3. Computation of Liquefaction Potential Index (LPI) for M_w=7 and PGA=0.18g.

Depth	(N1)60	FS	Z	H	W(z)	F	W(z).(F).H
2	5	1.02	1	2	9.5	0.014	0.26
3	3	0.71	1.5	1	9.25	0.29	2.68
4.5	3	0.62	2.25	1.5	8.88	0.38	5.06
6	14	1.7	3	1.5	8.5	–	–
12	4	0.72	6	6	7	0.28	11.76
13.5	2	0.63	6.75	1.5	6.63	0.37	3.68
15	7	0.85	7.5	1.5	6.25	0.15	1.41
							24.85

In the current study, a microzonation map of Benghazi sabkha was produced in terms of the liquefaction potential index and geological information. LPI values of 10 sites are shown on the microzonation map in Figure 3. The map has divided the Benghazi sabkha into 5 zones (A, B, C, D, and E) with respect to liquefaction potential index and considering the geological formations. Zone A consists of calcarenite deposits, which is a composite of shells, with some layers of clay and marl, the groundwater table being deep. Generally, such deposits are considered to be non-susceptible to liquefaction (Youd and Perkins 1978; Hayati and Andrus 2008). Zone B has low potential of liquefaction with LPI range of 2-5. Zone C is classified as high probability areas susceptible to liquefaction, LPI values varying from 5 to <15. Zone D is the area with the highest susceptibility, where the LPI is more than 15. It is also noted that Zone D occupies a large area of Benghazi sabkha. Zone E is beach sand deposits with 10- 15 m thickness, which is categorized as deposits highly susceptible to liquefaction, based on geological screening of liquefaction (Youd and Perkins 1978).

The liquefaction potential of layers was quantified and utilized to find the settlement resulting from post-liquefaction pore water pressure dissipation. The potential volumetric strain is influenced by the SPT-N of soil layer that was classified as a liquefiable layer. The average SPT value of all liquefiable layers for certain depths was 5 blows, corresponding to a potential volumetric strain value of approximately 4%. The results of post-liquefaction settlement analysis indicated high values for sabkha layer within 2-6 meters from the ground surface, varying from 50 – 250 mm in average.

7 CONCLUSION

Based on the analysis of results, it is noted that 2-10 m depth from the ground surface of coastal sabkhas of Benghazi pose susceptibility to liquefaction during an earthquake of M_w=6.5-7.0. Liquefaction potential index (LPI) estimates indicate a wide variation of results ranging from 2-24.85. A microzonation map of Benghazi sabkha is also produced with 5 zones (A, B, C, D, and E) based on borehole data. Zone C is classified as areas with high probability of liquefaction with LPI values varying from 5 to <15, whereas Zone D is the area with the highest susceptibility with LPI >15, which occupies a large area of Benghazi sabkha. The liquefaction potential of layers is also utilized to predict post-liquefaction settlements, and the results indicate high values of 50- 250 mm for sabkha layer within 2-6 meters from the ground surface.

ACKNOWLEDGMENT

The authors would like to express their appreciation to Arabian Gulf Oil Company, El Sahel Engineering and testing Ltd., Libyan Technical Consultancy Company, for providing the borehole and geological data of different sites in the study area, as well as to Mr. Ali Shoeb and Dr. Abdelaziz Abuaziza for their support and help in this project.

REFERENCES

Ahmed, H.R. and Al Shayea, N.A. 2017. Seismic behavior and zoning of the sabkha soils in Jubail industrial city, Saudi Arabia. Journal of Seismology, 21(5), pp.1145–1169.

Al-Karni, A.A. 2007. Evaluation of liquefaction potential of the soil at the university of Jazan in Jazan city in the Southwest of Saudi Arabia. In Proceedings of the world engineering congress (WEC'07), Penang, Malaysia (pp. 327–334).

Bilsel, H., Erhan, G. and Durgunoglu, T., 2010. Assessment of Liquefaction/Cyclic Failure Potential of Alluvial Deposits on the Eastern Coast of Cyprus.

Hassen, H.A. 1983. Seismicity of Libya and related problems. Doctoral dissertation, Colorado State University. Libraries.

Hayati, H. and Andrus, R.D., 2008. Liquefaction potential map of Charleston, South Carolina based on the 1886 earthquake. Journal of Geotechnical and Geoenvironmental Engineering, 134(6), pp.815–828.

Idriss, I.M. and Boulanger, R.W., 2006. Semi-empirical procedures for evaluating liquefaction potential during earthquakes. Soil Dynamics and Earthquake Engineering, 26(2-4), pp.115–130.

Idriss, I.M. and Boulanger, R.W., 2008. Soil liquefaction during earthquakes. Earthquake Engineering Research Institute.

Idriss, I.M. and Boulanger, R.W., 2010. SPT-based liquefaction triggering procedures. Rep. UCD/CGM-10, 2, pp.4–13.

Ishihara, K. and Yoshimine, M., 1992. Evaluation of settlements in sand deposits following liquefaction during earthquakes. Soils and foundations, 32(1), pp.173–188.

Iwasaki, T., 1978. A practical method for assessing soil liquefaction potential based on case studies at various sites in Japan. In Proc. Second Int. Conf. Microzonation Safer Construction Research Application, 1978 (Vol. 2, pp. 885–896).

Khan, I.H. and Hasnain, S.I., 1981. Engineering properties of sabkha soils in the Benghazi plain and construction problems. Engineering Geology, 17(3), pp.175–183.

Lagesse, R., Free, M., Lubkowski, Z., McCully, R. and Villani, M. Probabilistic Seismic Hazard Assessment for Libya.

Mallick, D.V. and Barony, S.Y., 1980. Earthquake Resistant Design Practice In Libyan Jamahtriya. In Proceedings of the World Conference on Earthquake Engineering (Vol. 7, No. 9, p. 185). publisher not identified.

Mallick, D.V., 1977. Seismic zoning of Libya. In Sixth world conference on earthquake engineering, Tokyo, Japan (Vol. 4, pp. 1–16).

Mourabit, T., Elenean, K.A., Ayadi, A., Benouar, D., Suleman, A.B., Bezzeghoud, M., Cheddadi, A., Chourak, M., ElGabry, M.N., Harbi, A. and Hfaiedh, M., 2013. Neo-deterministic seismic hazard assessment in North Africa. Journal of seismology, 18(2), pp.301–318.

Seed, H.B. and Idriss, I.M., 1971. Simplified procedure for evaluating soil liquefaction potential. Journal of Soil Mechanics & Foundations Div.

Yoshimine, M., Nishizaki, H., Amano, K. and Hosono, Y., 2006. Flow deformation of liquefied sand under constant shear load and its application to analysis of flow slide of infinite slope. Soil Dynamics and Earthquake Engineering, 26(2-4), pp.253–264.

Youd, T.L. and Perkins, D.M., 1978. Mapping liquefaction-induced ground failure potential. Journal of the Soil Mechanics and Foundations Division, 104(4), pp.433–446.