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Nasser M. Mansoor
*University of Missouri - Kansas City, Kansas City, MO*

Tina M/ Niemi
*University of Missouri - Kansas City, Kansas City, MO*

Anil Misra
*University of Missouri - Kansas City, Kansas City, MO*

# LIQUEFACTION POTENTIAL EVALUATION ALONG ACTIVE FAULTS AT THE HEAD OF THE GULF OF AQABA, JORDAN.

**Nasser M. Mansoor**[1]
[1] Department of Geosceinces
University of Missouri-Kansas City
5100 Rockhill Rd.
Kansas City, MO 64110.

***Tina M. Niemi*[1], *and Anil Misra*[2]**
[2] Department of Civil Engineering
University of Missouri-Kansas City
5100 Rockhill Rd.
Kansas City, MO 64110.

## ABSTRACT

The city of Aqaba, Jordan lies within a major seismic region along the active plate boundary of the Dead Sea Transform. A NE-trending, strike-slip fault that originates in the Gulf of Aqaba apparently terminates under the city along four NW-trending normal- to oblique-slip faults. These normal faults accommodate active tectonic subsidence at the head of the Gulf of Aqaba. Paleoearthquake data from five trench excavations across these faults were collected to characterize the closest seismic source to the city. Ground rupture from an earthquake produced a fault scarp sometime before A.D. 1045-1278. A minimum estimate for the magnitude of the earthquake is M 6, the minimum threshold for surface ground rupture. Several multiple event scarps suggests that a minimum of seven earthquakes have occurred since 5 to 6 ka. This yields a minimum recurrence of earthquakes on the Aqaba fault seismic source of approximately 700-850 years. Subsurface exploration of boreholes and trench exposures indicates that the stratigraphic sequence is composed of liquefaction susceptible sediments. Shallow subsurface deposits consist of aeolian and beach sand interbedded with alluvial silt, sand, and gravel in the upper parts of the Quaternary fan deposits. We evaluated the liquefaction potential using Seed's cyclic stress ratio approach. This method is based on the corrected field blow count of the Standard Penetration Test to an energy of 60% and effective overburden pressure of 100 kPa with corresponding attenuated peak ground acceleration of 0.1, 0.2g, and 0.3g. Preliminary results of the liquefaction mapping indicate that the coastal areas have a high potential to liquefy and could experience severe damage as a result of earthquake shaking. Our analyses suggest that the eastern parts of the city lie predominantly within a non-liquefaction susceptibility zone.

## INTRODUCTION

Strong ground shaking during an earthquake can transform saturated, unconsolidated sedimentary deposits from solid to semi-liquid form, a process termed liquefaction. Liquefaction often causes loss of bearing strength, ground settlement, and horizontal displacement (Hitchcock *et al.*, 1999). Liquefaction generally occurs under specific combinations of geological setting and earthquake intensity. The most critical aspects of liquefaction hazard evaluation are the combination of three parameters: the presence of sediment susceptible to liquefy and high groundwater conditions, a seismic source sufficiently strong to trigger liquefaction, and evaluation of what damage may occur (Kramar, 1996).

Previous studies in Aqaba have concentrated on regional geological information (Rashdan, 1988). This study does not include development of detailed seismic hazard zonation maps of the region. Malkawi (1997) showed that parts of the Aqaba city and the region have the tendency to liquefy. Our assessment of the seismic hazard of the city of Aqaba, Jordan is based on a multidisciplinary approach that combines paleoseismic and geotechnical data. The method includes characterizing the location of the active fault segments, estimating the paleoearthquake magnitude and recurrence interval, and evaluating the ground conditions and the potential response to seismic shaking.

As demonstrated throughout recorded history, seismic activity can cause severe damage and widespread destruction of the city of Aqaba and the surrounding areas. Historical records suggest evidence for two or maybe three large (M 6.5-7) earthquakes in the Gulf of Aqaba and the surrounding areas during the last 2000 years (Ben Menahem, 1979; Amiran *et al.*, 1994; Ambraseys *et al.*, 1994). The $M_L$ 6.2 Nuweiba earthquake of November 22, 1995 caused significant damage due to the absence of earthquake resistance design and the lack of a good regional planning for facilities.

Several areas along the shore of the Gulf of Aqaba suffered lateral movement and settlement from 10 to 20 cm as a result of the 1995 Nuweiba earthquake (Malkawi *et al.*, 1999). In Elat, the presence of sand blows indicates water table fluctuation and liquefaction occurred (Wust, 1997). Klinger *et al.*, (1999) investigated seismic induced failure of the coastal deposits along the Gulf of Aqaba after the Nuweiba earthquake. These authors report a system of ground failures with dip-slip motion arranged on an *en echelon* pattern and trending N20°E.

## TECTONIC SETTING AND FIELD INVESTIGATION

The Gulf of Aqaba, located between 28°-29° N and 34.5°-35.2° E, lies along the southern section of the Dead Sea Transform fault system (DST). The DST is a transform plate boundary that extends from the Red Sea spreading center in the south to the convergent zone in the Taurus-Zagros mountain belt in Turkey (Fig. 1). Left-lateral motion along the transform fault began in the Early Miocene (e.g. Quennell, 1958; Freund *et al.*, 1970; Garfunkel *et al.*, 1981). From regional plate kinematics data from the Gulf of Aden and the Red Sea and other data, Garfunkel and Ben-Avraham (1996) summarize the evidence for a total displacement of about 100 km at a rate of 6-10 mm/yr. Several pull-apart basins have formed at *en-echelon* left steps of the transform fault including the Gulf of Aqaba (Ben-Avraham, 1985).

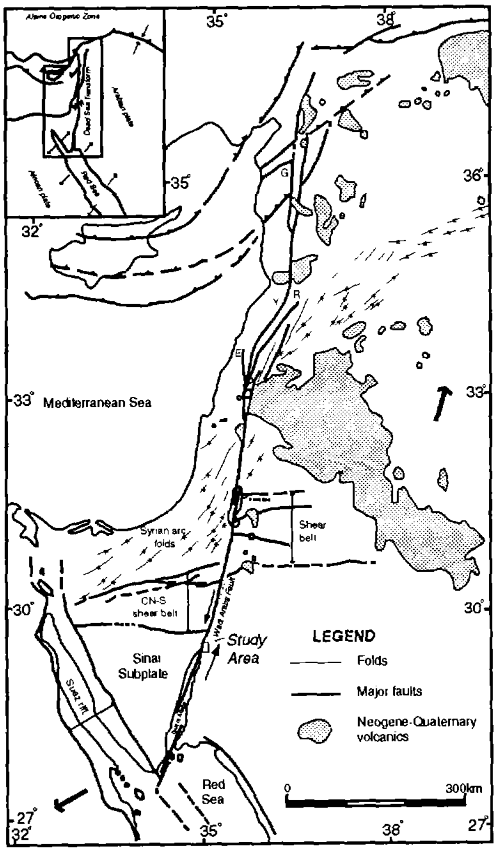


*Fig. 1. Regional map of the tectonic setting of the study area (modified after Garfunkel and Ben-Avraham, 1996). J- Jordan Valley Fault, E- Ed Damur Fault, R- Rachaya Fault, Y- Yammouneh Fault, and G- Ghab Fault.*

The city of Aqaba is located at the southern end of the Wadi Araba (Arava) valley. The valley formed by tectonic motion of the strike-slip Wadi Araba fault and normal faults along the valley margins. Two paleoseismic sites near Elat in Israel have provided much data on the paleoearthquake activity of the active faults in the southern Wadi Araba. Trenches excavated across normal fault scarps at the Shehoret fan site located 7 km north of Elat revealed evidence for at least one large (M>6.5) earthquake in the 2000 years with an estimated earthquake recurrence interval of 1200-2000 years (Amit *et al.*, 1995, 1996; Enzel *et al.*, 1994, 1996). Trenched normal faults at the Evrona playa site (Amit *et al.*, 1999) revealed at least six tectonic events in the past 14,000 years, with the penultimate event associated with 1 m of uplift that occurred in the past 1000 years. Zhang (1998) and Zhang *et al.*, (1999, and in review) collected geomorphic and stratigraphic data from airphoto interpretation and field mapping along the Northern Wadi Araba Fault near the Dead Sea. Their study yielded an average minimum late Quaternary slip rate for the DST of about 4.5 mm/yr and an average earthquake recurrence interval of the Wadi Araba fault about 670 ± 150 years. All studies in the Wadi Araba valley have concluded that the probability of a future major earthquake in the region is very high.

Field investigations during 1998-2000 reveal that the city of Aqaba is situated along part of the DST. A major NE-trending strike-slip fault that originates in the Gulf of Aqaba terminates under the city. Strain is accommodated on four NW-trending faults that Bender (1974) interpreted as shorelines. These cross faults are associated with a left stepover (or releasing bend) in the DST and accommodate active tectonic subsidence at the head of the Gulf of Aqaba (Mansoor and Niemi, 1999). The active faults cut the Quaternary Wadi Yutim fan sequence. From air photo interpretation and field mapping, Niemi and Smith (1999) divided the Wadi Yutim surficial deposits into four mappable fan units (Qf1, Qf2, Qf3, and Qf4) (Fig. 2). The oldest alluvial fan unit is designated Qf1 and is distinguished by a well-developed desert varnish. It is probably late Pleistocene in age. Qf2 fan surface is slightly inset into the older Qf1 surface and is distinguished by a moderately developed desert varnish. A middle Holocene age for the Qf2 is constrained by association with Chalcolithic aged (5-6 ka) archeological material (Niemi and Smith, 1999). The Qf3 alluvial fan deposits are generally incised across or bury Qf2 fan surface. Aeolian deposits and active channel deposits (Qf4) have accumulated at the distal portion of the fan complex.

The main strike-slip fault and the northwest and southeast extension of the cross faults have been eroded by the wadi wash of units Qf3 and Qf4. The cross fault scarps consistently separate older fan deposits on the northeast from younger fan deposits on the southwest. The scarp heights range from 25 cm

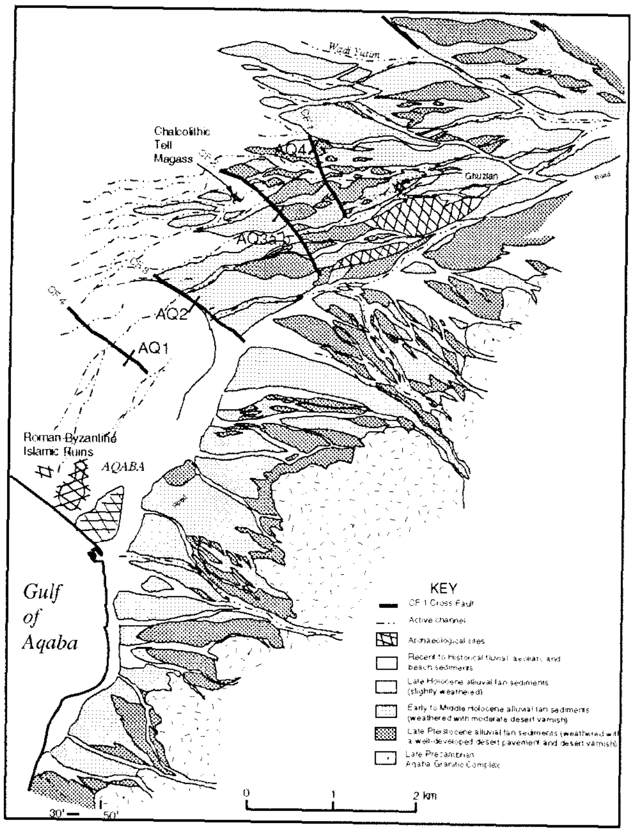


*Fig. 2: Geologic map showing the Quaternary sequences of the Wadi Yutim fan, the extention of the cross fault, and the location of the trench exposures.*

across the youngest Qf4 surface to 140 cm across the older Qf1 and Qf2 surfaces. These data indicate that the scarp heights reflect cumulative slip events. Several trenches were excavated to study the fault ruptures across the scarps. AQ1 and AQ2 were excavated across the southern two fault segments in 1998. AQ3a and AQ3b were excavated in 1999 across the highest fault scarp. Finally, in 2000, AQ4 was excavated across the northern fault segment (Fig. 2). The trench investigations across these faults reveal multiple earthquake ruptures (Fig. 3a and b). Interpretation of trench exposure AQ1 indicates a ground-rupturing earthquake produced a 25 cm scarp sometime before 1045-1278 A.D. which may correlate to the May 1, 1212 A.D or March 18, 1068 A.D. earthquake (Fig. 3a). Interpretation of trench exposure AQ3 across the Holocene fan (Qf2) suggests that a minimum of seven earthquakes may have occurred since deposition of the alluvial fan sediments around 5-6 ka (Fig. 3b). These data suggest that the recurrence interval of earthquakes on these faults is approximately 700-850 years (Mansoor and Niemi, 1999). It is not certain whether all the faults move simultaneously.

## LIQUEFACTION ANALYSIS

In order to establish liquefaction potential maps of the city, the cyclic stress ratio method (Seed and Idriss, 1971) was used. This method compares the earthquake-induce shear stress to shear strength of the soil and sediment. Cyclic stress ratio is defined as

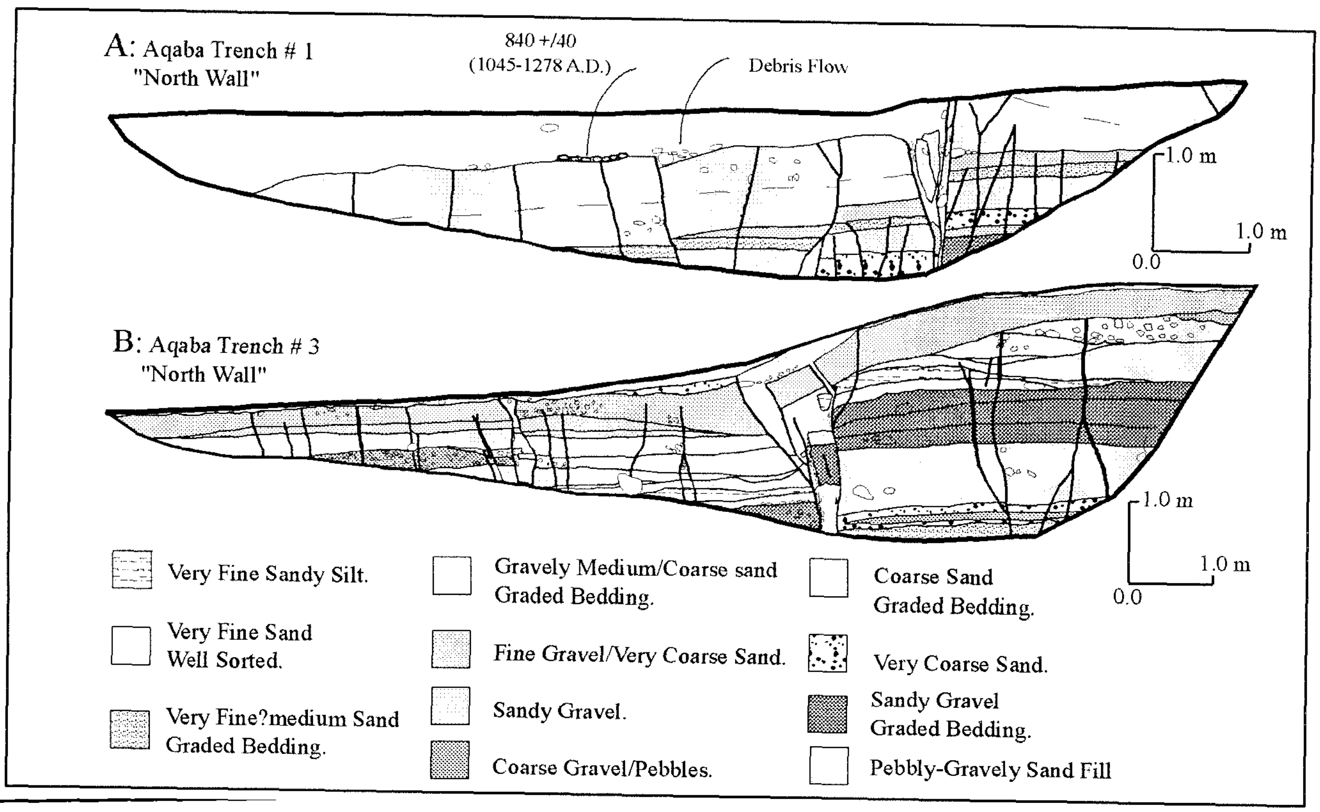


*Fig. 3: Trench exposures across the normal faults showing single and multiple earthquake ruptures, A: Across the southern fault segment (AQ1), B: across the third fault segment (AQ3a).*

$\tau/\sigma_o' = 0.65\ (a_{max}/g)(\sigma_o/\sigma_o')\ rd$, where

$\tau/\sigma_o'$ is the cyclic stress ratio, $a_{max}$ is the maximum acceleration at the ground surface, g is the gravitational constant, $\sigma_o$ is the total overburden pressure at depth under consideration, $\sigma_o'$ is the effective overburden pressure at the same depth, and rd is the stress reduction factor. The variable rd decreases from a value of 1 at the ground surface to a value of 0.9 at a depth of 35 feet.

In a previous study, Malkawi and Fahmi (1996) calculated a horizontal peak ground acceleration of 200cm/sec$^2$ (0.2g), which corresponds to 100 years exposure time at 90% probability of nonexceedance. The liquefaction resistance of the soil used to evaluate the earthquake-induced cyclic stress ratio is the corrected blow count $(N_1)_{60}$ of the Standard Penetration Test (SPT) to an energy of 60% and effective overburden pressure of 1 ton/ft$^2$. Each test value has geographical reference. The hazard analyses of Aqaba has utilized earthquake events with attenuated peak acceleration between 0.1 and 0.3g.

The database used in this study contains point-based geotechnical information, and detailed spatial coverage for the city. These data were provided by the Jordanian Natural Resources Authority, Royal Scientific Society, Aqaba Region Authority, and private geotechnical companies. The digital GIS coverage of the city of Aqaba was obtained from the Aqaba Region Authority. The coverage includes detailed information of the city that defines residential areas, major public facilities, and the major and the minor transportation network (Fig. 4). The locations of the boreholes were digitized onto the GIS base coverage of the Aqaba region. Borehole data includes lithological, water table depth, and Standard Penetration Test information that were used for point-based liquefaction evaluation.

## DISCUSSION

Quantitative analyses of the borehole data supplemented with evaluating the seismic source parameters provide preliminary overview of the liquefaction potential of the Aqaba region. Liquefaction susceptibility assessment of the Aqaba region was evaluated using the Seed simplified procedure (Seed and Idriss, 1971). This method combines the cyclic stress ratio, SPT values, overburden pressure, and the ground water conditions at different peak ground accelerations,. Preliminary assessment shows that under peak ground acceleration (PGA) of 0.1g, the Aqaba region is not likely to experience any liquefaction hazard. Under conditions of 0.2 PGA, significant liquefaction hazard could occur within the coastal areas (Fig. 5). At higher PGA of 0.3g, it appears that the coastal areas could experience severe liquefaction damage (Fig. 6).

Analyses of the surficial and subsurface geologic deposits indicate that the coastal areas of the Aqaba region are dominated by younger deposits consisting of poorly

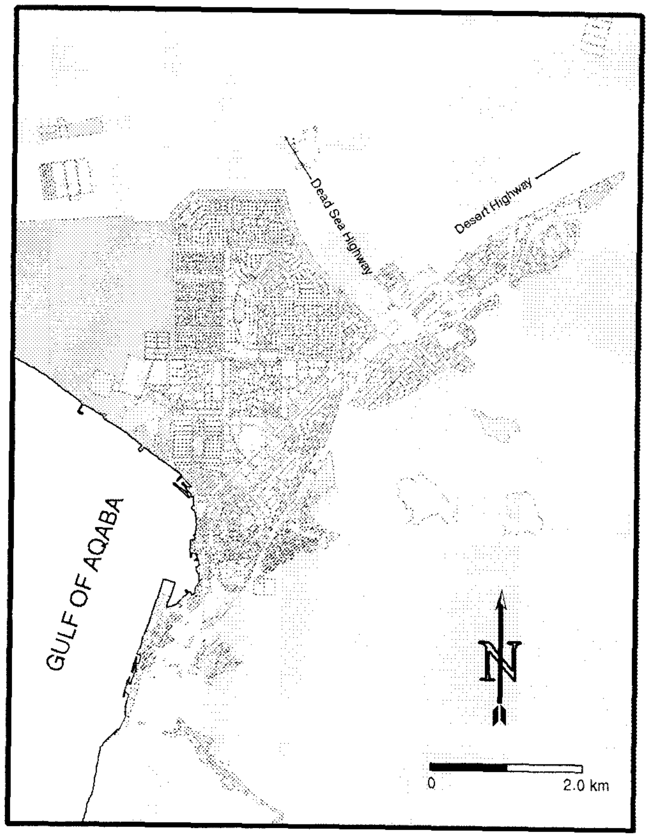


*Fig. 4: GIS coverage of the city of Aqaba showing residential areas and major transportation network.*

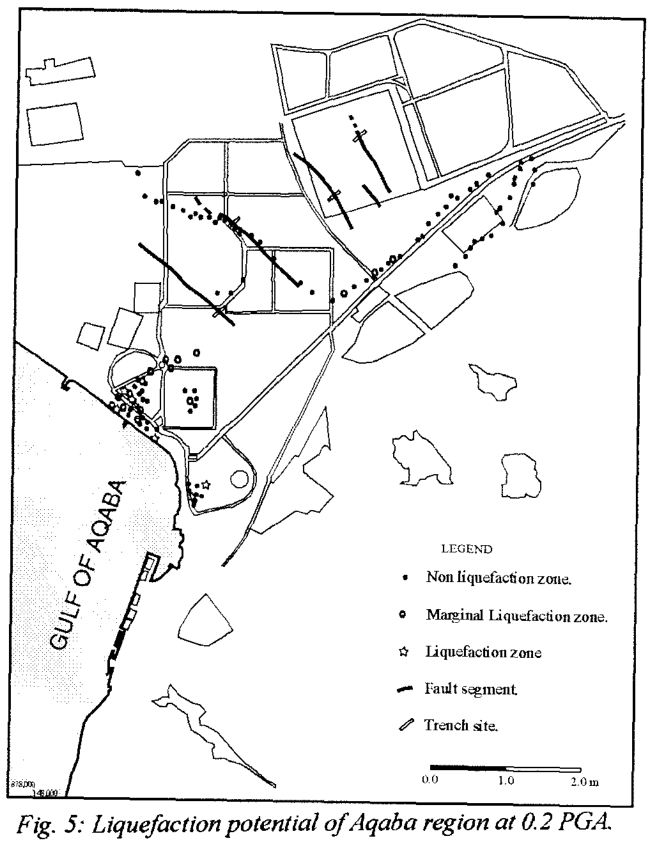


*Fig. 5: Liquefaction potential of Aqaba region at 0.2 PGA.*

consolidated beach and aeolian sand layers intercalated with alluvial layers with thin beds of silt, silty clay, and sandy gravel. The sediments are derived from erosion of the granitic bedrock that outcrops to the north and east of Aqaba.
The presence of younger (Holocene) deposits and shallow groundwater, between one and three meters below the surface within coastal areas of the Aqaba region, is the primary reason for failure from liquefaction. The saturation conditions of surficial sediments in the coastal areas reduces the normal effective stress. Areas of thick accumulations of older fan deposits and deeper groundwater levels within the northeastern sides of the region have much lower liquefaction potential.

Several factors could improve our liquefaction analysis of the Aqaba region. Seasonal fluctuation of the groundwater level can significantly affect the results of the liquefaction hazard. Additional data on both geotechnical and groundwater conditions will enhance the liquefaction potential evaluation. Furthermore, a larger area could be susceptible to liquefaction hazard under stronger ground shaking caused by higher peak ground accelerations. With additional subsurface data we hope to improve the spatial liquefaction analysis by incorporating linear interpolation or kriging to extend the point-based liquefaction hazard over a larger area.

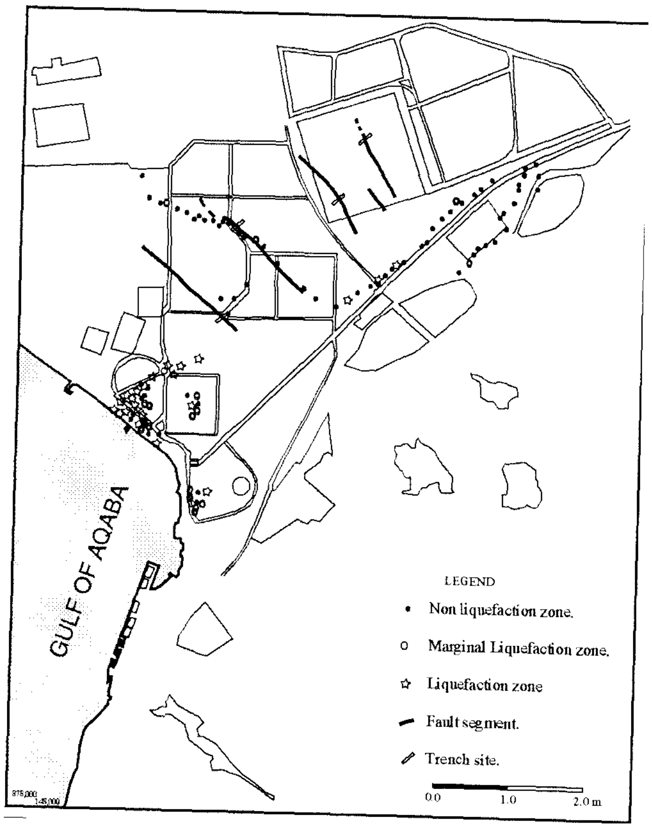


*Fig. 6: Liquefaction potential of Aqaba region at 0.3 PGA.*

## CONCLUSIONS

An average recurrence interval for earthquake rupturing normal faults within the Aqaba fault segment of the Dead Sea Transform is estimated to be about 700-850 years based on interpretation of trench exposures. A fault scarp height of 20 to 30 cm on one normal fault and a cumulative fault slip of over one meter on four faults during one ground rupturing earthquake corresponds approximately to a minimum magnitude M 6-7 earthquakes (Wells and Coppersmith, 1994). These data suggest that the probability of a future earthquake in the Aqaba region is very high and that ground shaking could be significant in Aqaba.

Using Seed simplified procedure for liquefaction evaluation combined with different estimated threshold peak ground acceleration values, we show that the coastal areas of the Aqaba region within the zone of young surficial deposits pose a significant liquefaction hazard. These areas are among the most populated areas in the region. The existence of shallow ground water (one to three meters below the surface) and distribution of subsurface sediments consisting of poorly consolidated layers of thick silt and loose, sorted beach sand contribute to conditions of high liquefaction hazard.

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## REFERENCES

Ambraseys, N. N. , C. P. Melville and R. D. Adams [1994]. The seismicity of Egypt, Arabia and the Red Sea. A historical review, Cambridge University Press., 181p.

Amiran, D. H. K., E. Arieh, and T. Turcotte [1994]. Earthquakes in Israel and adjacent areas: Macrosesmic observation since 100 B.C.E., Israel Exploration Journal, Vol. 44, pp. 260-305.

Amit, R., J. B. J. Harrison, and Y. Enzel [1995]. Use of soil and colluvial deposits in analyzing tectonic events, the southern Arava Rift, Israel, Geomorphology, Vol. 12, pp. 91-107.

Amit, R, J. B. J. Harrison, Y. Enzel, and N. Porat [1996]. Soils as a tool for estimating ages of Quaternary fault scarps in a hyperarid environment, the southern Arava valley, the Dead Sea Rift, Israel, Catena, Vol. 28, pp. 21-45.

Amit, R., E. Zilberman, N. Porat, and Y. Enzel [1999]. Relief inversion in the Avrona playa as evidence of large-magnitude historical earthquakes, southern Arava valley, Dead Sea Rift, Quaternary Research, Vol. 52, pp. 76-91.

Ben-Avraham, Z. [1985]. Structural framework of the Gulf of Elat (Aqaba), northern Red Sea. J. Geophys., Vol. 90, pp. 703-726.

Bender, F. [1974]. Geological map of Jordan, 1:100,000, Geological Survey of Federal Republic of Germany, Hanover.

Ben-Menahem, A. [1979]. Earthquake catalogue for the Middle East (92 B. C. – 1980 A. D.), Bollettino di geofisica teorica ed applicata, Vol. 21, pp. 245-310.

Enzel, Y., R. Amit, J. B. J. Harrison, and N. Porat [1994]. Morphologic dating of fault scarps and terrace risers in the southern Araba, Israel: Comparison to other age-dating techniques and implications for paleoseismicity, Israel Journal of Earth Science, Vol. 43, pp. 91-103.

Enzel, Y., R. Amit, E. Zilberman, J. B. J. Harrison, and N. Porat [1996]. Estimating the ages of fault scarps in the Arava, Israel, Tectonophysics, Vol. 253, pp. 305-317.

Freund, R., Z. Garfunkel, I. Zak, M. Goldberg, T. Weissbrod, and B. Derin [1970]. The shear along the Dead Sea Rift, Royal Society of London Philosophical Transactions, Vol. A267, pp. 107-130.

Garfunkel, Z., I. Zak, and R. Freund [1981]. Active faulting in the Dead Sea rift, Tectonophysics, Vol. 80, pp. 1-26.

Garfunkel, Z. and Z. Ben-Avraham [1996]. The structure of the Dead Sea basin. Tectonophysics, Vol. 266, pp. 155-176.

Hitchcock, C. S., R. C. Loyd and W. D. Haydon [1999]. Mapping liquefaction hazards in Simi Valley, Ventura County, California. Envi. and Eng. Geosceince, Vol. 5, No. 4, pp. 441-458.

Klinger, Y., L. Rivera, H. Haessler and J. Maurin [1999]. Active faulting in the Gulf of Aqaba: New Knowledge from the $M_W$ 7.3 earthquake of 22 November 1995; Bull. Seis. Soc. Am., Vol. 89, 4, pp. 1025-1036.

Kramer, S. L. [1996]. Geotechnical earthquake engineering. Prentice Hall, Upper Saddle River, New Jersey, 653p.

Malkawi, A. I. [1997]. Assessment of liquefaction potential and evaluation of settlement in sands due to earthquake shaking at Aqaba Bridge proposed hotel. Arab Center for Engineering Studies, Amman, Jordan, 95p.

Malkawi, A. I. and K. J. Fahmi [1996]. Probabilistic earthquake hazard analysis and dynamic site response evaluation of Aqaba Port City, southern Jordan. Jordan U. of Science and Technology and Yarmouk U., Irbid, Jordan, 86p.

Malkawi, A. I., K. S. Numayr and S. Barakat [1999]. The Aqaba earthquake of November 22, 1995. Preliminary reconnaissance report, Jordan U. of Science and Technology, Special Publication, 45p.

Mansoor, N. and T. M. Niemi [1999]. Active oblique-slip faults across the Wadi Yutim fan complex at the head of the Gulf of Aqaba, Dead Sea Transform, Jordan. Geological Society of America Abstracts with program, Vol. 31, p. A-377.

Niemi, T. M. and A. M. II. Smith [1999]. Initial results of the southeastern Wadi Araba, Jordan Geoarchaeological study: Implications for shifts in Late Quaternary aridity, geoarchaeology, Vol. 14 (8), pp. 791-820.

Quennell, A. [1958]. The structural and geomorphic evaluation of the Dead Sea rift. Quarterly J. Geol. Soc. London, Vol. 114, pp. 1-24.

Rashdan, M. [1988]. The regional geology of the Aqaba-Wadi Araba area, Map sheets No. 3049 III and 2949 II, National Resources Authority, Geology Directorate, Amman, Jordan, 87p., map scale 1:50,000.

Seed, H. B. and I. M. Idriss [1971]. Simplified procedure for evaluating soil liquefaction potential. J. of the soil mechanics and foundation division, ASCE, Vol. 97, pp. 1099-1119.

Wells, D. L. and K. J. Coppersmith [1994]. Empirical relationships among magnitude, rupture length, rupture area, and surface displacement. Bulletin of Seismological Society of America, Vol. 84, pp. 974-1002.

Wust, H. [1997]. The November 22, 1995 Nuweiba earthquake , Gulf of Elat (Aqaba): Post seismic analysis of failure features and seismic hazard implications. Geological Survey of Israel, report GSI 3-97, Jerusalem.

Zhang, H. [1998]. Late Pleistocene and Holocene slip rate of the northern Wadi Araba fault, Dead Sea Transform, Jordan, M. S. Thesis, Department of Geosceinces, U. of Missouri-Kansas City, 128p.

Zhang, H., T. M. Niemi, M. Atallah, and J. B. Harrison [1999]. Slip rate of the northern Wadi Araba fault, Dead Sea Transform, Jordan during the past 12,000 years. Geological Society of America Abstracts with program, Vol. 31 (7), p. A-114.

Zhang, H., T. M. Niemi, M. Atallah, and J. B. Harrison [submitted 1999]. Slip rate of the Northern Wadi Arava fault, Dead Sea Transform, Jordan during the past 12,000 years, Journal of Seismology.