Seismicity in a Red Sea coastal area

Sismicité dans un terrain côtier de la Mer Rouge

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SYNOPSIS In connection with the design by DANGROUP of Port Quadeema on the Saudi Arabian Red Sea coast north of Jeddah (Fig. 3), the authors undertook the earthquake engineering studies required by the presence of extremely soft layers surrounding the quay walls. - A main tectonic feature in the Red Sea area is the spreading of ocean floor associated with the continuous opening of the rift along the axis of the Sea. The positions of transform faults was compiled from existing geophysical investigations, and the distribution of main epicentres correlated with the kinematics of the African and Arabian plates. The frequency of earthquakes decreases from south to north. - The attenuation of acceleration from a potential future epicentre near the rift to the port site was determined by means of Californian curves. Finally, the risk of liquefaction was based on the SPT-values, N. - The risk of weak local tectonic events, which could not have been recorded by seismographic stations 2000 km away, was also considered in relation to the present concepts of the tectonic development of the Red Sea region and the local geology. - It was concluded that the soft soils should be vibro-compacted to N > 7 at elev. - 15 m before quay wall construction.

1. GENERAL GEOLOGICAL BACKGROUND

Fig. 1 shows the present concepts of the movements of the plates that have relation to the Red Sea as a major geotectonic feature. For the last decades the Red Sea has been subject to numerous analyses as to its initiation and development. Various models have been proposed to explain the observed geological and geophysical features, mainly in terms of plate tectonics and the initiation of sea floor spreading (Whiteman 1968, Coleman 1974, Le Pichon and Francheteau 1978, Cochran 1983).

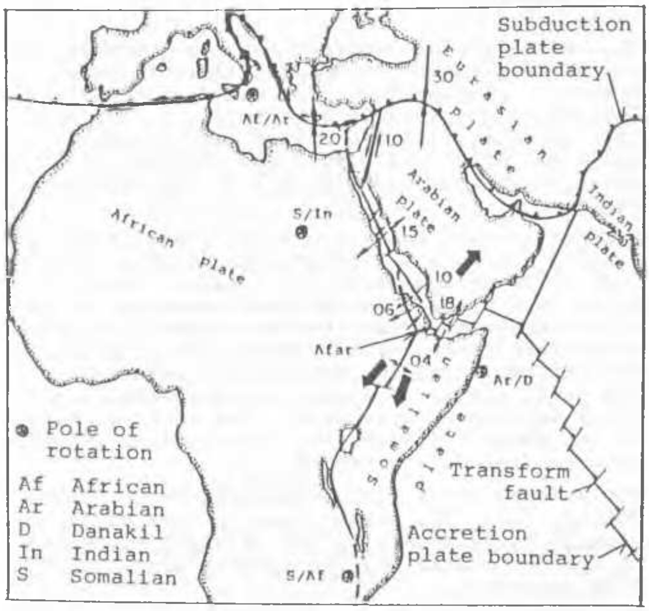

Fig. 1
Movements (thick arrows) of African, Arabian and Somalian plates relative to the Afar triple junction. The figures indicate relative plate movements in cm/a

The development started possibly in the early Tertiary (Eocene). Not until the Miocene (about 20 M.y.), however, the present elongate depression was formed, in which large amounts of evaporites (up to 4 km thick) were precipitated, cf. Fig. 2. Marginally to the basin coarse clastic sediments were deposited and, at the same time, volcanism took place in the bordering shield areas (Coleman et al 1975). In the Pliocene (about 5 M.y.) the Red Sea became connected to the Indian Ocean, as demonstrated by deposition of marine oozes and marginal clastics. The Pleistocene and recent development is featured by the formation of reef building in the coastal areas and deep sea sedimentation and volcanism in the axial zone.

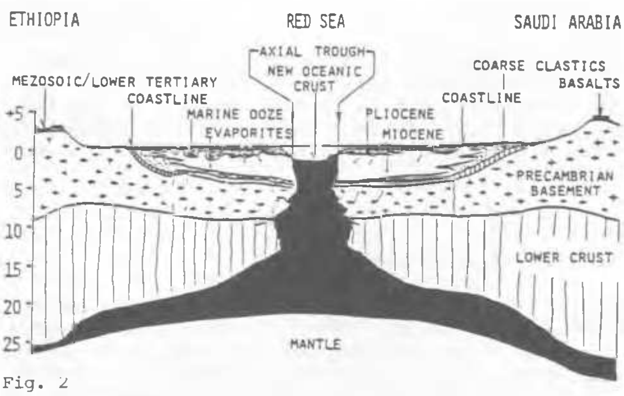

Fig. 2
Cross section of southern Red Sea with main geological units (modified after Coleman et al)

The structural process has traditionally been interpreted as a graben development related to a large scale crustal culmination in the sense of Cloos, 1953. No observable major normal faulting is present, however, along the main part of the Red Sea. Indeed, the Gulf of Suez is controlled by a true graben structure, probably as a result of the tension created by the 105 km horizontal relative movement along the complex sinistral wrench fault through the Gulf of Aqaba and the Dead Sea. Also, the southern termination of the Red Sea in the Afar triangle is fault bounded.

Because of the lack of major block faulting along the Red Sea, it is now generally accepted that the main structure of the Red Sea has developed as a result of a large scale stretching and thinning of the continental crust, accompanied by the down flexure of an elongate basin, rising of mantle material from below (Fig. 2), and large swells on the African and Arabian sides. In the Pliocene the thinning resulted in the formation of an axial rift, starting from the south (Cochran 1983). Magnetic and gravity data confirms that active sea floor spreading today occurs as far north as about 23° N, cf. Fig. 3 (Girdler 1969, Allan 1970).

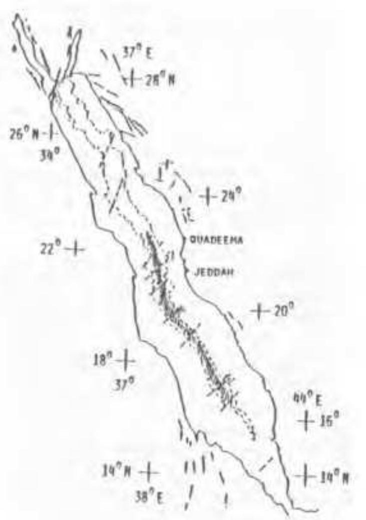

Fig. 3
Red Sea with 500 fathoms contour (---) and major faults. Large parts of the area of active sea floor spreading (hatched) are more than 1000 fathoms deep

To this corresponds a general rising of the coastal regions south of about 25° N, whereas the northern part is either static or sinking. However, local deviations from this general pattern are widespread, possibly due to salt tectonics.

2. SEISMIC ACTIVITY

Fig. 4 shows the epicentres of recorded major earthquakes before 1981. It should be noted that the three nearest seismographical stations are about 2000 km away from Jeddah, for which reason the minimum main body wave magnitude recorded is MB = 4.0.

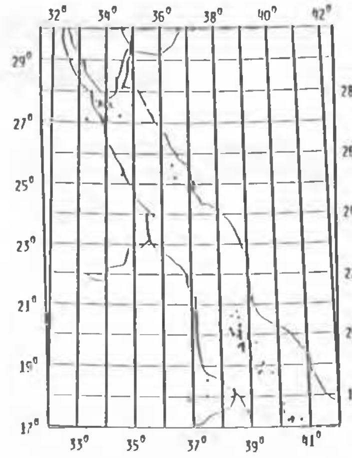

Fig. 4
Epicentres in the Red Sea

The earthquakes near the southern tip of the Sinai peninsula are of no interest for the Quadeema site, because they are related to the block faulting in the Gulf of Suez and to the wrench fault of the Gulf of Aqaba.

The three earthquakes between latitudes 26° and 25° are near the present coastlines and may be assumed to be related to major faults in the continental crust.

The many earthquakes along the axial zone south of 21° must mainly be due to movements along the transform faults (cf. Fig. 3), and to less extent to magmatic activity in the spreading sea floor zone. Thus, the seismic activity is compatible with the tectonic model discussed above (Fairhead and Girdler 1970).

3. SEISMICITY

The seismicity of interest for the Quadeema site cannot be directly calculated from the total number of earthquakes. For example, between 1967-03-10 and 1967-09-21 a total of 37 shocks were recorded, all associated with the main shock of 1967-03-13, 19.22 GMT with MB = 5.7. These shocks are counted as only one (genuine) event.

Defined in this manner, only 11 events have taken place near the axial zone north of latitude 17° over a period of 31 years. These events are plotted in the left hand side of Fig. 5 as a frequency distribution curve N per year, accumulated from north towards south. Thus, the stepped curve represents the frequency of the total number of events north of the latitudes written as abscissae. The vertical lines of the steps represent the latitudes of the epicentres of the main shocks.

The stepped curve is approximated by the dash-dotted line. The steep slope of this curve is clearly correlated with the relative movement of the two plates and the opening of the rift from the south.

By extrapolation of the dash-dotted line to 22°, it is seen that a frequency N = 0.01 per year is on the conservative side for all events north of this latitude. Fig. 3 shows that magnetic

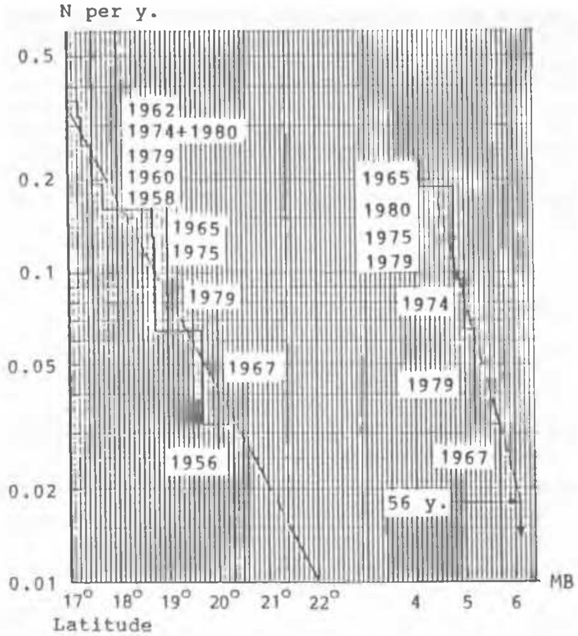

Fig. 5
Rift seismicity of the Red Sea. Distribution curves for frequency N (decreasing towards north) and for body magnitude MB

records have revealed a transform fault crossing the rift at 22°. Though no earthquakes from this fault have been recorded so far, it is a potential source, to which the value N = 0.01 should be assigned, because the frequency pertaining to the fault at 24° will be very much smaller. (The fault at 21.3° is also a potential source of earthquakes. These need not be considered, however, because of the longer distance to Quadeema.)

Accepting a risk of 5% for an assumed 100 year life of structures at Quadeema, the period to be considered is 2000 years, corresponding to 20 events at 22°.

In order to estimate the magnitude of the worst out of 20 events at 22°, the following approximate reasoning is applied: The 11 events between 17° and 21° required 31 years. 20 events would therefore require (20/11) • 31 = 56 years. The worst of these events would have a probability of 1/56 = 0.018 per year. In the right hand side of Fig. 5 the distribution curve of MB-values has been plotted for the 7 (out of 11) events for which the body magnitudes have been determined. The dash-dotted line gives by extrapolation a conservative value of MB = 6.1 as design earthquake.

4. SHAKING AT QUADEEMA

The transform fault nearest Quadeema is believed to cross the talweg of the central trough approximately at 22° (Coleman 1973). In order to be on the safe side, the potential epicentre has been assumed to be situated 25 km NE of the crossing point, i.e. with a distance of 100 km from Quadeema.

Only in the western United States a sufficient amount of strong motion data is available for the determination of the attenuation of the acceleration with distance and the dependence of the acceleration on local soil conditions.

The depth to bedrock being unknown at Quadeema, the surface acceleration has been determined from the curves given by Seed et al (1976) for deep cohesionless soil conditions. Including a correction for the magnitude of the earthquake, the maximum horizontal acceleration has been found to be 0.04 g.

Because of the short construction time available, a steel sheet pile wall had to be driven in front of a coral reef through very loose layers of sand, silty sand and sandy clay, in some cases with SPT-values as small as N = 0-1 through a layer of thickness 7 m.

It was decided to apply vibro-compaction of certain strata of vital influence on the stability of the quay wall. The necessary compaction was determined by various stability criteria, among which the earthquake considerations were also important.

Since small local earthquakes could not have been recorded by the distant seismological stations, it was necessary to carefully consider the local geology (see below). In this connection it was of utmost importance that the older theory of a graben structure could be discarded with because of the work by R. G. Coleman and others.

5. LOCAL GEOLOGY

The geology of the Quadeema area has been deduced mainly from geotechnical borings, information from the consulting engineers, 1:500,000 Geological map sheet (U.S. Geological Survey), aerial photographs and Erts satellite photos.

The area is possibly underlain by Miocene evaporites and/or coarse clastics capped by Pliocene marine ooze, all of unknown thickness and in unknown depths.

The area is a dissected shallow watered coast of numerous coral reef islands and bars intermittent with areas and lagoons of muddy, silty and sandy carbonates and silicic sediments. The subsoil in the seabed consists of alternating formations of marine sediments of carbonates and silicates, reflecting changes in sea level and climate possibly related to glacial-pluvial periods. These formations can be divided in zones or horizons of comparable strength, which also have comparable contents of carbonates and moisture. In the deepest parts around elev. - 35 m cemented carbonate siltstones and marlstones occur. Interfingering the formations of marine clastic sediments there are coral reef structures of solid limestone. These show discontinuous growth and erosion resulting in cemented coral rubble, likewise reflecting changing water level. The coastal zone rises to a level of about + 3 m, which is succeeded inland by a gravel plain with windblown sand at a level of about + 12 m. This plain, dissected by numerous wadis, rises inland for a distance of 5 km, where it terminates in the pediments of low table mountains. These consist of Precambrian basement gneisses capped by Tertiary sandstones and Mio-Pliocene basalts. This terrain is dissected by linear valley features, which appear to be fault controlled and of which some of E-W and NE trend may be post Pliocene as they displace the basalt lavas.

There is no sign of the existence of major coast parallel normal faults. Such might be covered by the gravel plain. On the other hand, this seems unlikely as promontory table mountains both to the north and to the south reach far west and come close to the coast, thus hardly leaving space for such major features.

On aerial photographs the coastal zone of reefs and recent marine sediments shows numerous linear features, bounding islands or cutting the solid coral limestone exposures (Fig. 6). One frequent system appears to be parallel to the

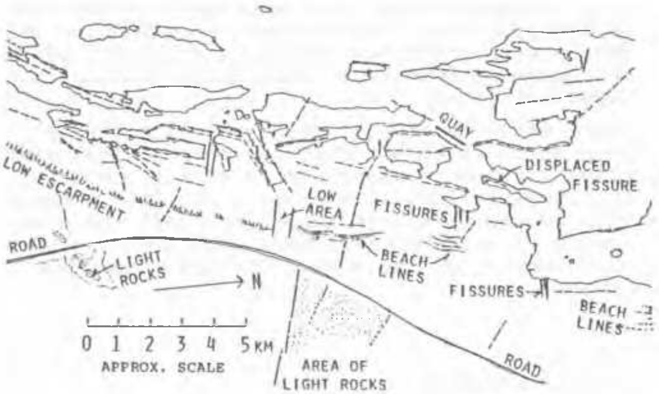

Fig. 6
Lineaments (---) found by interpretation of aerial photographs

general N-S trend of the coast, and other less prominent systems are more east-westerly directed or trend north-east. Displacements of up to 0.3 m related to the N-S system, as well as open tension cracks, have been observed.

The age of these features is uncertain. However, as the coral reef limestones possibly are Pleistocene or late Pleistocene and in their surface have been subjected to erosion related to a lower sea level, their age could be anything less than 100,000 years. Other features, which apparently can be followed into areas of soft unconsolidated sediments and which in the coral reef rock vertically displaces the present surface could be very young if not recent.

There is thus some reason to believe that the area as shown by the local geology has been subjected to movements of Pleistocene and possibly also recent age. These movements can hardly be directly related to earthquake generating faults. They are therefore regarded as secondary effects. Finally, it should not be excluded that the movements could be caused by salt diapirism.

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