Soil geotechnical characteristics for seismic risk mitigation at the southern extension of Marsa Alam city, Egypt

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\section*{ABSTRACT}
The seismic hazard assessment for mitigating the seismic risk is an essential step before starting construction of a new settlement. One of the tools that could help in achieving this goal is the application of seismic refraction method for evaluating the geotechnical characteristics and dynamic properties of the soil deposits. Dynamic characteristics are fundamental for understanding the response of the soil under dynamic loading. Shallow refraction technique is in-situ test depends on the computation of seismic wave velocities which penetrating the soil. A total number of 88 compressional (P) and Shear wave (S) seismic refraction profiles have been conducted at the southern extension of Marsa Alam city on the Red Sea coast. The average P- and S-wave velocities were estimated for the subsurface layers consequently. Microzonation map for each layer was released by the spatial interpolation of data. In addition, the iso-thickness map was created for manifesting the soil thickness all over the studied area. Geotechnical parameters of the subsurface sediments were computed, as well as the zonation maps for density and N-value parameters have been created. The obtained maps emphasize that the first layer could be considered as foundation soil due to it is relatively softness.

\section*{1. Introduction}
Establishment of a new project such as urban cities could encounter major problems as a result of the restricted comprehension of the sub-surface geology, especially when the geological setting shows presence of structural features or even horizontal variations in stratification, in addition to, classical geological interpretation from drillings alone delivers insufficient information. Then subsurface conditions must be evaluated by other techniques like those used in applied geophysics; consequently, this leads to acceptable evaluation of the geological conditions. The shallow seismic refraction approach is one of the geophysical techniques which is widely adopted in site investigations for engineering purposes (Hawkins 1961; Redpath 1973; Al-Shuhail and Al-Shaibani 2011).

This study is intended for application of seismic refraction technique to determine the elastic parameters for construction purposes at the study area. Both the compressional and shear waves’ ground profiles were conducted in a grid at the studied area. The estimated velocity values are used for calculating the geotechnical characteristics of relatively shallower sedimentary layers, which are of great significance in civil engineering applications. The current studied area exists at the south of Marsa Alam city at a distance of about 15 km. It is bounded by latitudes 24° 45’ 32.4” N and 24° 55’ 49.2” N and longitudes 34° 54’ 20.2” E and 35° 03’ 44.6” E and covers a surface area of about 75 km\textsuperscript{2} (Figure 1).

Marsa Alam city is located at the south of Red Sea coast, and is considered as an earthquake prone region, especially from Abu Dabbab active zone, which is situated on the Red Sea coast, with average distance about 41 km north of the study area, and is classified as one of the most active earthquake sources in Egypt. Recent studies presented by El-Hady (1993) showed that Abu Dabbab region is characterised by a fairly continuous seismic activity. Two relatively great earthquakes in November 1955 (mb = 6.1), and in June 1984 (mb = 5.1) occurred in Abu Dabbab active seismic zone. This zone generally characterised by micro-earthquakes occasionally accompanied by seismic swarms (e.g. swarms of 1976, 1984, 1993, 2003 and 2004), as indicated by Daggett et al. (1986) and Abu El-Nader et al. (2016). Seismic active zone can be noticed inside Abu Dabbab area, characterised by the distribution of seismic events, which are aligned and extended to the offshore area (Figure 2).

\section*{2. Geological setting}
The stratigraphic rock units that exist in the studied area are Miocene and younger sediments, Um Mahara Formation acts as the base of the rock units, this formation exists as small heights in the northwest and at the beginning of Wadi Ghadir (Figure 3).
Samuel and Saleeb-Roufaiel (1977) noticed that this formation formed of sandy limestone at the base and fossiliferous limestone with gypsum at the top. Um Mahara Formation rests above the Ranga Formation with small unconformity surface formed of a thin conglomerate layer. Akkad and Dardir (1966a, 1966b)
considered Ranga and Um Mahara as one unit called Gebel Rusas Formation. Um Gheig is the second formation, rests on the Abu Dabbab and distributed in the upper region of the studied site, is a dense dolomitic bed. Abou Khadrah and Abdel Wahab (1984) described this formation as a base of Samh Formation. Shagra Formation is located near or along the shoreline in the studied site (Figure 3); it is more calcareous than Gabir Formation. It could be distinguished by a hard layer at the bottom and consists of clay bands, sandstones, conglomerates, marls and reefal limestones (Philobbos and El Haddad 1983). The environment of sedimentation was a shallow marine with normal salinity. The fossiliferous remnants indicate that this formation is related to Pliocene age.

Akkad and Dardir (1966a, 1966b) noticed three stages of raised beaches that are related to Pleistocene age and distributed in different places on the sea-coast, which may associate with the reefal complexes system. In the ancient periods, the raised beaches are regarded as the shoreline comparable to the coral reefs in the recent time. Coral reefs were formed in the front of the sea coast 1–2 km in the east direction. These reefs are interrupted by several wadis, and the clastic sediments overlay the reefs as a result of sea-level changes. Deposits of Recent Sabkha are related to the sea level oscillations, they composed mainly of salts, anhydrite and gypsum lamina intercalations with unconsolidated sediments of silts and sands, and the thickness of Recent Sabkha is no more than 2 m. Finally, the unconsolidated recent wadi deposits can be identified in different locations in the studied region formed mainly of loose sands, clay and gravel. Fractures of several attitudes and ages are noticeably distributed all over the area.

The study area is plain, and tilts toward the Red Sea. The Red Sea Mountains are occurring in the western limits of the area, comprises essentially of high and rugged mountainous, built up of a series of mountain ranges, more or less coherency trending parallel to the coast and interrupted by number of detached masses and peak. Figure 4 shows that the contour values are decreasing from west to east. Slope gradient is mostly steep in the upper reaches of the study area and tend to be gentle to the east.

The structural map for the area and its surrounding indicates that the NNW-SSE and NE-SW trends are the predominant fault trend in the area. There is another minor fault trend in the direction of NNE-SSW, the previous studies indicate that this fault trend is younger than the above-mentioned one, and may relate to Aqaba trend (Figure 5).

3. Methodology and data set

The seismic refraction approach depends on the refraction of seismic waves at the borders between subsurface strata of various velocities. Dawood et al. (2012) mentioned that when the seismic survey conduct in a specific area the propagated waves...
encounter the border between two various rock units, some of the waves are reflected and the others refracted. The law that defines the principles of the refraction of incident rays is Snell’s Law, which relates the incidence and refraction angles to the seismic wave’s velocities in the two different units.

\[
\frac{\sin i}{\sin r} = \frac{v_1}{v_2}
\]

(1)

Where \(v_1\) and \(v_2\) are the velocity of the first and second layer, respectively.

Milsom (2003) declared that the refracted waves will move to the border if \(v_2\) is larger than \(v_1\), and if \(\sin i\) equals \(v_1/v_2\), this incident angle called critical angle at which the angle of the incident waves is 90°, this permits to refracted waves to move along the border at the unit which characterised by higher velocity \(v_2\) (Dawood et al. 2012). The term crossover distance \(X_c\) will appear when both the refracted and direct waves arrive simultaneously.

\[
X_c = 2h \sqrt{\frac{v_2 + v_1}{v_2 - v_1}}
\]

(2)

Where \(h\) is the depth of the refractor, \(v_1\) and \(v_2\) are the velocities of the two different units. The data resulted from a seismic survey consist of sets of arrival times recorded by sensors aligned at different distances from the shot point (Milsom 2003; Kearey et al. 2009). These times of first arrival are plotted against distances (Figure 6), and the obtained slope is equal to the inverse of a velocity (Milsom 2003). The term intercept time, \(T_i\), is known as the time at which the back-extrapolated refracted arrival line intersects the axis of time (Milsom 2003; Kearey et al. 2009).

The intercept time \(T_i\) is given as:

\[
T_i = \frac{2h \sqrt{v_2^2 - v_1^2}}{v_1 v_2}
\]

(3)

The false depths will result if the obtained velocities derived from inclined strata. So, in seismic survey, the

Figure 4. Topographic map for the study area and its surrounding (modified after EGPC 1987) surrounding.
term “reverse shooting” applied, and the times of arrival at each sensor are estimated from both terminals of the seismic profile. The concept of delay time should be employed here for computing the real velocities and thicknesses for each stratum. This concept was discussed by many authors (e.g. Wyrobek 1956; Barry 1967).

The shallow seismic refraction technique is widely used in Egypt to infer the subsurface ground model.
mapping bedrock depth, and in determination of elastic moduli and geotechnical characteristics with good and reliable results (e.g. Toni 2007, 2012; Toni et al. 2013; Selim et al. 2014; Basheer 2016).

Seismic refraction method provides an effective and efficient means to obtain general information about large volumes of the subsurface structures, but has limitations due to subsurface geometries such as thin layers and lower velocity horizons underlying higher velocity horizons (Wallace 1970).

The essential target of this research is the definition of the sedimentary structures and their geotechnical properties in the region according to their seismic velocities. For achieving this target, 44 compressional and 44 shear waves’ seismic profiles have been carried out at 44 sites distributed in a grid of 1 × 1.5 km in the studied area as shown in Figure 7. The directions of these profiles lies approximately North-South and Northwest-Southeast. Each profile formed of 24 detectors with spacing 5 m and total spread length of 115 m (Figure 8).

The utilised geophones in this research for recording the vertical and horizontal seismic waves have 14 Hz natural frequency and strongly coupled to the soil, they were produced with specific natural frequency that has the ability to record the frequencies of seismic signals, which has a strong effect on the data quality, and to avoid recording of surface waves which dominant in low frequencies (Brincker et al. 2005). The seismic

Figure 7. Location map of the seismic refraction profiles.
survey was implemented using a signal enhancement seismograph model StrataVisor NZ 48 produced by GEOMETRICS Co. A heavy sledgehammer (10 kg) and metallic plate were used as a seismic source. The goal of using seismic source is to produce a large sufficient signal into the subsurface strata to ensure enough depth and high resolution to model the subsurface layers. For generating P-waves, the ground should be hit vertically, thus the created seismic waves propagate inside the earth (Luna and Jadi 2000). The sensitive geophones record and convert the ground motions into electrical signals, these signals equivalent to the velocity of the motion. Three shots were conducted along the profile, at an offset of 5 m far from both ends (normal and reverse shooting), and at the mid-point (between geophones 12 and 13) (Figure 8). For increasing S/N’s ratio, the data were stacked 3–5 times at each shot point, with sampling interval 0.25 ms and total recording length 0.75 s. The technique, which is known as Kobayashi, was implemented to generate the shear-waves. In this method, a wooden plate was firmly coupled to the soil for acquiring three shots; forward, reverse and at the middle of the profile by hitting the plate horizontally (Luna and Jadi 2000).

4. Data processing and interpretation

The obtained seismic data is processed using commercial SeisImager/2D software package version 4.1.1.7 (Oyo cooperation), which is a complete software for processing and modelling seismic data, it depends on the ray tracing and time delay methods. The waveforms of compressional (P) and Shear-waves (S) that are already collected from each shoot point are analysed by selecting the first arrival time at each geophone. The picked times together with the distances between the shooting points and geophones were used to compute the travel time-distance (T–D) curves (Båth 1978; Figure 9(a,c)). To compute the velocities of different layers and construct 2-D ground models based on the refracted waves from subsurface interfaces (Figure 9(b,d)), the time term inversion approach should be applied (Scheidegger and Willmore 1957). In general, the outcomes of the current seismic survey and the previous geophysical studies, which indeed have been done at the north of the area of study display a good agreement (Salem 2000; Farrag et al. 2005).

Refraction tomography (Zhu et al. 1992; Stefani 1995; Lanz et al. 1998; Zhang and Toksöz 1998) is widely employed to invert seismic refraction data recorded for geotechnical and environmental investigations. Refraction tomography is one example of model-based inversion, in which an initial starting model is systematically updated through iteratively comparing the modelled response with the field data. Uncertainty in the tomographic inversion of near-surface seismic refraction data can be separated into aleatory variability, which describes the misfit errors and epistemic uncertainty, which describes the suite of acceptable models. Common implementations of refraction tomography usually focus on reducing aleatory variability and frequently disregard epistemic uncertainty. The concepts of aleatory variability and epistemic uncertainty correspond with precision and accuracy. Precision refers to how closely individual measurements agree with each other, while accuracy refers to how closely a measured value agrees with the correct value (Palmer 2011).

In this study, the tomograms generated using the generalised reciprocal method (GRM) are consistent with the traveltime data. The GRM based tomogram successfully detects, defines and differentiates narrow regions with low seismic velocities, which represent shear zones and a massive sulphide ore body. None of these zones is detected with the tomogram generated with the default starting model using smooth vertical velocity gradients.

The seismic velocities values are obtained from the in-situ seismic survey for the surface and subsurface geo-seismic layers beneath all profiles, then are represented in microzonation maps as drawn in Figures 11 and 12.

The first (surface) layer typically shows diversity in the velocities of compressional and shear wave velocity values of 420–2200 m/s and 260–1200 m/s, respectively. The relatively high values clearly be seen in the northwest to southeast of the upper part of the studied area, which refers to moderate to good competent materials due to the occurrence of compacted sandy limestones in some sites on the surface. While the relatively lower velocity values can be observed in the west at the entrance of the valley, this area characterised by loose sediments of gravels and sands may be as a result of running water throughout the season of rains which cause a disturbance in soil compaction (Figures 11(a)}
The zonation maps for the estimated P- and S-wave velocity values for the second layer show increasing in velocities values as a result of the overlying rocks compaction. The area that extends from northwest to southeast still shows relatively higher velocity values, 820–3200 m/s for compressional waves and 360–1450 m/s for shear waves (Figures 11(b) and 12(a)). The third layer disappeared at some seismic profiles, this layer is characterised by relatively high seismic wave velocity values with depth. The compressional wave's values are ranging from 1220 to 3920 m/s, while the shear wave values are ranging from 550 to 1950 m/s. The centre of the upper part of the map shows high velocities values of P- and S-waves, while, the sites located at the northeast and the south of the studied region display moderate seismic velocity values. The other parts of the region are characterised by lower values of seismic velocities (Figures 11(c) and 12(c)).

Figure 10 shows electrical resistivity and seismic refraction measurements were carried-out by Farrag et al. (2005), in order to determine the depth to the basement rocks in Wadi Alam adjacent to Red Sea and located at the north direction, near to the current study area, the resulted rocks units from these two methods consistence with those detected from the shallow seismic survey in the current study area. Unfortunately, no boreholes or logging for confirming the obtained data from the seismic refraction method.

Moreover, the iso-thickness map has been drawn for revealing the soil (or surface layer) thickness all over the studied area (Figure 13). It is obvious that the soil thickness of upto 4–6 m is prevailing at the north, west, southeast to northwest and the south of the studied area, while the other parts of the map exhibit an average thickness up to 8 m.

5. Geotechnical parameters estimations

The investigation of foundation soils requires a detailed description of soil characterisations using various geophysical and geotechnical techniques (Luna and Jadi 2000). The response of rocks to cyclic loading is governed mostly by the mechanical characteristics of the rocks (Vaneghi et al. 2017). There are various kinds of geotechnical parameters accompanied by dynamic loading, shear modulus, bearing capacity, Poisson’s ratio, etc. The familiar name for this type of characteristics is “dynamic soil characteristic”.

The selection of suitable testing technique for solving the geotechnical engineering problems needs an understanding of the accompanied level of strain. There are varieties of laboratory and field techniques that evaluate the high and low strain rocks behaviour. The current study relies on the results of seismic values that encompass the low-strain characteristics of the propagated seismic wave. All procedures of test that delineate soil
behaviour need to implement the primary stress conditions and expect cyclic loading. The advantage of the test takes place in-situ is that the state of stress is included in the procedure of the tests (Pegah et al. 2016). However, laboratory examinations are needed to confine and solidify the soil samples back to the state of stress to return to the field conditions. Moreover, a geophysical field test has the advantages of testing undisturbed soil in the conditions of the field with the actual stress conditions. In addition, what is being tested in-situ is a volume and average conditions of the substance or material between the receiver and source.

For evaluating the dynamic characteristics of the soil, a suitable tool should be used for triggering the rocks and generating measurable seismic waves. Geophysical tests in-situ introduce seismic waves into the rock at a low strain, this low level of strain permit to employ the elastic theory to link computations with mechanical characteristics, and hence the most part of the response is linear (Pegah et al. 2016). Woodward-Clyde
Consultant (1988) noticed little or no indication for nonlinear soil response for surface ground motion up to about 0.3 g. On the other hand, Wen et al. (1995) stated that a threshold acceleration level beyond which there is an appreciable departure of the ground response from linear to non-linear prediction in geotechnical engineering is approximately 100–150 gal (0.1–0.15 g). Hence, Hassan et al. (2017) and Sawires et al. (2016a) mentioned that the estimated Peak Ground Acceleration on the rocks in the study area is 0.08 and 0.11 g, respectively. So, soil response of the investigated rocks there could be linear.

6. Results and discussion

Many of elastic moduli parameters were computed using P-wave and S-wave velocities according to the presented equations in Table 1, and listed in Table 2. Then a set of zonation maps are prepared to clarify the spatial distribution of density and N-value parameters (as an example) at each layer in the studied region to identify the degree of compactness of this layer.

6.1. Density zonation maps

According to Gardner et al. (1974), there is a direct relationship between seismic velocities and density values. So, the higher the seismic velocity value the higher the density value and hence the higher the degree of compaction of soil/rock. Due to the strong link between the density and the seismic velocity value, density was chosen to clarify the degree of competence of different geoseismic layers at the studied area (Figure 14).

For the first geoseismic layer (Figure 14(a)), the maximum value of density was 2.14 g/cm³, which was observed at the northwest to southeast, northeast, south and southeast of the map, this value decreases gradually toward west, away from the sea coast, to reach to relative low value of density 1.46 g/cm³ at the central west of the map. On the other hand, the second layer characterised by noticeably rising in the density due to the compressibility of rocks with depth (Figure 14(b)). The northwest to the southeast zone of the upper part of the area still characterised by a maximum value of density 2.34 g/cm³, which indicate relatively high competent rocks at this zone, this value decreased gradually...
about 2.02 g/cm³ to cover a large area of the map especially in the east and middle of the studied region. The third layer noticeably disappeared at some parts of the investigated site, so the areas have not the third layer have been masked (Figure 14(c)). The maximum density 2.45 g/cm³ is seen in the centre of the upper part of the map, while almost the other parts of the studied region displaying density value around 2.06 g/cm³.

### 6.2. N-value zonation maps

The geotechnical N-value parameter or Standard Penetration Test (SPT) was primarily developed to examine the status of cohesionless deposits for construction and pile installation. Currently, it is widely used in both cohesionless and cohesive deposits for routine exploration for all types of foundation (Bowels, 1982). So, higher the N-value, higher is the...
durability of the rock to be penetrated, and hence higher is its degree of compactness and vice versa.

Figure 15(a) shows the spatial distribution of the N-value parameter for the first geoseismic layer in the investigated site. This layer shows maximum N-value of 700–1212 at the area, which extends from northwest to southeast at the upper part of the map, while this value relatively decreases in other directions. N-value shows obvious increasing at the second geoseismic layer due to the rocks compaction as a result of overlying rocks (Figure 15(b)). This value is still relatively higher in the upper and southern part of the map, while is comparatively decreases in all directions. Finally, the third layer displays relatively maximum N-value, as a result of the rocks consolidation. The area which extends from north-west to south-east of the upper part of the studied area shows high N-value about 9290, this value decreases to 1290 at the northwest and south of the study area. While the other parts of the investigated area are characterised by lowest N-value (Figure 15(c)).

According to Bowles (1984), N-value for most of the first layer refers to relatively dense to very dense soil (Table 3), so it could be considered suitable foundation soil from the geophysical aspect. However, the authors preferred to mention N-value, density and other geotechnical parameters for the second and third layers to give a comprehensive overview for the properties of all buried rocks.

### 7. Conclusion and recommendations

The evaluation of the geotechnical characteristics of soil deposits using seismic wave velocity measurements is the main objective of this work. For achieving the target, 88 shallow P- and S- wave seismic refraction profiles distributed in a grid of 1 × 1.5 km were conducted and interpreted. For each profile, the average compressional and shear-wave velocity for relatively shallower layers were calculated, several microzonation maps of P- and S-wave for each layer were drawn by data interpolations (is a method of constructing new data points within the range of a discrete set of known data points to produce a simple function which is still fairly close to original). The resulted maps show that the areas located north-west to southeast, northeast and south of the studied area, characterised by more competent soil deposits, while the other parts that have moderate to weak compacted sediments should be more considerable during construction operations. In addition, the iso-thickness map has been plotted for manifesting the soil thickness all over the study area.

Geotechnical characterisations at the studied area have been estimated based on the shallow seismic refraction results (\(V_p\) and \(V_s\)). Density and N-value are chosen as representative parameters, due to their direct relationship with the compactness of rock materials (Gardner et al. 1974; Bowles 1984). The obtained results emphasise that the areas located at the northwest to southeast, northeast and south have more competent soil deposits and less hazardous for any engineering purposes. N-value for most of the first layer indicates good competent rock materials (Bowles 1984), so it could be considered suitable foundation soil from the geophysical aspect. The presented results of the current work are helpful in civil engineering applications for determining which kind of buildings will be suitable for each site according to the dynamic loading and geotechnical parameters of the foundation soil. In addition, the estimated seismic velocities values for several rock units in the studied area could be useful in estimation of ground motion parameters on the surface.

Dynamic properties of soils such as shear modulus are important in the design of geotechnical engineering problems involving dynamic loading. These dynamic properties of soils are strongly affected by the magnitude of shear strain amplitude induced in the soil deposits during strong earthquakes motions. Therefore, it would be necessary to evaluate the dynamic properties of soil deposits for a wide range of shear strains. Geophysical tests propagate the seismic waves through the soil at

| N-value | Description | N-value | Description |
|---------|-------------|---------|-------------|
| <4      | Very soft   | 0–10    | Loose       |
| 4–6     | Soft        | 11–30   | Medium      |
| 7–15    | Medium      | 31–50   | Dense       |
| 16–25   | Stiff       | > 50    | Very dense  |
| > 25    | Hard        |         |             |

Table 3. Soil classification according to N-value (Bowles 1984).
a very low strain level (less than 10–3%). This level of strain allows using the elasticity theory for measuring the dynamic properties of soil deposits in the study area. Due to the geophysical test, in-situ introduces seismic waves into rocks at a low strain level, the response of the rocks should be linear. On the other hand, at a moderate level of strain this response starts to be non-linear, and remain non-linear at large strain. So, it is recommended to have integration between the results of the current geophysical field test and the proposed laboratory measurements.

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