Preliminary Assessment of the Soil Foundation Characteristics Utilizing the 2D Resistivity Imaging and Down-Hole Seismic Refraction Techniques: A Case Study in Tenth of Ramadan City, Egypt

Shokry A. Soliman*, Salah Shebl, Ahmed El Khafif, T.F. Shazley, M.H. Farag
Laboratory of geophysics, Egyptian Petroleum Research Institute, Cairo, Egypt

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Abstract
Two-dimensional electrical resistivity imaging and seismic refraction, in the form of down-hole survey, were applied to delineate the subsurface section and elastic moduli and identify geotechnical characteristics of subsurface materials in the 10th of Ramadan industrial area, Cairo, Egypt. The results of four 2-D profiles of electrical resistivity, in the form of dipole–dipole and Wenner configurations, revealed that the subsurface section contains two main geoelectrical layers; the first is made of sand, some silt, and gravels, reflecting low resistivity values ranging from 25 to 65.5 ohm m. This layer is overlying a high resistivity layer (65.5 to 135 ohm m), corresponding to medium to coarse sand, with gravel and calcareous materials. It is worth noting that the down-hole technique was used to measure velocities of P and S waves in order to derive the low strain dynamic elastic properties, such as Poisson’s ratio, Shear modulus, stress ratio, concentration index, N-value, and the ultimate and allowable bearing capacities of the subsurface soil, down to an approximate depth of 30 m in the borehole at the site. In addition, the Vs30 value was calculated and revealed that the soil is categorized as a NEHRP class (D). Furthermore, the results of geotechnical parameters and elastic moduli were found to be realistic and sensible for the purposes of engineering constructions and imply that the soil in the study area is characterized by fairly to moderately competent quality. A new empirical correlation is proposed between the obtained Vs and resistivity values, where $Vs = 1.0302 \rho + 172.74$.

Keywords: 2D resistivity imaging, seismic refraction, geotechnical parameters, down-hole, Vs30

التقييم الأولي لخصائص تربة الأساس باستخدام تقنيات المقاومة ثنائية الأبعاد وتقنيات الانكسار الزلزالي دراسة حقلية في مدينة العاشر من رمضان بمصر

شكري سليمان*، صلاح شبل، أحمد الخفيف، طارق شاذلي، محمد فرج
معمل الجيوفيزياء، معهد بحوث البترول المصري، القاهرة، مصر

الخلاصة
تم تطبيق التصوير المقطع بالمقاومة الكهربائية والانكسار الزلزالي (down-hole) لتحديد الطبقات تحت السطحية، ومعاملات المرونة، وتحديد الخصائص الجيوفيزيائية للمواد المدفونة تحت التبحث، فيما يتعلق بالعمليات الصناعية بالعاشر من رمضان. من الضروري إجراء دراسات جيوفيزيائية قبل أي تصميم هندسي مفترض.

*Email: shokry61@yahoo.com
Introduction

A geotechnical study is necessary before any proposed engineering design to construct any building to prevent the building from collapsing. It is important to know the geotechnical properties of the soil on which a new industrial zone, for example, is to be built in order to implement the development plans of this zone. Nowadays, the combination of geoelectrical resistivity and seismic refraction techniques for site investigations is very effective due to their distinct geophysical response with varying resolution. In some geotechnical problems, geophysical studies may be adopted to decide which execution measure should be taken to diminish costs, effort, time, and even the chance of accidents during any constructions.

Several studies used effective geophysical techniques in engineering problems, such as the detection of the ancient foundations, cracks and fractures of building [1, 2], planning on new cities, building new neighborhood, [3-5] and the investigations of shallow subsurface sections, environmental problems and geotechnical parameter [6, 7].

The City of Tenth of Ramadan has been witnessing civil and industrial development represented in constructing new industrial zones, since its establishment in 1977. It is located along the Cairo-Ismailia desert highway about 55 km from Cairo. It lies between latitudes 30°17’ and 30°25’N and longitudes 31°34’ and 31°49’E. The area of study is located within the northeast territory of 10th Ramadan City (Figure 1). The shallow seismic refraction and Dc resistivity were utilized in defining the geotechnical properties of the soil and rocks [8, 9], where shear waves velocity has an intimate relationship with the rigidity or stiffness of the soil or rocks [10], which can be expressed as the elastic shear modulus.

The present study aims to investigate the lateral and vertical variations in the subsurface sections, determine elastic moduli, and identify the geotechnical characteristics of the subsurface soil using integrated 2D electrical resistivity, borehole data, and down-hole (P and S) waves.

Geology of the Study Area

The investigated site and its vicinity are covered by sedimentary rocks (Figure 2) belonging to the Tertiary and Quaternary ages [11]. The subsurface sequences of the uppermost thirty meters of the soil consist of very dense sand, coarse to medium sand, and silty sand (Figure 3), based on the information derived from the two boreholes drilled at the investigated site.
Figure 1- Location map of the study area, electrical resistivity stations, and boreholes sites

Figure 2- Modified surface geological map of the area and its surroundings [12].
Figure 3- Lithological description of the boreholes BH1 and BH2, [13]

Methodology
2D Resistivity Imaging

The electrical resistivity imaging method was chosen in this study due to its ability to image the subsurface structure and thickness of layers. This technique has wide applications in environmental, engineering, and variable subsurface explorations [14, 15]. Four 2D resistivity profiles were carried out using dipole–dipole and Wenner arrays. The instrument used in the study is SYSCAL-Pro, 48 channels, with an automatic multi-electrode system made by IRIS Instruments, France. The first 2D profile (P1) is located between the two boreholes, while the second profile (P2) is orthogonal on P1 in the study area. Both profiles were measured using dipole–dipole array (Figure 1). In additions, another two profiles of Wenner array were executed at the same locations of dipole–dipole profiles, in order to compare the results of the two techniques. The data were processed and analyzed using RES2DINV program [16], which produces an image of the electrical resistivity distribution in the subsurface based on a regularization algorithm [17].
The inversion routine used by RES2DINV is based on the smoothness constrained least-squares technique [18] which offers three options, providing a very fast quasi Newton method [17]. The program automatically creates a 2D inverse model by dividing the subsurface into rectangular blocks and chooses optimum inversion parameters for the data, which include the damping factor, vertical to horizontal flatness filter ratio, convergence limit, and number of iterations. The program calculates the apparent resistivity values of the model blocks using either a finite difference or finite element method and compares these to measured data. The resistivity of the model blocks is adjusted iteratively until the calculated apparent resistivity values of the model agree with the actual field measurements.

**Seismic Refraction Tools**

Seismic refraction was executed by applying a down-hole technique to measures the compression wave (P) and the shear wave (S) in the borehole using a seismograph model McSEIS-SXW manufactured by OYO Company. During down-hole seismic testing, a seismic source is generated at distance of about 1m from a well. A sledge hammer (10kg) was used to generate both compression (P) and shear (S) waves by striking the loaded plate. Relying on the type of strike plate on the ground surface (vertical or horizontal), the seismic source can generate a signal containing a maximum of energy in the compression wave (P) or the shear wave (S), respectively. Within the borehole, a receiver geophone measured the arrival times by varying its location every 1m until the 30 m depth to determine the P and S wave velocities (Figure 1). The data were recorded and saved as separate files for each shot for both P and S waves corresponding to each depth location.

The down-hole technique is a vital method of the seismic refraction surveys for determining the shear wave velocity and, consequently, estimating the elastic situation (stiffness) of the soil or rock for geotechnical and engineering purposes.

**Elastic Moduli and Geotechnical Parameters**

The values of P- and S-wave velocities which concluded from the two boreholes measurements were used to evaluate the different elastic moduli, such as density (Eq.1), Poisson’s ratio (Eq. 2) [19-21], shear modulus (Eq. 3) [22], Young’s modulus (Eq. (4) [23, 24], and bulk modulus (Eq. 5) [25], as listed in (Table 4).

\[
\text{Density } (\rho) = 0.3V_p^{0.25}
\]

\[
\text{Poisson’s ratio } (\sigma) = \frac{V_f^2 - 2V_p^2}{2(V_p^2 - V_s^2)}
\]

\[
\text{Shear modulus } (\mu) = \frac{\rho V_s^2}{2}
\]

\[
\text{Young’s modulus } (E) = 2\mu (1 + \sigma).
\]

\[
\text{Bulk’s modulus } (K) = \frac{E}{3(1 - 2\delta)}
\]

**The Geotechnical Elements**

The geotechnical elements, such as the N-value, concentration index, material index, stress ratio, and bearing capacity were evaluated as follows.

**N-Value**

The N-value is one of the most common geotechnical parameters, known as SPT (Standard Penetration Test). It can be calculated in situ from a well to investigate the status of cohesion-less deposits, where the low competent rocks reveals low N-value and vice versa. The measurements of SPT N values depend on many factors, such as drilling methods, drill rods, borehole properties (e.g. diameter and stabilization, the sampler, blow count rate, hammer configuration, fine content), energy corrections, and test procedure [26,27]. Geophysically, the N-value is determined from the modified equation by [28]
Vs = 89.9(N) 0.341 \hspace{1cm} (6)

To calculate the N value, this equation can be rewritten as:

\[
\log N = 2.932 \log VS - 5.7295 \hspace{1cm} (7)
\]

Shear wave data can be converted to SPT N-values, to recognize the type of soil or sediment, and used in calculating bearing capacity. The N-value was originally adopted to investigate the status of cohesionless deposits, but it is widely used in both cohesionless and cohesive deposits for exploration in all types of foundations (Table 1).

### Table 1- N-value classes (modified after [29]).

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

### Table 2- Comparison between SPT N value, shear wave velocity Vs, and Poisson’s ratio according to [30-31].

| Soil type          | SPT N value | S-wave velocity m/s | Poisson’s ratio |
|--------------------|-------------|----------------------|-----------------|
| Loose granular soil| 0–20        | 130–280              | 0.2–0.4         |
| Dense granular soil| 20–50       | 200–410              | 0.3–0.45        |
| Soft clay          | 0–6         | 40–90                | 0.15–0.25       |
| Stiff clay         | 6–30        | 65–140               | 0.2–0.5         |

### Concentration Index

The concentration index is one of the engineering parameters that reveal the degree of the competence of materials used in the foundation and other civil constructions. It depends on two factors; one is the elastic moduli of the substance and the other is depth-pressure distribution [29].

\[
\xi = \frac{(3 - 4\alpha)}{(1 - 2\alpha)} \hspace{1cm} (8)
\]

### Material Index

From the engineering perspective, the material index clarifies the material quality for foundation purposes. This parameter implies the degree of competence based on the elastic moduli. This index depends on several factors, such as matter composition, grade of consolidation, fracturing, jointing, and presence or absence of fluids in pore spaces, which affect the medium of the materials and the wave velocities [29].

\[
\xi = (1 - 4\alpha) \hspace{1cm} (9)
\]

### Table 3- Soil description according to Poisson's Ratio and Material Index, after [32].

| Soil description | Incompetent to slightly competent | Fairly to Moderately competent | Competent Material | Very high Competent |
|------------------|-----------------------------------|--------------------------------|-------------------|---------------------|
| Poisson's Ratio  | 0.41-0.49                         | 0.35-0.27                      | 0.25-0.16         | 0.12-0.03           |
| Material Index   | (-0.5)-(-1)                       | -0.5-0.0                       | 0.0-0.5           | >0.5                |
Bearing Capacity

In geotechnical engineering, the bearing capacity is a gauge for structural stability of the soil. The failure criterion for any foundation soil is known by the ultimate bearing capacity and it is considered an important factor in soil mechanics [23].

Allowable bearing capacity (Qa)

It is defined as the maximum load to be considered to avoid shear failure. It can be reduced from the ultimate bearing capacity value by the value of safety factor (F), according to [33].

\[
Q_a = \frac{Q_{ult}}{F}
\]

(10)

where \(Q_a\) is the allowable bearing capacity and \(F_s\) is the factor of safety (F), which equals three for cohesive soils. This equation can be rewritten in terms of shear velocity in the case of cohesive soils, as follows:

\[
\log Q_a = 2.932 \log V_s - 4.729
\]

(11)

For cohesionless soil,

\[
\log Q_a = 2.932 \log V_s - 4.553
\]

(12)

Where \(V_s\) is the shear-wave velocity, \(Q_a\) is the allowable bearing capacity.

Vs30 and site classification

Shear-wave velocity has been utilized as an essential parameter for estimating the dynamic properties of soils since long time. VS30 is known as the average of shear-wave velocity in the top 30 meters, based on travel time from the surface to a depth of 30 m. It is used to classify the soil into six classes (A–F) according to the National Earthquake Hazards Reduction Program [34]. Vs30 can be calculated from Eq. (13).

\[
V_{s30} = \frac{30}{\sum_{i=1}^{N} (h_i / V_i)}
\]

(13)

where \(V_i\) is shear-wave velocity in m/s, and \(h_i\) is the thickness of any layer (between 0 and 30 m).

Results and Discussion

The integration between electrical, shear wave, and borehole data were used to estimate the dynamic characteristics of the subsurface soil, which could have direct effects on the constructions in the City of Tenth Ramadan. The geoelectrical data included 2-D resistivity data, where Wenner array indicated the vertical variation, while the dipole array reflected the horizontal and vertical variations. The results of inversion show that the dipole sections indicate horizontal variation, as shown in (Figure 4). The subsurface succession consists of two geologic units. The first layer consists of sand, silt, and gravel with low resistivity ranging from 25 to 65.5 ohm m. The thickness of this layer increases toward the south, reaching about 12m at nearest borehole 1. The second layer has moderate resistivity, corresponding to dry sand with gravels and calcareous materials. The thickness of this layer is observed to increase in the center of the section and decreases toward the north nearest borehole 2. It can be distinguished at the depth range from 9m at the north to 12m toward the south.

The data of primary and shear waves obtained from boreholes were used to calculate the different elastic moduli, as listed in (Table 4). The values of Young's modulus (E) ranged
between 0.029 and 0.537 GPa, Bulk modulus (K) range between 0.030 and 0.991 GPa., and shear modulus (μ) or rigidity range between 0.011 and 2.00 Gpa. Poisson's ratio (σ) was characterized by relative low ratio, ranging between 0.328 and 0.415, revealing that the soils belong to dense granular soil, according to Table 2. SPT value is one of the most important parameters used to determine the mechanical properties of subsurface soil. The N-values ranged from 15.30 to 31.29, which reflects medium to dense cohesionless soil, according to (Table 1).

**Figure 4** - The 2-D electrical resistivity inverted sections along the profiles of P1, represented by DD1 dipole–dipole array and WN1 Wenner array and P2, represent by DD2 and WN2.
Table 4 - The elastic moduli values based on shear waves measured in boreholes 1 and 2.

| Dep. E | Vp  | Vs  | ᵟ   | ρ   | µ   | E   | K   | Vp  | Vs  | ᵟ   | ρ   | µ   |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 1      | 195 | 97  | 0.336 | 1.16 | 11  | 29  | 30  | 264 | 130 | 0.340 | 1.25 | 21.1 |
| 56.6   | 58.9 |
| 2      | 352 | 173 | 0.341 | 1.34 | 40  | 108 | 113 | 357 | 176 | 0.339 | 1.35 | 41.7 |
| 111.8  | 116.1 |
| 3      | 438 | 208 | 0.354 | 1.42 | 61  | 166 | 190 | 390 | 190 | 0.344 | 1.38 | 49.7 |
| 133.7  | 143.2 |
| 4      | 495 | 245 | 0.338 | 1.46 | 88  | 235 | 241 | 457 | 226 | 0.338 | 1.43 | 73.2 |
| 195.9  | 201.7 |
| 5      | 559 | 283 | 0.328 | 1.51 | 121 | 321 | 310 | 474 | 229 | 0.348 | 1.45 | 75.9 |
| 204.5  | 223.8 |
| 6      | 583 | 287 | 0.340 | 1.52 | 125 | 336 | 351 | 532 | 261 | 0.342 | 1.49 | 101.4 |
| 272.1  | 286.1 |
| 7      | 614 | 303 | 0.339 | 1.54 | 142 | 379 | 393 | 551 | 269 | 0.344 | 1.50 | 108.7 |
| 292    | 311.1 |
| 8      | 642 | 314 | 0.343 | 1.56 | 154 | 413 | 438 | 567 | 281 | 0.337 | 1.51 | 119.4 |
| 319.4  | 327.1 |
| 9      | 856 | 326 | 0.415 | 1.68 | 178 | 504 | 991 | 563 | 277 | 0.340 | 1.51 | 115.9 |
| 310.6  | 324.2 |
| 10     | 851 | 324 | 0.415 | 1.67 | 176 | 498 | 978 | 576 | 279 | 0.347 | 1.52 | 118.2 |
| 318.4  | 346.2 |
| 11     | 647 | 316 | 0.343 | 1.56 | 157 | 420 | 446 | 596 | 290 | 0.345 | 1.53 | 128.8 |
| 346.5  | 372.3 |
| 12     | 638 | 302 | 0.356 | 1.56 | 142 | 385 | 445 | 590 | 284 | 0.349 | 1.53 | 123.2 |
| 332.5  | 367.5 |
| 13     | 655 | 311 | 0.354 | 1.57 | 152 | 411 | 471 | 592 | 288 | 0.345 | 1.53 | 126.8 |
| 341.2  | 366.8 |
| 14     | 658 | 320 | 0.345 | 1.57 | 161 | 433 | 465 | 588 | 289 | 0.341 | 1.53 | 127.5 |
| 341.9  | 357.8 |
| 15     | 667 | 329 | 0.339 | 1.58 | 171 | 457 | 474 | 616 | 300 | 0.345 | 1.54 |
| 139.0  | 373.8 | 400.7 |
| 16     | 686 | 337 | 0.341 | 1.59 | 180 | 483 | 506 | 604 | 308 | 0.324 | 1.54 |
| 145.8  | 386.1 | 366.3 |
| 17     | 682 | 333 | 0.343 | 1.58 | 176 | 472 | 503 | 641 | 322 | 0.331 | 1.56 |
| 161.7  | 430.6 | 425.3 |
| 18     | 688 | 340 | 0.338 | 1.59 | 184 | 491 | 507 | 640 | 322 | 0.331 | 1.56 |
| 161.7  | 430.2 | 423.1 |
| 19     | 689 | 340 | 0.339 | 1.59 | 184 | 492 | 509 | 634 | 312 | 0.340 | 1.56 |
| 151.4  | 405.9 | 423.4 |
| 20     | 695 | 335 | 0.349 | 1.59 | 179 | 482 | 531 | 639 | 316 | 0.338 | 1.56 |
| 155.6  | 416.5 | 428.9 |
| 21     | 696 | 339 | 0.344 | 1.60 | 183 | 492 | 527 | 614 | 308 | 0.332 | 1.54 |
| 146.4  | 389.9 | 386.6 |
| 22     | 701 | 343 | 0.343 | 1.60 | 188 | 504 | 534 | 653 | 320 | 0.342 | 1.57 |
| 160.5  | 430.7 | 454.3 |
| 23     | 701 | 343 | 0.343 | 1.60 | 188 | 504 | 534 | 647 | 321 | 0.337 | 1.56 |
| 161.1  | 430.7 | 439.7 |
The engineering parameters were calculated and the results are summarized in table 5, whereas the complete results are plotted in Figures 5 and 6. Interestingly, when these results were extrapolated, several noteworthy results were found.

The Concentration Index (Ci) value of the soil ranged between 3.41 at the depth of 9m, 4.08 in BH1, and 3.86 to 4.08 in BH2 (Figure 5). Stress Ratio (Si) values ranged between 0.505 and 0.710 in BH1 and 0.480 to 0.545 in BH2. The Material Index (Mi) values ranged from -0.41 to -0.31 in BH1 and BH2. Ultimate Bearing Capacity (Qult) values ranged between 459 and 939 in BH1 and 568 to 917 in BH2, while the uppermost layers, within 6m, had the lowest values of allowable Bearing Capacity (Qa) and the rest of the layers had the highest values (Figure 6).

N values ranged from 15 to 31.2 in BH1 and 19 to 30.5 in BH2. Most of the upper layers, above 6m, were characterized by the lowest N values, while these values increased with increasing depth in boreholes (Figures 5 and 6).

Table 5 - The calculated geotechnical engineering parameters from two boreholes data.

| No. | Ci value | Vs30 class | Si | Mi | Qult | Qa | N- value |
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Figure 5 - A graph of P and S waves, Vp/Vs, concentration index, N value, and allowable bearing capacity in borehole 1.

Figure 6 - Shows the graph between P and S waves, Vp/Vs and conc. Index, N value and allowable bearing capacity in borehole 2.

From the obtained results of the resistivity and seismic refraction surveys, a new empirical equation with a high correlation coefficient, $R^2 = 0.9751$, was derived to predict the S-wave (97.5 %) for the bedrock in the study area (Figure 7), as follows:

$$Vs = 1.0302 \rho + 172.74$$

where $Vs$ is S-wave velocity and $\rho$ is the true resistivity.

This study aids in the estimation and prediction of the properties of the subsurface material (soils and rocks). It is especially useful in reducing the cost of drilling based on
investigation as well as increasing the understanding of the Earth’s subsurface geotechnical parameters.

![Figure 7- True Resistivity (Ω.m) versus S-wave velocity (m/sec).](image)

The correlation between resistivity, borehole, and down-hole data showed that the subsoil, i.e. less than 8m, has low and variable resistivity and shear wave values. This reflects that the subsurface soil is heterogeneous with low compaction and rigidity. Soil with lower shear wave velocity is lower in bearing capacity [10]. The values of resistivity and shear wave increased from the depth more than 6 m to the end of the borehole. This indicates that the competence and bearing capacity increase, as shown in Figures 5 and 6. In addition, N values increased from top to bottom in the two boreholes. Finally, the NEHRP site classification revealed that soil classes in general reflect sites of class D.

**Conclusions**

ERT and shear wave data were used to delineate the subsurface soil’s structural elements, and calculate the dynamic geotechnical properties of the soil in the Tenth of Ramadan City, which is a suggested site for the construction of factories. The results of the geotechnical properties of the soil and competence scales reveal that the competence of the soil increases with increasing the depth, ranging from fairly to moderately competent material. The integration between the results of ERT, seismic interpretation, and geotechnical properties of soil show that the study site consists of two subsurface layers; the uppermost is weathered soil, with a thickness of 6 m, very low shear wave velocity, lower bearing capacity. The competence of the soil increase at depth more than 6m, characterized by not detectable subsurface structure (fracture or faults). Hence, it is concluded that this site is suitable for constructing factories. The present work can be utilized as a preliminary engineering site investigation technique to mitigate the potential hazards. It was intelligible that the information coming from ERT resistivity inversion and seismic refraction results allow describing the subsurface layers distribution with geoenengineering data in a low cost strategy. Finally, the present study aids in the estimation and prediction of geotechnical properties of soils and rocks.

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