Original paper

Subsurface Cavities Development Detection Using Resistivity and some Geotechnical Properties, Red Sea, Sudan

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Abstract
Resistivity method with some geotechnical properties (TOP, Densities and Bearing Capacities) were used to evaluate the development of cavities to sinkholes in the area between Port-Sudan and Suakin, Red Sea coast. The interpretation of resistivity values show that, the subsurface uncompact, unconsolidated layers are characterized by low resistivity values. The Standard Penetration Test (SPT) and wet densities in sites (Green area, Dama Dama and Suakin) were give a fit overlap results after data processing by Rockware -4 program. In contrast, the resistivity values define the approximately the same localities of weakness and under developing cavities.

Keywords: Red Sea Coast, sinkholes, cavities, resistivity method, geotechnical properties.

1. Introduction
Detection of the sinkholes and subsurface cavities is not always straight forward due to the highly variable and unpredictable target characteristics (Van Schoor, 2002). Resistivity Tomography (RESTOM) widely used in engineering purposes for shallow depths (Griffiths and Barker, 1993; Daily et al, 2004) and it is applicable for exploration, environmental science and engineering (Van Schoor and Duvenhage, 2000; Barker and Moore, 1998; Maillol et al., 1999). However, geophysical methods can provide a cost-effective solution to investigating the subsurface formation and detecting cavities, voids and galleries. The seismic methods have been tested for the potential of detecting underground voids based on the techniques of P-wave reflection and subsurface wave refraction.

The Sudanese coastal plain is characterized by rapid acceleration development and growth. Unfortunately, there is no geotechnical or hazard map for future or present planning except some information on geology and hydrogeological studies initiated by private companies or research students. The intensive geotechnical investigation have been done by Al-Imam (2005) followed by detailed studies extended to the continental shelf.

Four sites had been chosen along the Sudanese coast extended 60 km from Port-Sudan to Suakin harbor. These sites named; 1/ Green Area, 2/ Dama-Dama, 3/ Free Zone and 4/ Suakin respectively. It is boarded by19° 00’ ; 19° 50’ N, 37° 00 ; 37° 30’ E (Fig. 1).

2. Geology
All sites are located on karst formation which is characterized by different types of limestone such as coralline limestone, fossilized limestone, and chemical precipitated limestone. The coastal plain on which the drainage system running through has varied view of alluvial terrains deposits such as fans of Pleistocene debris spreading along seaward. The coastal plain has been dissected by more recent streams activity. In general, the alluvial deposits refer to the period of higher rainfall on the surrounding highland.

Recent sand is commonly coarse and arkosic associated with heterogeneous gravels. These are lateral gradation form unsorted screes stratified and current-bedded sands and more rounded gravels. Some paleo- outcrops of coral reef are overlain by clastic deposits and other Pliocene and tertiary exposed to weathering and erosion during the marine regression. However, the coastal plain of the Red...
Sea is underlain by Tertiary and Mesozoic sediments, overlying unconformably the basement rock.

Subsurface condition: more than thirty exploration boreholes were drilled to studying the stratigraphy and subsurface weathering grade (Al-Imam et al., 2015, 2013). The stratigraphy sequence of the area consists of two types of facies which are intercalated clastic deposits and coral reef limestone. In Suakin, sand and muddy siltstones are dominant. Solution channels appeared in Port Sudan area due to the intrusion of saline water causing chemical weathering. Suakin area has been subjected to the sea level oscillation and no evidence of solution channels prevalence of physical weathering condition. Compaction, consolidation, grain size and cementing materials are the controlling factors behind the formation of the solution channels which cause damage in the intermediate strata (Al-Imam et al., 2013).

3. Geotechnical properties of the area
The geotechnical properties of mixed marine sediments were studied by Al-Imam et al. (2013). Moisture content, specific gravity, dry and wet densities, saturation, void ratio and consistency were predicted as physical properties. Direct shear, compressibility, and consolidation in Dam-Dama (Table 1; Table 2) were also predicted for pile foundation in the continental shelf and shoreline in karst formation (Al-Imam et al., 2014).

The weathering grade variations depend on the mineral constituent, chemical condition and other geotechnical properties of carbonate rocks such as compaction and consolidation. However, according to weathering grade the surface and bottom carbonate layers in site (1) and (2) are moderately weathered (III) whereas, all the residual and coral limestone in between are highly (IV) and completely (V) weathered (Al-Imam et al., 2015).

4. Methodology
The resistivity data was derived from vertical electric sounding (VES) measurements, using ABEM Terameter SAS 1000. Profile of three VESES (650m) in sites 1, 2, and 4 have been done parallel to coastline and two VESs in site 3. And 54 boreholes distributed in whole area of study in range depths between 4 to 32m (Al-Imam, 2005). It is based on Schlumberger configuration and the data converted to 2D and 3D geological models by computer process using RockWare 2004 software program. The vertical profile changing used to provide information on the variation in the resistivity of subsurface layers with depth and compared with subsurface densities and SPT values which have been detected by Al-Imam et al. (2013). Other geotechnical properties may have been used for comparisons and relations with resistivity values such as the total overburden pressure (TOP) and bearing capacities.

Table 1: Physical Properties of Subsurface Sediments

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Sediments type</th>
<th>Moisture Content W%</th>
<th>Sp. Gr. GS</th>
<th>Wet Density γwet</th>
<th>Dry Density γd</th>
<th>Saturation Degree Ss</th>
<th>Void Ration</th>
<th>Atterberg Limit</th>
<th>Cc</th>
</tr>
</thead>
<tbody>
<tr>
<td>SB2-1</td>
<td>MS</td>
<td>27.7</td>
<td>2.72</td>
<td>1.96</td>
<td>1.53</td>
<td>97.6</td>
<td>0.772</td>
<td>29.7</td>
<td>20.1</td>
</tr>
<tr>
<td>SB2-2</td>
<td>C</td>
<td>45.9</td>
<td>2.72</td>
<td>1.77</td>
<td>1.21</td>
<td>100</td>
<td>1.242</td>
<td>60.1</td>
<td>38.3</td>
</tr>
<tr>
<td>SB2-3</td>
<td>C</td>
<td>27.9</td>
<td>2.70</td>
<td>1.90</td>
<td>1.49</td>
<td>91.3</td>
<td>0.831</td>
<td>45.3</td>
<td>28.2</td>
</tr>
<tr>
<td>SB3-1</td>
<td>C</td>
<td>33.1</td>
<td>2.73</td>
<td>1.90</td>
<td>1.43</td>
<td>99</td>
<td>0.912</td>
<td>56.8</td>
<td>30.7</td>
</tr>
<tr>
<td>SB4-1</td>
<td>SL</td>
<td>25.4</td>
<td>2.73</td>
<td>1.88</td>
<td>1.50</td>
<td>84.5</td>
<td>0.821</td>
<td>28.0</td>
<td>19.6</td>
</tr>
<tr>
<td>SB6-1</td>
<td>C</td>
<td>34.2</td>
<td>2.73</td>
<td>1.90</td>
<td>1.42</td>
<td>100</td>
<td>0.928</td>
<td>47.7</td>
<td>30.6</td>
</tr>
<tr>
<td>SB6-2</td>
<td>C</td>
<td>39.9</td>
<td>2.74</td>
<td>1.78</td>
<td>1.27</td>
<td>94.8</td>
<td>1.154</td>
<td>76.1</td>
<td>46.4</td>
</tr>
</tbody>
</table>
Table 2: Mechanical Properties of Sediments- Dama-Dama

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Direct Shear Test</th>
<th>Direct Shear Strength</th>
<th>Compressibility Mode</th>
<th>Compressibility Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C KPa</td>
<td>φ</td>
<td>KPa 25</td>
<td>KPa 50</td>
</tr>
<tr>
<td>DB2-1</td>
<td>38.2</td>
<td>36.4</td>
<td>50.44</td>
<td>68.39</td>
</tr>
<tr>
<td>DB2-4</td>
<td>25.5</td>
<td>39.6</td>
<td>44.88</td>
<td>69.11</td>
</tr>
</tbody>
</table>

5. Results and discussion

The formation of the area is in form of intercalation of carbonate and clastic materials that drifted by the active drainage system. The sequence based on carbonate layers are divided in two different resistivity characters, High value at the top and low value at the bottom in all sites except layer three in Suakin area. (Table3). The clastic materials forming the middle layer is varying in thickness from site to another. The top carbonate layer is covered by a thin uncompact clastic deposit. From the resistivity data, four geo-electric sections have been constructed (Fig. 2, a, b, c, &d). These results show that such site consist of five layers.

The karst is characterized by low resistivity and seismic velocities, (Table 3; Al-Imam, 2005) and by very strong lateral variations compared to compact carbonate rocks that characterized by high resistivity and seismic velocities. This indicated to the resistivity values in sites 1, 2, and 3, where high values were recorded (Table 3). It might be due to the compaction and consolidation of surface layers. In contrast, the low values may attribute to residual soil, porous, joints, fractures and shell fragments filled by solvable silt and clay when in countered in water. The anomalies readings in site (4), indicate te isolated lenses, non-homogeneous continuous strata and varying in their densities and weathering grade.

The 3D bulk models represent the subsurface zones which have low resistivity values in each site. However, in the Green area (site 1) a huge hole appears as sinkhole after encountered the low resistivity values (Fig.3a). The surface layer has extremely low density but a little bit high resistivity (Table 3; Fig.3b).

Table (3): Shows the resistivity data, each site consist of five layers converted to 2D&3D models (Figs.2, a, b, c, d).
From the resistivity data, four geo-electric sections have been constructed (Fig. 2, a, b, c, &d). These results show that such site consist of five layers.

Fig. 2: Geo-electrical sections of the sites
In Dama-Dama (site 2), the 3D bulk model show the weakness subsurface zone (Densities, SPT values) (Fig.4a) which significantly clarified when the low resistivity values (<9000) have been avoided (Fig.4b). The distribution of wet densities (Fig.4c) show the highly development processing indicated that the cavities under development represent, almost sinkholes towards the land. This confirmed by SPT test which reflect the state of density, compaction and consolidation and when the low values <20 were avoided the 3D resistivity model as such as density shows the cavities development (Fig.4 d).

The Free Zone (site3) is an area of salt marshes and mangroves and very fine saturated soil rich in organic matters looks like swamp area. These characters are contributed to decrease the resistivity values (less than 12 in the scale of 3D model (Fig.5) and the wet density were not detected. Generally, the resistivity decreasing with depth and the high values at the surface could be attributed to salt marshes and brine water.

Suakin (site 4) is characterized by high and completely weathered layers, high porosity, and high saturation degree reaches 100% in clay and muddy siltstone (Al-Imam et al, 2013). The 3D model shows the distribution of resistivity in the area (Fig.6a). The high resistivity value was recorded in the bottom carbonate layer (6241.6 Ohm-m) and when avoiding the values <400 (Fig.6b) gives an anomalous result
due to the complicated stratigraphy of the area. In contrast, the subsurface cavities appear when avoiding the density values <1.95 (Fig. 6c). For more conformation, the SPT data (Al-Imam, 2005) have been used after the values <20 have been avoided (Fig. 6c). Moreover, the ultimate bearing capacities were investigated by Al-Imam (2005) along the area between Port-Sudan and Suakin. In Dama-Dama and Suakin, the subsurface sediments are characterized by highly weathering grade and very low bearing capacity clarified after avoiding one third of the values (Fig. 7 a & B).

Fig. 5: 3D module of resistivity values, Free Zone

Fig. 6: 3D models in Suakin, a: resistivity values, b: After avoid low values (<400), c: After avoid low densities values (<1.95), and d SPT after avoid <20 values, Suakin.
However, the development potentiality should be high because of high degree of subsurface weathering, high creation processing of voids, cavities and loose soil were located at depth <25m anticipated to be high risk. The resistivity increase when voids and cavities filled with air and decrease if they filled with clay and saline water. In all sites, voids, cavities, fractures and joints are often filled either with saturated clay fraction materials such as carbonate minerals or salt crystals and shell fragments. However, climate and drainage system in the area are very important factors causing the interaction between fresh and subsurface saline waters.

The subsurface zones in sites 1, 2 and 4 are interpreted as highly weathered limestone. It is important to remark that the developed cavities occurred within the weathered carbonate layer. Nevertheless, the geophysical surveys are the best to provide geometrical information of subsurface structures. The electrical resistivity profiles in the area have provided information and distribution of the stratigraphic units, and subsurface weak zones. The SPT and wet densities results give a good investigation and information confirming the cavities development. .

6. Conclusions
The stratigraphy formation from Port Sudan to Suakin along the coastal line based on weathered carbonate layer subjected to intensive physical and chemical subsurface weathering. The deposition of clastic materials layers that could be attributed to tides and drainage system towards the sea has very poor geotechnical properties. The geo-electrical investigation with some physical and mechanical studies could be useful to explore the subsurface characteristics (Table 4). Moreover, bearing capacity studies should be encouraged in these substances for any engineering constructions as such as in Dama-Dama and Suakin. However, the allowable bearing capacity of sites (2 & 4) was calculated and gives very small bulk mass (Fig. 7, a & b). Strongly recommended is more geo-hazard investigation for future engineering events.

Table 4: The relationship between N. value, density, resistivity and weathering grade

<table>
<thead>
<tr>
<th>N. Value</th>
<th>Density</th>
<th>Resistivity Value</th>
<th>Weathering Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;10</td>
<td>Very loose</td>
<td>230</td>
<td>VI</td>
</tr>
<tr>
<td>10-20</td>
<td>Loose</td>
<td>500</td>
<td>V</td>
</tr>
<tr>
<td>21-30</td>
<td>Medium dense</td>
<td>1300</td>
<td>IV</td>
</tr>
<tr>
<td>31-40</td>
<td>Dense</td>
<td>1800</td>
<td>III</td>
</tr>
<tr>
<td>41-50</td>
<td>Very dense</td>
<td>2100</td>
<td>II</td>
</tr>
<tr>
<td>&gt;50</td>
<td>Highly dense</td>
<td>&gt;3000</td>
<td>I</td>
</tr>
</tbody>
</table>

References


