Engineering properties of Red Sea coastal plain soils

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ABSTRACT: The coastal plains north and south of Port Sudan cover vast areas between the Red Sea Coast and the Red Sea Mountains. Data was collected from extensive geotechnical studies made for construction projects within the area and a data bank consisting of more than 75 boreholes and test pits was developed in this study. The study revealed that the area is covered by recent deposits such as estuarine, delta, alluvial and sabkha deposits underlain or mixed with coral reef formations. The soils generally consist of a mixture of sand, silt and clays. The coastal plain soils are generally loose to medium dense (or soft to firm). The in-situ permeability is generally high compared to laboratory-measured permeability. Use of sea water slightly increased the laboratory-measured permeability. The unconfined compressive strength of samples compacted dry of optimum is much higher than that for samples compacted wet of optimum.

1 INTRODUCTION

The Red Sea extends from the Gulf of Suez and Gulf of Agaba southeastward to the Gulf of Aden in the Indian Ocean. Geologically the Red Sea province is a Tertiary cratonic rift (Lindquist, 1998). The coastal plains of the Red Sea in Sudan extends over a distance of 650 km. The length can increase to 750 km if the lagoons and gulfs are included (see Figure 1). The width of the coastal plains, however, is a few kilometers. The coastal plains are generally flat and bounded by the Red Sea in the east and the Red Sea Hills in the west. A number of seasonal water courses originate from the Red Sea Hills and deliver water to the Red Sea. Arbaat Delta Fan (North of Port Sudan) and Tokar Delta (South of Port Sudan) are the most well known of these seasonal water courses.

The Red Sea coastal area experienced rapid development in the recent years where new ports, oil refineries, oil storage tanks and fish facilities were constructed. Extensive geotechnical investigations were made before the construction of these facilities (BRRI 1995-1998). Information on soil properties was collected from these investigations and analyzed in this study. The data bank consists of more than 75 boreholes and test pits. The study area extends from 40 km north of Port Sudan to about 100 km south of Port Sudan (see Figure 1). Because of the variation of soil properties the data is analyzed using statistical methods.

2 SOIL CONDITIONS

The coastal plains north and south of Port Sudan contain delta fans and coastal lagoons (locally known as marsahs). The area is generally covered with grasses and bushes and some of the land is used as agricultural farms. The area generally has poor surface drainage as evidenced by the trapped rain water.

Soils exposed on the Red Sea coastal plains consists of recent deposits such as estuarine, delta, alluvial and sabkha soils mixed with corals and shells. The soils can be classified into three major groups:
1. Sand group which includes silty sand (SM) and clayey sand (SC).
2. Low plastic fine grained soils that consists of low plastic silty clay (CL) and low plastic clayey silt (ML)
3. Highly plastic fine grained soils such as highly plastic clay (CH) and highly plastic silt (MH)

A typical soil profile consists of fine grained soils (CL, ML, CH or MH) overlying silty sand (SM) and clayey sands (SC) (see Figure 2). The sand deposits grade into well graded sand (SW) and well graded gravel (GW) with depth. Thin seams of silty clay (CL) inter-bedded within the deeper sand deposits. The thickness of the upper layer of fine grained soil generally decreases from sea toward the land which is a typical trend for estuarine deposits (Mitchell 1993). In some locations (specially north of Port Sudan) fringing reef colonies cover the Portion of the coastal plains adjacent to the sea.
Figure 1. Study area.
3.1 General
The following engineering properties of soils were measured:
1. Grain size distribution (GSD)
2. Atterberg limits (LL and PI)
3. Natural moisture content (NMC)
4. Standard Penetration Test (SPT) value (N)
5. Unconfined compressive strength (q_u)
6. Compaction parameters (optimum moisture content OMC and maximum dry density MDD)
7. Coefficient of permeability (k)

Because of the variation of the soil properties within each soil group statistical methods were used to describe the soil properties. Sample statistics such as mean, median, standard deviation, coefficient of variation, minimum and maximum values, inter-quartile range and confidence interval for the mean are considered appropriate (Lo & McCabe 1984, Cherubini & Giasi 1993). In addition statistical methods such as box plots were used to reject any outliers (Montgomery & Runger 1999). The probability distribution of soil parameters can be assumed to follow those published in the literature (e.g. Harr 1977, Medani et al 1999, Ejezie & Harrop-Williams 1984).

3.2 Grain size distribution (GSD)
Extensive sieve analysis tests were performed to determine the GSD curves. The results of sieve analysis are summarized for each soil group in Table 1. For the sandy soil group the percentage of gravel, sand and fine fraction (silt and clay) are shown in Table 1. For the low and highly plastic fine grained soils groups only the percentage of fines is shown.

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Soil Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00</td>
<td>V. dense light brown fine silty SAND</td>
</tr>
<tr>
<td>2.00</td>
<td>Loose light brown fine sandy SILT</td>
</tr>
<tr>
<td>3.00</td>
<td>Medium dense silty SAND</td>
</tr>
<tr>
<td>4.00</td>
<td></td>
</tr>
<tr>
<td>5.00</td>
<td>Medium dense sandy clayey SILT</td>
</tr>
<tr>
<td>6.00</td>
<td>Loose silty clayey SAND</td>
</tr>
<tr>
<td>7.00</td>
<td></td>
</tr>
<tr>
<td>8.00</td>
<td>Soft sandy silty CLAY w. coral</td>
</tr>
<tr>
<td>9.00</td>
<td>Loose coralline clayey silty SAND with gravel</td>
</tr>
<tr>
<td>10.00</td>
<td></td>
</tr>
<tr>
<td>11.00</td>
<td>Medium dense silty SAND</td>
</tr>
<tr>
<td>12.00</td>
<td>Dense gravelly silty SAND w. cobbles</td>
</tr>
<tr>
<td>13.00</td>
<td>Very stiff brown silty CLAY w. limestone</td>
</tr>
<tr>
<td>14.00</td>
<td>V. dense grey gravelly SAND w. cobbles</td>
</tr>
<tr>
<td>15.00</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2. Typical soil profile.

3.2.2 Grain size distribution for low plastic fine grained soils group

The percentage of gravel in this soil group is generally very low and in most cases no gravel is present. The presence of gravel-size particles is mainly attributed to the presence of corals and shells. The percentage of sand particle varies over a narrow range (average value 63% and median 62%). This is also evidenced from the low coefficient of variation, the confidence interval and the inter-quartile range. The percentage of fines (silt and clays) is high for these type of soils (average value 27.5%). The coefficient of variation is also high (36%) but is much less than that for calcareous sand in the area (Medani et al 1999).

3.2.3 Grain size distribution for highly plastic fine grained soils group

Highly plastic soils are identified only in the area north of Port Sudan. The percentage of fines is very high for these soils (above 90%) which is typical for delta soils.

3.3 Atterberg limits

The Atterberg limits are shown for the different soil groups in Table 1. For sandy soils the fine fraction is generally low plastic. Some few samples of silty sand (SM) are non-plastic. The low plastic fine grained soils (CL and ML) show an average LL of 35 and an average PI of 13. Very few samples of ML are non-plastic. The highly plastic soils (CH and MH) possess a LL that varies in a narrow range (52 to 60) and a PI in the range 18 to 30. The variation of LL for all soils is generally low with coefficient of variation less than 20% which is much less than the values reported in the literature for similar soils (Ejezie & Harrop-Williams 1984). On the other hand
the variation in PI is generally high with coefficient of variation of up to 46%.

3.4 Natural moisture content

Table 1 shows the variation of natural moisture content for different soil groups. High moisture content values were measured even for the sandy soils due to presence of the high percentage of fine grained soils. The variation of natural moisture content (coefficient of variation up to 48% and inter-quartile range up to 16%) is high across the study area because of the difference in topographical details and the season of the site investigation.

3.5 SPT-N values

Extensive SPT tests were performed specially for sandy soils and a summary is given in Table 2. SPT tests were also conducted on fine grained soils because of unsuccessful attempts to obtain undisturbed (up to 75%). This is in agreement with published data (Medani 1999, Briaud & Tucker 1984). In the Red Sea coastal plains shells and corals are usually found intermixed with soils resulting in artificially high N values. In this environment special methods were suggested for foundation design based on SPT (Hagenaar 1982). The general practice in the area is to preload the site of loose or soft soils with a temporary surcharge (Mohamedzein et al 1997).

3.6 Unconfined compressive strength (q_u)

The unconfined compressive strength of few undisturbed samples of low plastic silty clay was measured and was found to vary between 13 to 25 kN/m², indicating this soil is soft. The measured moisture content ranged from 25 to 42%. Conversely, q_u for compacted soils is very high for all soil groups as shown in Table 2. The average value for SM and SC soils is about 113 kN/m²; 150 kN/m².
Based on the data the general trend is that $q_u$ decreases with increase in moisture content. This is clearly shown in Table 3 where the unconfined compressive strength for samples compacted dry of optimum is much higher than that for samples compacted wet of optimum.

<table>
<thead>
<tr>
<th>Sample number and type</th>
<th>Moisture content (%)</th>
<th>Wet or dry</th>
<th>$q_u$ (kN/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (CH)</td>
<td>28.3</td>
<td>Dry</td>
<td>323</td>
</tr>
<tr>
<td>1 (CH)</td>
<td>32.2</td>
<td>Wet</td>
<td>148</td>
</tr>
<tr>
<td>1 (CH)</td>
<td>37.0</td>
<td>Wet</td>
<td>60.2</td>
</tr>
<tr>
<td>2 (CH)</td>
<td>21.5</td>
<td>Dry</td>
<td>357</td>
</tr>
<tr>
<td>2 (CH)</td>
<td>24.4</td>
<td>Wet</td>
<td>255</td>
</tr>
<tr>
<td>2 (CH)</td>
<td>26.6</td>
<td>Wet</td>
<td>180.7</td>
</tr>
<tr>
<td>2 (CH)</td>
<td>30.0</td>
<td>Wet</td>
<td>83</td>
</tr>
<tr>
<td>3 (CL)</td>
<td>12.7</td>
<td>Dry</td>
<td>157.73</td>
</tr>
<tr>
<td>3 (CL)</td>
<td>15.7</td>
<td>Wet</td>
<td>73.2</td>
</tr>
<tr>
<td>3 (CL)</td>
<td>18.3</td>
<td>Wet</td>
<td>33.93</td>
</tr>
<tr>
<td>4 (SC)</td>
<td>8.9</td>
<td>Dry</td>
<td>178.7</td>
</tr>
<tr>
<td>4 (SC)</td>
<td>11.4</td>
<td>Dry</td>
<td>161</td>
</tr>
<tr>
<td>4 (SC)</td>
<td>14.2</td>
<td>Wet</td>
<td>92</td>
</tr>
<tr>
<td>4 (SC)</td>
<td>17.6</td>
<td>Wet</td>
<td>48.9</td>
</tr>
<tr>
<td>5 (SM)</td>
<td>13.3</td>
<td>Dry</td>
<td>121.6</td>
</tr>
<tr>
<td>5 (SM)</td>
<td>16.7</td>
<td>Wet</td>
<td>107.7</td>
</tr>
<tr>
<td>5 (SM)</td>
<td>20.0</td>
<td>Wet</td>
<td>38.5</td>
</tr>
<tr>
<td>6 (SM)</td>
<td>8.4</td>
<td>Dry</td>
<td>189.9</td>
</tr>
<tr>
<td>6 (SM)</td>
<td>11.6</td>
<td>Wet</td>
<td>71.2</td>
</tr>
<tr>
<td>6 (SM)</td>
<td>14.0</td>
<td>Wet</td>
<td>35</td>
</tr>
</tbody>
</table>

3.7 Compaction parameters

The compaction parameters (maximum dry density (MDD) and optimum moisture content OMC) are listed in Table 2 for all soil groups. As expected the optimum moisture content increases with the increase in fine contents with highest OMC for MH/CH soils and lowest OMC for SM/SC soils, while the CL/ML soils showing intermediate values. The trend for MDD is just the opposite. The variation of the measured compaction parameters, specially MDD, is small within a given soil group. This supports previously published results (Harr 1977, Cherubini & Giasi 1993).

3.8 Permeability

Facilities constructed at the Red Sea coastal plains, such as fish aquaculture and salt plants, require knowledge of the permeability of the soils. Data was collected from different field and laboratory permeability tests. Laboratory tests were conducted for undisturbed and compacted soil samples using tap water and sea water as permeates. Table 4 shows the measured coefficient of permeability for different soils and different testing conditions. Statistical summary for $k$ for both sandy and fine grained soils was performed and shown in Table 2. As expected the coefficient of permeability decrease as the percentage of fines increases. The average values are generally within typical range for these types of soils (Terzaghi et al 1996). Table 4 indicates that the values of coefficient of permeability obtained from the field are an order of magnitude higher than those obtained from the laboratory tests for undisturbed soil samples. On the other hand the $k$ values for compacted samples are smaller than those for undisturbed samples. It is likely that compression associated with collection of undisturbed resulted in a decrease in voids, thus giving a lower $k$ values than the measure field values. Also soil structure in the field such as fissures and preferred paths may have resulted in an increase in the coefficient of permeability. Therefore it is reasonable to assume that the correct value is somewhere between the field and laboratory values (i.e. a value similar to statistical average shown in Table 2).

The compaction results in a completely different structure and fabric of the soil leading to different $k$ values.

One test was performed using sea water as a permeate instead of tap water as shown in Table 4. The tap water slightly increases the value of $k$, however; this finding is not conclusive and further investigation is required.

4 SUMMARY AND CONCLUSIONS

Data was collected from more than 75 boreholes and test pits within the Sudanese Red coastal plain soils. The soils in this area generally consist of fine grained soils overlying silty and clayey sand. Highly plastic silts and clays (MH and CH) were identified north of Port Sudan. These soils are typical for a delta and lagoon deposits. Statistical summary of engineering properties of soils is given. High variability was observed for unconfined compressive strength, coefficient of permeability and SPT-N values.

The soils are loose or soft and will require preloading by a temporary surcharge to reduce the post construction settlement and improve the shear strength.

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Sample type</th>
<th>$k$ (cm/sec)</th>
<th>Type of test</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM</td>
<td></td>
<td>3.8E-04</td>
<td>Field</td>
</tr>
<tr>
<td>SM</td>
<td></td>
<td>7.6E-04</td>
<td>Field</td>
</tr>
<tr>
<td>SM</td>
<td></td>
<td>1.5E-03</td>
<td>Field</td>
</tr>
<tr>
<td>SM</td>
<td>Compacted</td>
<td>6.2E-05</td>
<td>Laboratory</td>
</tr>
<tr>
<td>SC</td>
<td></td>
<td>1.9E-03</td>
<td>Field</td>
</tr>
<tr>
<td>SC</td>
<td></td>
<td>4.0E-04</td>
<td>Field</td>
</tr>
<tr>
<td>ML</td>
<td></td>
<td>9.6E-06</td>
<td>Field</td>
</tr>
<tr>
<td>CL</td>
<td>Undisturbed</td>
<td>2.3E-08</td>
<td>Laboratory</td>
</tr>
<tr>
<td>CL</td>
<td>Undisturbed</td>
<td>1.0E-06</td>
<td>Laboratory</td>
</tr>
<tr>
<td>CL</td>
<td>Undisturbed</td>
<td>1.9E-06</td>
<td>Laboratory</td>
</tr>
<tr>
<td>CL</td>
<td>Compacted</td>
<td>5.5E-08</td>
<td>Laboratory</td>
</tr>
<tr>
<td>CL</td>
<td>Compacted</td>
<td>9.7E-08</td>
<td>Laboratory</td>
</tr>
<tr>
<td>MH/CH</td>
<td>Undisturbed</td>
<td>9.6E-08</td>
<td>Laboratory</td>
</tr>
<tr>
<td>MH</td>
<td></td>
<td>6.5E-06</td>
<td>Field</td>
</tr>
<tr>
<td>CH</td>
<td>Compacted</td>
<td>2.8E-08</td>
<td>Laboratory</td>
</tr>
</tbody>
</table>

* Same as the sample above it but permeate is sea water
REFERENCES


