

# Regional Report for the Middle East and Africa

T.M. Elkateb

*Ain Shams University, Cairo, Egypt/ Sogreah Gulf, Dubai, UAE*

**ABSTRACT:** This report presents the state of practice of the Cone Penetration Test (CPT) in the Middle East and Africa. A brief description of the regional geology is provided together with its implications on the use of CPT. The main geotechnical challenges in the area are briefly presented. Different CPT aspects related to the study area, such as equipment and standards, applicability, interpretations in different soils, and direct applications in geotechnical design, are discussed. Finally, the state of research and future trends in the use of CPT are highlighted.

## 1 INTRODUCTION

This report provides a summary of the state of practice of the Cone Penetration Test (CPT) in the Middle East and Africa. This region, which covers 56 countries in Africa and 12 countries in the Middle East, is bound by the Indian Ocean and the Persian Gulf to the east, the Atlantic Ocean to the west, and the Mediterranean Sea to the north; as shown in Figure 1.

Africa is the world's second-largest continent with a total area of about 30 million km<sup>2</sup> and a total population of about one billion people. The climate of Africa is mostly warm to hot with the humidity and rainfall varying significantly from the tropical central parts to the desert areas in the north, east and the south. The climate in the Mediterranean Sea countries and the southernmost countries is relatively moderate compared to other parts of the continent. The Middle East, excluding Egypt, occupies the western part of Asia with a total area of 5.2 million km<sup>2</sup> and a total population of about 125 million people, excluding Turkey and Iran. The climate of the Middle East is generally hot and dry with parts like the Arabian Peninsula considered one of the hottest and driest parts of the world. Winters are usually mild with some rain mostly localized in the areas around the Mediterranean Sea.

The use of the CPT is very limited in most of the countries in Africa and the Middle East due to several factors. These factors range from unsuitable geological conditions, as discussed in the following sections, in most of the Middle East countries to shortage of equipment and adequate experience in most of the Sub-

Sahara countries in Africa. Therefore, the use of CPT has traditionally been limited to countries like the United Arab Emirates (UAE), Egypt, some parts of North Africa, and South Africa. Recently, most of the CPT-related activities have been concentrated in the Persian Gulf countries due to the launch of several mega-scale projects that involve sand-reclaimed manmade islands, particularly in the UAE. Due to the limited information available on the CPT state of practice in South Africa at the time of this report preparation, emphasis in this report will be on the CPT practice in the UAE (as an example of the Persian Gulf countries), Egypt, and some parts of North Africa.



Figure 1. Political map of Africa and the Middle East (Courtesy of [www.learnnc.org](http://www.learnnc.org))

## 2 REGIONAL GEOLOGY

It is believed that a detailed description of the geology of Africa and the Middle East is impractical and may not be relevant to the scope of this report. Therefore, only a brief description of the main geological features of these areas is provided in this section.

Africa is generally made up of a large ancient stable crystalline basement, mainly of Precambrian age, that consists mainly of metamorphic and igneous rocks. This basement is divided into three large cratons, the Kalahari, Congo, and West African cratons, by mobile belts that were active in the late Precambrian and early Palaeozoic ages. Along the coastal areas, the basement was covered with sediments of Mesozoic and Tertiary age that were deposited in marginal marine basins. During these geological times, other features were formed, such as the Atlas Mountains in the North West and the Cape fold belt in the south. Very thick glacial deposits, such as sandstone and varved clay, were deposited with the start of glaciations in the Permo-Carboniferous age and continued throughout the Permian, Triassic, and Jurassic times. These glacial deposits were followed with coal, shale, sandstone, and finally with basaltic plateaus in the late Triassic and Jurassic times. Marine troughs were developed along the continent margins in the late Jurassic and early Cretaceous times. This was accompanied by faulting and flexing in the continental basement resulting in the formation of the East African Rift System. Soil covers in Africa are diverse and range from fluvial deposits along the route of various rivers, such as the Nile and the Congo, to soft marine deposits along the narrow coastal areas, to sand dunes in the Sahara desert. For more information, the reader may refer to the USGS Open File Report 97-470A "Map Showing Geology, Oil and Gas Fields and Geologic Provinces of Africa" by Persits et al. (2000).

The Middle East is also characterized by a large Precambrian crystalline basement that consists mainly of igneous and some metamorphic rocks. Epi-continental sediments, mainly sandstones of different kinds, were laid on the basement rocks in the Palaeozoic times. In the late Palaeozoic and Mesozoic ages, sandstone deposition was characterized by intercalations of limestone and inclusions of igneous rocks and large scale lava flows resulting in a complex geological profile. Tectonic movements during these times resulted in some intense folding and thrusting, which was manifested in the Zagros ranges and the Northern Oman mountains. These tectonic movements resulted also in the outpouring of volcanic basalts in some areas, particularly Jordan and Syria. Soil covers in the Middle East were of Quaternary age and consist of sand and gravel in addition to limited areas of lacustrine deposits and coastal sabkha. For more information, the reader may refer to the USGS Open File Report 97-470B "Maps Showing Geology, Oil and Gas Fields and Geologic Provinces of the Arabian Peninsula" by Pollastro et al. (2000).

### 3 GEOTECHNICAL CHALLENGES

As explained earlier in this report, the focus of this report will be on the geotechnical challenges in the Middle East and North Africa (MENA).

The site investigation practice in the MENA area mainly involves borehole drilling using the percussion technique in soil and rotary drilling in rock. The Standard Penetration Test (SPT) is the most commonly used field test and it is routinely performed at 1 to 1.5 m depth intervals during advancement of boreholes. The use of CPT in geotechnical ground investigation is mostly localized in the Persian Gulf area in general, and the UAE in particular. The CPT in these areas is primarily used as a quality control measure for densifications/improvement works in reclamation sand fills. The Pressuremeter test is sometimes used in the Persian Gulf countries to

provide information on the deformability of weak rocks and the insitu state of stresses.

Several geotechnical challenges are present in the MENA area. These challenges can be summarized as follows:

- Stability and serviceability of shallow foundations on the soft compressible clay commonly encountered along the route of the River Nile in Egypt and Sudan, and in deltaic areas in Morocco.
- Ground treatment for problematic soils, such as the collapsible and expansive soils commonly found in the arid to semi-arid regions in several countries in the area.
- Deep foundations in calcareous sediments ranging from weakly cemented sand to marl and calcareous sandstones.
- Dewatering and water tightness requirements for deep excavations in the coastal surficial sand with shallow groundwater table.
- Liquefaction mitigation measures for sand-reclaimed areas in the Persian Gulf area.
- Tunneling in water-bearing sand and squeezing ground conditions.
- Driving of piles and sheet pile walls in cemented soils and very weak rocks for off-shore geotechnical applications.
- Delineation of locations of cavities in the Persian Gulf calcareous sediments.
- The use of crushed stones with relatively high carbonate contents in reclamation works, primarily due to shortage of sand supplies in the coastal areas of the Persian Gulf.
- Offshore and near-shore earth structures, such as breakwaters, on loose sand and compressible clay.

## 4 CPT EQUIPMENT & PROCEDURES

### 4.1 *Equipment*

CPT equipment with capacities up to 200 kN is commonly used in the MENA area. The vast majority of these equipments are truck-mounted but few track-mounted equipment are also available. Most of the equipment used in the Persian Gulf are state-of-the-art European made. Examples of manufacturer of the equipment commonly used in the area are AP van den Berg of the Netherlands ([www.apvdberg.nl](http://www.apvdberg.nl)) and Pagani of Italy ([www.pagani-geotechnical.com](http://www.pagani-geotechnical.com)). The equipment available in other countries, e.g. Egypt, is relatively similar; but is usually older and sometimes second-hand. There is no adequate information currently available on the equipment used in North African countries, such as Tunisia, Algeria, and Morocco. It was noticed through the author's limited experience within this area that most of the equipment used are brought to the area on a temporary basis by European site investigation contractors for use in specific projects. A photograph showing a typical CPT rig used in Dubai, UAE is shown in Figure 2.

The cones used in the CPT practice in the MENA area are typically the standard 10 cm<sup>2</sup> Piezocones. Other cone sizes, such as the 5 or 15 cm<sup>2</sup> cones are rarely, if ever, used. The data acquisition systems are typically purchased as part of the CPT equipment package. Examples of these systems are the UNICANTM and the

GONSITETM by AP van den Berg and the TGSW01TM by Pagani. It is estimated that there are 30 to 40 CPT equipment in the UAE and about 6 to 10 equipment in Egypt.



Figure 2. A photograph showing a track-mounted CPT rig used in Dubai, UAE.

#### 4.2 Standards

There are no national or regional standards for CPT practice in the MENA area. Nevertheless, some national codes like the Egyptian Code of Practice for Geotechnical Engineering – Part 1 - (2001) provides guideline for interpretation of CPT results in different soil types. Generally, the standard practice in the area is that almost all projects follow international CPT standards, such as:

- The British Standards: BS 1377: Part 9 – Insitu tests (1990): Test 3.1 Amd. 8264-95;
- The ISSMFE Reference Test Procedure (IRTP) for Cone Penetration Test 1989 and updated in 1997; and
- The American Society for testing materials: ASTM D 5778 (2007) Standard test method for electronic friction cone and piezocone penetration testing of soils and ASTM D 3441:2005 - Mechanical Cone Penetration Tests of Soil.

To the author's knowledge, no special procedure is used with other CPT-related measurements, such as pore water pressure measurement in Piezo-cones or seismic

velocity measurements in seismic CPT (SCPT). Rather, these measurements are usually taken following the above-noted standard procedure and/or text books on CPT, such as the book by Lunne et al. (1997). A photograph showing the onsite saturation of a piezocone following the procedure of the IRTP standards is shown in Figure 3.



Figure 3. A photograph showing the saturation of Piezo-cone in Dubai, UAE following the IRTP procedure.

#### 4.3 Use of CPT in Geotechnical Investigations

The amount of use of CPT in geotechnical site investigation varies significantly from one country to another in the MENA area. The CPT is more commonly used in the Persian Gulf countries primarily as a quality control measure for the various projects that involve construction of sand-reclaimed platforms (man-made islands). The number of these projects has increased dramatically in recent years especially with the introduction of some of the biggest man-made islands, such as the Palm Deira and Palm Jumeirah in Dubai, UAE. The CPT is used to a lesser extent in other countries and is typically limited to selected investigations for projects in soft ground areas along the River Nile, at some coastal areas in Northeast Egypt and North African countries and in tailings facilities in South Africa. It should be noted that the use of CPT in ground investigation is not generally common in the North African countries that are influenced by the Pressuremeter-based French geotechnical practice. The CPT is used extensively for major offshore projects along the north and west coast of Africa, but this is beyond the topic of this Report.

Based on feedback from selected geotechnical practitioners in the UAE and Egypt, it is estimated that CPT is used in almost 10 to 20% of the geotechnical site investigations in the UAE and in 1 to 2% of the investigations in Egypt. There is no adequate information currently available on the percentage use of CPT in other Persian Gulf and African countries. Pore water pressure measurements are taken in

almost all of the CPT investigations in the UAE, and the Persian Gulf countries in general, and in about 10% of the CPT investigations in Egypt. Seismic wave velocity measurements are not common in the MENA area primarily due to the relatively limited experience in analysis of seismic waves.

#### 4.4 *Challenges facing the use of CPT*

The challenges facing the use of CPT in the MENA area can be summarized as follows:

- Influence of very weak soils, such as soft clay and loose to very loose sand, on the accuracy of the CPT results;
- Refusal to penetration commonly encountered at relatively shallow depths due to the presence of hard layers and/or obstructions, such as cemented sand, gravel, large shells, etc.;
- The lack of reliable interpretation methods for CPT results in calcareous soils; and
- The limited experience of ground investigation contractors with CPT equipment and procedure.

Details of the above challenges are provided in the following sections.

##### 4.4.1 *CPT in very soft/loose soils*

As previously discussed, soft clay is commonly found along the River Nile and the Northeastern coastal areas in Egypt and at some coastal areas in Morocco. Although these soils are theoretically suitable for use of CPT, extreme difficulties have been experienced in almost all of the CPT investigations conducted in them. These difficulties ranged from problems maintaining the verticality of the CPT equipment to measurement of negative sleeve friction values recorded in the upper 1 to 2 meters. An example of the negative CPT sleeve friction resistance recorded in very soft clay in Morocco is shown in Figure 4.

##### 4.4.2 *Refusal to penetration*

Refusal to CPT penetration is commonly encountered in the MENA area due to the presence of hard layers at relatively shallow depths below ground surface. These hard layers can take several forms, such as:

- The cemented calcareous/carbonate sands commonly encountered in the coastal areas of the Persian Gulf countries. These sands are sometimes encountered at depths as shallow as 3 m below ground surface;
- The gravel-sized shells and corals that are sometimes found in dredged reclamation fills obtained from borrow areas off the coast of the Persian Gulf countries;
- The dense to very dense alluvial sands with variable amounts of gravel that are commonly found in Cairo, Egypt; and
- The meta-stable cemented silty silica sands (collapsible soil), which cover large areas of the arid and semi-arid regions of the MENA area.

##### 4.4.3 *Interpretation of results in calcareous sediments*

One of the major challenges to the use of CPT in the Persian Gulf countries is the shortage of reliable CPT-based correlations for calcareous sands. These soils are commonly found in the MENA area and can be considered the most suitable

geological unit for CPT applications. However, almost all of the CPT-based correlations available in the geotechnical literature were originally developed for clean silica sand. To overcome this limitation, most of the CPT-based geotechnical design in calcareous materials in the MENA area has been traditionally done using:

- The existing CPT correlations for silica sand only when the behavior of calcareous sand is not expected to be significantly different, i.e. when the calcium carbonate content is not more than 50 to 70% (Lunne et al. 1997); and
- Modified versions of the classical silica sand CPT correlations, e.g. Jamiolkowski et al. (1985), to allow for the high compressibility of the calcareous sand.

These approximate design approaches have resulted in greater uncertainty in the geotechnical analyses of calcareous materials compared to routine geotechnical design in silica sand and other classical soils.

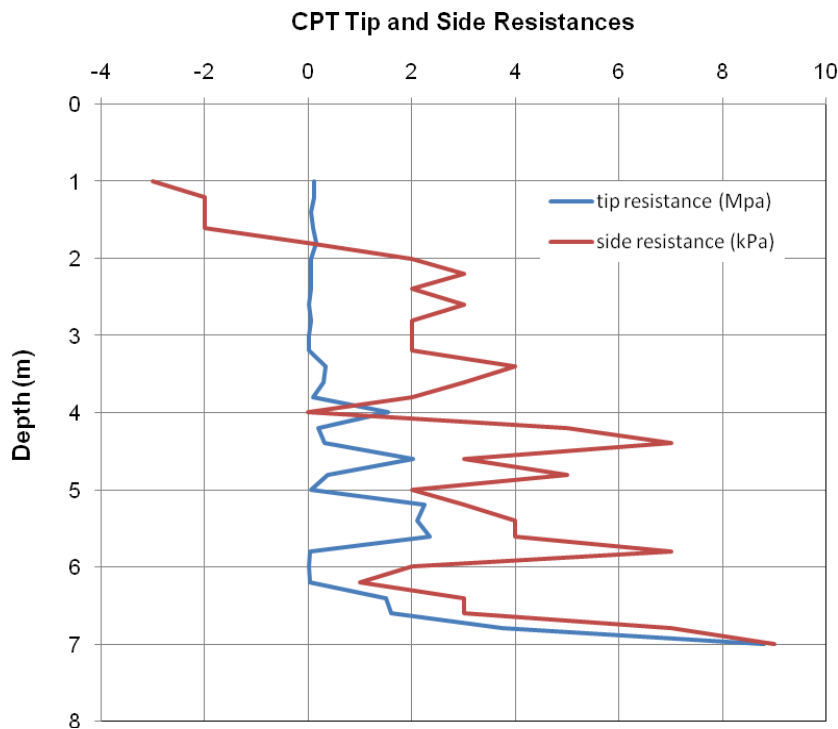


Figure 4. Mechanical CPT data in very soft clay in Northern Morocco showing the recorded negative sleeve (side) friction.

#### 4.4.4 Limited experience of ground investigation contractors

The author believes that one of the most critical challenges to the use of CPT in the MENA area is the inadequate training and experience of many of the CPT and site investigation contractors. This has been demonstrated in several projects where numerous experience-related difficulties were encountered, such as:

- inability to maintain verticality of the CPT in soft/loose geomaterials within the tolerable limits of the project specifications;
- improper saturation of the CPT piezometer, which typically resulted in unrealistic measurements of pore water pressure; and
- inability to identify the arrival times of compression (P) and shear (S) wave in seismic CPT.

## 5 CPT INTERPRETATIONS

### 5.1 *Soil Classification*

Most, if not all, of the CPT-based soil classification in the MENA area are based on either the Soil Behavior Type normalized chart of Robertson (1990) or the Soil Behavior Type Index of Jefferies and Davies (1991).

### 5.2 *Geotechnical Parameters in Granular Soils*

#### 5.2.1 *General*

The methods used to estimate engineering parameters for granular soils in the MENA area are exclusively based on correlations published in the geotechnical literature. To the author's knowledge, no region-specific correlations have been developed to estimate soil parameters from the CPT or any other field test.

A summary of the correlations commonly used to estimate soil parameters in the MENA is provided in the following sections.

#### 5.2.2 *Relative Density*

The two most commonly used correlations to estimate the relative density of granular soil from CPT data in the MENA area are:

- Jamiolkowski et al. (1985), where the relative density of sand is assumed to be directly proportional to the CPT tip resistance normalized to the square root of the effective vertical overburden pressure for sands with different compressibility; and
- Kulhawy and Mayne (1990), where the relative density of sand is mathematically correlated to the dimensionless normalized cone resistance (Robertson 1990), soil compressibility, age of deposits, and over-consolidation ratio of sand.

#### 5.2.3 *Friction Angle*

Two different approaches are usually followed in the MENA area to estimate the effective peak friction angle of granular soils from CPT data:

- Direct approach, where the friction angle of sand is determined from the CPT data using empirical correlations, such as Robertson and Campanella (1983) and Kulhawy and Mayne (1990); and
- Indirect approach, where the relative density is determined from the CPT data and then used to estimate the friction angle of sand using empirical correlations, such as Schmertmann (1975) and Peck et al. (1974).

#### 5.2.4 *Deformation Parameters*

Similar to the friction angle, two different approaches, direct and indirect approaches, are usually followed in the MENA area to estimate the elastic modulus of granular soils from CPT data:

- In the direct approach, the Young's modulus ( $E'$ ) is determined from the CPT data using empirical correlations, such as Bellotti et al. (1989); and
- In the indirect approach, the relative density is determined from the CPT data and then used to estimate the elastic modulus of sand using typical values in the geotechnical literature.

In some projects, the small strain elastic modulus ( $G_o$ ) of granular soils is determined from the results of seismic CPT (SCPT) using analytical solutions based on the theory of elasticity.

#### 5.2.5 *Other Parameters*

Other granular soil parameters, such as state parameter, insitu horizontal stress, and over-consolidation ratio, are rarely determined from the CPT results in the MENA area.

### 5.3 *Geotechnical Parameters in cohesive Soils*

#### 5.3.1 *General*

Similar to granular soils, engineering parameters for cohesive soils in the MENA area are exclusively based on correlations published in the geotechnical literature. These correlations are briefly discussed in the following sections.

#### 5.3.2 *Undrained Shear Strength*

Undrained shear strength ( $S_u$ ) of cohesive soils is usually determined in the MENA area using the well-known empirical correlation that estimates  $S_u$  from the ratio of total CPT net tip resistance and the empirical cone factor ( $N_{kt}$ ). The cone factor is usually determined using the empirical correlations of Aas et al. (1986) where  $N_{kt}$  increases linearly with the plasticity index of soil.

#### 5.3.3 *Deformation Parameters*

The undrained modulus ( $E_u$ ) of cohesive soil is rarely estimated directly from CPT readings in the MENA area. Rather, the undrained modulus is usually determined using the empirical correlation of Dunacn and Buchignani (1976) where the stiffness ratio ( $E_u/S_u$ ) is related to the over-consolidation ratio (OCR) and plasticity index of soil. The OCR is typically determined from laboratory tests on relatively undisturbed samples collected during site investigation.

Similar to granular soil, the small strain elastic modulus of cohesive soils is sometimes determined from the results of SCPT using analytical solutions based on the theory of elasticity.

The drained deformation parameters of cohesive soils are rarely estimated from CPT data. Rather, these parameters are almost exclusively determined from laboratory tests or empirical correlations with soil plasticity indices.

#### 5.3.4 *Coefficient of Consolidation*

The coefficient of consolidation ( $c_v$ ) is rarely estimated from CPT data in the MENA area as it is usually determined from classical laboratory consolidation tests. In very

few cases, particularly in the very soft clay in Northern Egypt and the coastal areas of Morocco,  $c_v$  is estimated from CPTU dissipation tests following the approach of Robertson et al. (1992).

#### 5.3.5 *Other parameters*

Other cohesive soil parameters, such as stress history (OCR), are very rarely determined from CPT data in the MENA area as they have been traditionally determined from laboratory tests on relatively undisturbed samples.

## 6 CPT APPLICATIONS

### 6.1 *Ground Improvement*

Ground improvement is the largest field of application of CPT in the MENA area, particularly in the Persian Gulf countries. This could be attributed to the launch of several large scale projects that involve construction of manmade islands off the coast of the Persian Gulf. These islands are constructed using reclamation sand fill dredged from the seabed of the Persian Gulf. The sand fill is usually dumped or hydraulically placed and hence is initially in loose to very loose conditions. Ground improvement techniques, such as vibro and dynamic compaction, are then used to densify the insitu fill. CPT has been heavily used to evaluate the adequacy of the ground improvement process through correlations between CPT tip resistance and sand relative density, as discussed in Section 5.2.2. This approach, however, has created some dispute between clients and contractors since these correlations were mainly developed for silica sand and hence tend to underestimate the insitu relative density of calcareous sands.

### 6.2 *Liquefaction Assessment*

Assessment of liquefaction potential of reclaimed sand fills is probably the second largest field of application of CPT in the MENA area. This is attributed to the numerous sand-reclaimed manmade islands constructed off the coast of the Persian Gulf, as discussed in Section 6.1.

Liquefaction assessment in the MENA area has traditionally been carried out using the empirical approach of Robertson and Wride (1998) where the Cyclic Resistance Ratio (CRR) of sand is correlated to CPT tip resistance. Earthquake-induced excitation forces are usually expressed in terms of the Cyclic Stress Ratio (CSR), which is typically calculated using the empirical approach of Seed and Idriss (1971). Liquefaction potential is expressed in terms of the factor of safety against liquefaction, which is simply the ratio between CRR and CSR.

### 6.3 *Foundation Design*

To the author's knowledge, CPT data is seldom, if ever, used in direct shallow and deep foundation application where allowable bearing capacities and settlement are directly correlated to CPT parameters. It is the author's experience, reinforced by communication with other consultants and geotechnical practitioners, that CPT data

are only used to estimate soil engineering parameters, which are then used in classical foundation design methods or in stability and deformation analyses.

#### 6.4 *Geoenvironmental Applications*

To the author's knowledge, CPT data is never used in geoenvironmental applications in the MENA area. Geoenvironmental engineering itself is still a relatively new science in the MENA area and lacks the presence of well established state of practice.

### 7 RESEARCH AND FUTURE TRENDS

To the author's knowledge, very little CPT-related research is currently undergoing in the MENA area. This could be attributed to the limited higher education and research budgets in most of the third world countries in the area. Moreover, the oil-rich Persian countries suffer from the shortage of qualified researchers and the absence of strategic plans to relate academia to the state of practice in the construction industry.

A little research, however, is currently undergoing on a project-by-project basis to correlate CPT data, particularly tip resistance, to the relative density of calcareous sands. These research trials are usually parts of large scale projects handled by reputed international consultants and aim at settling the ongoing dispute in the area regarding the quality of ground improvement works in these soils. This dispute has resulted from reliance on CPT-relative density correlations available in the geotechnical literature. As previously discussed, these correlations were originally developed for silica sand and hence tend to underestimate the field density of calcareous sands with high compressibility. This has frequently led to specifying extremely high target CPT tip resistance values in project specifications that are virtually impossible to achieve using classical ground improvement technique, such as vibro and dynamic compaction.

### 8 SUMMARY

This report provides a summary of the state of practice of the Cone Penetration test (CPT) in the Middle East and Africa with emphasis on the Middle East and North Africa (MENA) region where the use of CPT is more frequent. The main findings of this report can be summarized as follows:

- The regional geology of the area is not generally suitable for use of CPT due to the presence of near-surface rocks and/or hard soils. This has resulted in limiting the use of CPT to specific geographic regions in the MENA area.
- No regional/national CPT standards are available in the area. CPT practice is exclusively based on international standards, such as the ASTM and the British Standards (BS).
- No accurate information is available on the extent of CPT use in ground investigation in most of the MENA countries. In the UAE and Egypt, CPT is used in about 10 to 20% and 1 to 2%, respectively, of geotechnical investigations.

- Challenges facing CPT use include the presence of ultra soft/loose soils, refusal to penetration encountered in shallow hard layers, interpretations in calcareous soils, and inadequate experience of CPT contractors.
- The use of CPT data to determine engineering parameters of soil is more relevant to granular soils. Many engineering parameters of cohesive soils have been traditionally determined from laboratory tests on relatively undisturbed samples.
- Direct application of CPT in geotechnical design is mainly limited to ground improvement quality control and liquefaction assessment. CPT is very rarely, if ever, used in direct foundation or geoenvironmental applications.
- CPT-related research is very limited in the MENA area and mainly limited to development of correlations between CPT data and relative density of calcareous sands for use in ground improvement quality control.

## 9 ACKNOWLEDGEMENT

The author is grateful to the following individuals for their contribution to the production of this report through their valuable comments and feedback on the CPT state of practice in the MENA area:

- Prof. Ahmed H. Abdel-Rahman, Professor of Geotechnical Engineering, National Research Center, Cairo, Egypt.
- Dr. Hossam A. Ali, Assistant professor of geotechnical engineering, Ain Shams University, Cairo, Egypt / Senior Geotechnical Engineer, COWI, Dubai, UAE.
- Mr. Emad Sharif, Technical Manager, Arab Center for Engineering Studies (ACES), Dubai, UAE.

## 10 REFERENCES

- American Society for Testing and Materials. 2007. Standard test method for electronic friction cone and piezocone penetration testing of soils. Designation D-5778. *Annual Book of ASTM Standards*, Vol. 04.08, ASTM, West Conshohocken, PA: 19 p.
- Aas, G., Lacasse, S., Lunne, T. and Hoeg, K. 1986. Use of insitu tests for foundation design on clay. Proceedings of the ASCE Specialty Conference, In Situ '86: Use of In-Situ Tests in Geotechnical Engineering, Blacksburg, VA, USA, pp. 1-30.
- Bellotti, R., Ghionna, V., Jamiolkowski, M. and Robertson, P.K. 1989. Shear strength of sand from CPT. Proceedings of the 12th International Conference on Soil Mechanics and Foundation Engineering, Rio de Janeiro, Vol. 1, pp. 179-84.
- Duncan, J.M. and Buchignani A.L. 1975. An engineering manual for settlement studies. Department of Civil Engineering, University of California, Berkeley.
- Jamiolkowski, M., Ladd, C.C., Germaine, J.T. and Lancelotta, R. 1985. New developments in field and laboratory testing of soils. State-of-the-art report, Proceedings of the 11th International Conference on Soil Mechanics and Foundation Engineering, San Francisco, CA, USA, Vol. 1, pp. 57-153.
- Jefferies, M.G. and Davies, M.P. 1991. Soil classification by the cone penetration test: Discussion. *Canadian Geotechnical Journal*, 28(1): 173-176.
- Kulhawy, F.H. and Mayne, P.H. 1990. Manual on estimating soil properties for foundation design. Electric Power Research Institute, EPRI, August, 1990.

- Lunne, T., Robertson, P.K., and Powell, J.J.M. 1997. CPT in geotechnical practice. Chapman and Hall, New York, USA.
- Peck, R. B., Hanson, W. E., and Thornburn, T. H. 1974. Foundation Engineering. 2<sup>nd</sup> Ed., John Wiley and Sons, New York, USA.
- Persits, F., Ahlbrandt, T., Tuttle, T., Charpentier, R., Brownfield, M., and Takahashi, K. 2000. Map Showing Geology, Oil and Gas Fields and Geologic Provinces of Africa. USGS Open File Report 97-470A.
- Pollastro, R.M., Karshbaum, A.S., and Viger, R.J. 2000. Maps Showing Geology, Oil and Gas Fields and Geologic Provinces of the Arabian Peninsula. USGS Open File Report 97-470B.
- Robertson, P.K. 1990. Soil classification using the cone penetration test. Canadian Geotechnical Journal, 27(1): 151-8.
- Robertson, P.K. and Campanella, R.G. 1983. Interpretation of cone penetrometer test: Part I: Sand. Canadian Geotechnical Journal, 20(4): 718-33.
- Robertson, P.K. and Wride, C.E. 1998. Cyclic liquefaction and its evaluation based on the CPT. Canadian Geotechnical Journal, 35 (3): 442-459.
- Robertson, P.K., Campanella, R.G., Gillespie, D. and Greig, J. 1986. Use of piezometer cone data. Proceedings of the ASCE Specialty Conference In Situ '86: Use of In Situ Tests in Geotechnical Engineering, Blacksburg, pp.1263-80.
- Robertson, P.K., Sully, J.P., Woeller, D.J., Lunne, T., Powell, J.J.M. and Gillespie, D.G. 1992. Estimating coefficient of consolidation from piezocone tests, Canadian Geotechnical J., 29(4): 551-557.
- Schmertmann, J.H. 1975. Measurement of in situ shear strength. Proceedings of the ASCE Specialty Conference on In Situ Measurement of Soil Properties, Raleigh, North Carolina, USA, Vol. 2, pp. 57-138.
- Seed, H.B., and Idriss, I.M. 1971. Simplified procedure for evaluating soil liquefaction potential. Journal of the Soil Mechanics and Foundations Division, ASCE, 97(SM9): 1249–1273.