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Site characterization for Sheikh Al Jaber Al Ahmed Causeway Project

Caractéristiques de la localité du projet de la chaussée Sheikh Al Jaber Al Ahmed

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ABSTRACT
The realisation of a causeway across the Kuwait Bay, linking Kuwait City with the planned New Town Development in Subiyah, is an integral part of the current Kuwait Master Plan. The paper describes the geotechnical and geological studies which formed an integral part of the Stage 1 investigations for alignment selection. The project is very challenging in that the geology offers a wide range of soils with up to 34 m thick deposits of very soft Kuwait Bay clay overlying very dense Kuwait Group sand together with the presence of extensive intertidal mudflats. The results of the investigations the lessons learned and the implication on the choice of foundations are summarized in the paper.

RÉSUMÉ
La réalisation de la chaussée à travers du golfe de Koweït, liant la ville de Koweït avec la nouvelle ville projetée à Subiyah, fait partie intégrale du plan directeur actuel de Koweït. L'exposé décrit les études géotechniques et géologiques qui forment une partie intégrale des investigations de la première phase concernant la sélection de tracé. Le projet est très exigeant parce que la géologie offre plusieurs terres avec strates sédimentaires jusqu'à 34 m de grosseur d'un argile du golfe de Koweït très mou placé sur un sable koweïtien très solide avec des plaines de boue intertidales extensives. Les résultats des investigations, les leçons tirées et l'implication du choix de fondations sont rapportés dans l'exposé.

1 INTRODUCTION/PROJECT

The realisation of a Causeway across the Kuwait Bay linking Kuwait City with the planned New Town Development in Subiyah is an integral and important part of the current Kuwait Master Plan. The main planning objective of the Causeway is to promote the Subiyah New Town development and to integrate the northern parts of Kuwait with the central and southerly regions of the Country.

A large number of possible alignments within a wide (about 20 km) corridor across the Bay were studied and ranked based on environmental, socio-economic, traffic, landmark qualities and other considerations. Using a complex scoring and ranking technique the three highest ranking alignments, shown in Figure 1, were selected for more detailed studies in Stage 1 which took place in 2002. For a number of reasons the project was postponed after final recommendation of alignment. It was resumed in late 2004 where Stage 2A, Concept and Tender Design was initiated after selection of alignment 1B as the preferred solution.

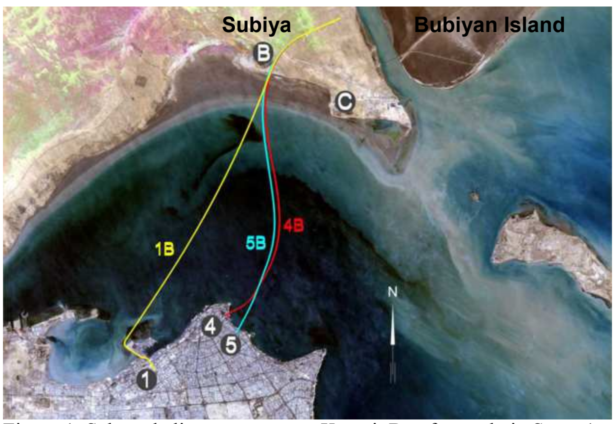

Figure 1. Selected alignments across Kuwait Bay for study in Stage 1

Figure 2. Main Bridge for Alignment 1B

This alignments circumvents Shuwaik Harbour and has a total length of 36 km. By choosing this alignment the maximum water depth is reduced from some 16 to 10 m. As this alignment does not interfere with the main navigational channel in the Kuwait Bay there is no need for a long span high bridge. However, to maintain the landmark qualities of the causeway and to accommodate the navigational channel to Doha Harbour a daring icon/landmark main bridge structure has been included as seen in Figure 2. The navigational clearance is 120 m by 23 m.

2 OBJECTIVE OF STAGE 1 GEOTECHNICAL STUDIES

The geotechnical and geological Studies undertaken in Stage 1 in 2002 form the backbone of the present paper as the Stage 2A investigations are ongoing early 2005.

The objectives of the Studies in Stage 1 were:

- to develop a geological/geotechnical model based on available geo-information in the region, including identification of problem areas and soil parameter ranges
- to carry out a soil investigation programme covering three selected alignments and report and analyse the results in order to present generalized sub-surface profiles and suggest preliminary recommendations of foundation types and solutions
- to perform a seismic hazard study, based on available seismic information, and provide seismic design parameters

In "real" site characterization one has to compromise due to economy, time constraints, local availability of equipment and local customs and ground conditions. Thus, a number of choices may seem backward, particularly in academic hind sight, but such is life. In order to benefit from competiveness of local ground investigation contractors it was necessary to refrain from using "off shore technology" for borings and CPT testing. Offshore CPT´s were deferred to Stage 2A and the borings were carried out from a barge. Despite very concerted efforts and good interaction with supervision it proved difficult to obtain reliable strength parameters from the offshore deposits of the very soft Kuwait Bay clay. Thus, a number of critical issues could not be addressed in full during the Stage 1 investigations. However, this is rectified during the Stage 2A studies in order to obtain a best possible background - within the time and financial limits - for the tendering of the project.

In every site characterization project, previous comparable experience and internationally available empirical rules play an important part. This is particularly true when data by necessity are limited as is the case in alignment investigations where a large area has to be covered and where borings thus are widely spaced.

The strong Danish tradition of interplay between geotechnical engineering and engineering geology was brought to bear on the current project. The effort paid off in that the results from the (relatively few) geotechnical boreholes and CPT soundings could be placed in a conceptual framework allowing fairly robust statements to be made concerning the identification and general properties or the different soil and rock units. Without a general geologic model, based on the geological history of the Kuwait area the site characterisation would have resulted in a perceived chaotic and anomalous subsurface condition which would have made inferences concerning foundation possibilities very difficult and uncertain.

3 SITE INVESTIGATIONS AND LABORATORY TESTING

3.1 *Extent*

The Stage 1 geotechnical field investigations comprised the following number of geotechnical boreholes and Cone Penetration Tests within the study area (cf. Figure 3), together with associated field and laboratory tests:

- 5 boreholes at Subiyah coastal area
- 12 CPT's at Subiyah coastal areas
- 6 offshore geotechnical borings in Kuwait Bay

The ground investigation fieldwork was carried out in the period from 20 July 2002 to 7 August 2002. The geotechnical investigations were carried by the Kuwaiti company "Gulf Inspection International Company" (GIIC) under COWI's day to day supervision. INCO lab has acted as subcontractor for GIIC regarding CPT's and part of the laboratory tests.

The geotechnical boreholes have been carried out as a combination of cased (6" and 4" casings were applied) auger drilling and rotary flush drilling. A total of 162 in situ Standard penetration tests, including split barrel sampling, were carried out in boreholes in sandy deposits and slightly cemented sandy deposits /soft (non-coreable) rock. SPT's were also carried out in the soft clay deposits met in onshore boring BHSU-103. The SPT tests were carried out at 1.0m intervals, where no undisturbed samples could be retrieved. In strata where undisturbed sampling was possible SPT's were carried out at 2 m intervals. The SPT's were carried out according to AASHTO T 206. Undisturbed soil samples were taken whenever fine grained soils were encountered. Two core runs of a total of 3 meter were cored in weak rock in boring BHSU-105. The maximum depth of the boreholes was 50 m below seabed level.

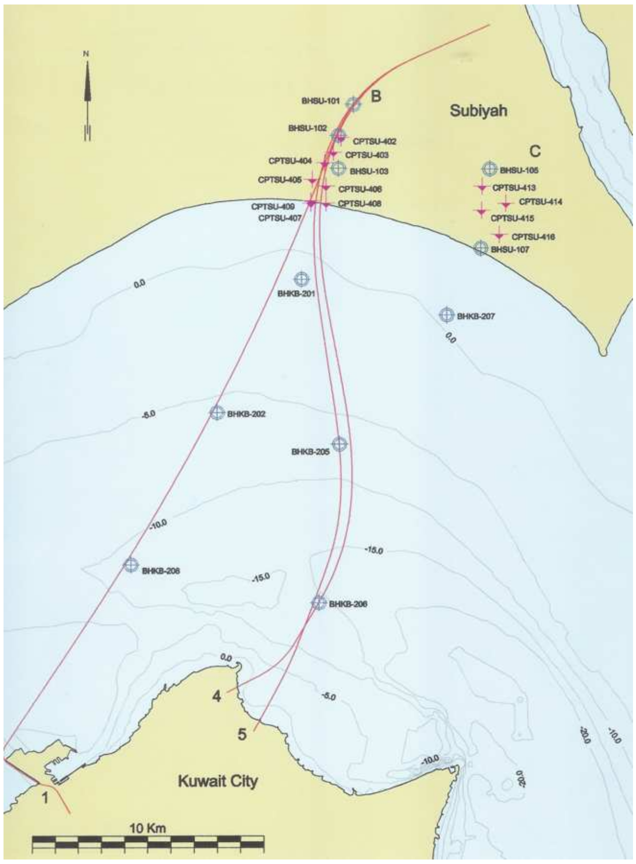

Figure 3. Borings and CPT soundings carried out in Stage 1

A total of 109 Field Vane tests were carried out in fine grained soils, according to AASHTO T 223, for assessment of the undrained in situ shear strength.

CPT's by use of piezo-cones were carried out in the Subiyah coastal area. The tests were performed in accordance with the ISMFEE Reference Test Procedure. A maximum of 10 tonnes thrust was applied by the CPT rig.

3.2 *Geological assessment*

3.2.1 *Location*

The state of Kuwait is situated at the North Western corner of the Arabian Gulf between latitudes 28° and 30° North and longitudes 46° and 48° East. It covers an area of approximately 17820 km2. Kuwait is bordered by Iraq to the North and West, Iran to the

Northeast, Saudi Arabia to the South and the Arabian Gulf to the East.

3.2.2 *Surface and Topography*

The mainland of Kuwait comprises a generally, flat, desert landscape, tilting toward north east from 270 m above sea level in the extreme south west to a few metre at Bubiyan Island at the extreme north east. A few oasis, undulating sand hills and occasional escarpment or depressions break the uniformity of the interior plateau. The Jal Az Zor escarpment north of the Kuwait Bay, stretching approximately 60 km towards northeast forms together with the Kuwait Bay another of Kuwait's physical features. The Bay is up to 15 - 20 meter deep.

3.2.3 *General Climate*

The climate of Kuwait is a dry, hot, subtropical desert climate. The average maximum summer temperature is 44°C and the average minimum temperature is 8°. Rains are scanty with a mean total of about 100 mm a year, but highly variable from year to year and from place to place. The number of rainy days for a given year may be less than 10. Dust and sandstorms are common throughout the year.

3.3 *Geological History*

In a geological regional sense, Kuwait lies at the edge of the Arabian Foreland where the northeast dipping monocline passes into the geosynclines of the Arabian Gulf and the Iraq Valley. The regional dip of Kuwait is roughly 2.5 metres per kilometre towards northeast. The Arabian continent is colliding with the Iranian Continent as evidenced by a long and broad zone of thrust faults activity in western Iran, known as the Zagros Fault System. West of the Zagros Fault, the collision of the Arabian and Iranian Continents presumably formed broad and gentle synclines and anticlines as evidenced by the depressed area of the Arabian Gulf and gently warped tertiary sediments below Kuwait and the eastern coastal area of Saudi Arabia.

The stratigraphy of the Kuwait area is basically known from the huge number of deep Kuwaiti oil wells, geotechnical borings and the exposed escarpments, most notably the Jal Az Zor escarpment north of the Kuwait Bay.

The upper part of the bedrock is the Damman formation which is met at depths of 100 to 150 metres below the ground level in Kuwait City. It is recognized as Damman "Eocene limestone bedrock". It consists of carbonate rock with thicknesses ranging from 150 metres in the south west of Kuwait to 275 metres in the northern Kuwait. It dips gently toward north-northwest.

The Eocene bedrock is covered by the so-called Kuwait-Group of sediments deposited in the late Tertiary period. These deposits are found in thicknesses of 100 to 300 metres, with the minimum thickness recognized in the Kuwait Bay Area (90 m in the deep Bahra 7 boring). During the Pleistocene period it is likely that the Kuwait group was exposed to erosional forces from water, which is believed to have formed both the Jal Az Zor Escarpment and the Kuwait Bay. The erosion scenario during the Pleistocene is well in keeping with both general topographic features, the exposed escarpments and logs from available deep oil wells.

During the Holocene period young deposits with thicknesses up to some 35 m has been deposited in the Bay as a result of tidally controlled water currents.

Based primarily on the geophysical logs from oil wells, Al-Sarawi (1980) has evidenced that at least two deep faults of Eocene origin in the Damman deposits are present in the Kuwait Bay. The direction of these old faults is parallel with the Jal Az Zor Escarpment. The faults are characterized as growth faults and covered by 100 to 150 m of younger Tertiary and Quaternary deposits belonging to the Kuwait Group. These deep, inactive faults of Eocene age (concurrent with the formation of the Alps in Europe) are not expected to affect the causeway project.

3.3.1 *Morphologic features of study area*

The terrain at landing point B at Subiyah is situated at ground elevation +35m. Towards the wide coastal, intertidal area the landscape is falling gently at an average slope of approximately 3%. The low lying, wide coastal area of Subiyah is extremely flat with a slope of approximately 0.1% towards the centre of the Bay at a the water depth of approximately 5 meter.

From the middle of the Bay toward the deepest point in the bay (a water depth of some 15 m) the slope of the sea bed is gradually increasing towards a slope of 0.2%. From the deepest part of the bay the seabed rises at a slope of 0.3% towards Kuwait City, where the landing points are at approximately elevation +5m.

3.4 *Geological Features*

The geological features are prevalent from the generalised cross section through the offshore borings carried out in the Stage 1 ground investigations in Kuwait Bay (Figure 4).

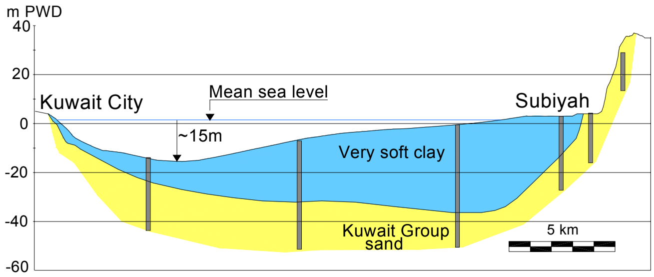

Figure 4. Generalised subsurface profile shown along alignment 4B

3.4.1 *Subiyah hinterland and inner coastal area*

At the Subiyah onshore side the Kuwait group deposits are present very close to the ground surface. The upper deposits in the location of boreholes BHSU-101 and BHSU-105 of Al-Subbiyah consist of white to light grey sand with lenses of gravel. The sand particles are in the range of medium to coarse and have some scattered pebbles. The gravel is highly weathered and is supported by fine sand and silt. The upper sediments are mostly dry, calcareous and gypseous strongly cemented sand and sandstone.

The soil formation is locally called Dibdibba and Jal Az-Zor formations. The boundary between the Dibdibba and Jal Az-Zor is hard to locate, because of gradational contact and lithological similarities and lack of biostratigraphical characteristics. The formation is very dense and the spurious indications of very high relative densities (D_r > 100 %) could be related to cementation processes.

The presence of Kuwait Group deposits from ground surface is a general trend between the coastal area and the mudflat area. Here the Kuwait Group is covered by Holocene deposits of soft clayey material. This change occurs just north of the geotechnical boring BHSU-102.

Salt-Bearing soil flats (saline flats) in Subiyah, popularly known as Sabkha, are found along the areas extending above the high tide level. They are covered by evaporate-rich clastic sediments. On the landward sides, these supra-tidal Sabkha flats are generally covered with Aeolian sand deposits. Shallow ponds occur in depressions and are generally covered by crusts of salts, gypsum and dried algal mats. The Sabhka deposits and Aeolian deposits are mentioned for geological completeness, but the occurrence and thickness of these deposits are limited and without significant consequences for the over all engineering soil profile.

The Kuwait Group deposits of dense (silty) sand and layers of greyish brown, very stiff to hard clay are found to the full boring depth (up to 30 m) in boreholes BHSU-102 and BHSU-107

3.4.2 *Subiyah Mudflats*

From Boring BHSU-102 and further towards the Bay the thickness of overburden soft soil deposits covering the Kuwait group of sediments increases up to a maximum of more than 34 metres as indicated by the CPT 407.

The maximum thickness of 16 m of the Subiyah soft soil was found in borehole BHSU-103. Lithologically it can not be distinguished from the recent offshore soft clay formation.

3.4.3 *Offshore across the Kuwait Bay*

The offshore investigation across the Kuwait Bay has revealed two major soil formations: the Kuwait Bay soft soil deposits of (silty) clay underlying the Kuwait Group sediments. The soft clay formation extends from the sea bed level down to level -30 m to -33 m (BHSU 201) from the Subiyah sub-tidal area to the middle of Kuwait Bay. The thickness reduces to a few metres as the alignments approach Kuwait City. The soft fine grained soils predominantly constitute soft, greenish grey to dark grey, calcareous, silty clay, containing varying contents of organic matter, sand and shell debris. During the course of the field works across the Bay it was noted that the undrained shear strength from the field vane indicated extremely soft consistency down to the bottom of the clay layer.

The origin of the soft deposits is believed to be the Tigris Euphrates river fine grained soils which find its way into the Arabian Gulf through the Shatt-al-Arab, carried by the tidal currents into Kuwait Bay. The consistently low strength with depth supports this depositional scheme as the deposits must be of Recent/Holocene age.

The Kuwait Group soils underlying the soft deposits predominantly consist of fine to medium sands, and silty sands. The fine to medium sand is a quartz sand/sandstone with strongly varying carbonate content and irregularly cemented with carbonate precipitate. The formation is very dense and the occasional extreme SPT-N values are attributed to the cementation. In the very dense sand the carbonate content is generally less than 10% and typically SPT-N > 200.

3.4.4 *Near shore Kuwait City*

Near the Kuwait City shore line the superficial fine grained deposits are almost negligible in thickness. Loose to medium dense Holocene Marine deposits of sandy silty deposits cover the Kuwait Group of sediments. On top or imbedded in these sandy deposits, spurious horizons of very weak to moderately strong coarse grained, bioclastic, calcarenite cap rock are found. In several soil investigations for different water front projects throughout the Arabian Gulf cap rocks occur as flat topped discontinuous horizons varying in thickness from 0.3 metres, or less, to as much as 2.0 metres. Cap rock deposits have not been met at the Subiyah side of the Bay.

3.4.5 *Kuwait City - onshore*

The top cover of soil on the coastal shore line consists of fill of sand and silt in loose to medium dense conditions. In some locations a lot of construction debris has been observed along the coast as fill material. This fill cover extends in some locations to 6 metres depth below existing ground level.

Generally, the soils encountered below the loose cover are the upper part of the Kuwait group formation.

The results of many detailed mineralogical analyses carried out on different projects along the Kuwait city shore line characterize the formation by major horizons of carbonate sand, geologically identified as caliche, and locally identified as Gatch, which belongs to the Kuwait group.

Gatch sand may contain 30 and 60 % gypsum and carbonates. If the gypsum content is high, the colour of the Gatch is brownish, whereas a low gypsum content leads to a beige, whitish colour.

3.5 *Geological/Geotechnical Model*

3.5.1 *General*

Based on available data from various local sources combined with the results of the site investigations carried out in Stage 1 a geological and geotechnical model has been established.

From the existing geological evidence and in agreement with the collected data in Stage 1 it is inferred that the investigation area (as part of the Kuwait Bay) has been formed by erosion in the geological Kuwait Group formation during Pleistocene time. During the Holocene period young deposits in thicknesses up to approximately 35 m have been deposited in the Bay as a result of tidally controlled flows of water.

The Kuwait Group formation consists mainly of dense to very dense sandy to fine sandy, silty deposits with excellent strength and deformation properties. These Kuwait group deposits are recognized very close to ground level at the Subiyah onshore areas and at moderate depth below ground level in Kuwait City, as so-called "Gatch". In the Kuwait Bay and particularly the tidal, mudflat area of Subiyah considerable thicknesses up to 35 meter of young and soft to very soft clay cover the competent Kuwait Group deposits.

The Kuwait Group deposits have been subdivided into two main units:

- Kuwait Group sand, which predominantly consists of dense to very dense sands to silty sands, and
- Kuwait Group clay, which appears as interbedded clay layers in the upper part of the dense Kuwait Group sand deposits
- The soft clay deposits have been subdivided into two units:
- Subiyah soft clay, which is a slightly preconsolidated silty clay found in the tidally affected Subiyah mudflat area. The strength and deformation properties of the Subiyah soft clay deposit are poor.
- Kuwait Bay soft clay, which lithologically is identical to the Subiyah soft clay, but appears as an underconsolidated, very soft to soft clay deposit with poor strength and deformation properties.

The Geological model for the study area is summarized in Figure 4.

3.5.2 *Problem areas*

The presence of the identified soft clay deposits in Kuwait Bay necessitates deep seated foundations for all offshore structures. Furthermore, these deposits present severe challenges due to the inherent high compressibility and low strength. Very large settlements and severe stability problems are anticipated in connection with construction of embankments and artificial islands.

3.5.3 *Recommended foundation types and solutions*

The base of the foundations for offshore piers must be below the soft soil deposits. The only feasible foundation techniques are piled or caisson type foundations.

The piling depth in the competent Kuwait Group dense sand will likely be at least 10 meter in order to achieve the necessary bearing capacity. This implies up to 50 meter long piles.

Embankments on the Subiyah side of the Kuwait Bay or artificial transition islands, where up to 35 meter of very soft to soft clay material is identified, can only be constructed after soil improvement of the soft soil deposits. Such improvement may be achieved by application and combination of vertical drains, sand or stone columns, vacuum consolidation, high tension Tensar grids and preloading. This will be decided in the final design.

3.5.4 *Seismic Hazards*

A seismic hazard study was carried out with input from KISR (COWI, 2002). The study has shown that moderate impacts corresponding to horizontal accelerations of 0.12 to 0.14 *g* should be taken into account in the design.

4 MEASURED AND DERIVED PARAMETERS

4.1 *Anomalies*

Working overseas it is important not blindly to transfer of the cuff values for g or γ_w. The local acceleration due to gravity (g = 9.7919 m/s^2), the temperature of the Bay water (monthly average between 11.8 and 33.5°; average 23°) and the salinity (monthly average between 34.8 and 42.7‰; typical value 40‰) have an impact on the density of the water (pressure can be neglected as the water depth is typically less than 15 m). Using the typical values a density of water of ρ = 1.029 Mg/m^3 is inferred. For the soils the temperature may be slightly lower and the salinity is lower (decreasing with depth). To be slightly conservative, a weighted mean value of the sea water and the pore water in the two soft clay deposits, ρ = 1.021 Mg/m^3, is used in the project. This corresponds to a representative unit weight of γ_{water} = 10.0 kN/m^3.

When the first classification tests were reviewed it became clear that the application of different standards, ASTM versus BS or Scandinavian Standards, has a significant impact on the perception of the fine grained soils in terms of their clay and silt content. For the soils at hand it was found that $ASTM_{CLAY\%} \sim 1.5\ BS_{CLAY\%}$ and $ASTM_{SILT\%} \sim BS_{SILT\%} + 10\%$. This is of course of major significance when using empirical correlations where the clay content, activity etc are used as input.

4.2 *Classification tests*

The classification tests (cf. Figure 5 to Figure 7) clearly show the difference between the main soil types and the influence from tidal interaction with the water in the Bay. The two soft soil deposits show the same lithology but the Subiyah soft clay has a significantly higher content of chloride and sulphate than the other soils.

The carbonate content (Figure 7) clearly distinguishes the soft clays from the Kuwait Group CLAY, with contents of 50-60% and 5-20%, respectively. However, the carbonate content is high in the Kuwait Group sand where this is found close to ground level. The trend is clearly a falling carbonate content with depth in the Kuwait Group with carbonate content about 5-15%.

The organic content is around 4% but highly variable. However, as the highest contents are in the stiff Kuwait Group clay the organic content is not considered an immediate problem.

The reflection seismic survey carried out across the study area failed to penetrate the soft near shore areas due to problems with multiples from the low lying seabed but also because of gas. The latter could be from decay of organic content in the soil or from the possible oil/gas deposits in deep layers.

All of the 19 samples analyzed for oil contamination proved negative.

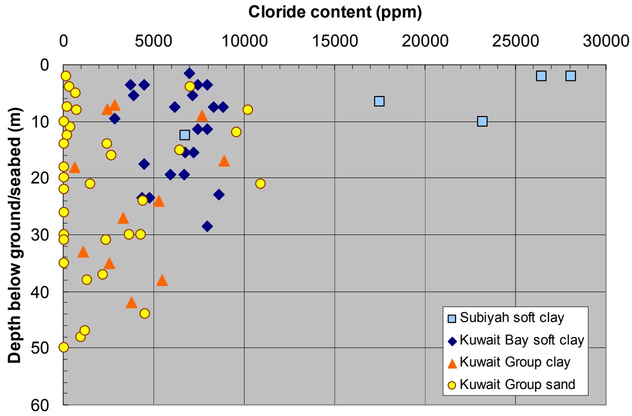

Figure 5. Distribution of Chloride content with depth

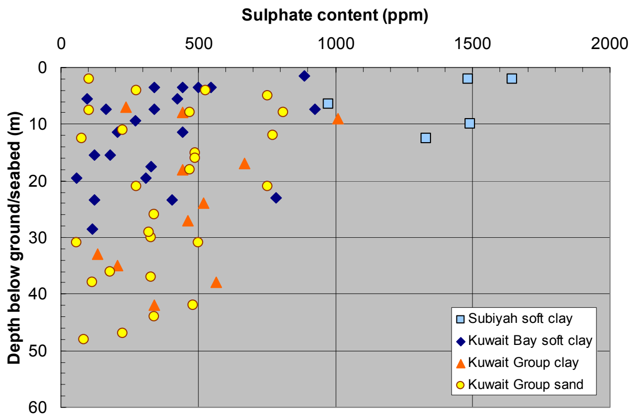

Figure 6. Distribution of Sulphate content with depth

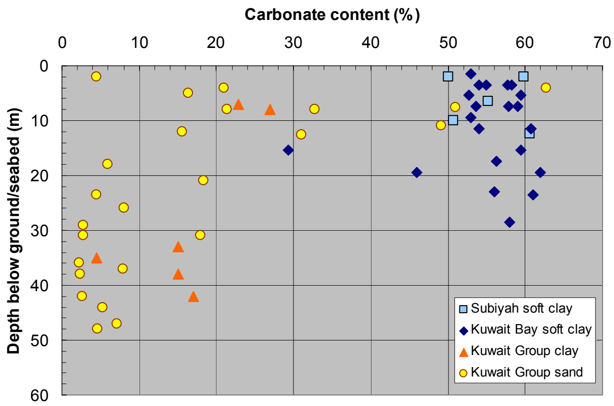

Figure 7. Distribution of Carbonate content with depth

The water content serves as a clear tell-tale of the differences between the three clay types. The difference is enhanced when the liquidity index, $I_L = (w - w_P)/I_P$, is included in the evaluation, as shown in Figure 8.

The high water content of the Kuwait Bay clay coupled with a liquidity index around 100% confirms the very soft nature of the clay. For the Subiyah soft clay the tidally controlled overconsolidation results in a lower water content and liquidity index, corresponding to higher undrained shear strength.

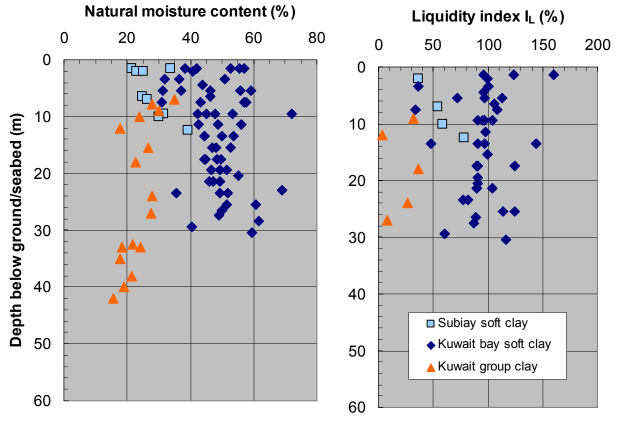

Figure 8. Distribution of natural moisture content and liquidity index with depth

The Subiyah soft clay and the Kuwait Bay soft clay are of medium to high plasticity where only two determinations fall below the A-line (signifying increasing organic content) as seen in Figure 9. The Subiyah soft clay values are at the lower end of the plasticity range. However, this is due to the trend of increasing liquid limit with depth, where the Subiyah soft clay is only met in a thickness of 10 m.

The Kuwait Group clay ranges from low to high plasticity but within the same main trend as for the soft clay types.

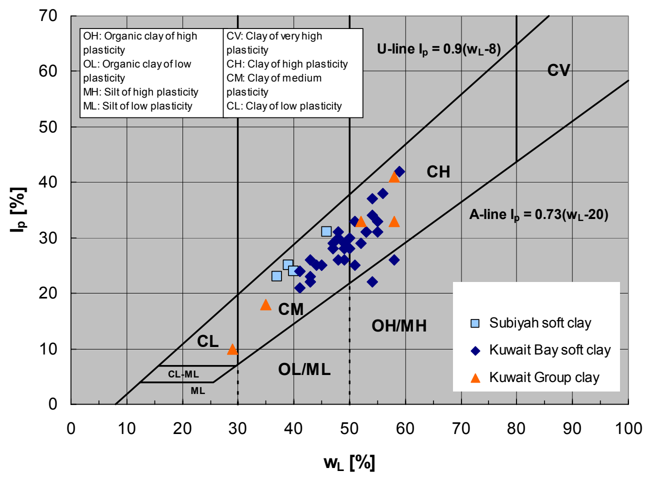

Figure 9. Plasticity chart showing position of the three clay deposits

4.3 *Strength tests*

The strength of the different soils have been determined by field testing, i.e. field vane tests (Acker equipment), SPT soundings in boreholes and CPT soundings using a piezocone Moreover, unconsolidated, undrained triaxial tests, unconfined compression tests and shear box tests were carried out.

The relationship $c_u = s_{u,FV}$ has been assumed for Stage 1, as conflicting evidence for factoring the vane shear strength $s_{u,FV}$, to obtain the undrained shear strength, c_u, exists in the literature.

The vane tests in the soft clay deposits reveal a dramatic difference in strength profile. For the Subiyah soft clay the (few) vane tests show a linear increase in strength with a cautious mean value of c_u = 4 kPa+ 2.5 kPa/m d, where d is the depth below ground level. This corresponds to $\Delta c_u/\Delta\sigma'_v$ = 0.28 which is in keeping with international experience for this type of clay and is supported by the UU tests carried out

In Borehole BHSU-103 SPT testing was carried out in the soft clay. Using the approximation $s_{u,FV} = 6\ N$ the shear strength from SPT supports the trend of the field vane tests.

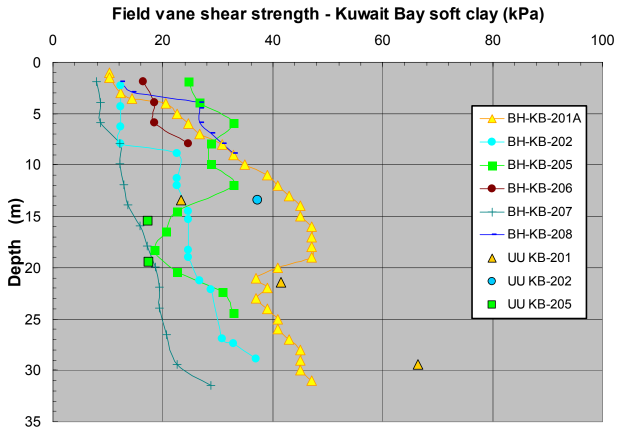

Figure 10. Field vane shear strength in Kuwait Bay soft clay and corresponding values of shear strength from UU triaxial tests

However, the vane shear strength in the Kuwait Bay soft soil (Figure 10) show a dramatic scatter with values from borehole BHKB-207 indicating very adverse strength values corresponding to a lower bound value of c_u = 10 kPa+ 0.4 kPa/m d. This translates to an extremely low c/p ratio of $\Delta cu/\Delta\sigma'_v$ = 0.06. This would correspond to a strong underconsolidation, i.e. high pore pressures either to an unfinished primary consolidation or to gas development (from deeper lying gas pockets or from decay of organic material). However the relatively high strength values close to the seabed cannot easily be explained.

4.3.1 *SPT testing*

SPT's have been carried out in coarse grained soil (sandy deposits). The SPT values corrected for overburden vertical stress vary considerably between borings, but are consistently higher than 50 and typically around 150 increasing with depth.

4.3.2 *CPT testing*

On the Subiyah mudflats CPT soundings were carried out for determination of the undrained shear strength profile of the soft clay deposits and for verification of the depth of these deposits.

The cone factor N_{kt} ranges from 8 to 20 in international practice. From COWI's general experience and the totality of the available site data a value of N_{kt} = 14 has been adopted in Stage 1.

The CPT's for the Subiyah soft clay (Figure 11) show a very uniform strength profile for the Subiyah soft clay deposit with a "desiccated crust" of higher strength in the top one meter and a linear increase of strength with depth. A cautious estimate of shear strength from the CPT tests would be, c_u = 4 kPa+ 2.5 kPa/m d, combined with a minimum value of c_u = 10 kPa at the top and a maximum cut off value of c_u = 50 kPa. The latter is due to the apparent drop in the increase in shear strength with depth, $\Delta c_u/\Delta\sigma'_v$ = 0.28, which is en keeping with a slightly overconsolidated to normally consolidated clay of this type.

At present there is no explanation for the "decreasing increase" around 20 to 25 m depth, which however is of no consequence for the anticipated construction elements in the area.

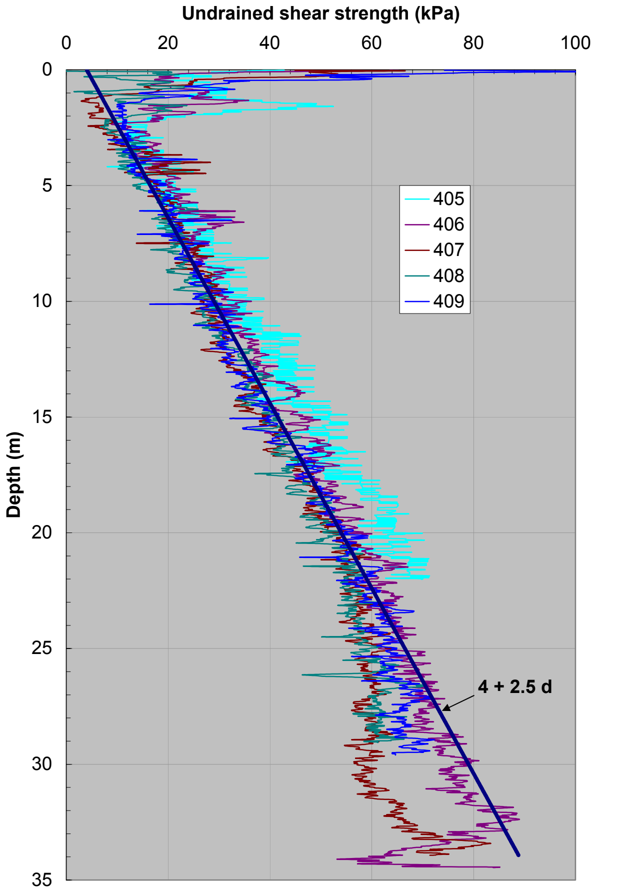

Figure 11. Composite undrained strength profile based on CPT sounding for Subiyah soft clay

4.3.3 *Laboratory strength tests*

The undrained shear strength of the clay deposits were also assessed by laboratory testing. The more reliable results are obtained from the unconfined undrained triaxial tests but these and the unconfined compressive strength tests are index tests only.

For assessment of the shear strength of the Kuwait Group sand, a series of direct shear box tests were conducted. The specimens were compacted in three layers to reflect the in situ density as determined from bulk density measurements from the sample tubes.

Due to the relatively high fines content (typically 13%) it is very difficult to saturate the samples. This means that it may be difficult to assess whether the tests are drained or undrained. Furthermore, the structure of the sand (overconsolidated and aged) is completely lost by sampling. The high fines content is also reflected in the obtained very low void ratios e = 0.332 to 0.672 which are well below the (classification) minimum void ratio of e_{min} = 0.64 to 0.83 (The values of achieved void ratios look suspiciously low and conversely the minimum void ratios look far too high, but it was not possible to pin point errors related to the testing).

The test results are shown in Figure 12. As the samples are prepared by tamping and at the very low void ratio, it is assumed that they are overconsolidated. This means that the failure criterion should be taken as $\tau = \sigma' \sin\varphi' + c'$, rather than the traditional interpretation, $\tau = \sigma' \tan\varphi' + c'$ (cf. Hansen, 1961).

The two interpretations lead to values of the friction angle of φ'_{DS} = 41.9° and 33.7°, respectively. As the angle of repose (usually taken to represent the critical state angle at the critical void ratio and zero dilation) was found to be 33.8 to 34.0°, the average value of φ'_{DS} = 41.9° is believed to be representative of the tests.

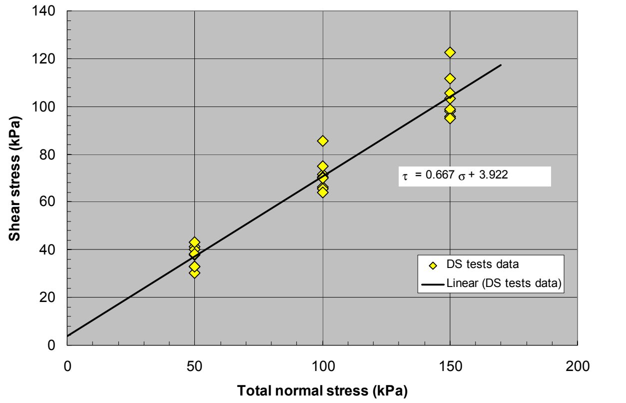

Figure 12. Failure shear stresses from direct shear box tests on Kuwait Group sand and best fit regression line

4.4 *Deformation tests*

The deformation properties of the clay deposits have been assessed by oedometer tests carried out as doubly drained tests on 50 mm samples with a height of 20 mm. Twenty-four oedometer tests were carried out in Stage 1. An example of the consolidation curves and the ensuing constrained moduli is shown in Figure 13.

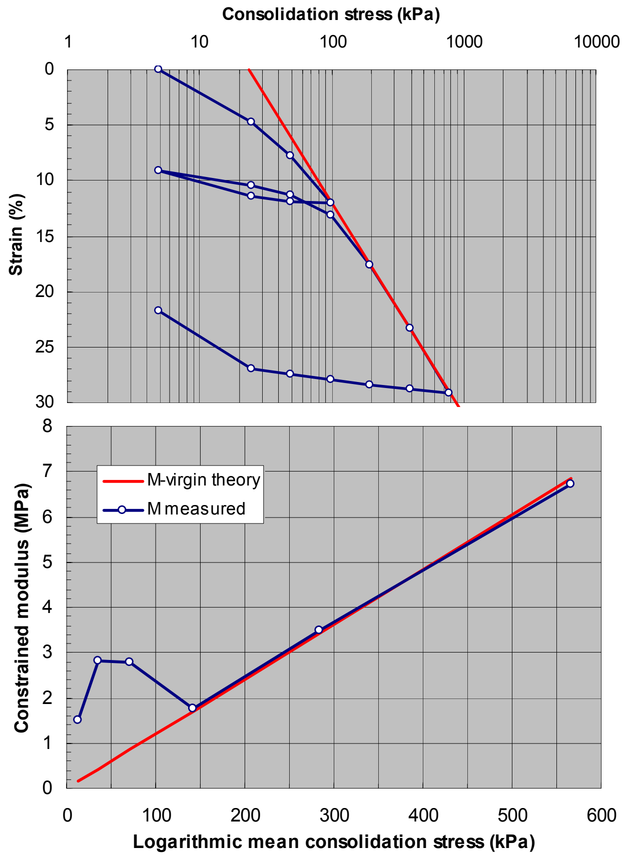

Figure 13. Example of measured values in consolidation test for BH-KB205 depth 5.45 m. Top: Consolidation curve; Bottom: Constrained M

Different stress paths have been applied with unloading -reloading loops to investigate both virgin compression and compression in the overconsolidated state.

All primary load steps have been maintained for 24 hours, whereas some of the unloading steps have been reduced in time.

The constrained modulus $M = \Delta\sigma/\Delta\varepsilon = (\sigma_2 - \sigma_1)/(\varepsilon_2 - \varepsilon_1)$ is normally plotted versus the arithmetic mean, $(\sigma_1 + \sigma_2)/2$, of the stress increment σ_1 to σ_2. However, using a logarithmic mean value $(\sigma_1 - \sigma_2)/\ln(\sigma_2/\sigma_1)$ ensures that the constrained modulus corresponding to load steps on the virgin compression curve also plots on a linearly increasing scale (irrespective of the magnitude of the stress increment). In Figure 13, the sample has been preconsolidated to 100 kPa and on the plot of constrained modulus it is apparent that the preconsolidation stress is exceeded in the load step between 100 and 200 kPa.

For each test the preconsolidation stress, σ'_{pc}, the compression index, C_c, the rate of secondary consolidation (in the normally consolidated state), C_α, the constrained modulus, M_v, for unloading /reloading and the coefficient of consolidation, c_v, have been determined. The test result show some scatter, but reflect very well the difference between the three types of clay.

However, in keeping with internationally recognized correlations the consolidation index increases almost linearly with increasing water content, as seen in Figure 14.

Based on the water contents and the shear strength the Kuwait Group clay is anticipated to be overconsolidated. The tests carried out so far have not been loaded to sufficiently high stresses to find the preconsolidation stress.

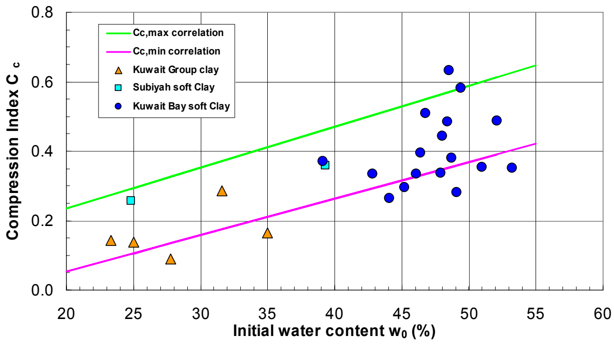

Figure 14. Compression index as function of initial water content for the three clay types

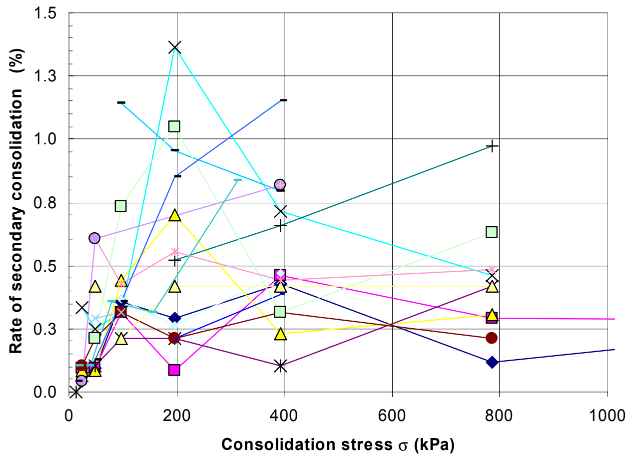

Figure 15. Rate of secondary consolidation $d\varepsilon/d\log t$; Kuwait Bay soft clay

The rate of secondary consolidation is highly variable as seen in Figure 15. As 24 hour steps (in accordance with the standard) were used the values tend to overestimate the creep rate.

Despite the organic content the rate of secondary consolidation is at the lower range of international experience, in that a safe estimate of C_α/C_c is about 3%. Average minimum and maximum values of the coefficient of consolidation, c_v, are 1.2 and 4.3 m^2/year, respectively.

For the Kuwait Bay soft clay the unloading reloading cycles show values of constrained modulus some 7 to 14 times higher than the values for the virgin compression line, i.e. in the range anticipated from international experience.

4.4.1 *Pressuremeter testing*

The stiffness of the Kuwait Group soils has been investigated by borehole pressuremeter testing using a Ménard GC-BX type pressuremeter (Due to the limitation on pressure in the instrument (4 to 5 MPa) the limit pressure could not be established in most of the tests).

The pressuremeter modulus is very variable. Very high values, in excess of 200 MPa are most likely in strata with cementation where there is little or no disturbance from the borehole wall. In the uncemented sand the pressuremeter modulus is lower and probably reflects the disturbance caused by the drilling operation.

However, the pressuremeter modulii determined are considered as a sort of index tests here, and do confirm that the Kuwait Group sand is a competent and stiff material.

5 LESSONS LEARNED/CONCLUSIONS

The combination of desk studies to provide geological/geotechnical base lines and a suite of site investigations and laboratory testing allowed a robust, albeit not detailed, model of the ground conditions in the alignment corridor for the causeway. This facilitated decisions regarding the possible foundation solutions for bridge piers, pylons, embankments and artificial islands constituting the main elements of the causeway.

It furthermore allowed informed choices regarding the more detailed investigations in Stage 2A, for the selected alignment, required in order to tender the project.

The investigations also revealed some anomalies, particularly pertaining to the properties of the very soft Kuwait Bay clay, which need resolving during the detailed investigations in order to facilitate safe and optimized foundation solutions.

The investigations demonstrated the inherent dilemma of site investigations where a delicate balance exists between time, costs, availability of equipment and contractors, reliability of results and interpretations based on relatively wide spaced investigation points.

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