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On the geotechnical challenges encountered in inland salina deposits

Sur les défis géotechniques rencontrés dans les gisements de Salina sur terre ferme

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ABSTRACT: Salina deposits are commonly found in the Middle East and are characterised by challenging ground conditions, typically comprising high compressibility, low shear strength, shallow groundwater table, collapsibility upon wetting, aggressive ground conditions and high capillary rise. Understanding the complex behaviour exhibited by these deposits requires a detailed ground investigation and interpretation. Specific engineering solutions need to be identified to mitigate the impact of the associated geohazards on buildings and infrastructure. This paper discusses the experience of the Authors in design and construction in salina deposits found in the Arabian Peninsula, from the definition of the in-situ and laboratory testing regime, the quantitative assessment of mechanical properties and the development of a hydrogeological ground model, to recommendations on practical solutions for ensuring stability and serviceability of earthworks and concrete structures.

RÉSUMÉ: Les dépôts de saline sur terre ferme se trouvent généralement au Moyen-Orient et se caractérisent par des conditions de terrain difficiles, comprenant généralement une compressibilité élevée, une faible résistance au cisaillement, une nappe phréatique peu profonde, une friabilité sous des conditions humides, des conditions de sol agressives et une forte remontée capillaire. Comprendre le comportement complexe de ces dépôts nécessite une étude et une interprétation du sol suffisamment détaillées. Des solutions techniques spécifiques doivent être identifiées afin d'atténuer l'impact des risques géologiques associés sur les bâtiments et les infrastructures. Cet article traite de l'expérience des auteurs dans la conception et la construction de gisements de salina trouvés dans le Péninsule Arabique, depuis la définition du régime d'essais in-situ et en laboratoire, l'évaluation quantitative des propriétés mécaniques et la mise au point d'un modèle hydrogéologique de sol, incluant les recommandations de solutions pratiques pour assurer la stabilité et la fonctionnalité des terrassements et des structures en béton.

Keywords: salina; sabkha; collapsible soils; capillary rise

1 INTRODUCTION

Inland Salina deposits are commonly found in the Middle East and are characterised by challenging ground conditions, typically comprising high compressibility, low shear strength, shallow groundwater table, collapsibility upon wetting, aggressive ground conditions and high capillary rise. Understanding the complex behaviour exhibited by these deposits requires a detailed ground investigation and interpretation. Specific engineering solutions need to be identified to mitigate the impact of the associated geohazards on buildings and infrastructure. This paper discusses the experience of the Authors in design and construction in salina deposits found in the Arabian Peninsula, from the definition of the in-situ and laboratory testing regime, the quantitative assessment of mechanical properties and the development of a hydrogeological ground model, to recommendations on practical solutions for ensuring stability and serviceability of earthworks and concrete structures.

2 FORMATION OF SALINA DEPOSITS

2.1 Salina formation

Salina deposits generally form in a hot inland saline low-lying depression, where evaporation exceeds precipitation resulting in aggressive and rapidly changing ground conditions, typically dominated by weak and salt-rich deposits. The depositional process is governed by transport of sediments by tributary rivers into the depression, with contribution from aeolian sources. Fookes (2018) states that salina soils and the varying physical and chemical regimes can be significantly different from sabkha soils (located on or near the coast and under the influence of tidal incursions), especially the salt content, ground materials, algal mats and absence of tidal flooding.

Thick deposits may develop over thousands of years, in changing depositional conditions, resulting in non-uniform spatial distributions of component lithologies. Salt deposition is due to evaporation of upward seeping groundwater in inland salinas. Water chemistry determines the nature of the salts precipitating within or at the surface of salina formations and how their characteristics affect salt forming processes resulting in highly variable superficial crust cementation and patterns (e.g. Figure 1). These are further remodelled by repeated flooding and direct heavy rainfall events.

Figure 1. "Polygonal" crust formation pattern

2.2 Site setting

The site is located in an inland salina with high groundwater table, in an extensive flat saline pan formed within a broad, low-lying depression, characterised by a salt crusted surface and capillary rise potential extending generally above the ground surface. The site area lies within a hyper-arid desert region but with high sporadic rainfall intensities and extremely hot summers. The Salina occupies the area of a paleolake, the margins of which are defined by low (up to 15m high) cliffs representing the former lake shoreline, small alluvial fans and areas of eroded bedrock ("Eroded Margins"). The former lake is postulated to have dried out several thousand years ago (Bedouyn, 1980) as the regional climate changed from humid tropical to hyper-arid, and dominated by a broad, salt flat which is fed by saline waters (brine) rising from a series of semi-confined aquifers, and sporadic floodwaters from surrounding Wadis or direct rainfall. Patterned ground and salt (halite) crusts are widespread due to evaporation of brine and repeated phases of salt accumulation, dissolution and re-precipitation. Variable surface patterns reflect differences in soil column, frequency of flooding, depth of groundwater, and the amount and chemistry of groundwater discharge.

2.3 Conceptual site model

A conceptual model for the site has been proposed in the literature by Heathcote and King (1998), which postulates a succession of lake sediments, formed during cooler, wetter climates and fed by inflow from surrounding Wadis, and salt precipitation within wind-blown sands and silts during hotter and drier climates, generating cemented sediments and salt crusts/pans. Repeated cycles of freshwater dissolution and re-precipitation in hotter climates resulted in complex depositional patterns of loose sand and normally consolidated or slightly overconsolidated clay and silt layers.

In its current state, the main active mechanisms within the Salina are groundwater upwards flow and evaporation (”evaporative pumping”), which recharges predominantly through the bedrock succession, and occasional freshwater inflow from direct rainfall or flooding from Wadi deltas. During dry periods, upward seeping groundwater continuously evaporates, forming a capillary fringe (vadose zone) above the water table, where salts precipitate. In the capillary fringe, soil moisture is recharged by groundwater, preventing further deflation of the surface. The vadose zone is characterised by high suctions, due to evaporation and high salt concentration, resulting in high capillary rise potential. Freshwater flooding or rainfall disrupts this equilibrium saturating the vadose zone, dissolving the precipitated salts, greatly reducing the mechanical properties of the surface deposits and causing a collapse of the soil matrix.

The capillary rise and further evaporation leads to minerals concentrating near the surface crust. Depending on their solubility they present in a variety of forms including slightly cemented sediments with a porous structure (Figure 2), salt crusts and pans, patterned ground (typically polygonal), “puffy”, soft surfaces and small hollows within the crust, which are thought to be pathways for upward-flowing brine and downwards drainage.

Figure 2. Weakly cemented porous halite crust

Due to the very high concentration of salts, the Salina represents an extremely aggressive environment towards concrete and steel structures.

3 GROUND INVESTIGATION

The aims of the ground investigations were to quantitatively evaluate the risks to structures typical of the challenging environmental conditions encountered in the Salina.

3.1 Fieldwork

Fieldwork comprised rotary boreholes with Standard Penetration Testing and undisturbed sampling using Shelby push samplers. Shallow standpipes and piezometers with data loggers installed, targeting the shallow aquifer and bedrock groundwater regimes. Piezo Cone Penetration tests with pore water pressure measurement (CPTu) were pushed to refusal on bedrock. Insitu testing included geophysical surveys, falling head tests to assess permeability, Dynamic Cone Penetration tests (DCP) and Plate Load Tests in dry and inundated conditions.

3.2 Laboratory testing

Laboratory testing was undertaken on selected samples and included classification, modified Proctor compaction tests, California Bearing Ratio (CBR), direct shear, unconsolidated and consolidated undrained Triaxial, Oedometer and soil and groundwater chemical testing. Double Oedometer testing and soaked CBR testing were also carried out to evaluate collapse potential of soil samples.

Additional specifications for classification and compaction testing on salt-rich desert soil samples have been proposed in the literature (Walker, 2012), to overcome issues due to the use of standard procedures. It has been recognised that oven drying temperature and duration have an impact on moisture content calculation, due to potential dehydration of gypsum, resulting in overestimation of water content. Also, calculation of moisture content as weight of water over weight of solids (soil particles and precipitated salt) might not be appropriate for desert soils, and an alternative calculation of "fluid content" as weight of brine (water and dissolved salt) over weight of solids has been proposed in the literature (Frydman et al., 2008). These issues affect determination of moisture content, liquid and plastic limits, and indirectly the plasticity index. Finally, the use of brine water has been proposed to prevent dissolution of salts and alteration of particle size distribution. To minimise loss of moisture in hydrated salts, all oven drying has been carried out at 60°C. In addition to this several laboratory trials were carried out to quantify the impact of the aforementioned issues.

4 GROUND MODEL

A conceptual ground model was developed based on the ground investigation data. Despite the marked variability in thickness and composition of the strata, a consistent sequence of Lithologies was identified across the site, as shown in Figure 3.

4.1 Stratigraphic profile

A typical stratigraphic profile, drawn across the Salina deposits is shown in Figure 3. The following main layers and associated lithologies were identified (in order of increasing depth):

Crust. Weakly cemented fine carbonate sand with halite crystals, occasionally distinct halite bands, several tens of mm thick. At the boundary between the active Wadi channels and the Salina deposits, overlying silty very sandy gravel, cemented with halite. Thickness about 1.0-1.5m across the whole area.

Uncemented Salina Deposits. Predominantly very soft, slightly sandy calcareous silt, becoming medium to high plasticity silty clay at depth. Near the Wadi delta, thickly laminated to very thinly bedded very silty sand inclusions. Thickness increases up to 6m (central part). Locally, the deposits may be characterised by a much greater sand fraction, grading into a silty sand.

Bedrock. Alternation of calcareous claystone and coarse grained dolomitic limestone, overlying a basal carbonate claystone formation. Rocks are extremely weak to weak, locally extremely weak in the top 2-3m weathered horizon, which was penetrated by CPTs. Occasional crystalline gypsum layers, about 1.0-1.5m thick at depth.

Away from Wadi deltas, the boundary of the Salina is constituted by the eroded margins of the paleolake where the profile generally comprises a thin gypcrete horizon overlying limestone or claystone bedrock. Across these boundaries, the stratigraphic profile follows the dashed line in Figure 3. At the base of the eroded margin cliffs, bedrock may continue to be found at about 1.0m below ground, directly under the Crust, then dip suddenly to about 6m below ground level. At the Wadi deltas, bedrock is more likely to dip gradually to the similar depths. The CPT results confirmed the above ground model and three representative profile types were identified across the Salina area (A, B and C as shown in Figure 3). Cone resistance and friction ratio profiles with depth for all profiles are presented in Figure 4 and Figure 5.

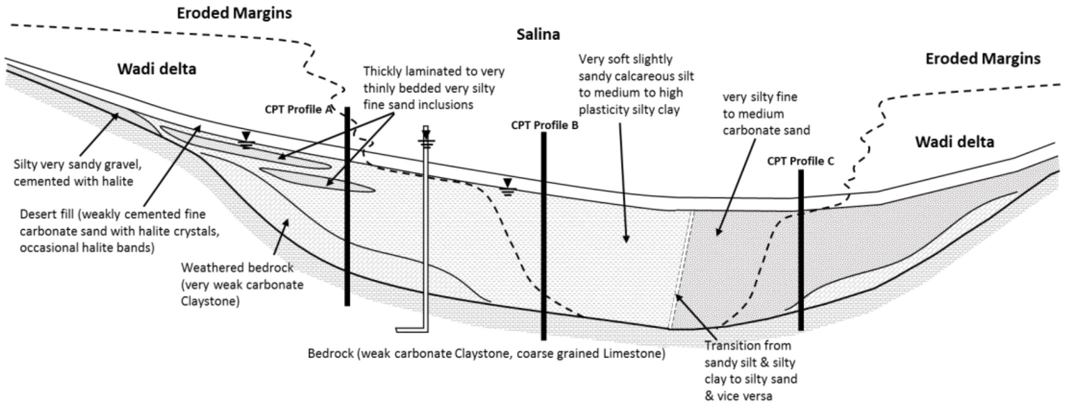

Figure 3 Typical stratigraphic profile across the Salina deposits

In proximity of Wadi deltas, deposits are richer in sand and of Type A or Type C. The Type A profile is characterised by limited depth (2-3m), interbedded silty sand beds in a sandy silt matrix, and completely weathered claystone (1-2m thick) over bedrock.

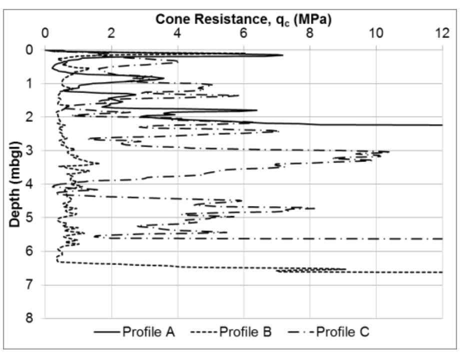

Figure 4. CPT Cone Resistance

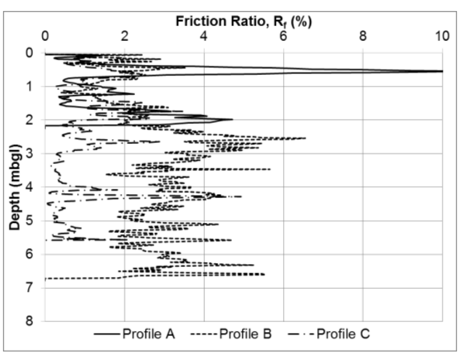

Figure 5. CPT Friction Ratio

The Type C profile consists of predominantly silty sands of greater thickness (4-6m) interbedded with thin sandy silt laminations, overlying bedrock, with an occasionally completely weathered top horizon. Due to the greater sand content, these profiles are characterised by greater strength, higher permeability, and lower compressibility. The Type B profile is prevalent in the central part of the Salina, constituted by very soft slightly sandy silts, grading to silty clay (>2m).

4.2 Groundwater

The groundwater table is found at about 1m below ground level, relatively consistently across the site, and at the boundary between Salina deposits and the desert fill. This level is the result of equilibrium between upward seepage from the underlying bedrock and surface evaporation. The groundwater head in the underlying bedrock was consistently found to be higher than in the Salina deposits. Occasionally, groundwater levels were encountered at greater depths, of up to 2m. These groundwater sinks could be a result of locally lower bedrock permeability, resulting in lower recharge rates. Thickness and composition of the Salina deposits did not seem to have a significant influence on groundwater levels. The average concentration of Magnesium, Sodium, Potassium metal ions and acid radical Chloride were found to be considerably higher than those found in seawater.

4.3 Geotechnical properties

The focus in the definition of mechanical properties for each engineering unit varied depending on the particular characteristics of interest and associated ground risks. The Crust clearly exhibited collapse potential upon wetting, and variable subgrade strength and stiffness. High compressibility, low permeability and poor shear strength were the parameters of interest for the Salina deposits and rock mass parameters for the Bedrock. Mechanical properties were either measured directly or derived by correlation with in-situ or laboratory testing data.

4.3.1 Crust

The potential for ground collapse upon wetting was determined through Plate Loading Testing (PLT) in dry and inundated conditions, and Double Oedometers (DO).

The collapse potential at a given stress level, I_c, is defined as the value of measured collapse relative to the original height of the soil specimen:

$$I_c = \frac{\Delta h}{h_0} = \frac{e_d - e_w}{1 + e_d} \quad (1)$$

Where e_d and e_w are the void ratios in dry and wet conditions, respectively. Based on the Ic value, different classes of collapse severity have been defined in the literature.

Collapse potential calculated for PLT and DO is reported in Figure 6 and Figure 7, respectively. PLT collapse potential increases from about 6% for low applied vertical stress to about 14% for high stress and appears not to be significantly affected by thickness of collapsible deposits. DO collapse potential is generally lower, between 1 and 6% on average, increasing with stress. PLT collapse potentials are expected to be higher than that measured by the DO, as PLT provides results representative of the entire column of collapsible desert fill deposits; whereas DO samples give results specific for the conditions at sampling depth (in this particular case 1 to 2m). PLT was also carried out in percolating water conditions, whereas DO in static soaking conditions. PLT data was also used to determine the magnitude of (secant) stiffness modulus (E'), its distribution across the Salina, and its changes from dry to wet conditions.

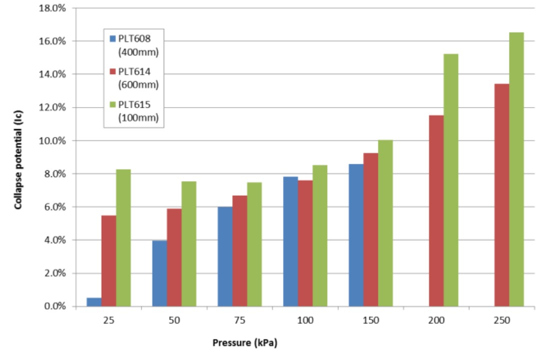

Figure 6. Collapse potential, PLT

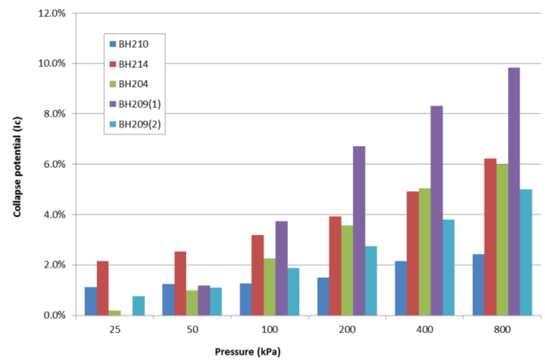

Figure 7. Collapse potential, DO

Values of E' for first loading (FL) to 100 and 200kPa, and reloading (RL) to 75 and 150kPa are reported in Table 4-1 (average values in brackets).

Table 4-1. Stiffness modulus E'

Loading conditions	E' (dry) (MPa)	E' (wet) (MPa)
FL, 100kPa	2-33 (15.7)	1-12 (5)
FL, 200kPa	2-28 (11.5)	1-6 (3)
RL, 75kPa	24-96 (61)	24-100 (53.7)
RL, 150kPa	30-99 (54.8)	35-47 (39)

In dry conditions, variability is significant across the site, with a factor of 15 in first loading and 3-4 in reloading. The complex metastable structure of the cemented deposits is likely to be the cause for the varied non-linear stiffness response, with a reduction of subgrade modulus with increasing applied pressure, and significant difference between first loading and reloading values. This is likely due to gradual breakage of salt cementation between soil particles and subsequent irreversible plastic deformation. The role of cementation is even more evident when looking at the severity (about three-fold) of reduction in subgrade modulus upon wetting in first loading conditions, compared to reloading. An alternative measure of subgrade response to loading is provided by CBR (California Bearing Ratio). This parameter has been evaluated indirectly through correlation with Dynamic Cone Penetration testing (DCP) and directly in the laboratory, in both dry and soaked conditions. The formulae proposed in HD29/08 of DMRB have been used for correlation with DCP. CBR values summarised in Table 4-2 were also obtained by correlation with PLT data in accordance with IAN73/06 of DMRB.

Table 4-2. Subgrade Reaction Modulus, CBR

Source	CBR_{dry}	CBR_{wet}*
PLT (%)	1-12 (5)	0-4 (1.4)
DCP (%)	3-20 (7)	2-8 (5)
Lab (%)	30-101 (50)	13-59 (27)

** Soaked in lab CBR; percolated in DCP/PLT*

PLT and DCP-derived values are representative of the in-situ conditions of the subgrade. The average CBR values in dry conditions are of comparable magnitude. Similarly to what observed for E', CBR significantly reduces in wet conditions (the DCP-correlated values are higher as DCPs were carried out at a certain distance from the location of the PLT, therefore potentially still in partially saturated conditions). Laboratory CBR values are instead representative of the in-situ material after (dry) compaction. CBR increases dramatically, as metastable/soluble cementation is removed and the material is brought to a denser state. In this state, the impact of wetting is still significant (reduction of about 50%) but resulting in CBR values much higher than in the wet, uncompacted state.

4.3.2 Uncemented Salina Deposits

The uncemented deposits, being fully saturated, are not as prone to collapse upon wetting as the Crust but are characterised by high compressibility and low shear strength.

Laboratory testing, CPT and SPT were the main data sources for determination of mechanical properties. Two main lithologies were identified, namely the clayey silts (predominantly in the central part of the Salina, profile B in Figure 3) and the silty sands (located in proximity of the Wadi deltas, and of variable thickness, from lenses or beds within the clayey silts to as thick as the entire soil column, profile C in Figure 3). A summary of the mechanical properties for these two lithologies is provided in Table 4-3.

While dry and saturated unit weight, natural moisture content (NMC), void ratio (e) and OCR profiles with depth are comparable for the two lithologies, the compressibility parameters are quite different. Compression Index (C_c) in the clayey silts was twice that of the silty sands, as was the constrained Young's Modulus (E'_s); the difference in Recompression Index (C_r) was three-fold. The coefficient of consolidation (C_v) was below 10 m^2/y in most of the tested samples of clayey silt, across a pressure range of 25 to 200kPa. No evident trend with applied pressure was identified. In the same pressure range, C_v in the silty sands ranged from 5 to 15 m^2/y, reducing with increasing pressure. Undrained shear strength (Cu) was directly measured in triaxial testing (UU and CIU) and correlated with CPT and SPT data. The cone factor that provided the best fit with Triaxial data was N_{kt}=24, which is within the range suggested in Lunne et al., 1997 for intermediate soils (clayey sands to silts).

Table 4-3. Properties of the Uncemented Deposits

Parameter	Clayey Silts	Silty Sands
γ_{dry} (kN/m^3)	16	18
γ_{sat} (kN/m^3)	20	21

NMC (%)	15 - 25	20
PI	< 33	<13
e	0.5 - 0.7	0.4 - 0.5
OCR	$(z/9.47)^{-0.77}$ (depth z in m)	
C_c	0.1 - 0.2	0.05 - 0.10
C_r	0.015	0.005
$E'_{s\ (100kPa)}$ (MPa)	2 - 4	5 - 7
C_v (m^2/y)	1 - 10	5 - 15
Cu (kPa)	10 - 50	25 - 100
ϕ' (°)	25 - 30	30 - 35

The angle of shear resistance ϕ' was derived from CPT data using the formula proposed by Kulhawy and Mayne (Lunne et al., 1997), applying a correction factor to match the results of Triaxial CIU tests. The best fit was obtained by reducing the CPT-derived data by 15%.

4.3.3 Bedrock

The bedrock encountered in the Salina comprised carbonate claystone, mudstone and limestone, variably distributed across the site. The rock mass properties are presented in Table 4-4 below (average values in brackets).

Table 4-4. Properties of Bedrock

Param.	**Claystone**	**Limestone**	**Mudstone**
RQD	28-100	21-95	38-100
(%)	(74)	(66)	(77)
UCS	0.2-3.4	0.2-8.5	0.2-4.8
(MPa)	(1.4)	(3.0)	(1.8)

The weathered mudstone was characterised by cone resistances of around 6MPa and friction ratios of 4%, with associated Cu values above 100kPa. High artesian pressures were measured in standpipes installed into the bedrock, with water level reaching and sometimes going above ground level.

5 CONCLUSIONS

Ground investigations in the Salina deposits highlighted the challenging conditions to building structures and infrastructure, as a result of the potential for large settlements, low bearing capacity and collapse of foundation soils upon wetting and high artesian pressure in the bedrock, feeding constant capillary rise of salt-rich moisture.

To reduce settlements and improve shear strength, surcharge preloading with installation of band drains is considered a viable and cheaper alternative to piling into bedrock, although requiring a longer construction time. Based on insitu and laboratory testing, surface compaction in dry conditions is expected to reduce collapse potential, improving subgrade CBR. Geogrids could also be incorporated into road embankments to improve response to heavy traffic loading. Capillary rise could be effectively mitigated by installation of capillary break geosynthetics, as opposed to more expensive rockfill layers.

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