Capacity of piles embedded in crystalline salt formations

Capacité des pieux ancrés dans les formations de sel cristallin

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ABSTRACT: Pile foundations were selected to support a number of offshore and onshore structures at the Dead Sea shore. Light structures were supported on steel tubular piles driven into crystalline salt formation, meanwhile a jetty structure was supported on driven steel tubular piles that ended with reinforced concrete sockets drilled into the massive crystalline salt.

This paper discusses the shaft skin resistance and the end bearing capacity of both driven and drilled piles that are embedded into crystalline salt formation. Properties of the crystalline salt were initially assessed based on results of in-situ and laboratory tests. The pile shaft and tip capacities were evaluated based on traditional analytical approaches. Evaluation of the driving records of the first driven piles and verification of the pile capacity by dynamic pile analyses, contributed to developing a driving criteria to ensure that the steel tubular piles were adequately driven into massive salt and that the required pile capacity has been attained. Static pile load tests were carried out on preliminary piles to confirm the geotechnical parameters of the crystalline salt formations. The design parameters of the piles in salt were found in agreement with those deduced from the pile load tests.

RÉSUMÉ : Des fondations en pieux ont été sélectionnées pour soutenir un certain nombre de structures offshore et sur le bord de la mer Morte. Les structures légères étaient supportées par des pieux tubulaires en acier battus dans la formation de sel cristallin, tandis que la structure métallique offshore était soutenue par des pieux tubulaires en acier initialement battus et puis forés pour achever un ancrage en béton armé foré dans le sel cristallin massif.

Cet article discute la résistance de frottement latéral et la résistance de pointe des pieux battus et pieux forés ancrés dans les formations de sel cristallin. Les propriétés du sel cristallin ont été évaluées sur la base des résultats d'essais in situ et de laboratoire. Le frottement latéral de fût de pieux et la résistance de pointe ont été évalués sur la base d'approches analytiques classiques. L'évaluation des dossiers de battage des pieux battus et la vérification de la capacité des pieux par les analyses des essais dynamiques ont contribué à l'élaboration d'un critère de battage pour s'assurer que les pieux ont été correctement ancrés en sel massif. Des essais de charge statique ont été effectués sur des pieux préliminaires afin de confirmer les paramètres géotechniques dans les formations de sels cristallins. Les paramètres de conception ont été trouvés en concordance avec ceux déduits des essais de charge de pieux.

KEYWORDS: *salt formations, steel tubular driven piles, concrete socket, pile load tests*

1. INTRODUCTION

Pile foundations were designed and constructed to support a number of offshore and onshore structures at the Dead Sea shore. The geological and ground conditions of the site are charecterized by the presence of thick soft clay layers that are underlain by deeply extending crystalline salt formations.

The properties of the salt formations are highly variable and extend between cohesion-less frictional material and weak rock regading its rock quality designation.

Driven steel piles were used to support the onshore light structures. Meanwhile, the offshore jetty structure was supported on driven steel tubular piles with reinforced concrete sockets drilled into the massive crystalline salt.

The subsurface conditions of the site and the main design considerations were presented in (El-Mossallamy et al 2009).

In this paper the geotechnical parameters of the salt formations that were considered in the design of driven and bored piles are discussed. The design parameters are then verified against the results of the preliminary pile load tests and the driving records of the piles.

2. SUBSURFACE CONDITIONS

The subsurface formations at the site of the driven and drilled piles can be divided into the following main zones:

- Upper Zone: Soft silty clay layers that extend down to about 15 m below the groundsurface or seabed. (Figure 1).
- Transition Zone: Alternating intercalations of soft clay layers and crystalline salt layers with a thickness ranging between 15 to 20 m (Figure 2).
- Bottom Zone: Highly fractured crystalline salt formation that extends below the Transition zone and dominated by crystalline salt layers with occasional thin intercalations of soft clay (Figure 3).

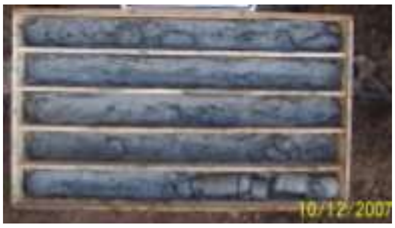

Figure 1, Soft Silty Clay

Figure 2, Transition Zone

Figure 3, Crystalline Salt

The onshore and offshore subsurface investigations were carried out in 2007 and 2008. Figure 4 show the total core recovery (TCR %) and the rock quality designation (RQD %) of the crystalline salt samples along the investigated elevations. It is noted that in the RQD% values of the salt formations in the 2007 investigation ranged between 0% and about 40%. This range is much lower than those obtained previously for the salt formation at a nearby location in 1995 where a pile load test on a preliminary pile socketed in salt rock was carried out and reported (El-Mossallamy et al 2009, Fayed 2015).

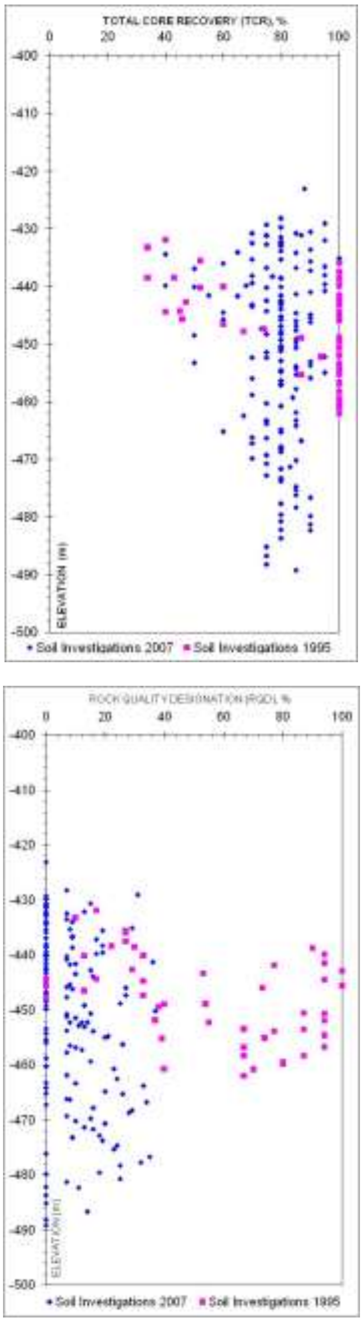

Figure 4, TCR% and RQD% of crystalline salt core samples

Laboratory test results showed that unconfined strength of the crystalline salt samples ranged between about 2.0 MPa and 10.0 MPa (Figure 5). These values matches those reported by others (Frydman et al 2008). On the other hand the deformation modulus of the crystalline salt core samples ranged between 30 MPa and 100 MPa which is much less than those given in the literature (Frydman et al 2008, Bell 1981)

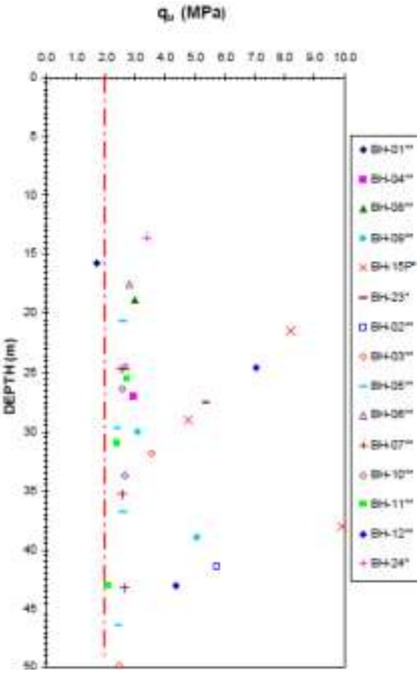

Figure 5, Unconfined compressive strength of Crystalline salt (Investigation 2007).

3. DRIVEN PILES

Steel tubular piles were driven to a depth of about 30m using diesel hammers type Delmag D80 and D62 of nominal maximum energy 288 kN.m and 224 kN.m, respectively. The piles outer diameter is 914mm and its wall thickness is 25mm. Pile were designed to support a structural service load of about 700 kN including negative skin friction from soft clay layers. The recorded number of blows per 250mm during driving a number of piles of the light structures are shown in Figure 6. Meanwwhile the accumulated driving energy is illustrated in Figure 7.

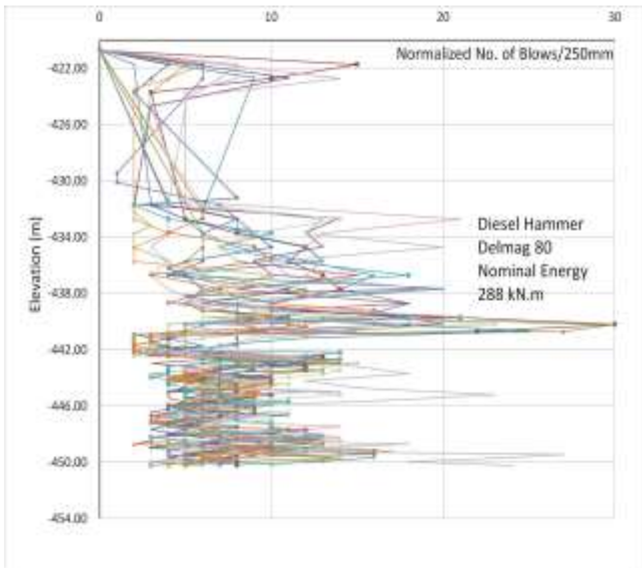

Figure 6, no. of blows per 250mm for onshore driven piles

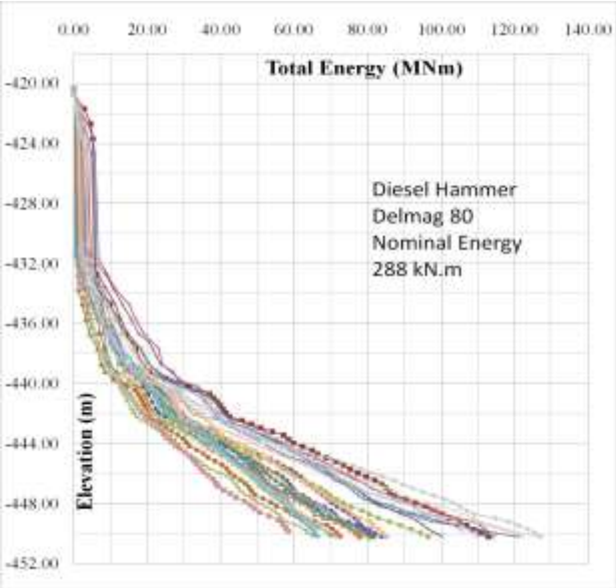

Figure 7. Accumulated driving energy of onshore driven piles

The design of the steel driven pile in the highly fractured salt was based on a skin friction of 30.0 kPa. The end bearing resistance of these piles was considered only in short term loading condition (seismic load case), to avoid the creep behavior of salt. The total driving energy of the piles ranged between 80 and 100 MPa (Figure 7), meanwhile the no. of blows per 250mm in the highly fractured crystalline salt was observed to range between 5 and 20. It is noted that the no. of blows was limited to not more than 40 to avoid overstressing the piles during driving.

4. PILES SOCKETED IN SALT

Both vertical and raked piles were designed to support the offshore jetty. The steel casing length was defined to penetrate the sea water, the soft clay layers, the transition zone and at least 1.0m into the crystalline salt formation. In addition to borehole data, a driving criterion of not less than 6 no. of blows per 250mm was selected and followed for assuring the penetration of the pile casing into massive salt and consequently providing the stability of the drilled socket wall.

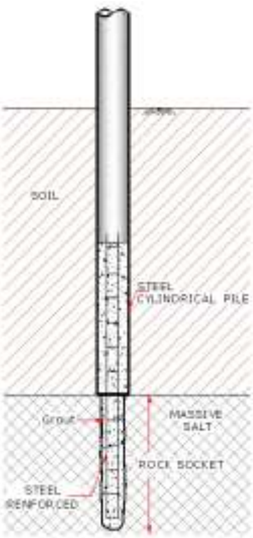

Figure 8. Pile socketed in salt

Driving of offshore tubular steel casings was carried out using Delmag D80 and D62 diesel hammers. The driving rig and ancillary equipment were mounted on steel rails that were installed on the executed steel driven casings and then extended and advanced progressively from onshore to offshore.

The excavation of soil from inside the casing and the concrete socket into massive salt was carried out using different techniques but mainly using Wirth reverse circulation drilling.

Based on a previous pile load test carried (El-Mossallamy et al 2009), the ultimate skin friction of the concrete socket into crystalline salt reached more than 275 kPa. Consequently, a conservative allowable skin friction value of 110 kPa was retained for the design of the concrete sockets embedded in salt.

It is also noted that due to creep behavior of the salt, the end bearing of the pile socket was not considered in the design under permanent load cases but considered only under seismic loading conditions.

The design length of the steel casings varied between 25m and 35m while the depth of the concrete socket of the piles varied between 5m and 20m according to the applied design loads of the Jetty.

5. STATIC LOAD TESTS ON PRELIMINARY PILES

To verify the design assunptions and the construction methodology, static pile load tests were conducted on a prelimnary driven steel pile (T2-P5) as well as on a prelimnary driven steel piles with drilled concrete socket (T1-P9). The data and results of the two tests (T2-P5) and (T1-P9) are presented in Table 1 and Figures 8 and 9.

Table 1. Preliminary Pile load Tests Data and Results

Pile Loat Test No.	T2-P5	T1-P9
Type	Driven steel tubular filled with concrete	Driven steel tubular with concrete drilled socket
Driving Equipment	Diesel Hammer - Delmag 80 - max energy 288 kN.m	Diesel Hammer - Delmag 80 - max energy 288 kN.m
Drilled socket length (m)	---	6
Pile outer Diamater (m)	0.914	0.914
Pile wall thick. (m)	0.025	0.025
Ground Level (m)	-418.65	-418.82
Cutt-off Level (m)	-418.15	-418.32
Steel Pipe Toe level (m)	-448.65	-448.82
Steel Pipe Length (m)	30.50	30.50
Steel Grade	52	52
Concrete Socket Toe Level (m)	---	-454.82
Concrete Socket Diameter (m)	---	0.8
Pile length in soft clay (m)	12	14
Pile length in fractured salt (m)	18.5	16.5
Drilled socket length into salt (m)	---	6
No. of blows per 250mm (End of driving)	12	50
CAPWAP shaft friction (kN) end of driving	2181	1683
CAPWAP end bearing (kN) end of driving	1819	5807
CAPWAP shaft friction (kN) two days later	4105	2749
CAPWAP end bearing (kN) two days later	1786	5955
Maximum test load (kN)	3750	10500
Settlement at maximum test load (mm)	162	139
Interpreted ultimate skin load (kN)	1780	1563
Interpreted ultimate skin friction in Transition Zone (kPa)	33	33
Interpreted ultimate skin load along socket (kN)	---	5457
Interpreted ultimate skin friction along socket (kPa)	---	360
Interpreted ultimate base load (kN)	2270	5200
Interpreted ultimate base resistance (kPa)	3460	10400

Dynamic testing and CAPWAP analyses reported in Table 1 were carried out on the driven steel casings of the piles prior to drilling and filling the pile/ pile socket with concrete. According to CAPWAP analyses, the shaft friction resistance at end of driving ranged between 2181 and 1683 kN. The set-up of shaft friction reached additional 50% to 100% increase after 2 days from end of driving. Meanwhile the base resitanve of the test piles varies significantly between about 1800 kN for the driven pile terminated in weak salt (No. of blows/250mm less than 12) and about 5800 kN for the driven pile terminated in massive salt (No. of blows/250mm about 30).

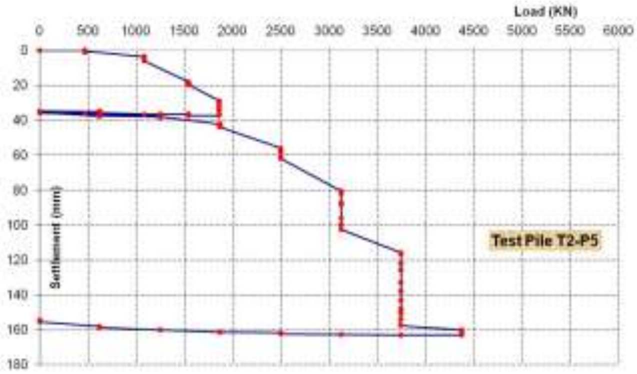

Figure 9. Load-settlement curve of pile load test on pile T2-P5

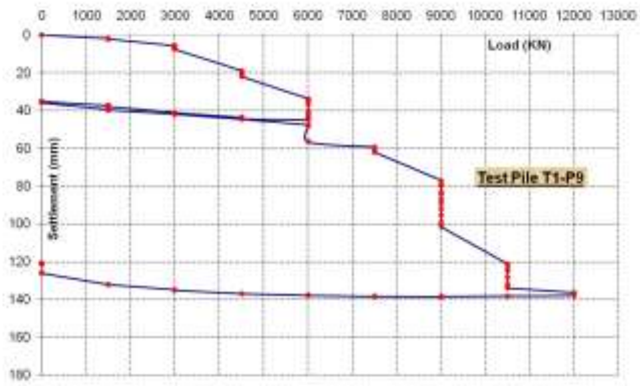

Figure 10. Load-settlement curve of pile load test on pile T1-P9

The modified Fleming method (Fleming 1992) is applied to distinguish between loads taken by skin friction and loads taken by base resistance. According to the conducted evaluation, the skin friction between driven steel pile and salt (pile load test T2-P5) reaches about 33 kPa. From these analyses, the ultimate base resistance of driven steel tube in the salt was calculated in the range of about 3500 kPa.

From the analyses of the results of pile load test T1-P9, the loads taken by skin friction along the socket pile was calculated as shown in Table 1. The corresponding ultimate skin friction along the socket pile length is 360 kPa. This ultimate friction value of concrete socket in salt commensurates with the values estimated in previous studies (El-Mossallamy et al 2009, Fayed 2015). From these analyses, the ultimate base resistance of the drilled concrete socket in the salt can be calculated in the range of about 10000 kPa.

6. CONCLUSION

Steel Tubular Piles were driven into salt formations to support relatively light structures. Also steel piles provided with concrete socket into salt formations were designed and constructed to support an offshore jetty structure at the Dead Sea shore. Design parameters of piles in highly fractured crystalline salt has been evaluated and presented.

For driven steel tubular piles of 30m length, 914mm outer diameter and 25mm wall thickness, the number of blows ranged between 5 and 30 blows per 250mm using a nominal driving energy of 288 kN.m per blow. Ultimate skin friction of 30 kPa was adopted for the design of steel piles driven in highly fractured salt.

For drilled concrete sockets in crystalline salt an ultimate socket skin friction of about 360 kPa can be considered. The ultimate end bearing resistance of the pile base in salt varied between about 3500 kPa and 10000 kPa accordign to the quality of salt.

The design parameters of the piles embedded in salt formations were verified by the results of the presented preliminary pile load tests.

7. REFERENCES

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