Review of Molikpaq Geotechnical Material

Second Report
(Draft)

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Prepared for:

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1 INTRODUCTION

At the request of Dr. R. Frederking, Canadian Hydraulics Centre, National Research Council of Canada, Dr. Law of Carleton University is to conduct a geotechnical review of the Molikpaq geotechnical material in two stages. The first stage relates to the 2008 report by Kevin Hewitt "Estimates of Ice Loads on the Molikpaq Based on Geotechnical Analysis", along with other materials. The second stage relates to the May 2009 report by Klohn Crippen Berger entitled "Molikpaq Ice Loading 1986 JIP Canadian Beaufort Sea Summary Document-Draft". The 2009 Hewitt' report entitled "Final Draft Report Estimates of I-65 based on Geotechnical Analyses and Responses" becomes available during the second stage of review. It is used as a reference in this second stage.

The two reports to be reviewed are known in the following as the KCB report and the Hewitt report.

The aim of this stage of review is to examine the opinions express in the KCB report and the Hewitt report regarding the state of the core sand, liquefaction, and the ice load from a geotechnical perspective.

2. CORE SAND BEHAVIOUR

The methods for assessing the in situ density or state in terms of relative density (D_r) or state parameter (ψ) have been discussed in the previous report (Law 2009). Here the discussion will focus on new materials that are presented in the KCB report and the Hewitt report.

2.1 State of the core sand

The core sand was placed hydraulically with a pipeline discharge near the sea surface. Experience shows that such a method of placement will produce a loose fill. Therefore Hewitt has maintained all along that the core sand is loose and contractive. The KCB report, however, argues that the characteristic state, taken as the lowest value of 80 percentile of the state parameter, ψ, from the Cone Penetrometer Test (CPT) results, is estimated at -0.03, implying a dilative sand. This characteristic value is similar to the original value suggested by Jefferies et al. (1986). The reasons for the divergence of these two opinions have been discussed in the earlier report.

There appears some closing of the gap between these two opinions in the KCB report and the Hewitt report, Both now agree that the core sand as placed has a relative density of about 35%. However the similarity stops there.

The KCB report insists that the core sand is dilative and Hewitt maintains that the core sand is contractive. The basis of their arguments can be illustrated using the information each provides in their reports.

The KCB report provides a graph relating D_r and ψ (Figure 1). Although the KCB report admits that there is no one-to-one correspondence between D_r and ψ, the data do show the possibility that at D_r = 35%, the core sand may be dilative. The report goes on to present new information on laboratory tests, theoretical study and statistical analysis. It also states that new studies have shown that the stress level shift in the interpretation of state parameter from cone penetration resistance noted by Sladen (1989) has been dealt with by using a shape factor. All these arguments lead to the conclusion that the core sand has a characteristic state of -0.03. Hence the core sand is in a mildly dilative state.

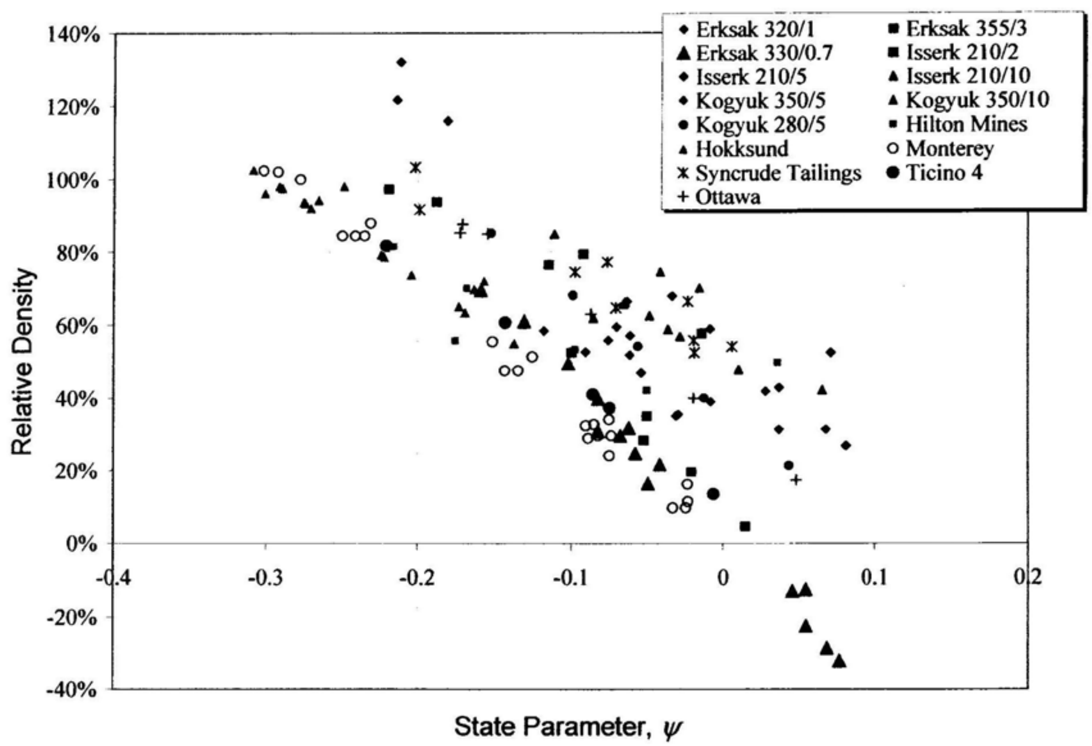


Figure 1 State parameter versus relative density in triaxial tests (KCB report)

On the other hand, Hewitt shows a table (Table 1) that relates compactness of sand to relative density and state parameter. According to this table sand at D_r = 35% is considered loose and contractive (or potentially liquefiable with ψ > 0). Hewitt further supports his position with pressuremeter test results and the successful densification of the core sand at Amauligak F-24. For the pressuremeter tests, Hewitt quoted the following statement from the contractor for GCRI: "The results… indicate that the sand as placed is 'loose' or at least, in a state that when sheared the sand structure would reduce in volume." One should, however, recognize that pressuremeter tests are normally conducted at vertical intervals much larger than those of the CPT. Therefore it cannot provide a soil profile as continuous as the CPT can. The densification by blasting at Amauligak F-24 yielded a surface settlement of 0.6m and drastic increase in relative density, indicating the core sand at Amauligak I-65, which is similar to that at Amauligak F-24, should be in a loose and contractive state without densification.

DESCRIPTIVE TERM	RELATIVE DENSITY (%)	'STATE PARAMETER' (APPROXIMATE)
Very loose	0 to 15	+0.20 to +0.14
Loose	15 to 35	+0.14 to +0.06
Medium dense	35 to 65	+0.06 to -0.06
Dense	65 to 85	-0.06 to -0.14
Very dense	85 to 100	-0.14 to -0.20

Table 1 Approximate correlation between relative density and state parameter (Hewitt 2009)

The closing of the gap is not insurmountable. With the high variability of the pipeline placed core sand and the close proximity of the characteristic state from the critical state line, it is likely that part of the core sand will be dilative and the other part contractive. Given the right applied shear stress during an ice event, the contractive part may liquefy and the dilative part remain intact. This appears to be a most plausible explanation for the observed local liquefaction and spatial variation of settlement during the April 12, 1986 ice event.

3. LIQUEFACTION

There is some general agreement on the issue of liquefaction related to the Molikpaq Amauligak I-65. As early as 1986 shortly after the ice event, Rogers et al. (1986) admitted that the pore pressure transducer E1, located at around the mid height of the core sand near the east wall, showed a significant pore water pressure rise during the April 12, 1986 ice event to the point that the fill there liquefied. Jefferies (1994) pointed out that there were two out of eighteen piezometers showing liquefaction. Hewitt (2008 2009) has been suggesting that an annulus zone of core adjacent to the caisson had liquefied during the ice event.

The KCB report introduces a small deviation on liquefaction of the Molikpaq. On p.35, the report states: "The soil behaviour during the 12 Apr 86 event was cyclic mobility, not liquefaction." Since the time "cyclic mobility" or "cyclic liquefaction" was mentioned by Casagarade (1975), this term has gone through a long road of many meanings, due partly to semantics and partly to different researchers giving it different meanings. Casagrande defined cyclic mobility as "the response of a test specimen of dilative sand to cyclic loading in a triaxial test when the peak pore pressure rises momentarily in each cycle to the confining pressure." He further stated that cyclic mobility normally cannot develop in dense (dilative) sand in the field. Since then there are many other definitions. For example, Kramer (1996) states that cyclic mobility can occur in the field during earthquake shaking when the static shear stress is less than the shear strength of the liquefied soil, implying cyclic mobility is a phenomenon of liquefaction. While "cyclic liquefaction" and "cyclic mobility" are synonymous in Casagrande's terminology, Robertson (1994) distinguishes a difference in these two terms based on whether or not the applied cyclic loads yield a shear stress reversal that leads to zero effective stress. Both terms are used to describe a mechanism for liquefaction.

In recent years, much of the difference in liquefaction terminology have been reconciled to consider cyclic mobility being a liquefaction phenomenon triggered by cyclic loading in soil deposits with the initial static shear stress lower than the soil strength. The resulting deformation is generally small unless the soil is contractive.

Based on this understanding and in view of the high excess pore pressures and large settlements, some parts of the core sand of the Molikpaq must have liquefied as supported by Rogers et al. (1986) and Jefferies (1994). Calling it “cyclic mobility, not liquefaction” is a matter of semantics.

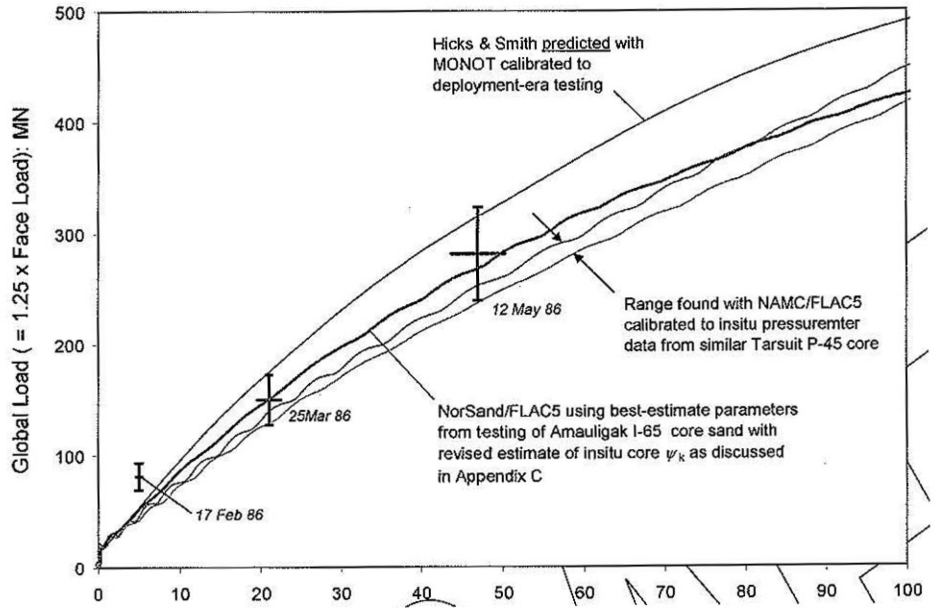
4. ICE LOAD

This is another contentious issue in the Molikpaq project. Rogers et al. (1986) reported shortly after the April 12, 1986 ice event that the maximum ice load is in the range of 500 to 700MN, while Hewitt since the 1990’s has maintained that the ice load is much lower and would not be more than 200MN. The KCB report and the Hewitt report provide some new insights on this issue. Their estimated ice loads now are marginally closer to each other but previously unsettled issues remain.

In the KCB report, the estimated maximum global ice load is now reduced to “at least 400MN” based on numerical simulation and measured deformation, or 475 MN based on simulation of ice-structure interaction. Taking some uncertainties into account, the Hewitt report now raises the estimated ice load to 220MN. The major reason for the disagreement still lies in the fact that the two reports are basing their arguments on different aspects of the Molikpaq project and on different understanding of the core sand behaviour.

4.1 Geotechnical ice load assessment in KCB report

One new work included in the KCB report is the use of the “ovalling” of the caisson ring in numerical analysis to aid the estimation of the ice load under static condition. “Ovalling” refers to the measured closure between the ice loaded side and the opposite unloaded side. The results of their analysis are summarized in Figure 2. This figure shows the theoretical peak ice load versus caisson “ovalling” based on the MONOT analysis of Hicks and Smith (1988) and on FLAC-2D with the Non Associated Mohr Coulomb (NAMC) soil model and the NorSand model. The figure also shows the peak load estimated based on the readings of Medof panels and strain gauges mounted on the Molikpaq recorded during some ice events. The data in the figure shows there is some general agreement between the computed and measured trends and that there is consistency between the different soil models and numerical analyses. Based on this, the KCB report asserts that “the Medof panels are as accurate as reported in the 1986 JIP”.



Caisson ring deformation ("ovalling") mm

Figure 2 Comparison of load-ovalling response of Molikpaq

The results of Hicks and Smith (1988) in Figure 4 are new in the KCB report and not in their original work. Presumably the soil models chosen correspond to ψ = -0.025 and -0.075 for the core sand and the berm material, respectively. These values are closely similar to those chosen in the KCB report in their new numerical analysis to evaluate the ice load-"ovalling" relationship.

The choice of the ψ value goes back to the question of the state of the core sand. While this value is consistent with the accepted value of GCRI, it has been persistently rejected by Hewitt.

The KCB report also cites the work of Altaee and Fellenius (1994) who use a sustained cyclic load with a peak of 400MN to support their estimated ice load value.

4.2 Geotechnical ice load assessment in Hewitt report

Hewitt's argument is based mainly on considering the loose nature of the core sand and the small measured horizontal movements of the Molikpaq. These two quantities together can only lead to an ice load significantly lower than that deduced from Medof panels or strain gauges. He summarizes the results of numerical modelling (FEM GCRI and FEM EBA) and physical modelling (centrifuge tests) in Figure 3. This figure shows that a loose core sand will displace a lot more than a medium dense or dense core sand. Based on a horizontal displacement after the ice event of about 30mm and a geotechnical model of a loose core sand, elastic strain being larger than the residual strain reflected after the ice event, and frictional resistance between the berm and the caisson base, Hewitt obtains an estimated ice load of 220MN. He also supports his estimate of low ice load with three case records in Beaufort Sea.

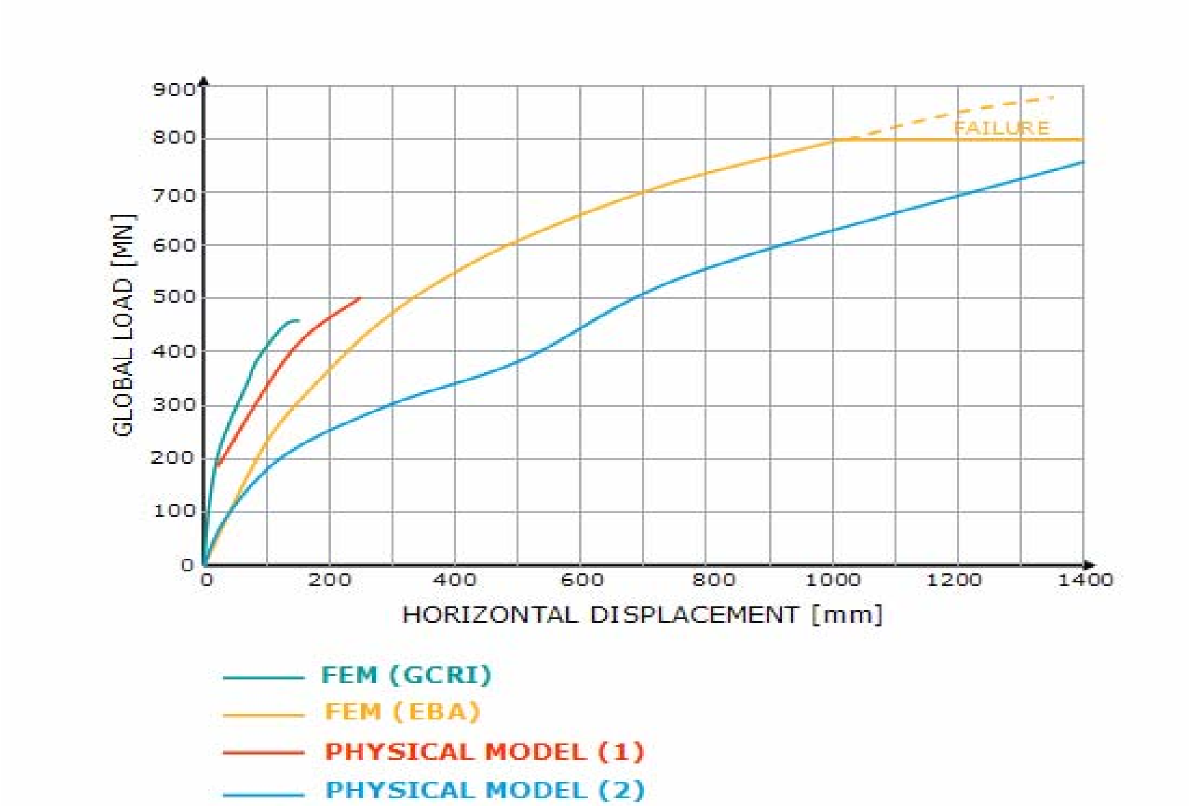


Figure 3: Predicted Horizontal Displacement at Point of Load Application (Hewitt 2009)

Note: Physical model (1) = centrifuge test on medium dense sand
Physical mode (2) = centrifuge test on loose sand
EBA analysis is based on loose sand
GCRI analysis is based on dense sand

5 DISCUSSION

5.1 Ice load versus horizontal displacement

There is a general agreement that the horizontal movements measured during the April 12 1986 event are small, in spite of some malfunction in some inclinometer casings. The KCB report (p. 39) states that "Overall, there is about a 20mm permanent movement of the down-ice side of the caisson in the direction of the ice load."

Different locations of horizontal movement have been considered in the different modelling of the Molikpaq performance during ice loading. Jefferies et al. (1985) discuss the horizontal movement at the top of the caisson on the ice loaded face. Hicks and Smith (1988), Altaee and Fellenius (1994) and Hewitt (2008) refer to the point of load application on the loaded side. While all numerical modelling should be able to yield the horizontal movements at any location within the core sand, only Hicks and Smith (1988) give the horizontal displacements both at the point of load application and at the core surface where the inclinometer casings are located. Their results on the horizontal movements are compared at these two different locations as follows.

Figure 4 shows the horizontal movements at the point of load application for different soil states and different drainage conditions. The three soil states A/B, C and D correspond to mildly dilative core and stronger dilative berm, loose~~s~~ core and berm and very loose core and berm, respectively. At applied loads producing small horizontal displacements at the measured value of about 20mm, the load-displacement relationship remains unchanged for the three cases. That means at such low horizontal displacement, the ice load is independent of the state of the core sand. At this displacement, the ice loads are estimated at 2.7 and 1.8 MN/m for the undrainded and the drained cases, respectively. Based on the KCB method of calculation (74m wide normally loaded face and a factor of 1.25 to give the global load), these ice loads per unit width correspond to global ice loads of 247MN and 167MN, respectively. On the other hand, at a horizontal movement of 20mm at the core surface at inclinometer I2, the corresponding ice load is estimated at 5.0MN/m for the A/B case under drained loading followed by drained unloading (463MN using the KCB calculation). This significant difference in the estimated ice load for the same magnitude of horizontal movement at two different locations has not been mentioned or explained by Hicks and Smith (1988).

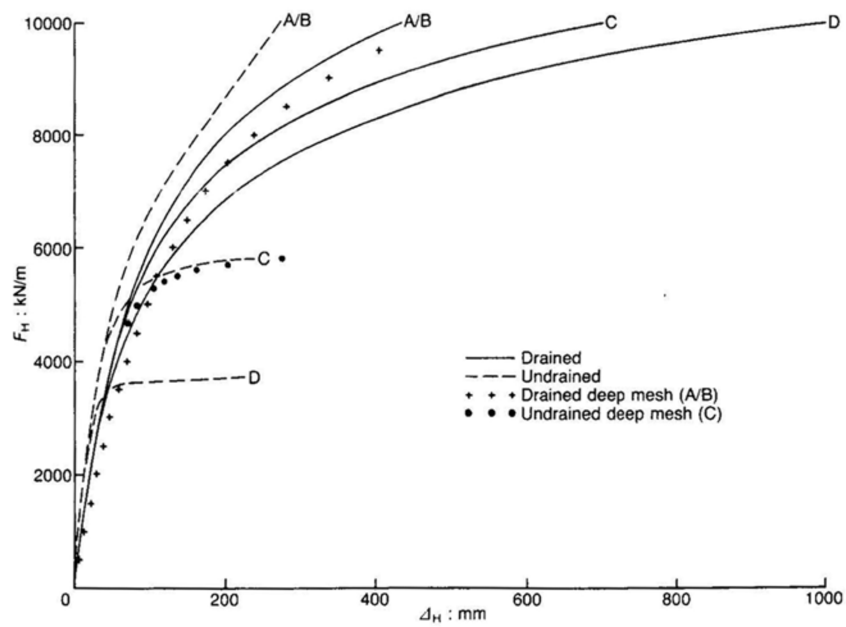
Interestingly, the first set of values of 247 and 167 MN agrees more with Hewitt's estimate of ice load while the second value agrees more with the KCB estimate. In the KCB report, the estimated ice loads at the inclinometer location have been discussed in details taking the out of plane displacement and other factors into account. The reported ice load based on "ovalling" (not horizontal movement of the core sand) is estimated at 425MN. This estimated ice load based on "ovalling" is not in the original work of Hicks and Smith (1988) and yet the KCB report still considers the work is of Class A prediction category.

If one considers the estimated static ice load by Altaee and Fellenius (1994) (Figure 5), one obtains a similar observation, i.e., the estimated ice load is independent of the compactness of the core sand at low displacement values. At 20mm horizontal displacement at the point of load application, the estimated global ice load is 231MN. Similarly, the ranges of the estimated ice load based on the information provided by Jefferies et al. (1985) and Hewitt (2008): are 183 to 262MN, and 57 to 200MN, respectively.

It is clear that one can obtain a large range of estimated ice load depending on the location of the induced horizontal movement, the numerical scheme, soil model, drainage condition, and the magnitude of the actual loading. Therefore there is a lot of room for interpretation.

It is of interest to note that the KCB report has downplayed the issue of small horizontal movements in the core measured using the inclinometer. Instead of relying on the horizontal movement in the core sand, the KCB report turns to the "ovalling" of the caisson ring for estimating the ice load and validating the measurements of Medof panels and strain gauges. While the report seems to have good results with other ice events, it admits failure to capture useful readings during the critical ice event of April 12, 1986.

The downplaying of the measured horizontal displacement implies the ignoring of the problem posed by the low measured horizontal movement leading to an ice load significantly lower than what GCRI estimated. The reason why this is the case has not been adequately explained in the report.



Horizontal displacement at point of ice load application

Figure 4 Summary of caisson load-displacement behaviour – Categories A/B, C, D (Hicks and Smith 1988)

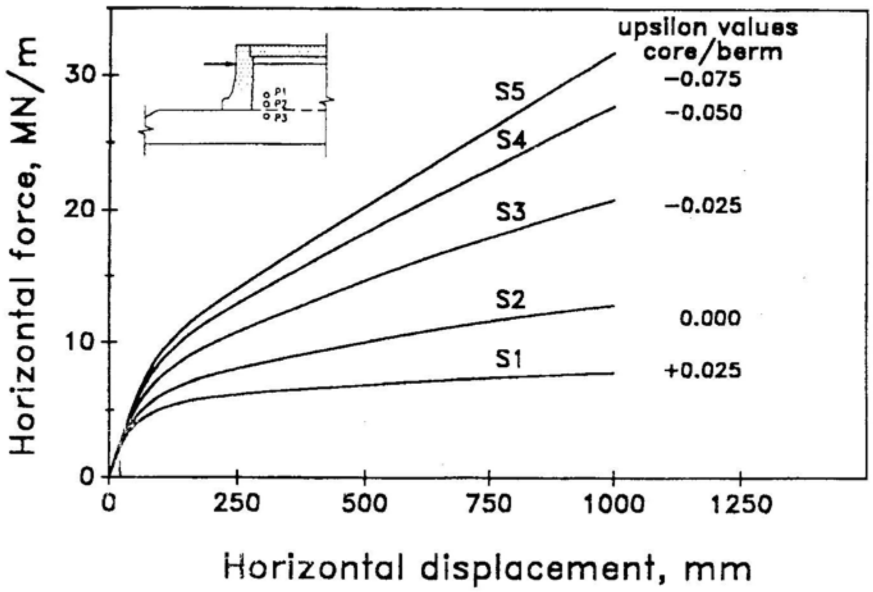


Figure 5 Horizontal force versus horizontal displacement at different compactness core/berm (+ve and –ve upsilons correspond to contractive and dilative state, respectively)

5.2 Shear modulus of core sand

In its new numerical analysis, the KCB report uses a shear modulus G_{max} based on seismic tests conducted at Tarsiut P-45, presumably of the same core sand as the Amauligak I-65. As G_{ma} is considered the initial shear modulus, a factor of 1/3 has been applied both to the core sand and the berm material for the elastic analysis. However, the same shear modulus formula and the same density are assumed for both the core sand and the berm (Page IV.3). In other words, the core sand is considered as dense as the berm. This is in contrast to the views held by all parties in this investigation.

5.3 Best estimate of ice load

In Hewitt report, a best estimate of the geotechnical model is used to estimate the ice load. This model consider the drained condition, loose core sand, low horizontal displacement in the core sand, friction between the base of the steel caisson, finite element analysis by EBA and drained static loading. He then estimates the ice load at 240MN for a horizontal displacement in the order of 50mm.

The new study of KCB actually provides more insight to the estimated ice load. Besides considering ice-structure interaction, the KCB report does substantiate its position with more data including laboratory triaxial tests, and numerical analysis using the “ovalling” data. It also provides better understanding of the CPT data for assessing the state parameter of the core sand. On the other hand, the major problem in this estimated ice load is the downplaying of the low measured horizontal movement. This measured low horizontal displacement unavoidably leads to low ice load, particularly with the state parameter of the core sand so close to the critical state line or close to being loose (contractive).

6 CONCULIONS

1. The core sand is considered loose based on textbook definition. Existing data based on an enhance understanding seems to support that the core sand is mildly dilative and its state parameter is close to the critical state line.

2. Because of high variability of the core sand and its state parameter lying closely to the critical state line, it is likely that some part of it liquefied while other part remained intact during the April 12, 1986 ice event.

3. There is general agreement on the issue of liquefaction. The entire core of the Molikpaq did not liquefy. However, some local zones did suffer liquefaction or cyclic mobility. This is consistent with the spatial settlements measured after the event, some being quite substantial.

4. There is still a significant gap between the ice load estimated in the KCB report and that in the Hewitt report. The reason lies partly in each party making reference to different aspects of the project and partly due to the different understanding of the core sand behaviour.

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