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A REVIEW OF THE PERFORMANCE OF MEDOF PANELS INSTALLED ON THE MOLIKPAQ STRUCTURE IN THE CANADIAN BEAUFORT SEA

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ABSTRACT
Medof Ice Load Panels were deployed near the waterline of the Molikpaq structure and were the primary source of ice pressure information when the structure was subjected to first-year and multi-year ice impacts. The method for load determination is to monitor the volume of fluid pushed out of the panel when the series of internal urethane buttons deform in response to the applied ice load. The performance of these Medof panels has been reviewed previously since these ice load and pressure data have been used in the generation of recommendations contained in the ISO 19906 standard. In this paper we provide a critical review of the various sources of systematic and random error in the load inferred from this Medof Panel data. We will discuss the creep performance, the static performance and the frequency response of these panels. Recommendations for addressing some of the errors in the load values are also presented in this paper.

INTRODUCTION
The ice pressure and load data obtained from Medof Panels (Metge et al., 1983) mounted near the waterline of the Molikpaq Exploration Structure (Jefferies and Wright, 1986) have been extensively used in the establishment of Global Load Design Pressure guidelines (ISO, 2010). Since the mid 1980's, the magnitude of the loads experienced by the structure has been investigated (eg Jefferies and Spencer, 1989) and has been the subject to ongoing controversy (eg. Jordaan et al., 2011 and Jefferies et al., 2011). An overview of the instrumentation on the Molikpaq is given by Frederking et al. (2011) who state, "*The load estimates based on the original calibration of the Medof panels have strongly influenced estimates of multi-year ice loads on the Molikpaq in past publications" and "The 2007 JIP team believes that the "Best Estimate Case" ice loads determined here, about half previous estimates, are an improved representation of multi-year ice loads on the Molikpaq over the 1985-86 season.*". This is now the so-called factor-of-two. Jordaan et al. (2011) state "*It is a reasonable conclusion that the Medof panel calibrations changed with time, with a softening process, indicating higher loads than actually occurred. Design pressures based on the Medof panels for the 1985-86 deployment, likely overestimate the loads by about 50%.*"

In this paper, we review identified sources of random and systematic error in the Medof Panel response to ice loads. As will be demonstrated, the conclusions differ from the earlier work by Frederking et al. (2011) and Jordaan et al., (2011).

OVERVIEW OF MEDOF PANELS

Thirty one Medof panels, 1.135 m wide and 2.715 m high, each with a capacity of 20 MN were installed on the north, northeast and east face of the Molikpaq caisson. The panels are designed so that they measure the total force acting on the plate, regardless of how it is distributed or where it acts (Metge et al., 1983). The method of load determination is to monitor the volume of fluid pushed out of the panel when the set of internal urethane buttons deform in response to the externally applied ice load. The fluid volume is determined from the fluid height in a site tube connected via a hydraulic line to the panel. The ice load is resisted by the urethane buttons not by the internal fluid. A schematic showing the internal arrangement of these Adiprene L-100 urethane buttons (Adiprene, 2011) is shown in Figure 1. Note that the buttons cover 44.1% of the panel internal area.

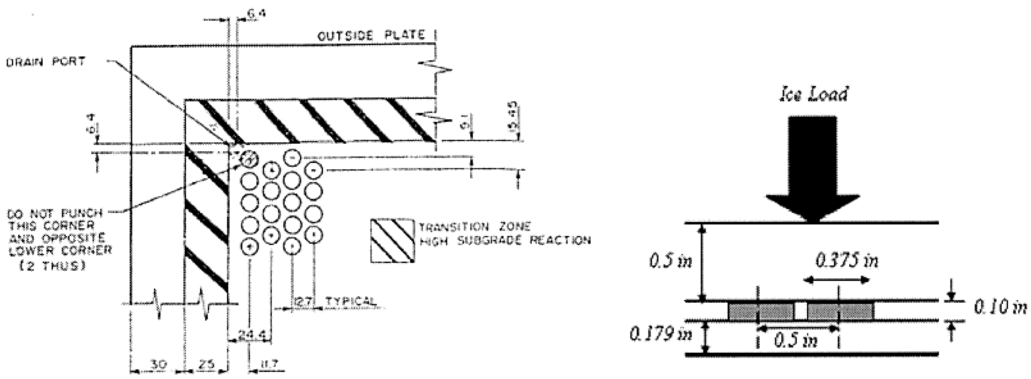

Figure 1. Details of Panel construction (Fenco 1983a)

The material properties of the urethane buttons result in various non-idealities of the panel response. The button material ages and hardens, when subjected to large strains the material can soften, the modulus of the material is temperature dependent and the material can creep when subjected to long term loads. In addition, the configuration of the panel in combination with the external tubing resulted in a low frequency response of the panels.

HIGH FREQUENCY RESPONSE OF PANELS

A Medof panel was tested in a rigid MTS load frame (Cox, 1990). The panel contained a calcium chloride solution, a reinforced hydraulic hose 10m long with an internal diameter of 0.64cm, was connected to a 1.27cm inside diameter site tube. Tests were conducted at an ambient temperature of -10C. The output of the pressure transducer at the base of the site tube was recorded electronically and the fluid level in the site glass photographically recorded. A sinusoidal load of varying frequency between 0.01and 3.0Hz was applied. The applied load was 0.557 ± 0.334 MN (125 ± 75kips). The results of the frequency response tests are given in Table 1 and Figure 2. The step response measured by the pressure transducer was also recorded and is also shown in Figure 2

Table 1. Medof Panel Frequency Response

Frequency (Hz)	Transducer Gain	Transduce Time Shift (s)	Sight Tube Gain	Site Tube Time Shift (s)
0.0000	1.0000	0.0	1.0000	0.0
0.0001	0.9800	10.14	No data	No data
0.001	0.9500	5.50	No data	No data
0.01	0.8953	3.07	0.8831	4.00
0.03	0.8237	2.16	No data	No data
0.05	0.7547	1.96	0.8378	1.00
0.10	0.5941	1.58	0.7926	0.66
0.15	0.4581	1.50	0.7473	0.66
0.20	0.3428	1.38	0.6907	0.66
0.30	0.1868	1.25	0.5774	0.66
0.50	0.0485	1.04	0.3850	0.56
1.00	0.0266	0.17	0.1132	0.39
3.00	0.0172	0.11	0.0340	0.39

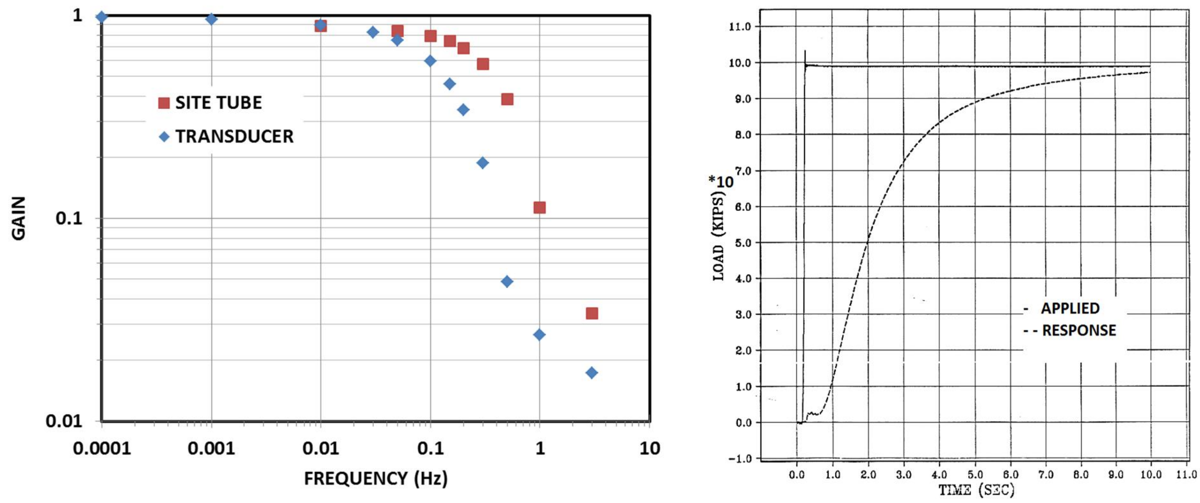

Figure 2. Frequency Response (left) and Step Response (right) of Panel

As can be seen from Table 1 and Figure 2 the sight tube fluid level responds more rapidly than the output of the pressure transducer. This is due to additional low pass filtering in the electronic pressure transducer. The frequency response of the panel was modelled by Spencer (1991) who showed that it could be represented as a first order system and that the panel frequency response was dominated by fluid viscosity effects in the tube connecting the panel to the site glass and not by the panel internals.

Tests at different load levels were also performed (Cox, 1990) and the results shown in Table 2. From Table 2 it can be noted that the panel gain varied by about 10% between the various tests at 0.05Hz and 0.30Hz. This indicates a non-linearity in the panel response. Our interpretation of the data in Table 2 indicated that it is consistent with the panel stiffening at increased load levels. Thus high amplitude loads would be systematically under-represented.

The step response test indicates that a 50% and 90% response occurs at 2.0 s and 5.1s respectively. Testing of Medof Panels by Geotech (1988) using air filled flatjacks to load the panels, indicated that the response to rapid changes in load was faster to that indicated in

Figure 2. In these Geotech (1988) tests, the site glass was directly connected to the panel bypassing the long connecting hose.

Table 2. Panel Gain at different Loading Levels

Load (MN)	Gain at 0.05Hz	Time Shift at 0.05Hz (s)	Gain at 0.30Hz	Time Shift at 0.30Hz (s)
0.222±0.111	0.8004	1.84	0.2294	1.21
0.557±0.111	0.7208	1.92	0.2057	1.10
0.557±0.222	0.7374	1.76	0.1945	1.19
0.557±0.333	0.7547	1.96	0.1868	1.25
0.787±0.111	0.7166	1.88	0.2014	1.07

In summary, the frequency response data given in Table 1 can be used to de-convolve signals recorded using the Medof panels thereby allowing a better measure of the actual ice load. Note that the model of the panel presented by Spencer (1991) can be used as a guide for the appropriate parameters for different panels. The load value adjustment depends on the frequency content of the ice load signals, but representative calculations indicate that it is likely to be in the 0 to 20% range, ie the true load peaks may be 0 to 20% larger than inferred from the as-recorded measurements. The non-linearity in response shown in Table 2, suggests that a linear de-convolution method will then only be approximately correct.

RE-CALIBRATION OF MEDOF PANELS

A number of Medof panels were installed in the ice sheet around the Tarsuit drilling structure, the ice loading on these panels was low (Fenco 1983b). These panels were then re-tested to determine if the elastic response had changed from the original calibration value (Fenco 1983b). It has been reported that this recalibration shows evidence of panel softening (Jordaan et al., 2011). Note that the original and re-calibration of the panels were performed by the same organisation using essentially the same methodology. The original panel calibrations were performed at three tests temperatures and the re-calibration at two test temperatures. In the re-calibration tests it is interesting to note that the panels appeared to be softer at lower test temperatures. Because there are significant variations in elastic response between individual panels, the analysis reported here used the ratio of the re-calibration to initial calibration. Using this metric, the mean response ratio for the data presented in Table 3 is 1.05, the standard deviation is 0.37 and the standard error of the mean is 0.12. These data indicate that there is not any evidence for a systematic panel softening but there is evidence for a large uncertainty in the calibration values. Assuming that there is the same uncertainty in the original and re-calibration results, then the uncertainty in an original calibration would be 0.26 or 26%. The mean elastic calibration factor from Table 3 is 1.40kPa/mm with a standard deviation of 0.40kPa/mm.

Table 3. Original and Recalibration of Medof Panels deployed at Tarsuit

Panel	Original (kPa/mm), (C)	Original (kPa/mm), (C)	Original (kPa/mm), (C)	Recalibration (kPa/mm), (C)	Recalibration (kPa/mm), (C)
p12	1.057, -1.5	1.043, -8.5	1.076, -12.5	0.99, 0.0	0.84, -10.0
p16	1.219, 0.0	1.186, -10.0	1.329, -20.0	1.239, 0.0	0.87, -10.0
p17	1.166, -1.5	1.140, -8.5	1.189, -12.5	1.858, 0.0	1.32, -10.0
p18	1.728, -1.5	1.887, -8.5	1.855, -17.5	1.732, 0.0	0.74, -10.0
m16	1.860, 0.0	1.847, -8.5	1.726, -20.0	1.481, 0.0	0.64, -10.0

PROPERTIES OF THE URETHANE BUTTONS

From Jordaan et al. (2011) the panels are postulated to change their elastic calibration constant by a factor-of-two due to softening of the Adiprene L-100 urethane buttons. The softening, called the Mullins effect (Mullins, 1969) is assumed to be caused by the large local pressures that occur in "high-pressure-zones" during crushing of ice (Jordaan et al., 2001). The experimental work by Qi and Boyce (2005) on urethanes is used by Jordaan et al. (2011) to support the argument. Qi and Boyce (2005) showed that in uniaxial compression testing on similar urethanes (but not Adiprene L-100), at a true stress of 5 to 10MPa, significant material softening occurred in only four loading cycles. The first loading cycle data at two different maximum strains are shown in Figure 3 (left). Teflon sheets were inserted between the sample and the loading platens to ensure that the tests were conducted under uniaxial loading conditions. Qi and Boyce (2005) also indicate that the material softening is related to the sample strain, not the applied stress.

In the Medof Panels, the urethane buttons are bonded to the metal plates and the uniaxial pressure and strain values measured by Qi and Boyce (2005) cannot be directly transferred to the Medof Panels because of the restraints. The effective button stiffness is calculated from the material modulus using a so-called shape-factor (Anderson et al., 2004) which accounts for the ratio of restrained surface to free surface. For the cylindrical buttons bonded on both faces, S = (Diameter/4*Thickness) and is equal to 0.93. The effective stiffness E_{ff} of the button in axial compression is given as a function of S and the material modulus E (Anderson et al., 2004).

$$E_{eff} = E*(1+2*S^2) \quad (1)$$

From (1) the buttons have an effective stiffness 2.72 times larger than the material stiffness. For large Shape Factor urethane sheets used as earthquake isolation bearings in buildings (Earthquake 2012), the allowable normal Load in the bearing is proportional to S. Thus on this basis, the Medof button can withstand a larger load than the same material in uniaxial loading.

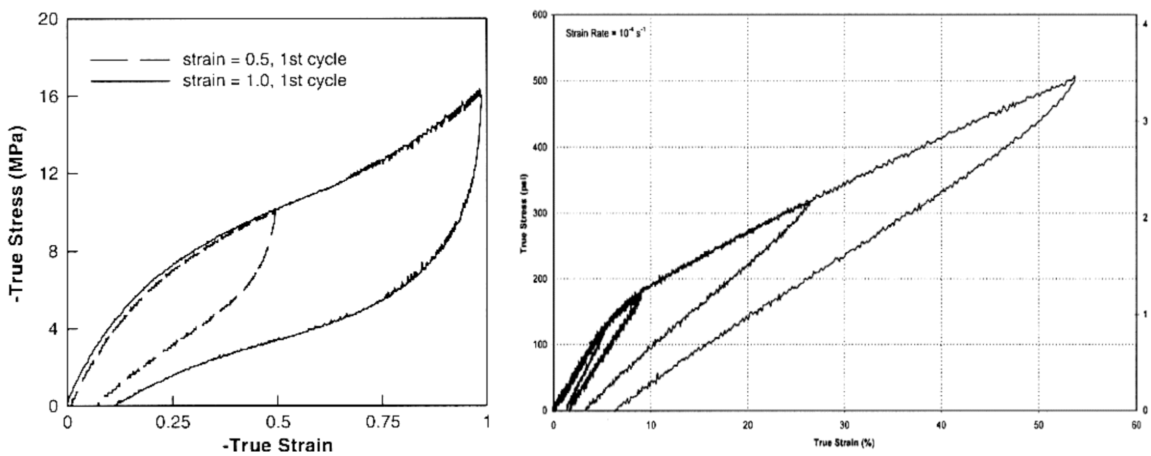

Figure 3. Initial Compression Data (Qi and Boyce, 2005), (Khan and Lopez-Pamies 2002)

The urethane tested by Qi and Boyce (2005) had a Durometer hardness of 92A immediately after manufacture and increased to a hardness of 94A after 1 year at room temperature. From the manufactures data sheet Adiprene, (2011) Adiprene-L100 has a hardness of 90A. The hardness is approximately related to the sample modulus (Wikipedia, 2013) and these three

Durometer values correspond to 100% modulus of 13.3, 15.1, 17.4 MPa for 90A, 92A and 94A respectively. Thus the stiffness of the material testing by Qi and Boyce (2005) is stiffer than Adiprene L-100. Note also that the material modulus had increased by 15.4% after aging for one year.

Using the average elastic calibration factor of 2mm/kPa (±0.6mm/kPa 1stdv) in a 12.7mm diameter site tube (Frederking et al., 2011), and treating the urethane buttons as incompressible (Kahn and Lopez-Pamies, 2002), the displacement of the front plate of the Medof Panel under a 1MPa uniform load is then 21.1 µm. Since the buttons are 2.54mm in height, this displacement corresponds to an axial strain in the buttons of 0.83%. The Effective elastic modulus of the buttons is then 263MPa. Using equation (1) the material elastic modulus is then calculated to be 97±29MPa. Compression data on Adiprene L-100 are given in Kahn and Lopez-Pamies (2002). While the initial elastic modulus is a function of both strain rate and test temperature, from Kahn and Lopez-Palmies (2002) the elastic modulus is approximately 25MPa. From Qi and Boyce (2005) the initial elastic modulus is 41MPa. It would appear that the material in the Medof Panel is stiffer than both the standard Adiprene L-100 material and the material tested by Qi and Boyce (2005).

In uniaxial compression tests, both Qi and Boyce (2005) and Kahn and Lopez-Pamies (2002) observed that up to a strain of approximately 10%, the stress-strain curve in essentially linear and at 10% strain the softening of the material amounts to 10% of the initial elastic modulus. The 10% strain in the buttons corresponds to a face pressure of 12MPa. Assuming that the stress strain curve shape is as indicated in Qi and Boyce (2005), then the true strain of 50% would correspond to a Medof panel pressure of at least 30MPa. Note that at the 50% true strain the softening corresponds with the stiffness of the material being approximately 50% of the initial value. Thus loading of the panel face at 20MPa would not be expected to produce such a significant softening.

A review of the Mullin's effect has been published by Diani et al., (2009) who indicate that along with a reduction in material stiffness there is a permanent set in the material after only one loading cycle. This permanent set may be recoverable but generally requires annealing at temperatures much above room temperature for it to occur. Kahn and Lopez-Pamies (2002) and Qi and Boyce (2005) both show a large (about a factor of two) reduction in stiffness when the sample is strained to a true strain of 50%. In addition, both Kahn and Lopez-Pamies (2002) and Qi and Boyce (2005) clearly show a permanent set (in compression) of approximately 6% after only one loading cycle which is illustrated in Figure 3. In other words, the large sample strain results in more than simply a change in material modulus. If this urethane button permanent set were applied to the whole panel it would then result in an **increase** in the site glass baseline level of 3.6m equivalent to a Medof panel pressure of 7.2MPa. As indicated in Jordaan et al. (2011) no overflowing of the site tube was noticed apart from one event with the softest panel. Since the baseline level changes due to panel creep and temperature expansion effects, we shall assume that a conservatively large baseline shift of 500mm would be detected. This baseline shift represents 14% of the panel has softened by 50% giving an average softening for the complete panel of only 7%.

The 12.7mm thick steel front plate of the panel is analysed as a plate on an elastic foundation (eg ISO 19906). From the analysis, the characteristic length (λ) for the system is 0.03m. While this length is small compared with the panel dimensions, it does significantly alter the maximum displacement of the panel under the load patch and hence the strain in the urethane buttons from small radius circular load patches. When the radius of the load patch diameter is less than 3λ then the plate displacement is less than the displacement for an equivalently distributed load over a larger diameter patch. For example, when the load radius is 0.5λ, 1λ or 2λ, the maximum panel displacement is 9%, 31% or 79% of the displacement that would occur for a uniformly distributed load. Thus for small localised load patches (high pressure zones), the front plate distributes the applied load over a number of individual buttons reducing the strain experienced by any individual button. A 0.03m diameter load patch of 55MPa on the face of the panel would produce the same axial button strain (4.15%) as a 5MPa uniformly distributed load on the face of the panel.

The Medof Panel integrates the load from the whole panel, thus the large local pressure events in one region of the panel would only soften that part of the panel. Using the example of there being on average 3 high pressure zones, each having an area of $0.1m^2$ then at least 67 randomly located loading events would be required for 90% of the face to experience at least 4 loading cycles.

In summary, while there may have been softening of the panel buttons due to large local loading, the magnitude of the softening is not likely to be as severe as indicated by Jordaan etal (2011). The factors contributing to this conclusion are the additional stiffness and strength of the urethane when bonded to the Medof Panel from and back plates, load distribution due to the 12.7mm thick steel front plate, the statistical nature of the HPZ loading and the absence of an observed large rise in the site tube level that would be generated if the buttons significantly softened.

CREEP RESPONSE

The creep response to long term loading of the panels has been documented in the manufacturers testing and subsequently by Gulf (Jefferies and Spencer, 1989). The creep response can amount to a 30% shift in the baseline and was represented as a single exponential function with a time constant in the range of 4 to 20 mins. The actual value being determined during panel calibration tests. Given that the data adjustment method is not perfect, we estimate that the error in the load value is ±5% due to the uncertainties in the creep adjustment.

DISCUSSION

There have been concerns regarding the possibility that a button may become dis-bonded from the front or back plate. If this occurs and there are not sufficient lateral constraints from the button/metal friction, then the effective stiffness of the buttons will decrease. If dis-bonding occurs, then the outer panel of the panel will expand outwards due to the hydrostatic head provided by the site glass and connecting tube resulting in a large drop in the fluid level in the site glass. This possibility was considered at time of deployment and operation of the panels on the Molikpaq. No such changes were observed by field personnel during the Molikpaq deployment (A. Strandberg pers. com 2011).

A certain amount of judgement has been used to estimate the random and systematic error on the load measurements from the Medof Panels. The errors given in Table 4 are for a single panel. Loads determined from groups of Medof panels will have a smaller random error but the systematic error will not be reduced. Since most of the load information used in determining guidelines in ISO 19906 are related to peak values, the limited frequency response will tend to provide load values that are too low. For the panel non-linearity, the curvature in the response has the effect that low loads are over-estimated whereas high loads will tend to be under-estimated. The creep response and baseline error will tend to overestimate peak loads if the chosen baseline is before the event but underestimate the load if the baseline is after the event. The Total Random error value given in Table 4 is calculated assuming that the random errors listed are uncorrelated. The systematic errors indicated in Table 4 could produce load values that are either too large or too small or there may be compensation under particular conditions.

Table 4. Error Estimates for a Single Medof Panel

Source	Estimated Error
Initial Elastic Calibration	±20%
Non-linearity	±5%
Creep and Baseline	±5%
Panel Frequency Response	15% underestimate
Urethane Softening	Requires additional data (~20% overestimate)
Total Random	±21%
Systematic	~15%

Testing of urethane buttons bonded to steel plates could be done. There is uncertainty in the stiffness in the actual material used in the Medof Panels. However testing would provide data on softening and permanent set in the appropriate geometry of the buttons. The question of the amount and timing (ie. exposure) to high pressure zones would still be unanswered.

CONCLUSIONS

There was not any evidence of systematic softening of the Medof Panels from the recalibration tests. The frequency response tests allow correction due to the limited frequency response of the panels to be performed. The softening of the urethane is estimated to be not as severe as to produce a factor-of-two in the elastic calibration. Tests could be conducted on the urethane buttons to determine at what applied panel pressure, softening and permanent set of the panels occurs and what is the magnitude of the potential change in panel elastic response. The missing link is determining the effect of softening is the number of “high-pressure-zone” loading events that have occurred for each panel and when these loading events occurred. Notwithstanding, the potential systematic error from panel softening, there are uncertainties (random error) in the basic elastic calibration data and the frequency response of the panels and other factors such that it is unlikely that load data from a single Medof panel would be known to better than about ±20%.

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