HYDRAULIC FRACTURE EXPERIMENTS IN A FRICTIONAL MATERIAL AND APPROXIMATIONS FOR MAXIMUM ALLOWABLE MUD PRESSURE

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ABSTRACT

Small scale laboratory mud loss experiments are reported for granular material. The tests were designed to evaluate the effectiveness of the maximum allowable mud pressure solutions and to understand the strength characteristics of the filtercake. The experiments simulate the end of a borehole, such that hydrofracture measurements associated with pilot drilling could be obtained. Current blowout solutions used in this industry are for long open boreholes responding under plane strain conditions. These solutions are considered reasonable for blowout during pullback, but may not be directly applicable to blowout during pilot borehole drilling.

RÉSUMÉ

Les expériences de laboratoire a petite échelle pour perte de boue sont rapportées pour les matières granuleuses. Les essais étaient désignés a évaluer l'efficacité des solutions pour le maximum de pression de boue pérmi et de comprendre les caractéristiques de la force de la boue de forage. Les expériences représentent la fin d'un forage d'une manière a ce que les mesures de hydrofracture associées au forage a pilot pourraient être obtenues. Les ruptures actuelles utilisées dans cette industrie sont pour des forages a longues ouvertures réagissant contre les déformations axiales. Ces solutions son considérées raisonnables pour rupture durant le retrait, mais peuvent ne pas être directement applicable a la rupture durant le forage a pilot.

1 INTRODUCTION

Directional drilling has become a popular method used by design engineers for the construction of new subsurface pipelines while minimizing the social and economic impact on the surrounding community. In recent years, the development of Horizontal Directional Drilling (HDD) practices within sand materials have increased as the demand for more crossings through glaciofluvial and fluvial deposits increases. Drillers often experience problems when HDD alignments pass through granular layers located relatively close to the ground surface. Glaciofluvial and fluvial deposits commonly occur throughout the southern regions of Ontario, Quebec and the prairies as a result of glacial and postglacial processes. The physical characteristics of these deposits can vary significantly in gradation and relative density creating a multitude of difficulties in terms of estimating the maximum allowable mud pressures in directionally drilled holes.

The use of pressurized drilling fluid during the advancement of the borehole is necessary to provide borehole stability, cool the auger head, and to remove the cuttings from the borehole drill path. It is also critical within sand layers to maximize the efficiency of the drilling fluid such that borehole cave is minimized and the return of the cuttings is maintained regardless of the deposit gradation. It is well known that the infiltration of the drill fluid into granular host soils results in the formation of a soil-drill fluid composite commonly referred to as a filtercake. It is believed that the shear strength of the filtercake material can influence the maximum allowable mud pressure that may be applied to the borehole before shear failure or tensile fracture (hydrofracture) occurs, resulting in mud loss at the ground surface. Mud loss must be prevented, as in addition to delaying construction, mud loss can result in environmental and social difficulties that are not easily solved. Previous studies carried out in Europe and in the United States have provided methods for use by design engineers to estimate the maximum allowable mud pressure for a given cohesionless host soil. However, while there have been a number of theoretical studies based on the use of cavity expansion theory, there have been few if any experimental investigations designed to examine the efficiency of the proposed design equations.

Currently there appears to be a dearth of insitu physical data related to the maximum allowable downhole mud pressures within granular materials. There is also an absence of laboratory data related to the formation and physical characteristics of the granular filtercake, and the manner in which the filtercake impacts the overall strength of the borehole. It is the goal of this research to develop a method to determine the expected infiltration depths and the shear strength of the filtercake material. The impact of the physical interactions between the filtercake and the host soil are beyond the scope of this study.

2 REVIEW OF PAST RESEARCH

The current state of practice is based on the belief that most cases of mud loss commonly referred to as

Hydrofracture or ‘Frac-out’ occur as the down hole mud pressures acting radially on the borehole walls increase, and these reduce the hoop stress in the soil around the borehole. Once that hoop stress around the boring changes from compressive to tensile, the stresses begin to exceed the tensile strength of the host soil, assumed for granular material is assumed to be zero or very close to zero. This results in the formation of tensile cracks at either the crown or the springlines of the borehole depending on the insitu stress (Kennedy et. al, 2004). Several small scale tests have been carried out in cohesive and cohesionless materials in an attempt to determine the respective modes of failure, all with little to no success (Keulen et. al, 2001). Observations of the failures within the cohesionless materials have shown that the precise mode of failure, whether initiated by the formation of tensile cracks, radial expansion of the borehole or a combination of the two modes is difficult, if not impossible to ascertain.

Recent theories related to cavity expansion have also been incorporated into several design codes, most notably by the US Army Corps of Engineers (USACE), (Conway et al, 2002). The USACE suggests that a solution developed at Delft University of Technology (Delft) based on the expansion of a cavity in a continuous medium may be used in order to estimate the maximum allowable mud pressures within a borehole under certain conditions. This solution is based upon several closed form solutions as derived by Vesić (1972) and by Luger and Hergarden (1988). The latter is the key basis for the derivation of the Delft equation and assumes equilibrium, Hooke’s law for increments of elastic deformation, the Mohr-Coulomb failure criterion, and the absence of isotropic deformations within the plastic zone. Experiments designed to determine the effectiveness of these assumptions were carried out by others and determined that at great depths, indeed some form of cavity expansion or ‘ballooning’ of the borehole similar to the theories derived by Vesić and Luger and Hergarden did occur (Keulen et. al, 2001). However, at lower depths of overburden, these theories do not always hold true and some form of hydrofracture occurred.

Other forms of the cavity expansion theory were also explored, notably the closed form solutions provided by Carter, Booker and Yeung (1988), who developed a small strain solution assuming an associated flow rule. Of particular interest to this research is the work of Yu and Houlsby (1991), who developed a closed form solution for cavity expansion within a cohesive-frictional soil. Their solution allows for the calculation of large strains within a cylindrical or spherical cavity in a continuous, non-associated dilatant material.

The final theory suggested to be potentially responsible for mud loss was recently suggested by Wang and Sterling (2006). Their theory assumes that in addition to cavity expansion, pore pressures may develop within the sand during deformation and that these ultimately reduce the effective shear strength of the host soil, resulting in liquefaction and consequently loss of borehole stability. This theory was based upon a numerical model designed to determine the effect of filtercake thickness on the overall strength of the borehole. It was found that in cases with little or no filtercake, the effective stresses within the borehole would increase rapidly even at very low fluid pressures and likely result in liquefaction. In cases where a sufficient filtercake was developed, the hydraulic gradient was increased, reducing the problem to that of the cavity expansion shear failure or blowout of the borehole. The theory of liquefaction occurring in some cases would explain the types of mud flows to the ground surface observed in the field and in some previously conducted small scale laboratory tests. It is for this reason that attempts have been made to ascertain the potential for liquefaction and to determine the physical characteristics of the filtercake material as well as typical infiltration depths of drilling mud within a granular host material.

Based on all of the above hypotheses, a series of medium scale laboratory tests have been designed for a slightly cohesive to cohesionless, frictional material. The tests were designed to help determine the maximum allowable mud pressures typical for a granular material as well as the physical properties of the filtercake material and typical infiltration depths as stated above. It is also the goal of these laboratory experiments to make an attempt to determine the possible modes of failure of the borehole under a variety of test conditions. These laboratory tests are designed to help project engineers and planners choose a suitable theory to estimate the maximum allowable mud pressure for HDD applications and mitigate any potential problems that may arise from mud loss.

3 TEST PROCEDURES

The initial arrangement for the laboratory testing was designed to carry out a conventional hydrofracture packer test in a small biaxial cell in a clean, open graded sand commonly referred to as a ‘hydrosand’. The sand is typically used as bedding material for lightweight structures such as small diameter pipelines. The material was obtained from a source pit local to the Kingston area, though it is similar to any open graded sands typically used in small diameter pipeline applications. The material is used primarily for its drainage characteristics allowing for groundwater and surface water infiltration to freely drain to underlying layers away from the pipeline. Standard Proctor testing was carried out on a representative sample to determine the relative density of the material prior to testing and thus estimate optimal conditions for compaction within the test cell.

Tests to determine the physical characteristics of the sand were also conducted both prior to and subsequent to the packer tests in order to determine any changes in the gradation, unit weight, moisture content, and the hydraulic conductivity as a result of drilling mud intrusion. Ideally consolidated, drained tri-axial tests would be carried out to determine any changes in the shear strength between the host hydrosand and a reconstituted, mud impacted filtercake material. The filtercake material must be reconstituted for the tri-axial tests because the configuration of the test cell does not readily allow for relatively undisturbed samples of filtercake material to be recovered from the borehole walls.

The host sand material was placed into the cell in 200 to 300mm lifts and compacted to at least 98% of the standard Proctor maximum dry density (SPMDD) for moisture content within ±2% of optimum. The compacted relative density of the sand was estimated using both a sand cone test as well as a nuclear gauge set to measure using the backscatter mode. Both compaction testing methods were employed in a manner designed to minimize the disturbance to the compacted material and to minimize potential paths of least resistance for the mud to travel through. Two methods were used, as the configuration of the test cell would likely interfere with the results obtained from the nuclear gauge. As such, the results of the nuclear testing were considered to be approximate and the results of the sand cone tests were assumed to be more accurate. Once the cell was completely filled and manually compacted, a simulated overburden pressure was applied to the surface of the sand by means of a calibrated 100kN actuator. The overburden stress was held at approximately 100kPa for ten to twenty minutes, allowing for additional displacement and further compaction of the host material. Following the mechanical compaction of the sand, an additional thin lift was added to the cell and compacted mechanically in order to maintain the maximum possible thickness of real overburden material within the test cell. Once the compaction of the material was complete, the overconsolidation stress was reduced to a pressure consistent with a typical overburden depth based on the calculated unit weight of the soil. Depths to the borehole centre, assuming that they represented an actual depth below the ground surface ranged from 0.5 to 2.1m, which are similar to very shallow installations typical for most communication and residential infrastructure installations. The simulated overburden was applied to the sand material using the actuator loaded onto the centre of a welded steel frame which was placed on top of a removable hardwood platform designed to distribute the applied load to the entire surface of the sand while at the same time minimizing any gaps under the loading surface.

Three tests were also carried out using an extension box affixed on top of the test cell. The use of the extension box allowed for the application of an actual overburden material as opposed to a simulated overburden pressure. In the cases where the extension box was used, the sand material was filled and compacted using only vibratory compaction to 98% SPMDD within ±2% of the optimum moisture content. The application of a mechanical compaction pressure was not used in these test scenarios.

Following the compaction of the sand, a horizontally aligned 45mm diameter hole was advanced using a thin walled Shelby Tube sampler to a depth of 500mm. The borehole was advanced using a thin walled sampler in order to minimize the disturbance to the native soil such that additional laboratory testing such as shear strength and hydraulic conductivity tests could be carried out on the host material. The Shelby tube also ensured that the borehole walls were of a uniform nature and predominantly clear of all loose debris and slough material similar to a well reamed borehole. The borehole initiated through the centre of the narrow side of the test box so that the borehole extended lengthwise into the cell in order to maximize the penetration of the packer and allow for separation from the end wall of the cell.

Once the preparation of the host material and the borehole were complete, a low pressure packer was inserted into the borehole to a depth of approximately 300mm. A pressure transducer with a pressure range of 0 to 350kPa accurate to 0.1kPa was installed into the borehole. The pressure transducer signal cable was fed through the opening in the centre of the packer so that the transducer extended an additional 100mm into the borehole, allowing for a total of 100mm free space at the end of the borehole. The signal cable for the pressure transducer was fed through a 'Y' connection installed between the source hose and the packer. A seal was provided for the signal cable by means of a like-sized compression fitting. Observations of the flow around the pressure transducer were made prior to commencement of testing to determine if the location of the transducer impeded the relatively uniform flow from the packer.

The bentonite-based drilling mud – Baroid 'Bore Gel' – was mixed using a displacement pump in a 170L drum using various concentrations ranging from 50 to 75 grams of bentonite drilling mud per Litre of water. In all cases, an additive with the trade name 'Quik-Trol' was included to provide additional stability to the borehole, as recommended for granular materials. The concentration of the stabilizer was kept constant for each mixture at 1 gram of stabilizer per Litre of water. The concentrations of the drilling fluid and the stabilizer were combined and mixed using the manufacturer-recommended concentrations and mixing methods. A purple and red dye was then added to the mud mixture to help identify the filtercake in cases where saturation was difficult to positively determine.

Once the bentonite slurry and stabilizer were mixed and the low pressure packer and transducer were inserted into the borehole, the packer was inflated to approximately 300kPa to create the seal necessary to carry out the hydrofracture test. In all cases, a small amount of drilling mud was hand-pumped into the borehole to fill the cavity and to allow for saturation of the borehole walls prior to loading. In order to apply the internal pressure to failure, two methods of drill fluid application were examined. The first method involved the application of mud through a column of mud pressurized using an air compressor and regulator. This method was abandoned after several tests were carried out and resulted in maximum mud pressures that were significantly lower than anticipated. Upon examination of the system, it was believed that the application of the air pressure resulted in air bubbles forming within the fluid and subsequently being forced into the borehole. These air bubbles likely created a local fracture into which the bulk of the drilling fluid followed, resulting in lower than anticipated failure stresses. The second configuration utilized a displacement pump and a mechanically powered drive train to provide the rotation necessary to generate the desired fluid pressures. The rotation of the displacement pump and subsequently the fluid pressure were controlled by a centrifugal clutch and a variable speed motor. Several preliminary tests using the displacement pump at variable speeds readily produced consistent results. This method was then used for the remainder of the tests.

The tests were carried out by steadily increasing the flow and consequently the downhole pressure until mud loss was observed on the surface of the sand, indicating that complete failure had occurred. Typically, most packer tests are carried out until the first pressure drop is observed. In the case of sands, however, it had been previously shown that if a tensile crack forms, there are typically several spikes in the fluid pressure. As the drilling mud fills the newly opened cracks, the mud filters into the sand close to the crack opening, forming new filtercake and redistributing the stresses within the area of the crack opening. This ‘healing’ process subsequently allows fluid pressure to build up again. Monitoring of the mud pressure within the borehole was by means of a stainless steel pressure transducer programmed to record fluid pressures in time intervals of a tenth of a second (0.1 second). The data was stored in a dedicated data logging computer system and following the completion of the test, this was converted into tabular format.

Once the test was completed, the material was slowly excavated by hand and the location and size of the saturated or failure zones were documented. In each case the number, location, orientation, and size of all of the observed soil fractures were recorded and photographed. Changes in observed failure zones were recorded with depth in 50mm increments providing a three dimensional image of the failure zone. All likely and obvious voids and cavities were also observed in cases where fractures were not readily observed. The radius of the filtercake was determined by measuring the depth of the sand at the crown of the filtercake, noted by a saturated zone extending the entire length of the borehole. At this point, the excavation proceeded at 10mm intervals in order to provide a detailed picture of the filtercake thickness and degree of saturation with distance from the borehole centre. Once the crown of the borehole was reached, the source of the mud flow or the likely point of failure initiation was noted in each case. The thickness of the filtercake was recorded in all cases at the crown, springlines and invert of the borehole.

4 TEST RESULTS

The test results raise interesting questions and suggestions for future research and testing. First, there were little or no changes in the physical characteristics between the host and filtercake materials, with the exception being a dramatic increase in moisture content as expected. Samples of the filtercake from various positions around the borehole were also chosen in order to establish the degree of saturation with distance from the borehole centre. In most cases, the moisture content was found to decrease very slightly with distance from the centre of the borehole, as was expected. The moisture content was found to range from 2 to 6% in the native host material and up to 20 to 24% in the filtercake. The difference in the grain size analyses was minimal with a slight shift towards the finer materials as a result of the bentonite concentration within the sand, again as expected. The change in grain size distribution featured a 3% increase in the clay sized particles; all other aspects remained unaffected. The percent of fines did not warrant carrying out Atterberg testing as the filtercake material was clearly non-plastic. Direct shear, unconfined compression (UC) or consolidated drained tri-axial testing is proposed for future experiments.

The hydraulic conductivity of the two materials was tested using a standard falling head test apparatus. In each case, the host sand and the filtercake were fully saturated and all entrained air was removed from the samples. It is possible that bentonite clay particles that had adhered to the surface of the sand grains could have been washed so extra care was taken during the de-airing of the samples. The hydraulic conductivity of the host sand material was observed to be relatively high, as expected, and was measured to be approximately 3.2×10^{-3}cm/s. The hydraulic conductivity of the filtercake was found to be significantly reduced and was measured to be approximately 7.0×10^{-6}cm/s. The changes in hydraulic conductivity (k) represent a significant decrease in permeability of over three orders of magnitude of that of the native material. The reduction in the hydraulic conductivity is due to the addition of the drilling mud and stabilizer and the slight increase in percentage of fines within the host soil as a result of the infiltration of the drilling fluid. Although the material is non-plastic and does not exhibit an obvious cohesion, the reduced hydraulic conductivity does not allow the fluid to drain freely and subsequently promotes the development of pore pressures resulting in a reduced effective shear strength. By reducing the effective stress of the filtercake, the maximum allowable mud pressure would be dramatically reduced should shear failure be the cause of mud loss. As the development of pore pressures is likely, this suggests that in addition to shear failure, there is clearly the possibility that liquefaction is a potential cause for mud loss. This will be discussed in further detail in subsequent sections.

The results of the simulated overburden tests are shown below in Figure 1. As the simulated overburden pressure was increased, the maximum mud pressure also increased. In most test cases, the flow to the surface was generally rapid and once the surface was breached, the mud exited the sand at an explosive rate similar to that of a fountain, indicating the fluid was under pressure. Once the breach of the ground surface occurred, the mud flow reduced quickly to equal the flow rate of the displacement pump, indicating that the flow path to the surface was completely formed and stable, and that the confining pressure of the soil was no longer active. In all cases, the test results indicated a residual strength of the failed material which also increased with increases in confining stress. Any variations to the mass of drilling mud per litre of water did not have any obvious impact on the maximum mud pressure observed in the borehole as the results appeared to follow a similar trend in all cases.

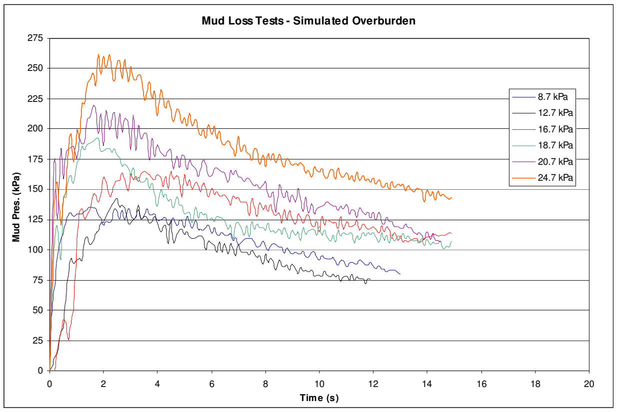

Figure 1 - Mud Loss Pressure - Simulated Overburden

Attempts to estimate the maximum mud pressure based on the observed line of best fit provided predictions of failure pressure that matched subsequent tests well. This was shown by using the curve to estimate the maximum internal mud pressure at a specific overburden pressure. The error associated with the estimate was less than 1%. In addition to providing a good estimate of the maximum internal pressure, additional tests carried out at the same confining stress provided consistent results. The average range of error associated with tests at a similar overburden pressure was typically around 1 to 10% between comparable tests. It was found that the tests with a larger percentage of error usually corresponded to tests involving complications in procedures, including pump failure prior to borehole failure, leakage from various seals, or loss of packer pressure around the borehole opening. In general, this low percentage of error indicates that the test methods were effective in producing consistent results that could be readily interpreted.

Observations of the failure mode showed that typically there was an area of localised failure and mud movements following a specific path to the ground surface. In all cases, the failure was initiated at the end of the borehole and resulted in a single flow path, typically indicated by a horizontal crack or a void forming at some location at the end of the borehole and subsequently propagating to the ground surface. The thickness of the filtercake around the voids would taper from a maximum at the borehole to a minimum at the surface. The path of the mud through the sand was generally vertical with slight to very little deviation from the direct path to the surface. In some cases, small voids several centimetres in diameter would open near the ground surface, extending several centimetres below the surface of the sand. As with other tests carried out in sand materials, there was no positive way to confirm the exact mode of failure or rather if the sand had failed in shear, a tensile crack had formed, or if the sand had liquefied. The initial source of the failure was estimated based on void formation near the start of the washed out flow path. In no cases were there any failures observed to initiate from the sprinlines or invert of the borehole, though like the mode of failure, the precise location of the initial failure was difficult, if not impossible to ascertain definitively.

The thickness of the filtercake was observed in the material surrounding the flow path to the surface as well as around the borehole itself. In general, the dye added to the mud did little in the way of helping in the identification of the extent of the filtercake. The thickness of the filtercake was therefore identified by the limit of the saturated material surrounding the borehole as well as the saturated zone around the flow path to the surface. As stated above, the thickness of the filtercake generally tapered from the thickest zone located at the likely point of initiation at the crown of the borehole, to a minimum thickness at the surface of the sand. The typical thickness was about twice the diameter of the void (if one was observed) up to 50 to 75mm in cracks or voids that had re-closed following cessation of mud flow. As expected, the degree of infiltration and soil saturation increased slightly with depth and proximity to the borehole.

The thickness of the filtercake surrounding the borehole was normally concentric and extended radially around the borehole in all directions. The only observed deviations from this observation were at the end of the borehole, where a ‘bulb’ or sphere of filtercake formed, as shown in Figure 2 below. Measurements of the borehole length indicated that though the length of the borehole increased during the test, the increase in length was considered to be small (from 20 to 50mm). In no cases did the borehole extend the entire length of the test cell. The thickness of the filtercake surrounding the borehole was observed to be approximately 50mm in each direction around the pilot hole. The infiltration of the drilling fluid was generally consistent, irrespective of the concentration of the mud.

Three tests were carried out in the sand using an extension at the top of the test cell, designed to study the effectiveness of the simulated overburden and the possibility that sand liquefaction above the borehole is the cause of mud loss when directional drilling though cohesionless materials.

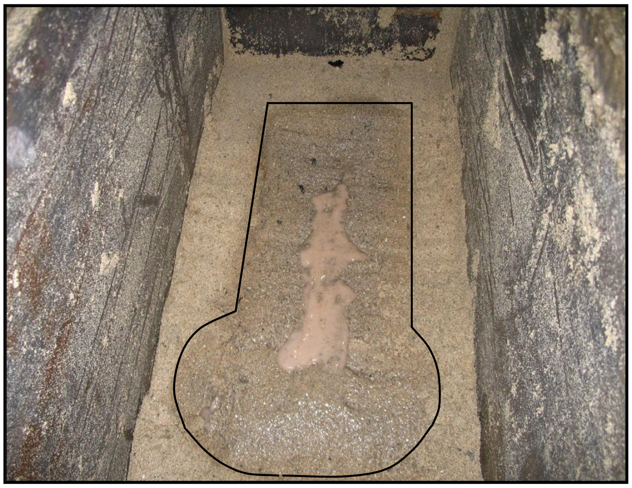

Figure 2 – Filtercake at the borehole crown

These tests were carried out under conditions similar to the abovementioned tests, with the exception of the application of the overburden stress. In these tests, the small actuator was not used to apply a stress to the surface; insitu stresses near the borehole were provided using overlying sand alone.

The tests undertaken using the extension box did not result in hydrofracture and mud loss at the ground surface. In all cases, mud loss always occurred through the connection between the upper and the lower boxes. The sidewall friction reducing measures (a polyurethane barrier between the sidewalls and the sand material) did not provide sufficient resistance to mud flow, as the plastic developed a tear in each case resulting in mud loss.

Ground heave was not measured during the three tests given the difficulty of placing a linear potentiometer on the ground surface (when the surface was being loaded by the actuator). All ground displacement measurements were made by observing the surficial displacements relative to to a scale located along the side of the test cell.

In each case the volume of the mud pumped into the borehole was considerably greater than the volume pumped for tests with simulated overburden pressure. Following failure of the borehole, excavation of the host soil was carried out for the simulated overburden pressure. The excavation of the sand indicated that the infiltration of the drilling mud was also considerably greater than with the simulated overburden. During the tests, it was observed that an entire section of the host soil up to 350mm in thickness above the crown of the borehole was completely filled with drilling fluid. The excavation also indicated that there was no obvious failure of the sand in the form of a crack, and there was no obvious region of liquefied material or flow tube, whereas an obvious path of fluid to the surface was observed in the previous tests carried out with the simulated overburden.

When the maximum mud pressures were observed following completion of each test and compared with those obtained from the simulated overburden tests. The results of the extension box tests, were considered to be relatively unsuccessful, in that no breaches of the ground surface were observed. The tests did however indicate, that depending on the relative density of the host sand material, the simulated overburden tests provide an adequate estimation of an actual overburden pressure. The results with full depth to surface (i.e. with the extension to the test box) were considered to be comparable to those obtained from overburden simulated by mechanical loading (i.e. without the extension), as the distance that the mud was required to travel to breach the confinement of the soils were similar in all cases (the mud loss occurred from a lateral boundary of the bottom part of the test cell). In two of the three tests carried out with the extension box, the maximum observed mud pressures were slightly lower than those observed in the tests using simulated overburden pressure

5 DISCUSSION

The results were compared to the results of several closed form solutions based on expansion of a cavity from a pre-existing hole. As stated above, these cavity expansion theories assume that all deformations of the cavity are axisymmetric (uniform around the circumference and directed radially), that the material is an elastic-perfectly plastic material, and that the material is isotropic and homogeneous in nature. Failure of the borehole is represented using the Mohr-Coulomb failure criterion, and elasticity is modelled using Hooke's law up to the onset of yield. Once yield has occurred, all particles within the yielded zone are considered to be plastic and exhibit large deformations, while all particles outside of the yielded region are considered to be elastic. The deformations within the elastic region are considered to be negligible compared to the plastic deformations.

Comparisons of the maximum mud pressures in the borehole were made calculated using the various theories and measured in the laboratory test. The cavity expansion theories that were explored included the Delft equation, as stated above, and theories developed by Yu and Houlsby (1991) as well as by Carter, Booker and Yeung (1986). The Delft equation is based on the assumptions outlined by Vesić, that is zero dilation ($\Psi=0$), and negligible elastic strains within the yielded region. Carter, Booker and Yeung adopted an associated flow rule ($\Psi=\phi$), and included explicit consideration of the elastic strains within the plastic region. Carter et al. (1986) also examined the possibility of non-associated flow and large strains. The theory of Yu and Houlsby (1991) is based on non-associated flow rule and large strains, and also considers the possibility of elastic strains within the plastic zone. The Yu and Houlsby solution is the most versatile, and when dilation angle is zero, it reduces to the Delft equation. For associated flow rule, the Yu and Houlsby solution reduces to the Carter, Booker and Yeung solution.

In addition to the theoretical cavity expansion methods described above, the laboratory results were compared to force equilibrium in the sand and its resistance to failure due to liquefaction. These results were calculated for a compact sand material similar to the host material used during the laboratory experiments.

The comparisons of the theoretical values and the test data show similar trends. The average error associated with the maximum or limiting pressures for the cavity expansion theories was found to be 9.5% for the Delft solution. The average percentage of error assuming that the accumulation of pore pressures leads to liquefaction is approximately 7%.

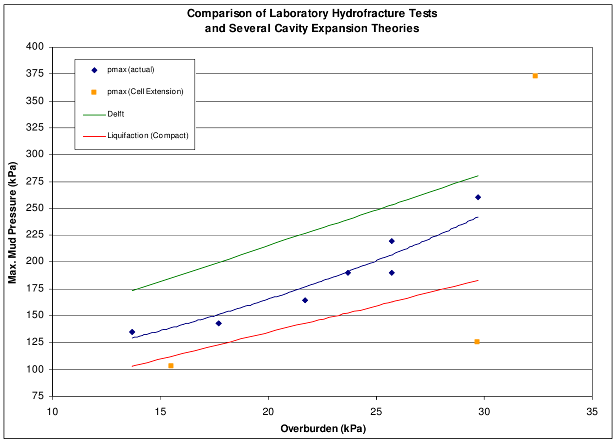

Figure 3 – Comparison of cavity expansion theories

The closed form solutions described by Carter et al. (1986) and Yu et al. (1991) tend to produce maximum mud pressures up to three times those observed during the tests. Based on these findings, it is recommended that additional numerical modelling should be carried out to ascertain the validity of these models with respect to the hydrofracture blowout problem. Though the two solutions may not be useful in these cases, it is still critical that they be considered for the possible analysis of an insitu case where boundary conditions are not a factor.

6 CONCLUSIONS

Laboratory tests to determine the material properties of the filtercake show that in general, there is little improvement in terms of the physical characteristics of the sand material once it has been saturated with the drilling fluid. However, shear strength tests are still required to determine whether there is any improvement with respect to the shear and residual strengths of the filtercake when compared to the host sand material. Clearly, further tests and numerical models are required to estimate the impact of the potential increases in stability and shear strength as a result of drill fluid intrusion. It is also important to carry out additional testing to determine the effects of the interaction between the filtercake and host soil and the potential impact with respect to maximum allowable mud pressures.

Through the course of these laboratory experiments, it has become clear that certain limitations exist that prevent the determination of pore pressures that would contribute to liquefaction. As the drill fluid will naturally seek the path of least resistance, is nearly impossible tp place closely spaced pressure transducers designed to indicate the development of a hydraulic gradient within the narrow zone of infiltration, while maintaining the integrity and minimize disturbance of the host soil, though this would be valuable to explore. The experiments clearly show however, that once a path to the surface is activated, the mud will seek this path and continue to liquefy the overlying material until the ground surface is breached. Furthermore, once a breach has occurred, the mud exits the ground under pressure, which is similar to shear failure/hydrofracture tests carried out by others.

It is suggested that for future tests, a system of pressure transducers designed to determine the horizontal stresses acting on the sidewalls of the cells should be incorporated. Such pressure cells mounted into the sidewalls of the cell could also provide an accurate determination of K_o resulting from compactive efforts and prestressing of the sand material. The determination of K_o can help provide a more complete picture of the stress profile of the recompacted material, facilitating comparisons between these laboratory experiments and mud loss phenomena insitu. .

Current practice suggests the use of the Delft equation for most HDD applications based on limiting plastic radius (R_p) extending from the borehole not more than two thirds of the total burial depth. By comparing the observed and the estimated limiting mud pressures from different cavity expansion theories, it appears that for sands and gravels, this design limit on maximum plastic radius produces somewhat conservative maximum mud pressures, regardless of the mode of failure, be it shear failure or liquefaction.

ACKNOWLEDGEMENTS

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