Some Factors Affecting Deep Excavation in Clay Over Gassy Bedrock

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ABSTRACT: A study of excavations within normally to slightly over consolidated deposits over a gas source is presented with reference to the potential for gas venting from a bedrock aquifer. The effects of key design factors on excavation integrity and potential of inducing hydrofractures are examined. Based on the calculated gas distribution, the study introduces the gassy effect to the deepest 6 m of the clayey layer by: a) increasing pore fluid compressibility, b) reducing Young's modulus of soil skeleton. The study illustrates the importance of considering hydrofracturing potential and gassy behaviour when assessing the stability of excavations in deposits overlying a gas source.

1. INTRODUCTION

While much has been written about excavations in deep soil deposits (e.g., Hashash and Whittle (1996), Jen (1998), Hashash et al. (2002) and Whittle and Davis (2006)), relatively little has been written regarding excavations in deep deposits of gassy soil. Gassy soils may range from very soft unconsolidated recent sentiments with significant organic matter, where the gas has a biogenic origin such as is found offshore in many parts of the world (Wheeler 1988a, 1988b; Sills et al. 1991; Chillarige et al., 1997; Grozic et al. 1999, 2000), to dense overconsolidated hydrocarbon rich deposits such as the oil sands of Alberta, Canada where the gas has a petrogenic origin (Dusseault and Morgenstern 1978; Sobkowicz and Morgenstern 1984), to normally to slightly overconsolidated clay deposits overlying bedrock with gas of petrogenic origin such as found in southern Ontario Canada (Rowe et al. 2002; Dittrich et al. 2002, 2010).

Between 1886 and 1892 problems were encountered when excavating an approach to a railway tunneling near Sarnia, Ontario Canada. These problems included (Rowe et al., 2002) clay soils becoming soft to very soft and flowing upwards into excavation as fast as they were removed, natural gas discharge from a fissure that opened up, and several slope failures. A century later the excavation was being widened to accommodate the approach to a second tunnel when an unanticipated deep-seated slope movement occurred on a slope that was not directly affected by the construction activities (Dittrich et al., 2002). Dittrich et al. (2010) found that the problems encountered during construction of both tunnels were related to the presence of dissolved gases in the pore water.

In the late 1990's, the excavation of a 24m deep cell in an approximately 40m thick clayey deposit encountered unexpected slope movements on the sides of the excavation and venting of gas and water from the low permeability soils at the base of the excavation although there was no significant basal heave (Rowe et al., 2002; Mabrouk and Rowe, 2011). The potential reasons for this unanticipated soil behaviour have been examined by Rowe and Mabrouk, (2007), Mabrouk and Rowe (2011) and Mabrouk (2012). These studies concluded that the unexpected slope movements were the result of gassy sand lenses contained by the low permeability clay losing their shear strength due to the exsolution of dissolved gas causing the maintenance of high pore pressures when the total stress was substantially reduced thereby causing liquefaction of the sand. They also concluded that the gas venting resulted from the soil unloading (due to the excavation) that was enough to initiate hydrofracturing in the clayey soil between the bedrock aquifer and the base of the excavation. Hydrofractures created a path for gas and water movement from the bedrock to the base of the excavation.

The studies of excavations in gassy soft normally to slightly overconsolidated gassy soil cited above have focused on a forensic identification of the specific conditions that could explain the observed behaviour. In contrast, the objective of this paper is to examine the effect of some key design factors that warrant consideration when excavating in these unusual soils. This paper involves a parametric evaluation of factors that could affect the development of hydrofracturing during excavation in a thick clayey soil deposit such as that where problems were encountered as examined by Mabrouk (2012). Thus while this paper adopts the actual site stratigraphy, soil properties and landfill geometry for this specific site that has been examined previously, this paper conducts a parametric study intended to evaluate the potential significance of factors that could initiate potential problem when excavating in gassy soils rather than focusing on what actually happened at a particular site.

2. GEOLOGICAL CONDITIONS AND STRATIGRAPHY

The site stratigraphy examined in 2D analyses by Mabrouk and Rowe (2011) is adopted as a starting point for this parametric study. From the surface to depth the stratigraphy involved:

- 6m of weathered, fractured and hydraulically active overconsolidated clayey silt,
- 8m of unweathered overconsolidated massive clayey silt of low hydraulic conductivity ($\approx 8 \times 10^{-10}$ m/s),
- 24-26m of predominantly normally consolidated clayey silt of low hydraulic conductivity (typically less than 2×10^{-10} m/s) Infrequent, discontinuous silty sand lenses, ranging in thickness between 0.5-2m are encountered between depths of 24m and 29m below ground surface.
- A discontinuous weak, 1-2 m thick layer of sandy clayey silt directly above the bedrock.
- An organic rich bedrock with a fractured upper portion of high hydraulic conductivity ($\approx 1 \times 10^{-5}$ m/s) that is part of a regional aquifer and the source of the gas.
- The initial pore water distribution in the soil prior to excavation is hydrostatic with a water table approximately at the soil surface.

3. PROBLEM DESCRIPTION

The landfill was divided into cells then to smaller waste disposal trenches to facilitate sequential construction and waste disposal operations planning. Construction involved excavation of selected area to create an initial plateau at a depth of 14mBGL (BGL = below ground level), and then downward to a second plateau at 18mBGL. These excavations had 1:1 (horizontal:vertical) slopes. Subsequently, a 6m trench was excavated ahead of advancing placement of waste to a depth of 24mBGL. The trench length and width were limited (≈ 35m x 35m) in the hope of ensuring slope and base stability. The trenches were unsupported.

A trench was being excavated in Cell 3 (Figure 1) when venting of gas (predominantly methane) and water under pressure was observed at several locations. Geochemical analyses of the vented water indicated that it mostly originated from the underlying confined bedrock aquifer (although mixing of water from the aquitard and aquifer was evident in one of the seeps). The vented gas (which was at gas pressures in excess of 70 kPa above atmospheric pressure) was methane originating from the underlying bedrock.

Mabrouk (2012) used 2D and 3D finite element analyses to perform a numerical forensic study of the potential reasons for the venting. The analyses indicated that the primary explanation for the venting was hydrofracturing initiated at the interface of clayey silt with the bedrock. Unloading due to the excavation caused a significant reduction in the total stress in the clayey silt. However, at the interface between the clayey silt and bedrock aquifer relatively high pore pressures were maintained. When the effective stress in the clayey silt at the interface was reduced to less than the soil tensile strength, local hydrofractures were initiated. The hydrofractures propagated upwards from the interface aquifer until they reached the excavated surface and resulted in gas and water venting. The concave bedrock formation below Cell 3 created a region for accumulation of gas migrating upwards through the fractured bedrock which was entrapped at the interface of the bedrock aquifer and clayey silt (Dittrich, 2000).

Hydrofracturing is of a local nature and, in the case of a landfill, can be expected to close up again on reloading. However once formed, even a single hydrofracture could create a preferential path for leachate migration and hence an environmental hazard. Thus, precautions should be followed while excavating a landfill even in what may be considered an ideal containment environment – thick low permeability clay. The following sections present a study of some design considerations to avoid initiation of hydrofractures.

4. NUMERICAL MODEL AND GEOMETRY

The following analyses were performed using a modified version of the finite element software ABAQUS. An effective stress analysis was adopted using an elasto-plastic model with a Mohr Coulomb failure criteria and a non-associated flow rule with zero dilatency angle. The elastic behaviour was taken to be linear and isotropic. For the 2D analyses, 8-noded elements with a biquadratic displacement function, bilinear pore pressure and reduced integration was used. The element has three degrees of freedom (*ux, uy*, and pore pressure at the corners). The average element size was 2 m square. For 3D analyses, a 10-noded modified quadratic tetrahedron element with reduced integration was used. These elements had 4 degrees of freedom (*ux, uy, uz* and pore pressure at the corner nodes). Element size ranged from about 3 m near the excavation, to 24m at the boundaries (Figure 1 and 2). The effect of mesh refinements was examined by Mabrouk (2012). The model was validated against the observed field behaviour to the extent that field data was available (Mabrouk, 2012).

The excavation was modelled by deactivating elements. Based on the geological evidence, the bedrock geometry had a concave shape with elevations varying from 40mBGL at the east to 42mBGL at the west and with a peak elevation of 37.6mBGL below Cell 3.

The base boundary was rough and rigid; the lateral boundaries were smooth and rigid. The initial pore pressure distribution was hydrostatic and hydrostatic boundary conditions were assigned along the lateral boundaries. Zero pore pressure conditions were assigned along the original soil surface and any surface exposed by the excavation.

Effective shear strength soil parameters were assigned to the different soil units based on field and laboratory test data where available while soil stiffness and hydraulic conductivity parameters were selected based on Dittrich's (2000) study of a nearby site (St Clair railway tunnel) in the same soil deposit. The key soil parameters are given in Table 1.

Hydrofracturing was accounted for in the model using an approach described by Mabrouk (2012). Due to the size of the problem, limited computer power to solve a detailed hydrofracturing criterion in addition to the effective stress analysis (even with the use of a supercomputer) and the lack of some experimental data needed to evaluate soil strength against hydrofracturing, the study used an effective media approach to simulate hydrofracture growth. The modelling neglected the soil tensile strength (an approach conservatively adopted in many studies: e.g., Bjerrum el at., 1972; Massarsch, 1978, Panah, 1989) and assumed that the hydrofractures were initiated when the minor principle effective stress decreased to zero. Inspired by the element extinction algorithm of Beissel et al., (1998), the model simulated hydrofracture growth by substantially increasing the hydraulic conductivity of elements in tension (Mabrouk, 2012). The approach allows the pore pressure to grow in weak regions where hydrofracturing is more likely to nucleate. The technique adopted is approximate and will over predict the width of the hydrofracture zone since it does not allow localization along a thin hydrofracture zone.

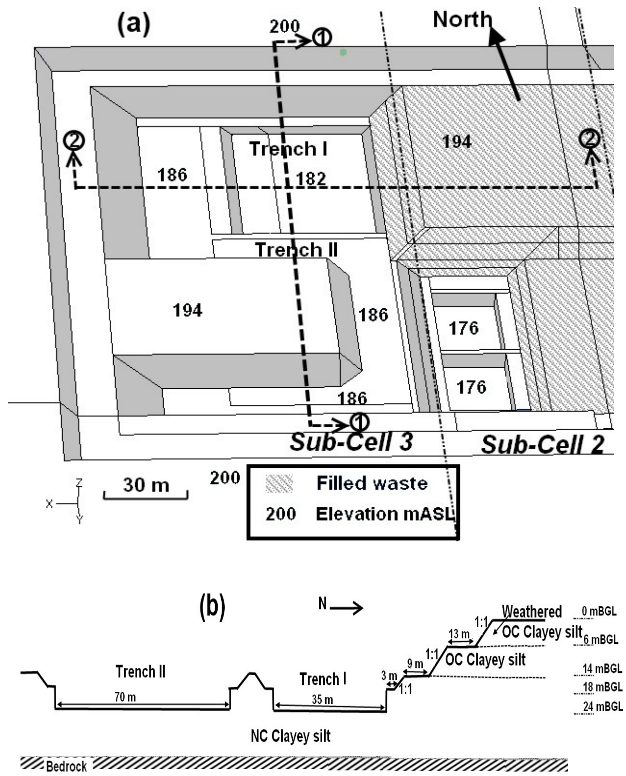

Figure 1 Site geometry : a) Plan view of 3D model of the excavation during excavation and filling of different sub-cells showing the locations of the cross sections examined (Section 1 and Section 2) b) Vertical profile showing soil deposits and construction profile along Section 1

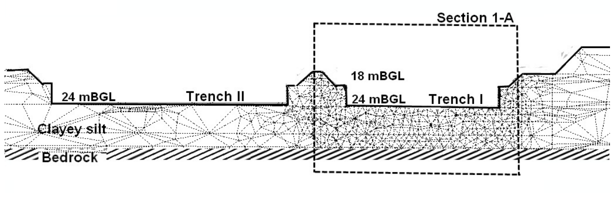

Figure 2 Cross section 1 of the 3D model showing the final design excavation elevations for Trenches I and II of Cell 3. Several future figures will show results for the region inside the box denoted "Section 1-A". mBGL= meter Below Ground Level

Table 1 Key parameters
(Poisson's ratio = 0.4 and K_o' = 0.67 for all layers)

Depth (mBGL) *	γ (kN/m^3)	c' (kPa)	Φ' (^{o})	E' (kPa)	e_0 (-)	k (m/s)
0-6	21.5	24	25	55000	0.47	$8x10^{-8}$
6-14	21	16	27	55000	0.49	$8x10^{-10}$
14-16	20.5	24	24	55000	0.56	$2x10^{-10}$
>16*	19.6	24	24	30000	0.74	$2x10^{-10}$
36-38**	18.2	9	18	15000	1.2	$1x10^{-8}$
Bedrock	23	40	40	200000	0.25	$1 x10^{-5}$

5. HYDROFRACTURING

5.1 Excavation geometry

The landfill design included excavation of trenches, approximately 35m x 35m x 6m deep, within the cells. Trenches were filled with waste soon after excavation with the objective of preventing drained conditions from developing in the clayey silt (which might affect the slope stability; Rowe and Mabrouk, 2007). This section investigates the effect of trench geometry on the potential for initiation of hydrofracturing.

5.1.1 Excavation depth

A 3D analysis was performed, simulating the excavation of Trench I in Cell 3. Unloading steps were performed with 1 m vertical increment to investigate the critical depth at which hydrofracturing would be initiated at the clayey silt - bedrock interface. The results suggest that in the critical Cell 3 area, hydrofractures were not initiated in the normally consolidated clayey silt layer until the excavation depth reached 24mBGL (Figure 3). Thus, had the excavation depth been limited to 23m (≈14.6m clayey silt remaining to bedrock) in Cell 3, no hydrofracturing and venting would have occurred.

The 3D analysis showed that the adjacent Cell 2, where the top of bedrock was 38.2mBGL compared to 37.6mBGL for Cell 3, could be (as indeed was) fully excavated to the maximum design depth of 24mBGL without the initiation of hydrofractures at the clayey silt-bedrock interface. Thus it may be inferred that had the bedrock not risen an extra 0.6m below Cell 3, no venting would have occurred. This highlights the importance of what might appear to be relatively minor changes in the geology when dealing with sensitive designs similar to that being considered in this paper.

5.1.2 Trench dimensions

The 3D redistribution of horizontal stress arising from an excavation is typically directed into the soil around and at the base of the excavation. This 3D effect could be sufficient to prevent hydrofracturing if the trench dimensions were sufficiently small. The actual typical trench dimensions were 35m x 35m. A 3D analysis was performed to examine the effect of trench dimensions for Trench I of Cell 3 excavated to its full depth (24mBGL). The trench was taken to have a constant length of 35 m (out of plane) and analyses were performed for a range of widths starting at 10m.

There was no hydrofracturing predicted in the normally consolidated clayey silt when a 10m wide trench was excavated (Figure 4a). However, increasing the excavation width to 20m was sufficient to induce hydrofractures at the clayey silt-bedrock interface (Figure 4b). It may be inferred that had the trench widths been limited to approximately 10m in this particular case, no venting would have occurred. This highlights the importance of what might appear to be relatively minor changes in the excavation geometry when dealing with sensitive designs similar to that being considered in this paper.

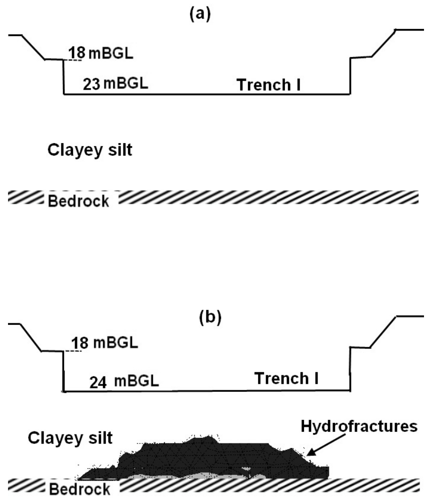

Figure 3 Examination of the maximum excavation depth that can be reached before the initiation of hydrofractures for the case of Trench I (Section 1-A on Figure 2) at the location of the highest bedrock elevation (≈ 37.6mBGL) :
(a) No hydrofractureing when excavation was 23mBGL
(b) hydrofractures initiated when excavation reached 24mBGL; these fractures continued to extend upward with time until they reach the excavated surface

5.1.3 Hydrostatic uplift pressure

The removal of the overburden soil by excavation while the interface aquifer was exerting an almost constant uplift pressure on the base of the normally consolidated clayey silt has the potential to induce basal heave and cracking (Figure 5). The site was monitored for basal heave and although the venting of gas and water was observed, as discussed earlier, there were no unusual vertical movements or evidence of basal heave.

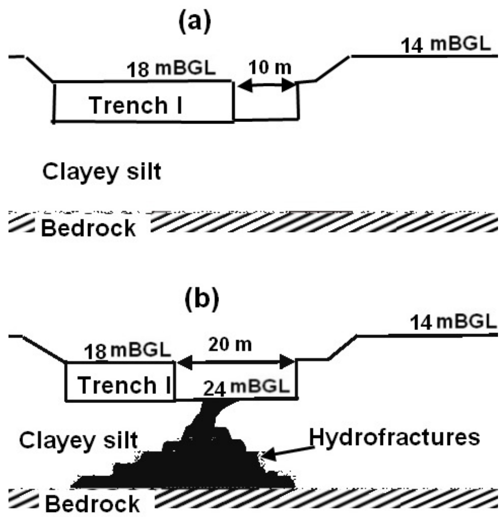

Figure 4 Examination of the effect of trench dimensions on the potential for initiation of hydrofractures for Trench I at the location of the highest bedrock elevation (≈ 37.6mBGL), full trench excavation to 24mBGL, fixed trench length of 35m, and variable thrench width in Section 1-A (Figure 2) :
a) No hydrofractures were initiated when width was limited to 10m.
b)Hydrofractures were initiated when excavation width was increased to 20m and propagated upwards untill reaching the excavation surface

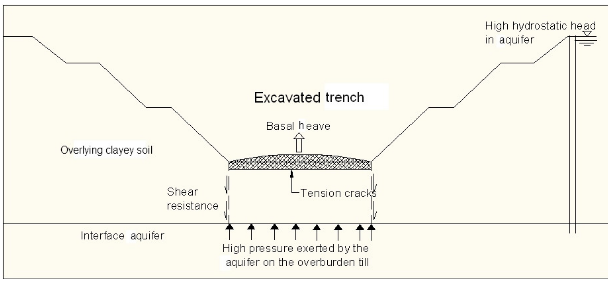

Figure 5 Schematic section showing hydrostatic uplift pressure on the clayey soil layer below the base of an excavation

The undrained shear strength of the normally consolidated clayey silt ranged between 80-100 kPa with an average value of 84 kPa. Excavation of a trench to 24mBGL in Cell 3 left 13.6 to 14 m of normally consolidated clayey silt between the base of excavation and the bedrock aquifer. A simple design calculation based on basic stress equilibrium was conducted to calculate the overburden thickness between base of excavation and the interface aquifer required for a factor of safety of unity for different trench widths (length 35m) and three undrained soil shear strengths (Figure 6). For the expected average undrained shear strength of 84 kPa, the design calculation indicated that a trench of the size actually excavated (35m x 35m) would be at the point of basal heave had the overburden thickness been consistently 13.6m and marginally stable (but very close to failure) if the overburden thickness had been consistently 14m. Thus, while no excessive basal heave actually occurred, the factor of safety based on the average remaining overburden thickness was only about 1.0 for Trench 1 (critical thickness 13.7m) and 0.91 for Trench 2 (critical thickness 14.9m) which had almost double the width of Trench I (i.e. ≈ 70m versus 35m). Thus while simple basal heave calculations are not a direct indicator of hydrofracturing, the very low factor of safety with respect to basal heave appeared to be an indicator of a potential problem and hydrofracturing and venting did in fact occur.

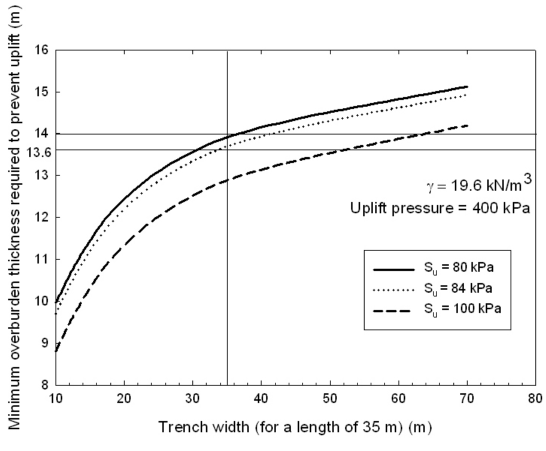

Figure 6 Minimum thickness of soil between the base of the excavation and the interface aquifer required to counter the uplift pressure (factor of safety = 1) for different trench widths (length assumed to be 35m) and undrained soil shear strengths

To maintain a factor of safety of 1.3 for a 35m x 35m dimension of Trench I, the depth of the excavation should have been limited to 20mBGL (leaving 17.6m of overburden). Alternatively, to excavate to 24mBGL leaving an average of 13.6m of overburden, it would be necessary to limit the width of Trench I to 12m to have a factor of safety of 1.3. This is consistent with the absence of hydrofracturing in the 3D analysis for a trench of this width and thus it would appear that a factor of safety of 1.3 against basal heave would have been sufficient to have also prevented hydrofracturing and the venting that was observed at the site. Thus with a good definition of the bedrock elevation, the venting problem that did occur probably could have been prevented by use of a simple design calculation.

6. GASSY SOIL MODEL

The modelling described above considered hydrofracturing which could have occurred in the absence of any gas. Consideration will now be given to gassy soil behaviour. Gassy soils contain gas in the pore fluid in the form of dissolved gas, undissolved gas or gas hydrates (Grozic et al., 1999) under conditions of positive pore pressure. This is in contrast to traditional unsaturated soils where gas (usually air) co-exists with negative pore water pressures (suctions - Fredlund and Rahardjo, 1993). The gas in a gassy soil can be formed as a result of biogenic process (bacterial activity), petrogenic process (organic precursors at high temperatures and pressures) or destabilization of gas hydrates (Grozic et al., 1999). A gassy soil may be initially saturated (i.e., all the gas is in the dissolved phase) but on unloading dissolved gas will exsolve generating a gaseous phase. Generally, the gaseous phase is discontinuous, in the form of bubbles under neutral (atmospheric) or positive pressure (Pietruszczak and Pande, 1996; Rowe et al., 2002). For a degree of saturation above a critical value which is typically about 85% (Sparks, 1963), the gaseous phase in the gassy soil is likely to be discontinuous. Many failures have occurred during construction of offshore structures (Grozic et al., 1999) and to a lesser extent due to onshore excavations (Rowe et al., 2002) as a result of the presence of gas under positive pressure in the soil; hence the potential effect of gas on the clayey silt sediment should not be neglected.

Based on gas bubble size relative to soil particle size, gassy soil is divided into soils with “large” bubbles and “small” bubbles (Wheeler, 1988a, 1988b). For coarse grained soil, the occluded gas bubbles within the pore fluid are small relative the particle and pore size (Figure 7a). For fine grained soil, the gas bubbles are large relative to the particle and pore size (Figure 7b).

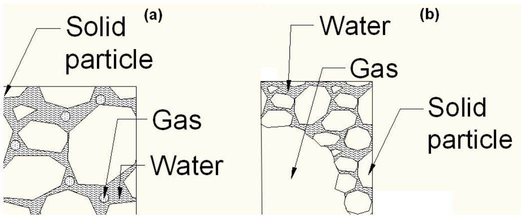

Figure 7 Schematic of soil-bubble structure (not to scale):
(a) for coarse grained soil, the bubbles are small relative to the particles and pore size,
(b) for fine grained soil, the bubbles are large relative to the particle and pore size

6.1 Pore fluid bulk modulus

It is generally agreed that the formation of large cavities (gas bubbles) within fine soil structure significantly increases its compressibility and reduces its stiffness (Sobkowicz and Morgenstern, 1984; Wheeler and Gardner, 1989; and Dittrich et al., 2010). For fine grained soil, Brandes (1999) stated that small amounts of gas (gas bubble concentration of less than 1 %) can cause a 95% reduction in the undrained bulk modulus of the soil-water system (Dittrich et al., 2010). A simple and effective approach in modelling fine grained gassy soil was proposed by Grozic et al. (2005) where the gassy behaviour was introduced to the soil skeleton as a reduction in pore fluid bulk modulus. This section adopts a similar approach in which the fine grained gassy soil behaviour was modelled by reducing the pore fluid bulk modulus (to 1000 kPa, as explained later) and the effect on the excavation was explored.

Analyses examining the diffusion of gas through the clayey silt over the approximately 13500 years since its deposition suggest that the approximately 6m closest to bedrock (gas source) would have concentrations of dissolved gas that might significantly alter its mechanical behaviour upon exsolution with unloading (Dittrich et al., 2010; Mabrouk and Rowe, 2011). These diffusion analysis results were consistent with observations of self-extrusion of soil from Shelby tubes collected from the deepest 6m of the clayey silt layer (Dittrich et al. 2010). Accordingly the remainder of this section models a 6 m thick gassy zone in at the bottom of the clayey silt having a relatively low pore fluid bulk modulus of 1,000 kPa selected based on an estimate for gassy soil containing a mixture of 85% methane and 15% carbon dioxide (Mabrouk and Rowe, 2011).

A 2D simulation of the excavation using with this idealization of the gassy soil indicated that excavating Trench I down to 21mBGL would cause hydrofractures to initiate and propagate until they reached the bottom of the excavation. The mechanism for gas venting can be briefly described as follows: when the excavation reached 21mBGL, hydrofractures were initiated from the bedrock and extended across the gassy layer (Figure 8a). The hydrofractured area expanded laterally within the gassy clayey silt (Figure 8b). The hydrofractures then began to migrate from the gassy layer up into the overlying clayey silt layer. Hydrofractures occasionally tended to close within the compressible gassy layer due to horizontal compressive stresses, and thus ceased the continuous connection with the bedrock aquifer at sometimes (Figure 8c). However the high fluid pressure within fractures would be sustained because they are surrounded by relatively impervious clayey layer (Figure 8d). Subsequent stress redistribution re-initiated the hydrofracturing from bedrock through the gassy layer until it broke through to the excavated soil surface forming gas vents (Figure 8e).

A 3D analysis gave generally similar results to those described above using the 2D model. Hydrofracures were initiated on trench excavation down to 21mBGL (Figure 9a) and continued to develop in a manner similar to that described for the 3D analysis until they reached the excavated surface causing gas venting (Figure 9b).

The similarity of the 2D and 3D results suggest that with a reduction of pore fluid bulk modulus due to gassy soil, an out of plane trench width greater than the 35m modelled in the 3D analysis would not have a significant effect on the initiation of hydrofracturing or the propagation mechanism. In these analyses, the low pore fluid bulk modulus associated with gassy soil resulted in discontinuous/ intermittent gas venting. This was also the case for some of the observed venting incidents after which continuous venting was observed. However this approach appears to predict that venting would occur earlier than when it actually occurred (i.e., at 21mBGL rather than 24mBGL). When a higher pore fluid bulk modulus value (10,000 kPa) was used, similar results were obtained but there was a better estimate of the depth at which hydrofracturing would occur (i.e., 24mBGL). Thus the simplified approach to modelling gassy soil by considering it as the layer of low pore fluid bulk modulus is conservative but perhaps too much so for modelling the venting observed at this site unless one is judicious in the selection of the pore fluid bulk modulus.

6.2 Young's modulus

Another approach for modelling the reduction in the soil-water stiffness of gassy fine grained soils involves reducing the Young's modulus of the soil skeleton. Dittrich (2000) showed that gassy fine grained soil samples extracted from the St Clair site turned from stiff clay into spongy soft to very soft upon excavation (Rowe et al., 2002). Thus the adopted approach examines the potential effect of the gas on the soil matrix (rather than on the pore fluid examined above). Generally, stiff layers provide a better media for hydrofracture propagation than softer layers. This can be attributed to the tendency of stiff material to concentrate stresses around a crack tip and hence induces further crack propagation (Brenner and Gudmundsson, 2004).The softer the material, the more likely it is that the tensile stresses generated by hydrofractures will dissipate, and hence the layer can act as a hydrofracture barrier.

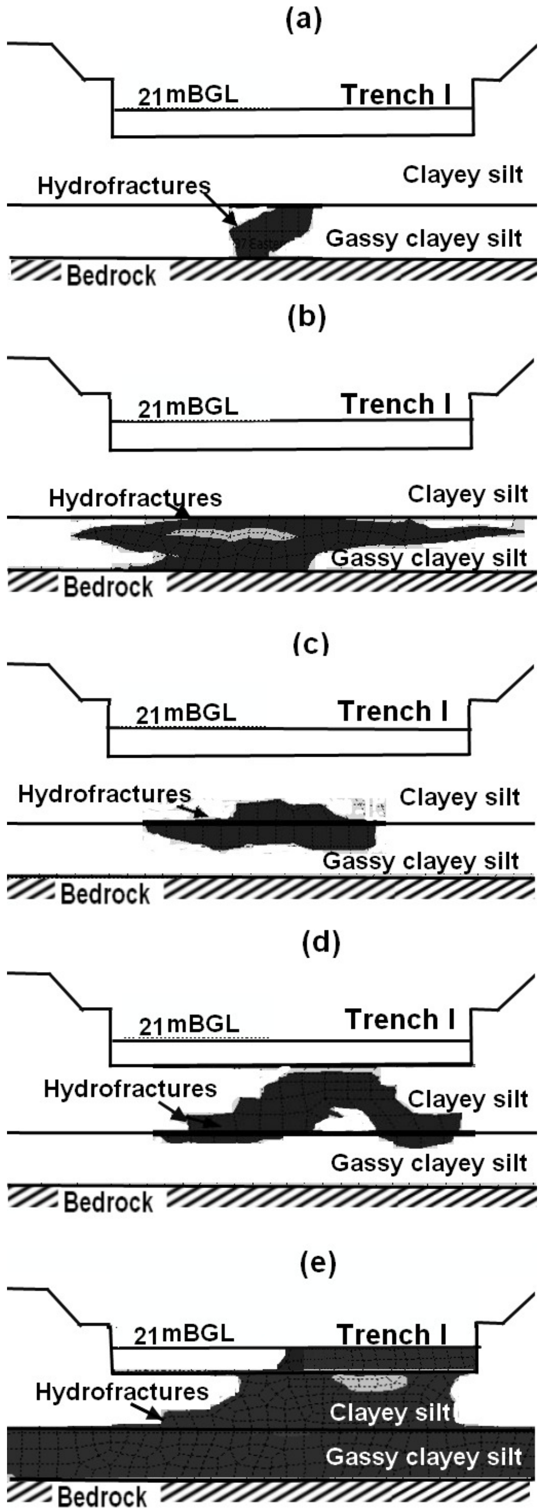

Figure 8 Predicted hydrofracture path based on 2D analysis (Section 1-A on Figure 2); gassy clayey silt layer modeled with pore fluid having a bulk modulus of 1,000 kPa):
a) hydrofracture is formed across gassy layer,
b) hydrofractures area expands in the gassy layer,
c) hydrofracture moves upwards through the gassy layer and concentrates at the interface of the gassy layer with clayey silt,
d) hydrofracture propagates through clayey silt layer to the excavation surface but has largley disappeared in the gassy layer,
e) hydrofracture connected the bedrock aquifer and the excaveted surface forming a gas vent

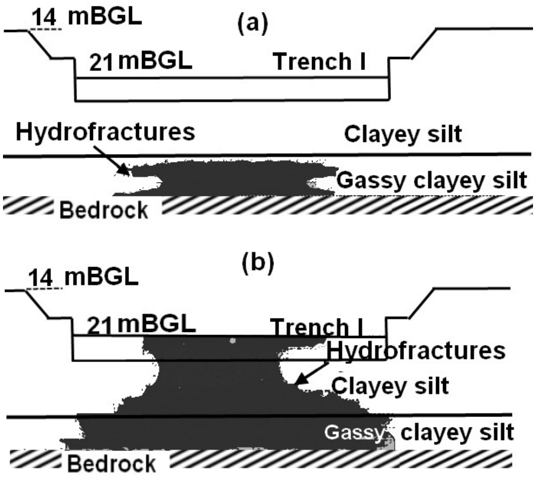

Figure 9 Predicted hydrofracture path based on 3D analysis (results for Section 1-A on Figure 2); gassy clayey silt layer modeled with pore fluid bulk modulus of 1,000 kPa):
a) Hydrofractures formed across the gassy layer.
b) Hydrofractures concentrate at the interface of the gassy layer with clayey silt layer and propagate upwards towards excavation surface

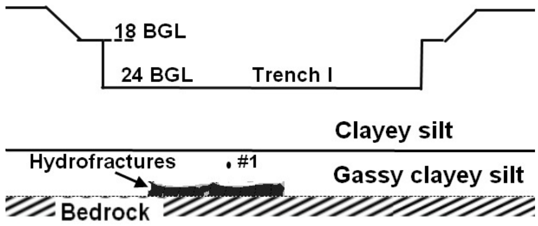

Figure 10 Hydrofracturing based on 2D analysis (Section 1-A on Figure 2) with a gassy layer with E=12,500 kPa. Here the gassy layer acts as hydrofracturing barrier and hydrofracturing was contained below Point #1

To study the effect of Young's modulus on the potential for hydrofracturing, the modelling was performed using different Young's modulus values for the gassy clayey silt unit (Young's modulus E'=3000 kPa (very soft); 12500, 15000 kPa (soft clay); 30000 kPa (medium)) to investigate whether a reduction of Young's modulus due to the presence of gas would increase the potential for hydrofracture formation or cause the layer to act as hydrofracture barrier. The behaviour of a key point (denoted as #1) within the gassy clayey silt region, located at 33mBGL under the center of excavation, was examined during excavation for a Young's modulus value of 12,500 kPa (Fig. 10 and 11).

The 2D and 3D analyses also were performed for the different Young's modulus values. After full excavation of Trench I, the propagation of the hydrofracture through the gassy clayey silt unit varied depending on the assigned Young's modulus for the layer. When Young modulus (E') was significantly reduced (< 15000 kPa), the hydrofractures could not propagate through the full thickness of the clayey silt (Figure 10 and 11). Figure 12 shows the variation in the effective stress at Point #1 for different assumed Young's modulus values for the gassy layer. For E' ≥ 15,000 kPa, as hydrofractures reached Point #1 and the pore pressure significantly increased leading to a sudden reduction in effective stress (Figure 12). However for E' < 15,000 kPa, hydrofracture did not reach Point #1 and the effective stress remained in compression throughout the analysis. This implies that the gassy clayey silt can act as a continuous barrier to hydrofracturing provided that the Young's modulus is low enough (≤15,000 kPa in this case). Hence, unlike the effect of gas on pore fluid bulk modulus discussed earlier, a large reduction in the Young's modulus of the clayey silt does not increase the potential for hydrofracturing and in the extreme case (E' < 15000 kPa) could reduce the potential. However in the case under consideration the reduction in Young's modulus due to the presence of gas in the clayey silt was not sufficient to prevent hydrofracturing (hence it may be inferred that E' ≥ 15,000 kPa) since venting of water and gas did in fact occur.

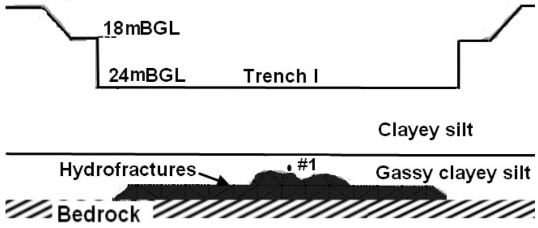

Figure 11 Hydrofracturing based on 3D analysis (Section 1-A on Figure 2) with a gassy layer having E=12,500 kPa. Again. the gassy layer acts as hydrofracturing barrier and hydrofracturing was contained below Point #1

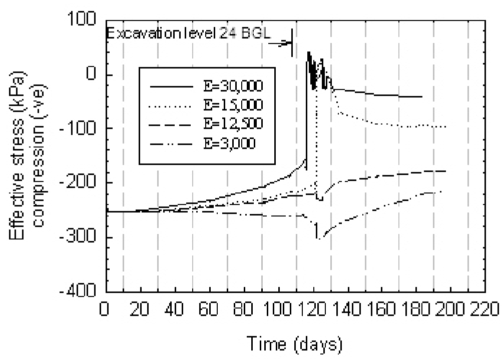

Figure 12 Effective stress at Point 1 calculated for different assumed Young's modulus values for the the gassy layer
(E= 30000, 15000, 12500, 3000 kPa)

Similarly results were obtained from both 2D and 3D analyses with the gassy layer acting as a barrier to hydrofracuring when the Young's modulus value was less than 15000 kPa for both cases. Thus it can be inferred that the gassy property of the soil (Young's modulus effect) was solely responsible for hydrofractures inhibition regardless of the width of the excavation in excess of the 35 m modelled in the 3D analysis. Thus in the analysis of excavations in gassy soil, it would be appropriate to examine the effect of uncertainty regarding Young's modulus and pore fluid bulk modulus of the gassy soil on the predicted response.

7. SUMMARY AND CONCLUSION

The effect of some key factors affecting the performance of an excavation in a deep deposit of gassy soil was examined. The risk of hydrofracturing was shown to depend on the excavation depth and the bedrock elevation. For the problem studied, it was found that a small local rise in bedrock elevation beneath one cell reduced the remaining overburden thickness to below the critical depth of 14.6 m between excavation surface and bedrock. The analyses reported herein suggest that had an overburden thickness of greater than 14.6 m been maintained between the base of the excavation and the bedrock aquifer then hydrofracturing and venting would not have occurred at the site examined. Alternatively if the 35m long trenches have been restricted to a width of about 10 m (rather than 35m actually used) the 3D effects may have been sufficient to have revented hydrofracturing and the consequent venting of water and gas from the overburden aquifer into the base of the excavation.

There were no unusual vertical movements or evidence of basal heave. The stability calculations for the excavated trenches against basal heave showed that both trenches ranged from being marginally stable to marginally unstable (FS: 1.0 - 0.91). While no excessive basal heave occurred onsite, the low factor of safety was an indicator of the potential for hydrofracturing. The subsequent venting that occurred may have relieved the uplift pressure and thus prevented excessive basal heave.

The minimum required overburden thickness required to overcome the hydrostatic uplift pressure exerted by the aquifer depended on the excavated trench dimensions. For a factor of safety of 1.3 and a typical trench size of 35m x 35m, a minimum of 17.5m of overburden would be required between the base of the excavation and the bedrock aquifer even if the soil was not "gassy". Complying with the minimum overburden thickness limit, or limiting trench dimensions, as need to ensure an adequate factor of safety against basal heave is predicted to have been sufficient to prevent hydrofracturing and subsequently venting.

The presence of gas in bottom 6m of the clayey silt deposit was modelled using two approaches: a) decreasing the pore fluid bulk modulus; b) decreasing the soil skeleton Young's modulus. The analysis showed that an increase in pore fluid compressibility (pore fluid bulk modulus = 1,000 kPa) was conservative as it predicted hydrofracturing earlier than it actually occurred (i.e., at 21mBGL rather than 24mBGL) and suggested that the expected venting would be of intermittent nature (which was the case for some venting at sometimes). The analysis would give a better estimate to what actually occurred (i.e., hydrofracturing when the excavation reached elevation 24mBGL) if the pore fluid bulk modulus was greater than 10,000 kPa.

Modelling gassy soil by decreasing the Young's modulus below a threshold level (15000 kPa in this case) reduced the potential for hydrofracturing. Hence, it was concluded that gassy effect on the clayey silt does not necessarily mean an increase the hydrofracturing potential of the soil. This paper suggested that the potential of hydrofracturing through the soil can be better estimated if the values of different parameters (Young's modulus and pore fluid bulk modulus) are known.

Similar results were obtained with respect to gassy soil behaviour for both the 2D and 3D analyses. In both cases, hydrofracturing was predicted once the trench dimensions exceeded a threshold of between 10m and 20m in this case. Hence for projects involving a deep excavation in gassy soil, it is important to carefully examine the effect of both hydrofracturing and gassy soil behaviour in any assessment of stability and the likelihood of gas and water venting into the base of the excavation.

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9. NOTATION

γ : Unit weight
c' : Cohesion
Φ' : Friction angle
E' : Young's modulus
e_o : Void ratio
k : Hydraulic conductivity
K_o' : Coeffecient of lateral earth pressure at rest

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