

Soil Characterization of Deep Sea West African Clays: Is Biology a Source of Mechanical Strength?

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ABSTRACT

This paper considers the characterization of clay crusts in deep sea locations off the West African coast. The presence of high strength material at shallow penetration depths is confirmed through laboratory mini-ball penetration and Cam-shear testing. Visual logging of split-cores indicates invertebrate burrows are present within the crust. Fecal pellets, presumably from burrowing invertebrates, are also abundant within the cores. Results from initial Cam-shear tests comparing reconstituted sterile and bacterially-inoculated samples are presented. These tests indicate an inherent structure of natural sediments that is destroyed during reconstitution and sterilization; but no proof that bacteria are the cause of the crust has been observed.

KEY WORDS: Clay; shear strength; pipeline; fecal pellets; bacteria

INTRODUCTION

The mechanical properties of deep sea sediment in water depths of between 500m and greater than 2500m off the coast of West Africa (WA) are of interest to oil pipeline designers. Pipelines installed into these sediments undergo several hundreds of thermal cycles during operation and therefore an understanding of the soil-pipe coefficient of friction (μ) and the undrained shear strength (s_u) is required for design. A better understanding of the short and medium-term behavior of these sediments under hot-pipe loading is also required.

Penetrometer tests undertaken in offshore locations such as those shown in Figure 1 confirm the presence of ‘crusts’, below which s_u drops back onto the normally consolidated line following Skempton (1954) and shown modified in Equation 1.

$$s_u = \left(\frac{s_{u,nc}}{\sigma'_{v,0,nc}} \right) \times \gamma' \times d \quad (\text{Eq. 1})$$

$\left(\frac{s_{u,nc}}{\sigma'_{v,0,nc}} \right)$ is a material constant rising from 0.2 to about 0.5 with

increasing plasticity; γ' is the soil’s unit weight and ‘d’ is the depth below seafloor.

Experience also suggests a value of 0.5 for the high plasticity WA clays. Therefore, at 2.5m depth, normally consolidated clay may be expected to exhibit $s_u=3.1\text{kPa}$; which is confirmed by Figure 1. Within the crust, however, s_u may exceed 10kPa compared with an expected $s_u=1\text{kPa}$ for normally consolidated clay.

The origin of these crusts, and why they only occur within the top few meters of sediment is currently unknown. Furthermore, this phenomenon has been observed in several offshore oil and gas locations world-wide. The origin and mechanical behavior of deep ocean clay crust, allowing for any changes that must be anticipated during a pipeline’s working lifetime, is therefore a significant issue for pipeline designers.

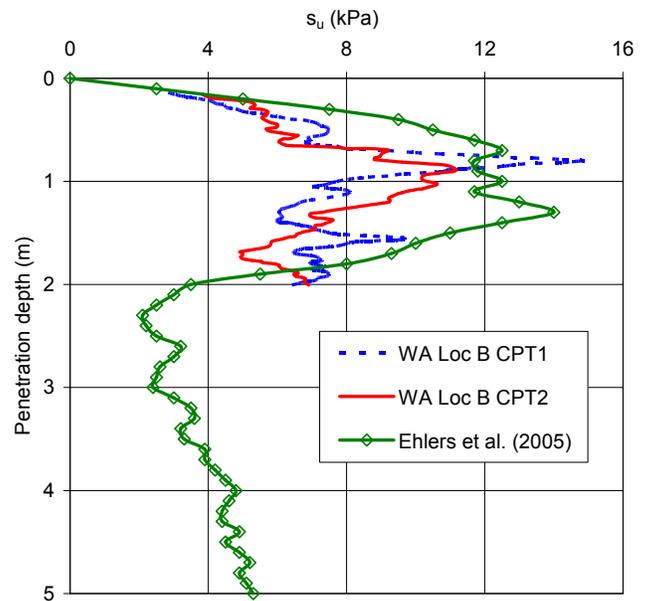


Fig. 1: In situ CPT profiles showing anomalously high strength ‘crust’ material at shallow depth (modified after Ehlers et al., 2005).

LITERATURE REVIEW

Previous Work on WA Clays

The sediments encountered in West African offshore sites represent a wide range of depositional environments. Based on laboratory test results on samples taken within the top two meters, Puech et al. (2005) demonstrate that these clays have very high water contents ($w=150\%$ to $w=250\%$) and very high plasticity ($PI=70$ to $PI=150$ at seabed), significantly higher than clays from the Gulf of Mexico.

Carbonate contents generally range between 5% and 15% of the total soil weight, in the form of crushed skeletons less than $30\mu\text{m}$, as shown by Puech et al. (2005). The total organic content of these sediments ranges between 2% and 6%, following Thomas et al. (2005).

Hypotheses for Crust Origin

Overconsolidation. Bennett et al. (1991) discuss the generation of 'crust' zones within the Mississippi Delta, defined on the basis of shear strength profiles with burial depth. Sharp decreases in shear strength are observed between depths of 8m and 14m, as described by Doyle et al. (1971). Bennett et al. (1991) suggest these are related to submarine slumping of soft, highly porous, deltaic sediments and the movement of massive amounts of sediment seaward on gentle slopes.

It has been suggested that at 1m depth, the age of the sediment is approximately 10,000 years. This equates to a relatively slow sedimentation rate of about 1 centimeter per 100 years. No known mass-movement has occurred that could have led to significant unloading of the sediment. Puech et al. (2005) suggests the uniformity of a high number of CPT profiles in the tested areas, indicate a region "unaffected by the presence of geohazards" (Puech et al., 2005 (p1051)). An overconsolidation, therefore, does not appear to be a realistic explanation for these West African crusts.

Bacterial Activity. If mechanical strength gain through overconsolidation is not the origin for the WA crust, another hypothesis may be the influence of biological activity within the clay. McCave (1984) proposed that "given the substantial bacterial populations of bottom sediments, binding by polymer bridging may be important in accounting for some of their cohesive properties". The formation of polymer bridges between bacteria and clay platelets may occur during their fall through the water column, as suggested by Turley et al. (1995). This action may possibly enhance aggregation of clay platelets at the seabed. Parkes et al. (2000) supports these observations by indicating that the top meter of marine sediment contains the highest population of bacteria.

Burrowing Invertebrates. Meadows and Tait (1989) show that the two species of burrowing invertebrates can individually increase the undrained shear strength of clay by about 1kPa after 24 hours. Their influence on sediment permeability varied, however, with one species increasing and the other decreasing the permeability. Murray et al. (2002) suggests in instances of increased permeability, invertebrate burrows may be accelerating pore water dissipation and 'shear strength development'.

Meadows et al. (2000) presents undrained shear strength measurements from the Oman continental slope and abyssal plain, in the Arabian Sea. The rate of increase of strength with depth is greater below the zone of influence of burrowing invertebrates (between 0.02 and 0.1m below the sediment-water interface). Shear strengths of up to 20kPa were measured at a depth of approximately 0.3m depth. No information is given regarding the previous geological history and therefore the results

do not provide a conclusive relationship between the presences of burrowing invertebrates and shear strength.

METHODOLOGY

Previous investigations of WA crusts have included in situ cone and T-bar penetration tests. The current investigation has supplemented the previous information with the collection of additional box and piston cores. A mini T-bar was used to measure the undrained shear strength of the box-cores immediately after sample recovery out on the boat.

Laboratory characterization of the shear strength was undertaken using a mini hand-vane and a mini-ball penetrometer and Cam-shear testing. Geological logging and examination using a scanning electron microscope of the samples were also completed.

Ball Penetrometer Tests

A mini-ball penetrometer ($D=25.4\text{mm}$) was used to measure the undrained shear strength of two undisturbed core samples (87mm diameter) from West Africa by pushing through the centre of the cores at 2cm/s (see Figure 2). Yafate and DeJong (2005) and Randolph (2004) suggest that remolding occurs within 1 to 2 ball diameters. The remolded zone around a ball penetrometer is therefore approximately 2.5D and thus, boundary effects caused by the core liner (greater than 3D) are unlikely to influence the results. 10 cycles (push-in; pull-out) were undertaken on both cores to obtain the remolded strength. To avoid excessive mixing with supernatant water, ball cycles were not carried out within 1.5D of the surface. Figure 2 shows that a 'core' of mud on top of the ball was removed at the end of the cyclic test.



Fig. 2: Mini-ball penetrometer testing in undisturbed core samples and hole caused by sample removal after cyclic testing.

Cam-Shear Tests

The Cam-shear device (Figure 3) allows the simulation of axial pipe-soil interaction behavior by dragging a small sample of clay with relatively low undrained shear strength over a flat sheet of pipe coating material such as polypropylene. Different pipe roughness values can be tested. The shear strength of clays at the seabed usually varies from 0.5 to 5 kPa. Due to the relatively large internal friction generated by the self-weight of moving parts, these strengths lie below the reliable range of conventional shearing devices. Therefore, by using a low-friction PTFE 'box' to retain the clay, the Cam-shear device allows 75mm diameter; 40mm thick samples to be sheared at either the soil-coating interface or on a split-plane (see Figure 3). It can be seen that the vertical load tilts forwards during internal shearing of the very soft clay; however, this would not influence a simple analysis of average shear stress on the horizontal plane.

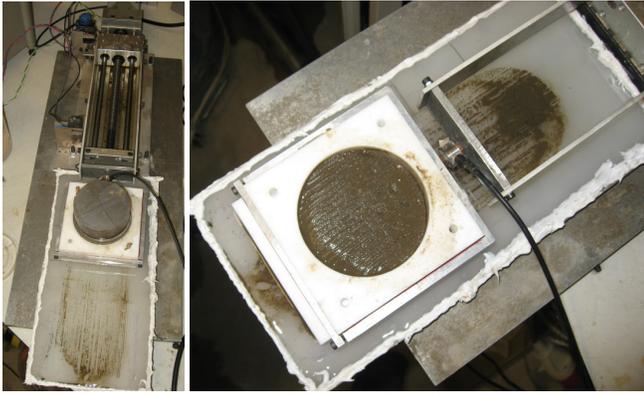


Fig. 3: Cam-shear apparatus during testing showing PTFE shear box and polypropylene pipeline coating material.

Two undisturbed box-core tube samples were tested from depths of 0.04m and 0.2m. The undisturbed samples extruded from the core liners and trimmed using a stainless-steel cutter of 75mm diameter. The trimmed samples were then extruded into the Cam-shear box and the shearing interface trimmed using a cheese-wire. The box is then placed on the pipe coating material and the bottom half of the box sealed with a silicon sealant. This allows single upwards drainage during consolidation under a prescribed pipe weight prior to shearing. The pipe stresses used were 2kPa for the 0.04m sample and 4kPa for the 0.2m sample.

In addition, reconstituted clay slurries were sterilized by autoclaving at 121°C for 20 minutes. One sterilized slurry was inoculated with seawater agar liquid media containing *Marinobacter aquaeolei* which had been incubated at 30°C for 3 days. The same volume of sterile seawater agar liquid media was added to the second sterilized slurry to act as a control. Both samples were thoroughly mixed in sterile conditions. Both samples were placed into Cam-shear boxes and consolidated under a normal vertical stress of 2kPa.

Soil-coating interface tests were undertaken at 0.5mm/s ('fast'), 0.05mm/s ('normal') and 0.005mm/s ('slow') shear rates and internal split-plane tests were undertaken at 0.05mm/s.

Logging of Core Samples

Both box-core and piston-cores were logged using a Multi-Sensor Core Logger (MSCL) at the National Oceanography Centre, Southampton, UK. This allowed non-invasive measurements of P-wave velocity, bulk density, and porosity to be determined. Cores were then split, visually logged and photographed prior to sub-sampling for further laboratory testing.

Scanning Electron Microscopy (SEM)

SEM work was conducted using a Leica Stereoscan 430 at the Cambridge University Engineering Department. To allow imaging of un-smeared surfaces, sub-samples were collected at 10cm intervals by making sharpened aluminum tubes with 2mm internal diameter. These were then oven-dried and then fractured to create a fresh surface. Environmental SEM imaging was also undertaken on samples at similar depths; however, as moist samples were used, the results were not as clear as the SEM images.

RESULTS and DISCUSSION

Mini-Ball Penetrometer Tests

Figure 4a shows undrained shear strengths obtained using the mini-ball penetrometer in cores taken at two locations ('A' and 'B'), compared with mini T-bar tests undertaken within the same box-core samples, shortly after extraction. The following observations may be made of Figure 4a:

1. All tests show s_u rising to about 10kPa \pm 3kPa at 0.25m; representing 'crust';
2. Laboratory ball tests generally give higher s_u values than T-bar tests that were undertaken on-ship and in the same box-cores.

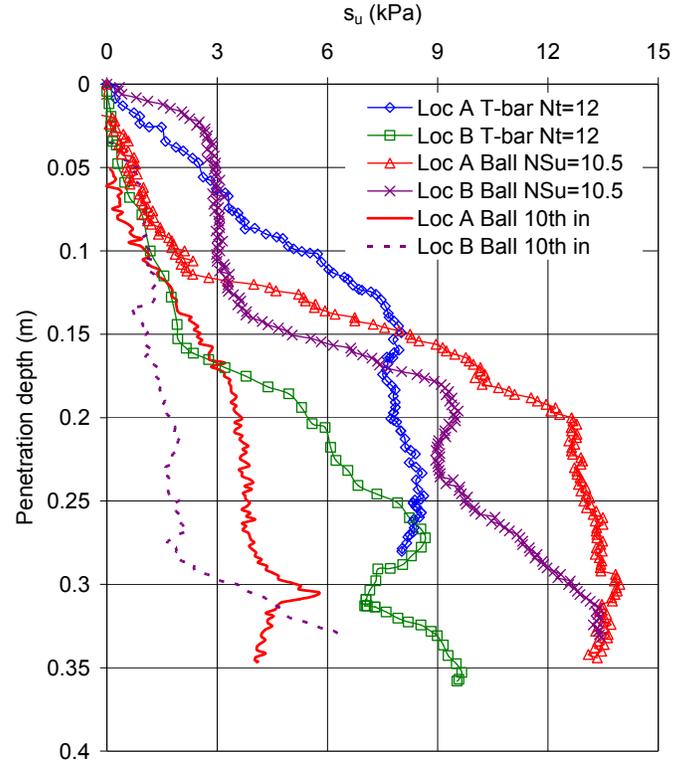


Fig. 4a: 'First in' and 'last in' mini-ball penetrometer and T-bar tests for location 'A' and 'B' samples.

The sensitivities of both core samples are shown in Figure 4b. Sensitivity (S_r) was determined by the ratio of penetration resistance of the first push/last push after 10 cycles. The sensitivity of location 'B' is relatively large at $S_r=6$. Previous in situ T-bars undertaken in location 'A' indicated sensitivity ranging between $S_r=1$ and $S_r=3$ (Figure 4b). Puech (2005) measured sensitivities of $S_r=2$ to $S_r=3$ in similar material. The measured liquid and plastic limits for sample 'B' at depths of 0.25m and 0.35m depth are $w_L=178\%$ (fall cone test) and $w_p=55\%$; with initial water contents of 214% and 201%, respectively.

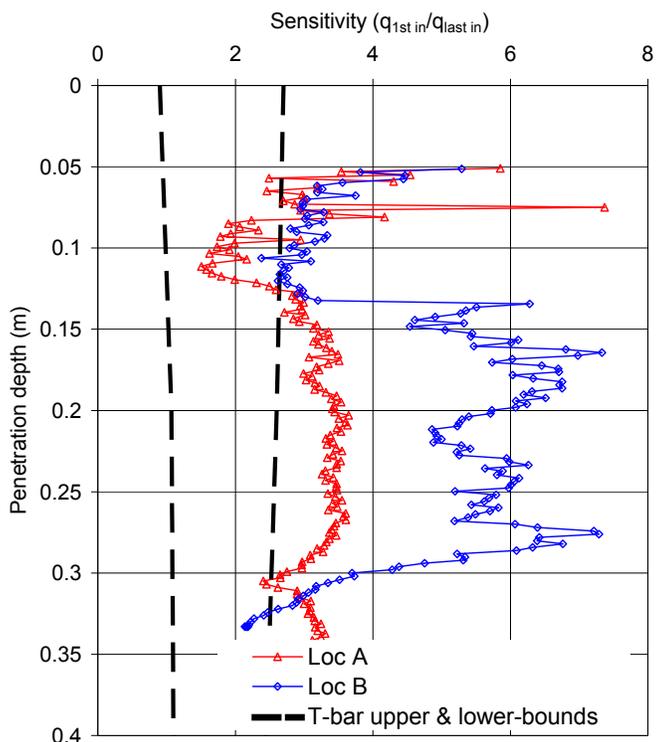


Fig. 4b: Sensitivity values for mini-ball penetrometer tests and upper and lower bound limits for T-bar tests for location 'A' and 'B' samples.

Cam-shear Tests

In what follows, the measured shear stress τ is normalized by the pre-existing normal effective stress $\sigma'_{v,0}$, which is numerically equal to the total normal stress σ_v during the shear test. These values of $\frac{\tau}{\sigma'_{v,0}}$

given the symbol μ , and relate to the 'consolidated-undrained' strength of the soil at the interface. It is important to understand that this will not generally equal the coefficient of friction μ' based on *current* effective stresses. Nevertheless, this is one of the parameters required by pipeline designers who need to estimate the resistance to axial displacement of a pipeline that is suddenly caused to move.

Cam-shear tests of a location 'A' sample from 0.2m depth; and therefore representing crust material exhibited initial and final (after test) water contents of $w=199\%$ and $w=186\%$. The total normal pipe stress applied was 4kPa. Three interface tests at 0.5, 0.05 and 0.005mm/s and one internal strength test at 0.05mm/s were conducted. The following general observations were made from these tests:

1. A high $\mu = \frac{\tau}{\sigma'_{v,0}}$ of greater than 1 was measured; corresponding to $\phi'_\mu > 50^\circ$ on a smooth pipe coating;
2. Positive pore pressures caused μ to drop by about half per log cycle of shearing-rate, resulting in μ_{res} about 0.2 for the 0.5mm/s rate;
3. Soil-soil μ^* peaked at greater than 1 before (presumably) generating positive pore pressures and resulting in $\mu^* \approx \mu$ about half of μ^* at same the shearing rate;
4. Peak s_u values were about 4.5kPa.

Initial μ_{max} is due to excess pore pressures induced during undrained shearing and subsequent decreases to μ_{res} due to rearrangement or

destructuring of the clay fabric inducing positive pore pressures at the sheared zone. The drained test (0.005mm/s) did not show an initial μ_{max} which may be due to an initial undrained response in the sample. No reduction with large shear displacement to μ_{res} due to 'residual polishing' was observed.

The sample tested at location 'A'; 0.04m depth, represented ooze previously mentioned in the ball penetrometer results with extremely high initial and final water contents of $w=273\%$ and $w=246\%$. This sample was consolidated under a total normal pipe stress of 2kPa. The following are general observations were made:

1. $\mu \approx \mu^*$ about 1 which was similar to the 0.2m depth test; however, in this case, corresponding to a much smaller $s_u \approx 1.5\text{kPa}$ and smaller σ'_v ;
2. μ tended to increase as shear rate increased: which was a completely different behavior to that observed in the 0.2m depth test;
3. Peak s_u values were about 2kPa.

Figures 5a~5b show the Cam-shear results for a reconstituted, consolidated sterile (control) sample and a reconstituted, consolidated bacterially-inoculated sample.

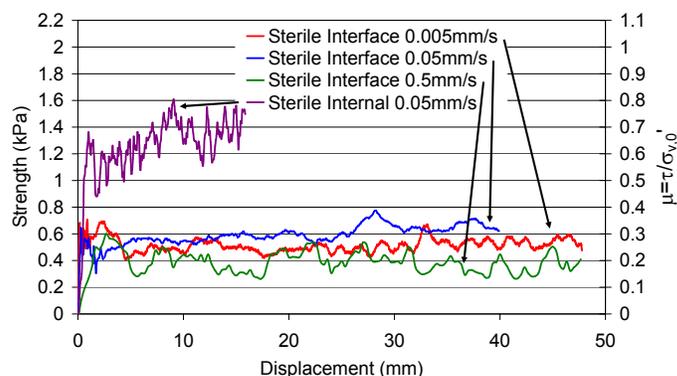


Fig. 5a: Cam-shear test results for reconstituted sterile sample; $\sigma'_{v,0}=2\text{kPa}$.

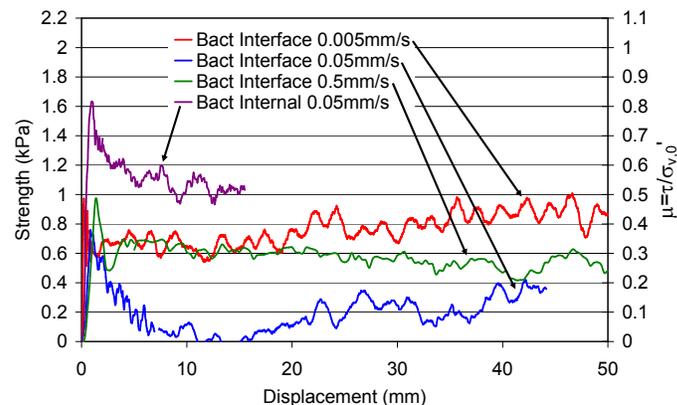


Fig. 5b: Cam-shear test results for reconstituted, bacterially-inoculated sample; $\sigma'_{v,0}=2\text{kPa}$.

The reconstituted sterile sample shown in Figure 5a has a water content of 175% which is significantly smaller than the natural sample tested in Figure 5b; and presumably lacks the 'structure' present in the natural sediment. This results in $\mu \approx 0.3$; about 60% of the value observed for the natural sediment and μ^* of about 0.7. Shearing rate does not influence the value of μ .

Figure 5b has water content similar to Figure 5a; with the following observations:

1. $\mu^*_{max} = 0.8$ reducing to $\mu^*_{res} = 0.5$;
2. μ of approximately 0.35;
3. Shearing rate erratically reduces μ .

The following can be concluded from the Cam-shear testing:

1. Compared with ball and T-bar penetration testing, Cam-shear s_u values are similar above the crust (about 2kPa) and about half (about 4.5kPa) within the crust;
2. μ values do not reveal significant differences between crust and 'no' crust material;
3. $\mu^*_{natural} > \mu^*_{reconstituted}$;
4. Shearing rate has a variable influence on the different sediments tested; presumably different sediment structure and sample preparation can lead to different pore pressure responses during testing.

Logging of Core Samples

Results of MSCL tests are shown in Figure 6. The aim of these tests was to identify whether the anomalously high undrained shear strengths could be linked with other sediment physical properties, and therefore to provide further information on their possible origin. The results show that the increase in s_u does not coincide with noticeable changes in any property logged with the MSCL. The increased scatter in the bulk density and porosity results between 0.6m and 1.1m depth are due to sample disturbance at the base and top of the core sections.

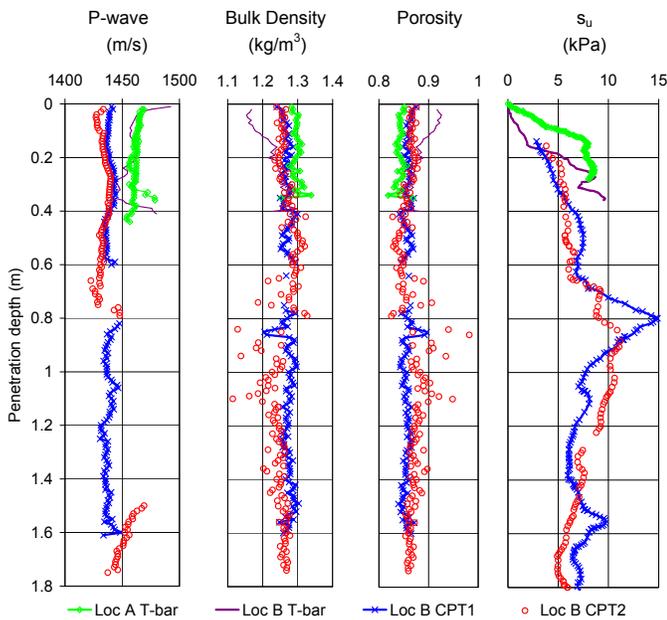


Fig. 6: MSCL P-wave, bulk density, and porosity compared with s_u .

Two piston core samples of 1.8m length from location 'B' were split for visual logging. Sections of core photographs are presented in Figure 7. These show, as expected, oxidation (pale brown) has occurred at the ends and along edges of the cores. However, oxidation is also observed at the centre of the cores between depths 0.7 and 1.2m, which may indicate the presence of open invertebrate burrows allowing air to enter the sample. Furthermore, large (up to 14mm diameter) open burrows are also observed in these sections. When compared with in situ CPTs undertaken prior to sampling, the presence of the open burrows appears to coincide with the zone of increased undrained shear strength.

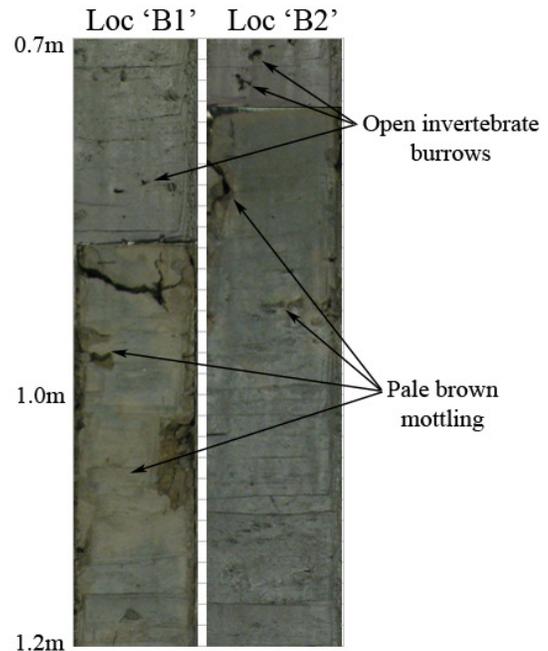


Fig. 7: Sections of core photographs from location 'B' showing large open burrows and associated mottling.

Both box-core and piston-core samples demonstrate the presence of abundant fecal pellets, most likely sourced from benthic invertebrates. These pellets (Figure 8) range from 0.5x1mm to 2x4mm in size, and prior to sample disturbance, appear to be the sole structural matrix of large pockets of sampled sediment. The fecal pellets do not exhibit a preferential orientation and are encased by mucus, likely to be produced by the burrowing invertebrates. Between 0.1m and 0.4m, some core samples consist of up to 60% pelletized sediment crossed with thin, (0.7 to 1.5mm) branching burrows. Hot pipelines are generally installed to a comparable embedment depth and therefore, during their operational lifetime, are in direct contact with the pelletized sediment.



Fig. 8: Location 'B' sample showing fecal pellets of several sizes within crust.

The variance in pellet size and burrows may suggest that numerous invertebrate species have occupied the sediment at different times. In the limited core material, however, there was no visual evidence of open burrows connecting the pellets to the seafloor, and no invertebrate species were visually identified.

Lopez and Levinton (1987) show that sediment that has been ingested by some invertebrate species will be expelled as compacted fecal pellets that are orders of magnitude larger than the ingested particles. These pellets may contain significantly larger numbers of bacteria than the surrounding environment. Hargrave (1976) suggests the increased bacterial activity may be the result of selectively feeding on particular sized particles. In shallower waters, the capitellid worm (polychaeta class) “repackages fine sediment into large, robust pellets” (Horn and Taghon, 1999, p42). Gallagher and Keay (1998) suggest that such pellets may remain ‘packaged’ for a half-life between 5 and 33 years.

Mucus and/or polysaccharides produced by the gut of invertebrates and bacteria are amorphous and relatively insoluble in water. Their presence may therefore result in decreased soil permeability and allow fecal pellets to maintain negative pore pressures once expelled by the invertebrate. This could contribute to the apparent strengthening of the sediment resulting in a crust.

Fecal pellets, however, eventually disintegrate into their component parts by mechanical abrasion and the decomposition of “the various mucus glues and other pellicles that bind pellets” (Lopez and Levinton, 1987, p247) by microbial activity. Presumably, the fecal pellets observed in Figure 8 are very recent in comparison to the age of the sediment itself, and would not have experienced mechanical abrasion. Either self-weight compression or bacterial decomposition could explain the absence of fecal pellets in deeper samples, and hypothetically, the loss of crustal strength.

SEM Imaging

Typical SEM images are shown in Figure 9 following the methodology outlined previously.

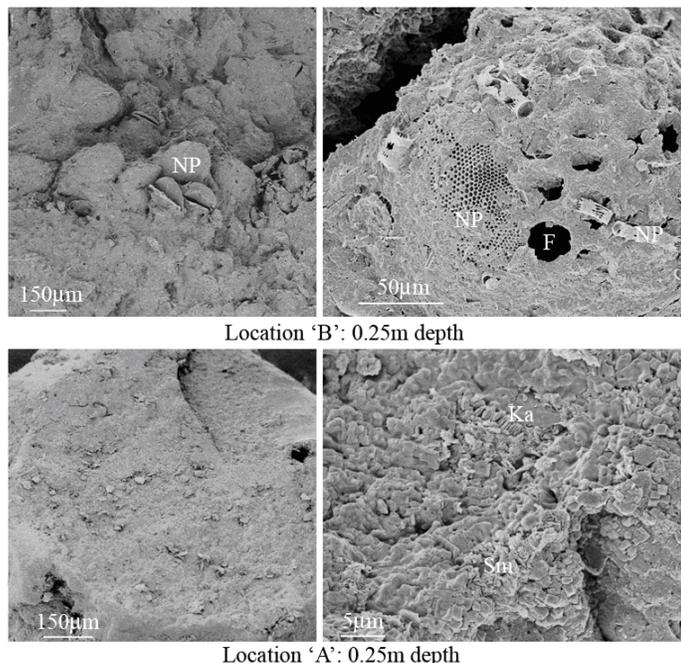


Fig. 9: SEM images of location ‘A’ and ‘B’ samples showing nano-plakton (NP), foraminifera (F); and smectite (Sm) and kaolin (Ka)

These images show that the location ‘B’ sample contains a significant amount of detritus material including nanoplakton (e.g. diatoms) and foraminifera. The location ‘A’ sample predominantly comprises clay aggregates of smectite and kaolin. A comparison of penetration tests (Figure 4a) suggest that the undrained shear strength of location ‘B’ (containing more detritus material) is lower than that of location ‘A’.

CONCLUSIONS

The following points summarize the present findings:

1. The presence of the crust has been confirmed through penetrometer and Cam-shear testing; with $S_u \approx 10.S_{u_{nc}}$.
2. Abundant mucus-covered fecal pellets are present within the crust suggesting that high bacteria numbers may also be present.
3. Natural clay behaves differently to reconstituted and sterile clay as observed from μ values.
4. The WA clay is sensitive to disturbance so the discrepancy between T-bar and ball s_u measurements may be due to positive excess pore pressures still present when onboard T-bar tests were conducted.
5. Cam-shear tests indicate μ has a very erratic response to variation in shear rate; and no proof is yet forthcoming that bacteria were the cause of the crust.
6. Further sampling and testing of natural sediment for strength and consolidation characteristics after periods of heating to model a hot-pipe is required.
7. Further testing of sterile, bacterial and bioturbated / pelletized samples are required.

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