# Geotechnical Behaviour of Annapolis Basin Intertidal Sediments

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# Abstract

Intertidal fine-grained sediments from within Thorne Cove, Annapolis Basin appear to possess unusually high shear strengths over the uppermost 50 cm. This indicates that those sediments are overconsolidated compared to present in situ stresses. The origin of this unusual behaviour is not well understood at present and requires further investigation.

## Introduction

The purpose of this study was to assess the in situ physical properties of the superficial intertidal sediments within a specific site (Thorne Cove) in Annapolis Basin to provide an insight into the potential for behaviour modification by normal intertidal processes. Undrained shear strengths measured were overall much higher than would be expected for a normally consolidated sediment of this lithology and it is concluded that the sediment profile is overconsolidated to the depth of investigation, possibly due to the loads imposed by the grounding of winter pack ice.

## Methodology

To determine the present state of stress within the sediment, some basic engineering parameters must be measured. The saturated unit weight $\gamma_s$ of the sediment is required to calculate the total stress, from which the in situ pore pressure is deducted to obtain the effective stress, which corresponds to the net force per unit area transmitted through inter-particle contacts within the sediment mass. This parameter is often referred to as the effective overburden pressure $\mathbf{P'_o}$.

Saturated unit weight is computed from the saturated bulk density $\rho_s$ by multipying it by the gravitational constant **g** (9.81 m/sec$^2$). Unit weights are used to directly calculate the effective stress because they are an expression of the gravitational force within the sediment deposit. Stress is simply the force exterted divided by the area over which it acts. The equation to calculate $\mathbf{P_o'}$ is:

$$P_o' = \gamma_s * Z - u_o \tag{1}$$

where $\gamma_s = \rho_s * \mathbf{g}$, $\mathbf{u_o}$ is in situ pore water pressure, and **Z** is the depth below the mudline. Therefore we can say that

$$P'_o = \gamma_s * Z - \gamma_w * Z \tag{2}$$

If we define the bouyant or effective unit weight $\gamma'$ as the difference between the saturated unit weight of sediment $\gamma_s$ and the unit weight of water $\gamma_w$ then equation (2) reduces to

$$P'_o = \gamma' * Z \qquad (3)$$

The effective vertical stress $\mathbf{P_o'}$ is directly comparable to the preconsolidation pressure $\mathbf{P_c'}$, which is a direct measure of the maximum effective vertical stress imposed on the sediment column during its geologic history. The ratio of the preconsolidation pressure to the overburden pressure is defined as the overconsoidation ratio **OCR**. When **OCR** falls between 0.8 and 1.2 the sediment is said to be normally consolidated and has not been preconsolidated under load in the past in excess of the present gravitational load exerted by the overlying sediments. If **OCR** exceeds 1.2 we say that the material is preconsolidated or overconsolidated (Lambe and Whitman, 1969). **OCR** values below 0.8 indicate that pore pressures within the sediment mass have not fully dissipated to a free-draining boundary and consolidation is incomplete.

Direct measurement of the preconsolidation pressure is difficult to impossible in very soft sediments and was not attempted in this study. In the absence of direct measurement of preconsolidation pressure, indirect techniques are available that adequately predict **OCR** based on knowledge of the intact or in situ peak undrained shear strength $\mathbf{S_u}$. This approach was developed by Ladd and Foott (1974) (**SHANSEP**) and its applicability will be discussed later.

It was felt that a drawdown of the water table might occur while the sediments drained as the flat was exposed, resulting in a net increase in the effective stress. This increase occuring on a diurnal basis could cause a preconsolidation effect. Therefore, suction probes capable of detecting a drawdown in pore pressure from 0 to 100 kPa were installed during ebb tide and recovered at flood tide.

A number of techniques are available for determining the in situ undrained shear strength profile, many of then requiring that an undisturbed sample be collected and transported to a geotechnical laboratory for analysis. A better alternative in the case of very soft sediments is to perform tests in situ by inserting an appropraite probe to the test depth and then shear the sediment quickly to cause an undrained failure. This is easily done with the Pilcon vane which can be conveniently fitted with a long set of extension rods which allow the measurement of strength at a number of levels in the sediment profile.

The cone penetrometer test (CPT) fails the sediment in front of the tip as it is pushed into the ground, and records a continuous record of sediment resistance measured with a small load cell, which is then analysed to yield a profile of undrained strength. A miniature CPT apparatus was developed at the Atlantic Geoscience Centre in association with the University of British Columbia (Parrott et al., 1987).

The CPT was modified for manual insertion for use on intertidal mudflats, utilizing the weight of the operator as a reaction. The electronics package was upgraded to aquire strength data at 2 cm depth intervals and is capable of measuring undrained strengths from 0 to 200 kPa, which is equivalent to a reaction force ranging up to 150 pounds. The tip sensor can resolve shear strength to within 1 kPa. An onboard 8-bit analog to digital converter converts the analogue signal from the cone into digital data for storage on a microcomputer. Data is transmitted through an RS-232 interface and is displayed on the screen during the test.

Subsamples were also obtained for later analysis in the laboratory to determine the classification parameters of the sediment (Atterberg Limits, specific gravity, and grain size distribution). A small piston subsampler was used to take constant-volume samples from the side of the test pit at each study site. Since the volume of the sample was predetermined, it was a simple matter to later record the weight of the saturated sample and then calculate the bulk density. The natural water content was determined by then drying the subsample in an oven at 110 degrees C for 24 hours and dividing the mass of water by the mass of solids

$$w_n = M_w/M_s \qquad (4)$$

Assuming a salinity of the pore water of 35 ppt. the corrected fluid content can be calculated as suggested by Noorany (1984) whereby

$$w_n = \frac{w_n}{1 - r - r*w_n} \qquad (5)$$

where **r** is salinity in decimal form.

### Observations

Three sample locations were selected along a transect perpendicular to the shoreline near Thorne Cove beginning immediately offshore from the zone where sands directly overlie boulders and ending at the low intertidal zone (Figure 1). An intermediate site was chosen nearby the site in Thorne Cove where the Sea Carousel was deployed. The sample sites were numbered from TC-2 to TC-4 from high to low water.

TC-1 was located at the same location as TC-3 and was tested at 2000 hrs. on May 12 using both the Pilcon Vane and the cone penetrometer. Suction pressure probes were installed as the tide ebbed and registered immediately the state of porewater drawdown within the sediment. These were removed as the tide covered the sites again. Density and fluid content subsamples were obtained by excavating a test pit.

The following day, sites TC-2 to TC-4 were tested and subsampled. Grain size and Atterberg Limits subsamples were obtained. Table 1 lists the site, depth interval below the mudline, an the type of sample taken.

Table 1. Summary of subsamples from Thorne Cove.

| Site | Z (cm) | $w_n$ (%) | $\rho_s$ (g/cm$^3$) | Grain Size | Atterberg Limits | Comments |
|---|---|---|---|---|---|---|
| TC-1 | 7 | 48.3 | -- | -- | -- | EBB TIDE |
| | 14 | 35.3 | 1.612 | -- | -- | EBB TIDE |
| TC-2 | 7 | 26.0 | 1.868 | -- | -- | EBB TIDE |
| | 24 | 35.9 | 1.841 | -- | -- | EBB TIDE |
| | 35 | 50.4 | 1.719 | -- | -- | EBB TIDE |
| TC-3 | 0 | 74.0 | 1.546 | -- | -- | EBB TIDE |
| | 1 | 72.5 | 1.532 | -- | -- | EBB TIDE |
| | 5 | 41.0 | 1.528 | -- | -- | EBB TIDE |
| | 10 | 42.3 | 1.762 | -- | -- | EBB TIDE |
| | 20 | 31.2 | 1.899 | -- | -- | EBB TIDE |
| | 25 | 36.3 | -- | -- | -- | EBB TIDE |
| TC-4 | 1 | 35.1 | 1.701 | -- | -- | EBB TIDE |
| TC-2 | 1 | 27.4 | 1.944 | -- | -- | FLOOD TIDE |
| TC-3 | 1 | 49.2 | 1.664 | -- | -- | FLOOD TIDE |
| TC-4 | 1 | 45.2 | 1.749 | -- | -- | FLOOD TIDE |
| TC-1 | 10 | -- | -- | Y | Y | EBB TIDE |
| TC-2 | 0-6 | -- | -- | Y | - | EBB TIDE |
| TC-2 | 24-30 | -- | -- | Y | Y | EBB TIDE |
| TC-3 | 0-1 | -- | -- | Y | Y | EBB TIDE |
| TC-3 | 0-5 | -- | -- | Y | Y | EBB TIDE |
| TC-3 | 15-20 | -- | -- | Y | Y | EBB TIDE |
| TC-3 | 20-25 | -- | -- | Y | Y | EBB TIDE |

A summary of in situ testing is given in Table 2. Note that cone penetrometer tests were only carried out at TC-1 but that this site corresponds to TC-3 which was sampled and tested the following day.

Table 2. Summary of in situ tests at Thorne Cove.

| Site | Z (cm) | $u_o$ (kPa) | $S_u$ (kPa) | CPT |
|---|---|---|---|---|
| TC-1 | 14 | 0 | -- | -- |
| | 23 | 0 | -- | -- |
| TC-2 | 9 | 0 | -- | -- |
| | 29 | 0 | -- | -- |
| TC-3 | 18 | -1 | -- | -- |
| | 38 | -2 | -- | -- |
| TC-4 | 18 | -2 | -- | -- |
| | 38 | -1 | -- | -- |
| TC-1 | 8 | -- | 9 | -- |
| | 14 | -- | 18 | -- |
| TC-2 | 5 | -- | 3 | -- |
| | 10 | -- | 14 | -- |
| | 15 | -- | 20 | -- |
| | 20 | -- | 34 | -- |
| | 25 | -- | 15 | -- |
| | 30 | -- | 18 | -- |
| TC-3 | 5 | -- | 2,3 | -- |
| | 10 | -- | 12,12 | -- |
| | 15 | -- | 22,19 | -- |
| | 20 | -- | 27,18 | -- |
| | 25 | -- | 16,19 | -- |
| | 30 | -- | 32,18 | -- |
| | 35 | -- | 21,16 | -- |
| | 40 | -- | 16,15 | -- |
| | 45 | -- | 11,15 | -- |
| | 50 | -- | 16,11 | -- |
| | 55 | -- | 17,14 | -- |
| | 60 | -- | 16,13 | -- |
| | 65 | -- | 14,13 | -- |
| | 70 | -- | 16,13 | -- |
| TC-4 | 5 | -- | 3,5 | -- |
| | 10 | -- | 18,17 | -- |
| | 15 | -- | 24,18 | -- |
| | 20 | -- | 24,30 | -- |
| | 25 | -- | 25 | -- |
| | 30 | -- | 20,16 | -- |
| | 35 | -- | 14,18 | -- |
| | 40 | -- | 13,19 | -- |
| | 45 | -- | 15,17 | -- |
| | 50 | -- | 15,16 | -- |
| | 55 | -- | 17,19 | -- |
| | 60 | -- | 16,19 | -- |
| | 65 | -- | 15,17 | -- |
| | 70 | -- | 19,16 | -- |
| TC-1 | 0-48 | -- | -- | Y |
| | 0-50 | -- | -- | Y |
| | 0-50 | -- | -- | Y |

## Discussion

Fluid contents $\mathbf{w_n}$ and bulk density data $\rho_s$ are shown in profile form in Figure 2 for all sites. Notice that there is a general reduction in fluid content from a maximum of about 80 percent in the vicinity of the mudline to a minimum of 35 percent at 20 cm depth, after which it increases again. Without grain size and plasticity data, it is not possible to rule out varying texture as a possible explanation for this behaviour.

Wave activity can affect the density of the uppermost sediment which often exists as a fluid suspension rather than a coherent sediment mass that is capable of transmitting shear stress and is therefore much more mobile. The existence of relict buried shell agglomerations at Thorne Cove enhances the stability of the mudflat and may directly affect the shear strengths reported in this note. For this reason, a portion of the strength data has been ignored (higher peaks) and a general trend has been fitted to the data in Figure 2 that is believed to represent the best estimate of the intact undrained shear strength. This best-fit line corresponds to a ratio in $\mathbf{S_u/P'_o}$ equal to 3.4 kPa per meter. A normally consolidated sediment profile possesses a ratio of 0.25 (Skempton, 1970); therefore it was concluded that this deposit was overconsolidated and was more stable than a freshly deposited sedimentary clay sequence.

A technique of relating undrained shear strength to stress history (**SHANSEP**) has been developed by Ladd and Foott (1974) and is useful in cases where stress history data is not directly available. Application of **SHANSEP** in this environment is based on undrained strength data produced by the cone pentrometer, coupled with an effective stress profile derived from equation (3) which makes use of the bulk density data collected from test pits and listed in Table 1.

Predicted values of **OCR** are very high (typically over 100) and therefore preconsolidation pressures are similarly high (typically 50 to 100 kPa). This supports the previous observation that the sediments at the surface of the mudflat are overconsolidated to a high degree relative to the present overburden stress.

The actual magnitude of the preconsolidation pressure are so high that they shed doubt on the accuracy of the **SHANSEP** technique at such low working stresses. Generally, **Su/P'** ratios exceeding 10 have not been widely observed, however they occur frequently in the marine setting close to the mudline where effective stresses are very low. Since the SHANSEP database is largely based on terrestrial clays tested at relatively high stress, we may have encountered a limitation in its application.

## Conclusions

The assessment of the stability of a mudflat is a complex problem that involves the sediment bulk properties, the stress history, and the environmental loading processes, all of which affect the available shearing resistance. It is not the purpose of this study to investigate the interrelationships between these factors, rather to undertake an initial assessment of the present-day profile of bulk properties at one selected site within a large estuarine system. The observations made herein are preliminary and are subject to revision since they represent the relatively small scale of the field investigation.

One can arrive at some tentative conclusions about the Thorne Cove superficial sediments as they presently exist in the Annapolis Basin system. The clays are preconsolidated based on undrained strength observations. This is supported by a high ratio of undrained shear strength to vertical effective stress as compared to reported ratios for normally consolidated clays.

Other processes that could give rise to such a high level of shearing resistance might be loading by grounded winter ice, cyclic wave loading, cyclic dessication, and biological reworking. The actual origin of this phenomenon at Thorne Cove cannot be ascertained without further detailed study relating the physical behaviour of the sediments to the global environmental processes and establishing a more definitive cause-and-effect relationship.

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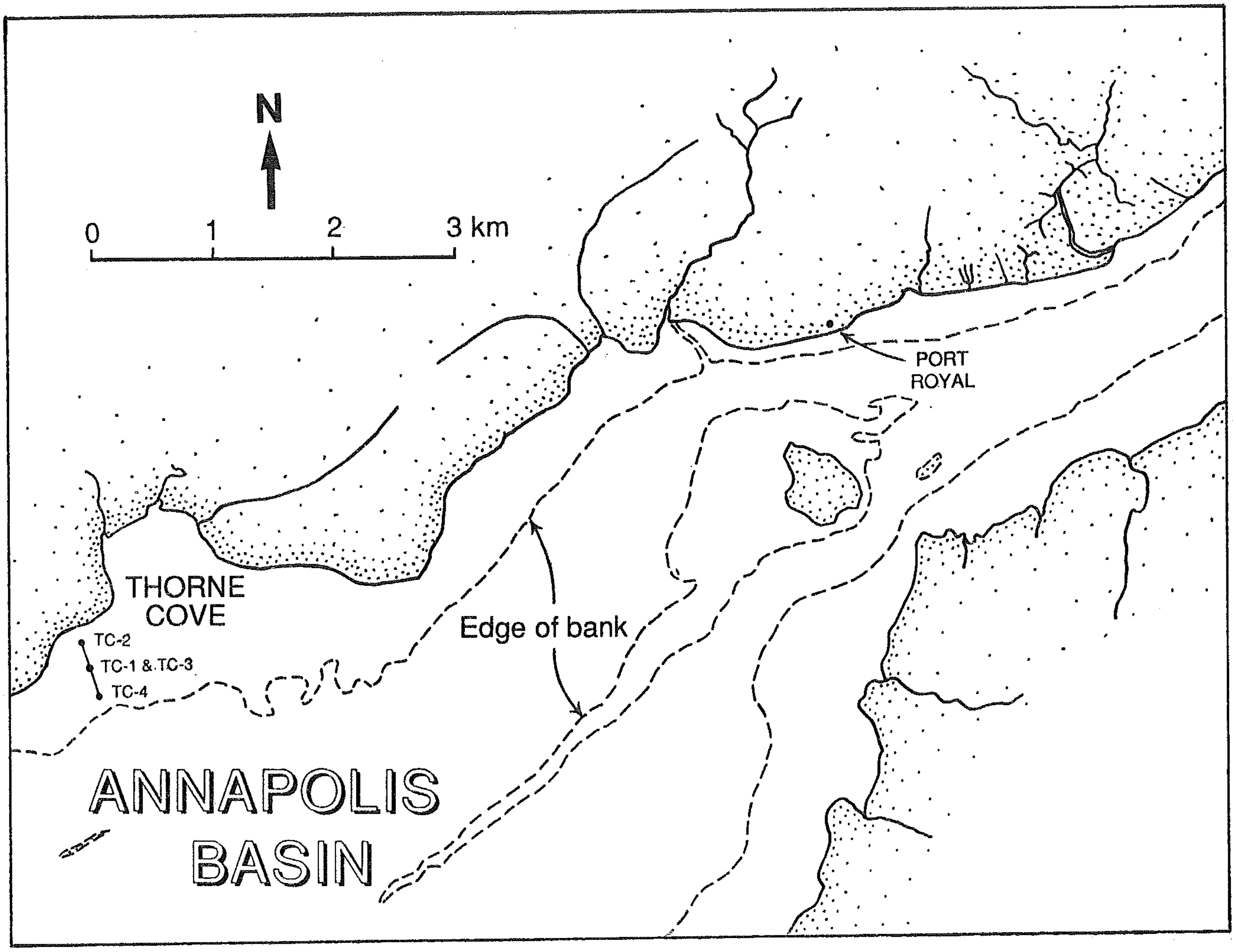

Figure 1. Map of Annapolis Basin illustrating the location of the sample sites in Thorne Cove.

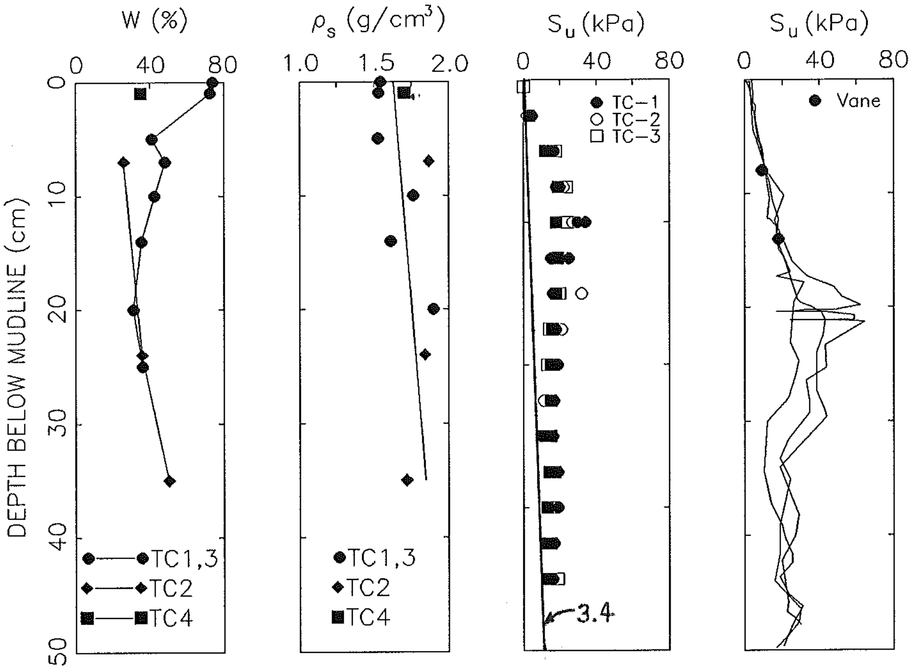

Figure 2. Profile of geotechnical properties from Thorne Cove. **Right**-hand undrained strength data comes from cone penetration and vane tests conducted at the site at the mid-tide level while the **left**-hand profile summarizes the results from Pilcon vane testing at three sites from high to low water.