# SOME APPLICATIONS OF MARINE GEOTECHNICS

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**Summary**
This paper summarises new research initiated by the Marine Geotechnics Working Group (MGWG) of the International Geological Correlation Programme (IGCP) project no. 396 Continental Shelves in the Quaternary. This research has included microfabric analysis of sediments, development of image analysis methods, high-resolution stratigraphy using moisture content and related methods, and the use of geotechnical methods to deconvolute sediments for self-weight consolidation. These topics are summarised in this paper.

**Introduction**
The MGWG of IGCP-396 has been prominent in identifying new areas of research in the study of sediments on the continental shelves. These areas of the world are of increasing importance for many reasons such as: i) the reclamation of land for new airports such as Kansai (where post-constructional settlements amounted to 1mm per day) and Hong Kong; ii) the exploitation of hydrocarbon and other resources; and iii) the scientific study of the sediments as a guide to past climatic change. Topics of importance have included:

i. microfabric methods to study detailed stratigraphy particularly during the Holocene and last glacial maximum periods;
ii. detailed stratigraphic analysis using high resolution moisture content analysis;
iii. image analysis methods for high resolution borehole logging;
iv. application of geotechnical methods to deconvolute sediment column to allow for self-weight consolidation and thereby obtain true sedimentation rates.

Marine Quaternary deposits on the inner continental shelves are often characterised by a repeated soft marine sequences interspersed by thinner layers of more compact, and usually weathered sediments. During high sea-level stands significant marine sediment deposition may take place, but during low stands, the upper most layer is exposed to pedogenesis, desiccation and terrestrial processes (Yim and Tovey, 1995). These are now referred to as palaeo-desiccated layers. Yim (1994) has identified 4 such repeated sequences beneath the Holocene (Table 1) which appear to correlate with the various oxygen isotope stages identified in the Vostok ice core (Petit et al., 1999). Yim has classified them as marine (M) units and terrestrial (T) units.

| |
|---|
| Unit M1 of Holocene or stage 1 age |
| Unit T1 of last glacial or stage 2 age |
| Unit M2 of last interglacial or stage 5 age |
| Unit T2 of 2nd last glacial or stage 6 age |
| Unit M3 of 2nd last interglacial or stage 7 age |
| Unit T3 of 3rd last glacial or stage 8 age |
| Unit M4 of 3rd last interglacial or stage 9 age |
| Unit T4 of 4th last glacial or stage 10 age |
| Unit M5 of 4th last interglacial or stage 11 age |
| Unit T5 of 5th last glacial or stage 12 age |

Table 1. Classification of inner continental shelf deposits in Hong Kong according to Yim (1994).

**Microfabric Studies**
Microscopic studies of sedimentary fabrics can provide evidence of previous desiccation, reworking, or modification of sediment properties. Fig. 1 provides proof of desiccation from the halite crystals within a crack from the uppermost palaeo-desiccated layer formed during the last low sea-level stand. Other evidence comes from microscopic halite crystals formed on roots of salt tolerant species growing during the low stand periods. Remarkably such crystals do not redissolve even when in gross chemical imbalance with the salt concentration of the rising sea (Tovey, 1986). It is probable that such crystals are coated with organic matter providing a permanent record of the desiccation event.

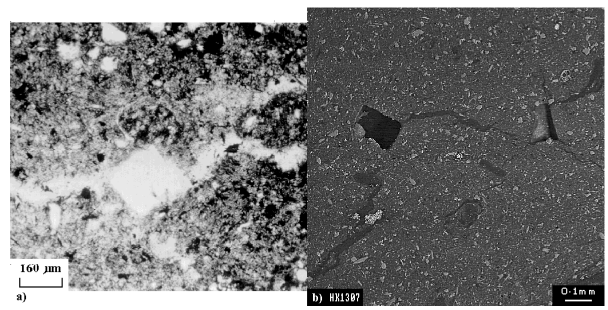


Fig. 1 Halite crystals forming in palaeo-desiccated layer – (a) optical micrograph, (b) imprint of halite in back-scattered electron microscope (BSE) image.

Evidence of reworking comes from samples such as Fig. 2 which was taken just above the T1 unit at the base of the Holocene. The back-scattered electron image shows sand/silt particles embedded in a clay matrix. Selected X-Ray maps are also shown.

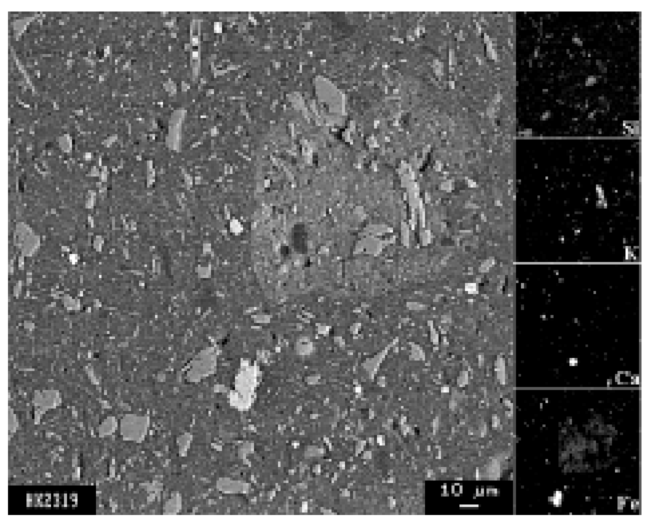


Fig. 2 BSE and X-Ray imaes of Holocene deposit just above palaeo-desiccated layer. Areas of higher atomic number appear lighter in the BSE image. The iron-rich aggregate has a more compact matrix and is evidence of reworking,

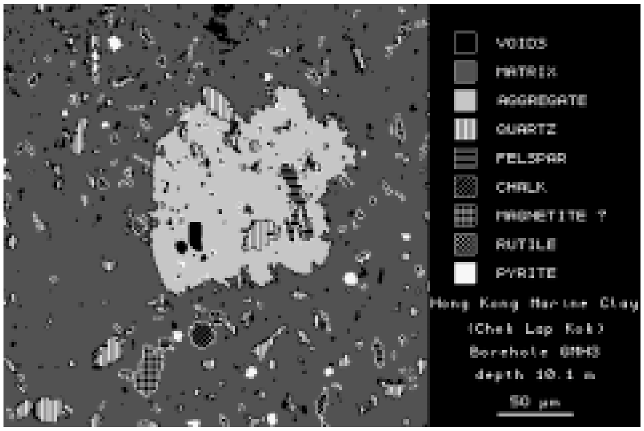

Fig. 3 *Mineral-segmented* image after multi-spectral analysis and post-processing of image

Using advanced multi-spectral image analysis (Tovey et al., 1992), it is possible to segment the image into the different mineral species and highlight the iron-rich aggregate. Further analysis allows the orientation of features in the fine clay matrix to be determined, Fig. 4, providing information of the degree of compaction revealing that the iron-rich ball was significantly more compacted than the surrounding matrix. It is the size and packing of such aggregates that will determine the geotechnical properties of the sediment rather than the individual particles which would normally be determined in particle size analysis.

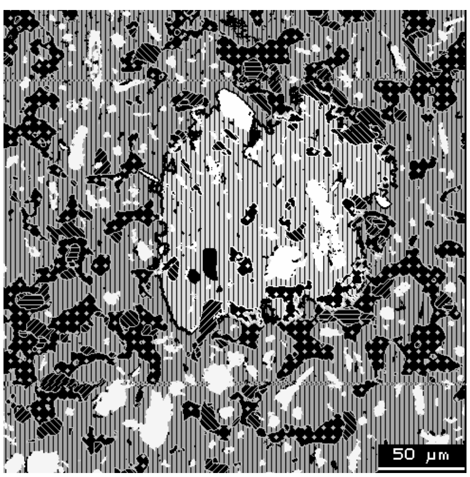

Fig. 4. *Domain-segmented* image showing general orientation patterns (indicated by hatching).

**High-resolution Stratigraphy from Moisture Content Analysis**

High-resolution seismic profiling provides information on stratigraphic sequences, but there has been limited correlation between the traces obtained and ground truth from borehole data. One problem has been the difficulty in obtaining long continuous boreholes. In some locations, such as Hong Kong, there is a wealth of information from approximately 2000 high quality boreholes drilled as part of the new Hong Kong Airport Project providing a unique opportunity for correlation. Careful analysis by Yim and his co-workers (e.g. Yim, 1994) has identified the individual units listed in Table 1. Generally the M units are medium to dark grey except at the palaeo-desiccated crusts formed during the periods of low sea level stand may range from light grey to yellow, brown and red and are often mottled. The thickness of these palaeo-desiccated crusts does vary, and is probably a function of the depression of the local water table and also the duration of that depression at periods of the low sea-level stand. In some cases a relevant T unit is missing, probably as a result of erosion, and it is here that high-resolution moisture content analysis becomes important. Fig. 5 illustrates the sharp demarcation between the M1 and M2 units where the T1 unit is absent. Moisture content determinations were made at 5-cm intervals (see Yim et al., in press).

Within the Holocene, the sediments are characterised by high moisture contents often exceeding 100% and high liquidity indices. The degree of saturation is always at or very close to 100%. The moisture content within the Holocene M1 unit does not appear to change with depth as one might expect from self-weight consolidation. The occasional lower values of moisture content (~60%) are often associated with the presence of thin layers of coarser materials (a few mm thick), possibly formed during storm surges.

During low sea-level stands the top of the M2 unit will be modified by pedogenesis and significant desiccation. However, below this the sediment will experience a stress increment arising from the removal of the buoyancy effect of the water formerly filling the voids in the palaeo-desiccated layer and will become more compact. The lower parts of the M2 unit tend to have high degrees of saturation (approx. 100%), while in parts of the palaeo-desiccated layer the saturation may only reach 96-97%. This, in part, explains why the moisture content increases with depth in this unit. Similar trends are also seen between the lower M units.

**Image Analysis of Cores**

Photographs of cores contain valuable information about the stratigraphic sequence. One particular study has attempted to examine remotely, variations in particle size distributions within a core comprising predominantly sandy material. Fig. 6 shows a core sample with discrete layering within the sequence. The digital image was processed using a grey-level morphological algorithm which successively passed circular structuring elements of different sizes across the image. Each pass involved a morphological ***opening*** i.e. a double stage involving an initial

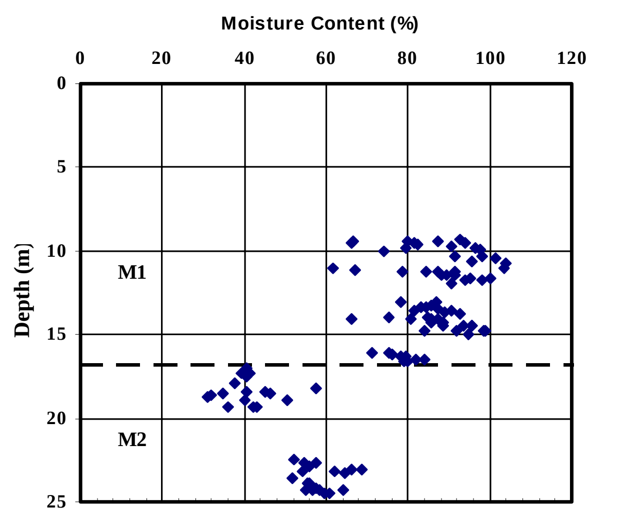

Fig. 5. Variation in moisture content with depth. There is a sharp change between the M1 and M2 units – based on data from Yim et al. (in press).

grey-level ***erosion*** followed by a grey-level ***dilation*** on the resulting image. By careful housekeeping it is possible to attribute the amount of image lost at each pass to a particular size range.

Cumulative size distribution curves may then be generated (Fig. 7). Since the image may be split into many different layers it is possible to examine variations in size distribution in even small layers, something which would be difficult to achieve using conventional mechanical sieving. A comparison using a standard sieving method produced a size distribution curve which lay in within the range of the curves is shown in Fig. 7.

**Deconvolution of Self-Weight Consolidation**

The Holocene marine deposits in Hong Kong began accumulating around 6500 years ago as the sea level rose to its present level. This sequence is typically 10m thick, but in places can be much thicker. On a raw uncorrected basis, the accumulation rate is about 1.5mm per annum, however, this does not allow for self-weight consolidation. If the gradient of the consolidation in voids

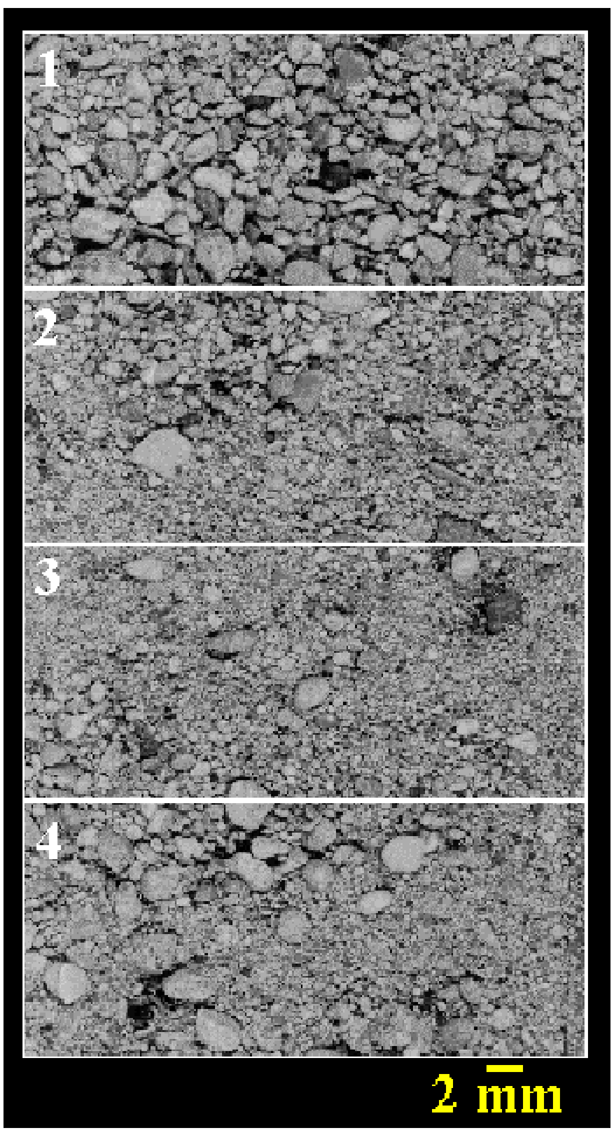


Fig. 6 Core sample from a sandy sequence showing variations in size distribution with depth

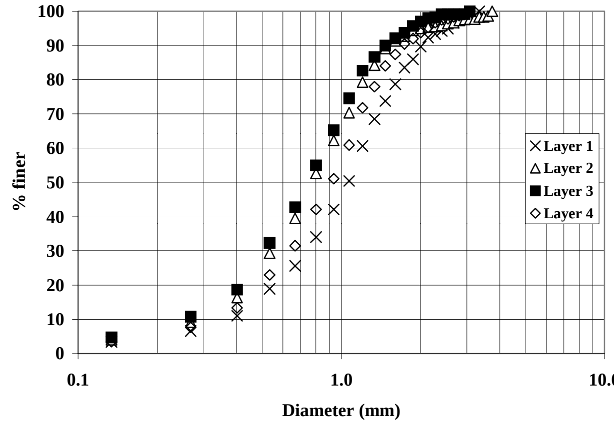


Fig 7. Particle size distribution curves derived using image analysis methods for the different layers in Fig. 6.

ratio – log stress space is known ($C_c$ ) and also the void ratio at unity stress level ($e_1$ ), then it becomes possible to estimate what the true sedimentation rate would have been. Such data must be obtained from high-quality cores which are rarely obtained in continental shelf studies. However, the numerous high quality boreholes in Hong Kong waters provide probably the best resource of such data. Fig. 8 shows consolidation data from one such sample.

The equilibrium bulk unit weight may be determined provided that the equilibrium void ratio is known, but this will depend on the *in situ* stress at the point in question which can only be known if the bulk unit weight of the overlying sediment is known. By dividing a sequence into a number of layers, each one assumed to have a constant void ratio, it is possible to obtain the void ratio and stress distribution according to the depth.

A problem in the analysis arises in that the choice of the thickness of the layer significantly affects the results and the predictions, particularly in the top 2 m of the sequence. Choosing layer thicknesses normally used for consolidation analysis e.g. 0.1-1m, are likely to give answers which are seriously in error when the sedimentation rate is of the order of 1 mm per annum. Consequently, layer thicknesses of 1 μm corresponding in physical terms to the size of clay particles were used for the uppermost layers, but this thickness was progressively increased with depth to 0.1m. In this manner, a true indication of the void ratio (or moisture content) variation with depth can be obtained. Using the mean measured value of $C_c$ of 1 $kPa^{-1}$ for the Holocene

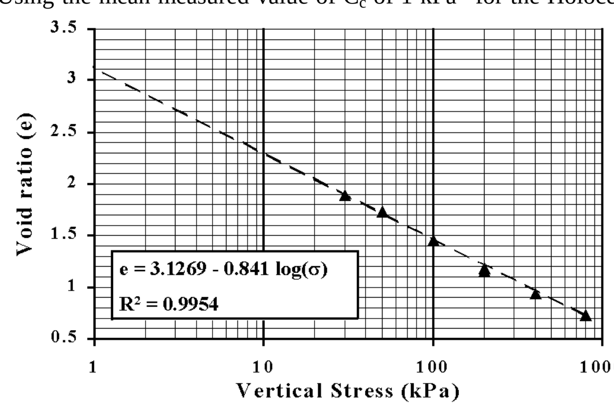


Fig. 8 Typical consolidation curve from M1 Holocene unit from Hong Kong (only the virgin consolidation data are shown).

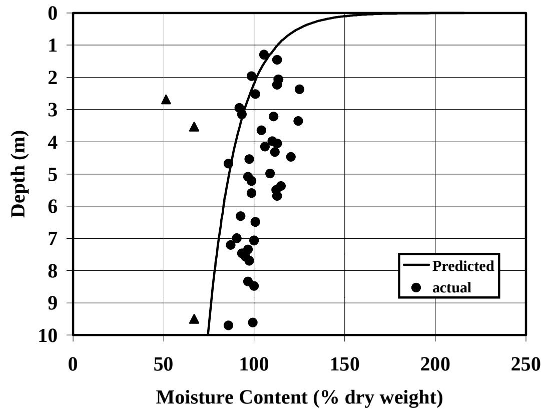


Fig. 9. Predicted and actual moisture contents within the Holocene marine sequence at Chek Lap Kok Airport. The triangular points represent samples from thin sandy layers.

deposit, this variation is computed in Fig. 9 together with measured values.

As each layer in the sequence is laid down, its initial void ratio will be high (typically e = 9 to 10), but the void ratio at the base of the Holocene will have been compacted to around 2.0. The determination of the true sedimentation rate thus requires that all layers are decompacted to the equilibrium void ratio in the top most layer. The true sedimentation rate is typically more than twice the raw linear rate indicating that profiling using age data and linear interpolation may be significantly in error.

With the exception of three data points from samples with vastly different liquid limits, all point lie to the right of the predicted line and furthermore the actual values increasingly diverge with depth. This suggests that less consolidation has taken place than predicted leading to more open and higher moisture content values at depth. While any excess pore pressure in newly deposited layers will be dissipated almost as soon as they are deposited, this is not true for previously deposited layers, particularly those near the base of the Holocene. Indeed, estimating the rate of consolidation from permeability that for layers thicker than about 4m, most of the excess pore pressure will still remain undissipated even at the end of a year irrespective of the drainage conditions.

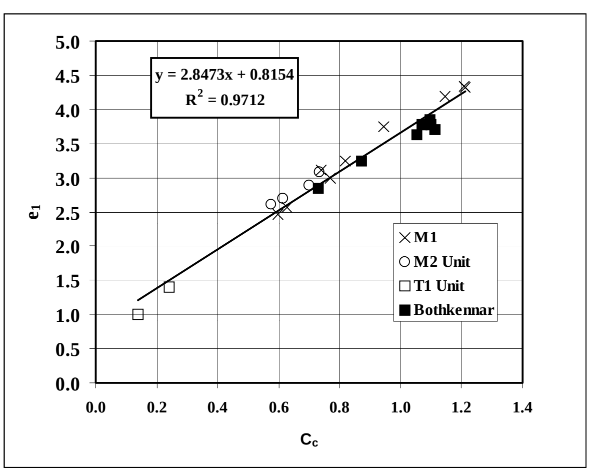


Fig. 10. Variation of $e_1$ with $C_c$ for M1, T1 and M2 units in Hong Kong and also the Bothkennar deposit, Scotland.

Though decompaction and further analysis is possible, provided that $C_c$ and $e_1$ are measured, the difficulty in obtaining suitable undisturbed cores for testing presents a challenge to the wider use of decompaction routines. However, Fig. 10 shows a strong correlation between Cc and $e_1$ even when data from three separate geological episodes are included – i.e. M1, T1, and M2. Further, data from the Holocene Bothkennar site in Scotland (Paul, Peacock & Wood 1992) also lie on the same line suggesting an unique relationship which is not unlike the Ω - point idea proposed by Schofield and Wroth (1968). With this assumption, then only $C_c$ need be determined, and since there already exist relationships relating the liquid limit to $C_c$ it becomes possible to develop decompaction of wider applicability. All that is need are measurements of the Atterberg Limits which can be done on disturbed samples.

**Conclusions**

The IGCP-396 annual meetings have provided a fruitful forum in which new areas of research have been identified, and new research undertaken. It is clear that:

i. Microfabric studies have considerable potential by providing confirmation to hypotheses as well as identifying issues which would be missed by other means,
ii. High-resolution correlation of seismic data with continuous borehole logs is important, and the detailed moisture content methods provide important additional information,
iii. Remote, non-destructive analysis of samples using image analysis methods provides the potential for rapid analysis and abstraction of new information.
iv. Deconvolution of self-weight consolidation of sediments is critical in the understanding of sedimentary processes. Raw sedimentation rates may well be in error by 50% or more, and this has implications for age dating of sediments.

**Acknowledgements**

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