A COMPARISON OF MARINE CLAYS FROM ARIAKE BAY, JAPAN AND THE SOUTH NATION RIVER LANDSLIDE SITE, CANADA

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ABSTRACT

The smectite-dominated Ariake Bay marine clay, the sensitivity of which can increase upon leaching to yield quick clay, is found to conform to the general model for quick clay development that has been proposed on the basis of the properties and behaviour of the Canadian and Scandinavian quick clays. While the Ariake Bay soil is more plastic than the Leda clay from the South Nation site, its plasticity and its yield stress at constant water content, as determined using a coaxial viscometer, decrease with salinity in the same manner. The removal of citrate-dithionite soluble materials decreases the yield stress in both soils although the Ariake Bay soil, from which more is removed, is more dramatically affected. Dispersants decrease the yield stress of both soils. Why, in contrast to most smectites, the smectites in the Ariake Bay marine clay are of low activity and have their activity decrease upon leaching, thereby allowing the development of quick clay behaviour, remains uncertain but it may be related to dominance by high-iron smectites.

Key words: sensitivity, physico-chemical properties, clay, leaching, weathering, rheology (IGC: D2)

INTRODUCTION

The Ariake Bay marine clays described by Egashira and Ohtsubo (1981) and Ohtsubo et al. (1982) represent an interesting addition to the range of materials which can exhibit the combination of high sensitivity and low remoulded shear strength required for designation as quick clay (Norsk Geoteknisk Forening, 1974). In common with the Canadian and most Scandinavian quick clays these deposits are of marine origin but, in contrast to them, they are dominated by smectites rather than by the quartz-feldspar-illite-chlorite mixture that is dominant in both Canada and Scandinavia.

Ohtsubo et al. (1982) have clearly demonstrated, with leaching and salt addition experiments, that the very high sensitivities are a response to leaching of salt from the pore water. Leaching appears to be essential to the development of a high sensitivity,
### Factors Producing a High Undisturbed Strength

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<td>Cementation Bonds</td>
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<td>- &quot;shrinkage&quot;</td>
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<td>processes</td>
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### Factors Producing a Low Remoulded Strength

<table>
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<th>DEPOSITIONAL</th>
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<td>Material properties</td>
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<td>- low-activity</td>
<td>Leaching $^1$</td>
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<td>minerals dominate $^{1,2}$</td>
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<td>Dispersants $^2$</td>
<td>- decrease in $w_r$, decrease in $w$</td>
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$^1$ Essential in marine clays

$^2$ Essential in fresh water clays

**Fig. 1. General model for quick clay development (from Torrance, 1983)**

as it is for the marine clays of Canada and Scandinavia. Torrance (1983) has proposed a general model for the development of quick clays (Fig.1), expressed in terms of the requirements for the development of quick clay behaviour in a sedimentary deposit. The material property requirements are that the sediment must be dominated by minerals of low activity (i.e. non-swelling minerals), and that it must have a high-water-content flocculated structure, such as develops upon sedimentation in a marine environment. Finally post-depositional factors can lead to this material having a high sensitivity and a sufficiently low remoulded strength to behave as a liquid after disturbance and thereby qualify as a quick clay. For marine clays that meet the materials requirement, the only essential post-depositional factor is leaching to decrease the pore-water salinity, but other factors such as cementation, which increases the undisturbed strength, or dispersants, which can further lower the remoulded strength below that produced by leaching alone, can enhance the sensitivity developed but are not generally required. It is interesting to compare the Ariake Bay marine clays with this model.

It is assumed that the Ariake Bay clay is flocculated as this is the normal state for clays sedimented in marine or brackish environments. Likewise, there is no reason to suspect that cementation (if present) or slow load increase would have a different effect than in the better known deposits.

Of those factors that contribute to a low remoulded strength, minimal consolidation would have the same effect of maintaining high water content, and Ohtsubo et al. (1982) have demonstrated that leaching of salts also has the effect of decreasing the remoulded strength of the Ariake Bay clay. The effect of dispersants is similar, as is demonstrated by experiments reported in this paper. The smectite-dominated mineralogy of the Ariake Bay clays is the major difference. The critical factor allowing the development of quick clay is that these smectites are of a low-swelling, low-activity character (Egashira and Ohtsubo, 1981). This material would appear to conform, in essentially all respects, to the general model proposed by Torrance (1983).

As Egashira and Ohtsubo (1981) note, the smectite is unusual in that it responds to salinity and ion saturation in a manner similar to the low-activity minerals, illite and chlorite, rather than in the manner normally associated with smectites. Egashira and Ohtsubo (1983) suggest that this unusual behaviour is caused by the occurrence of considerable substitution of Fe$^{2+}$ for Al$^{3+}$ in the octahedral layer and that this suppresses the swelling tendency normally associated with smectites. While this paper does not attempt to evaluate this possibility, it does report experiments which compare the viscometric response of the Ariake Bay marine clay with a Leda clay from Eastern Canada. The remoulded re-
RESPONSE AND FACTORS AFFECTING IT HAVE BEEN FOUND TO BE SURPRISINGLY SIMILAR.

MATERIALS AND METHODS

The materials used in the experiments were: 1) Ariake Bay marine clay from Megurie Kantaku, Saga Prefecture, Kyushu, Japan (Fig. 2), kindly provided by Dr. M. Ohtsubo and henceforth called the Megurie sample, and 2) Leda clay from the site of the South Nation River landslide of 1971 (Eden et al., 1971) which is approximately 50 km east of Ottawa, Ontario, within the area that was occupied by the Champlain Sea in the immediately post-glacial period.

The Megurie sample, as received, had a salinity of 23.5 g/liter, as determined by the conductivity of porewater squeezed from the soil using the apparatus described by Torrance (1976, Fig. 1). Its water content was 134% and its liquid and plastic limits were 131% and 73% respectively. The South Nation material, as received, had a salinity of approximately 1 g/liter and its liquid and plastic limits were 36% and 22% respectively.

The effect of salinity, sesquioxide extraction and dispersants on the Bingham yield stress over a range of water contents was assessed using a Haake Rotovisco RV12 coaxial viscometer equipped with the MVII and MVIII sensors. The soil was brought to the desired chemical and water content state and was thoroughly homogenized using a mechanical mixer. This material was placed in the viscometer and the Bingham yield stress was determined from the shear rate–shear stress curve generated by reading the torque required to maintain constant rotation rate 15 seconds after the rate had been decreased stepwise, by a factor of two in each step, from 512 to 1 rpm.

The Megurie sample was tested: under its natural chemical conditions; at a range of salinities obtained by diluting the pore water with deionized water and centrifuging to obtain the desired water content at a lower salinity; in the Na-saturated state over a range of water contents and salinities; and in the Na-saturated state after being extracted by a single and by four extractions with citrate–dithionite according to the Mehra and Jackson (1960) procedure. The South Nation soil was tested under Na-saturated conditions and under Na-saturated conditions after a single citrate–dithionite extraction.

RESULTS AND DISCUSSION

Viscometric assessment and Atterberg limits are both means of measuring the rheological response of remoulded soil material. The liquid and plastic limits of the Megurie soil (Fig. 3) did not vary as regularly with salinity as those reported by Egashira and Ohtsubo (1981) and were greater, in all cases, than those for the South Nation soil. In both materials the liquid limit decreased greatly at low salinity while the plastic limit was relatively little changed, except with the citrate–dithionite extracted Megurie soil. Both the natural and Na-saturated Megurie soil showed unusually high liquid and plastic limits at 2.2 g/liter, compared with at higher and lower salinities. It is not believed that this represents a measurement error, however no explanation for this is currently available. Regardless all materials exhibited a considerable decrease
in liquid limit at low salinities.

It should be noted that after a single citrate-dithionite extraction, the liquid limit of the Megurie soil was changed very little at high salinity, but at intermediate and low salinities it was greatly reduced compared with the unextracted soil. After four extractions the liquid limit was greatly reduced at all salinities. The effect of citrate-dithionite extraction was much more dramatic for the Megurie soil than for the South Nation soil, presumably indicating that the extracted material, mainly oxides, plays a more important role in the Megurie soil.

The yield stress response of the Na-saturated soils over a range of water contents and salinities is shown in Fig. 4(a) for the Megurie soil and in Fig. 4(b) for the South Nation soil. A family of curves was obtained for each material and it was observed that the yield stress at any water content decreased as the salinity decreased. The yield stress difference between curves was greatest at low water contents, and the greatest change in response per unit change in salinity occurred in the low salinity range. The integer numbers along the yield stress-water content curves represent the liquidity index values. Aside from the Megurie soil always being at higher water contents, but in the same liquidity index range, there is little difference in the overall character of the curves.

In Fig. 4(a), the yield stresses obtained for the Megurie soil when the salinity was altered by dilution and centrifugation are plotted (the points identified by letters). The yield stress for this material, with a variety of ions satisfying the exchange sites, generally plotted at higher values than Na-saturated samples of corresponding salinity. This is contrary to what would normally be expected for smectites but is entirely consistent with the observations of Ohtsubo et al. (1982). The yield stress for the natural material at 1.3 g/liter plotted on the curve for the Na-saturated soil at the same salinity.

The yield stress-water content results for the Na-saturated, citrate-dithionite extracted clays are presented in Figs. 4(c) and 4(d). The integers along the curves again present the liquidity index values. After a single extraction the yield stress curve for the Megurie soil at high salinity was displaced to higher yield stress values at all water
Fig. 4. Yield stress–water content relationships for: a) the Na-saturated Megurie soil at a range of salinities (the points identified by letters represent the yield stress–water content values for natural Megurie soil at: A=15.5 g/l; B=4.5 g/l; C=2.2 g/l; D=1.7 g/l; E=1.3 g/l; F=0.4 g/l); b) the Na-saturated South Nation soil at a range of salinities; c) the Na-saturated, citrate-dithionite extracted Megurie soil after 1 and 4 cycles of extraction; d) the Na-saturated, citrate-dithionite extracted South Nation soil after 1 cycle of extraction.

Table 1. Fe₂O₃, Al₂O₃ and SiO₂ extracted by citrate-dithionite extractions

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<thead>
<tr>
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<th>Fe₂O₃ extracted (g/100g)</th>
<th>Al₂O₃ extracted (g/100g)</th>
<th>SiO₂ extracted (g/100g)</th>
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<tbody>
<tr>
<td>Megurie soil, single extraction</td>
<td>1.8</td>
<td>0.1</td>
<td>0.13</td>
</tr>
<tr>
<td>Megurie soil, four extractions</td>
<td>4.1</td>
<td>0.34</td>
<td>1.04</td>
</tr>
<tr>
<td>South Nation soil, single extraction</td>
<td>0.53</td>
<td>0.04</td>
<td>0.16</td>
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The citrate-dithionite extraction removed iron, aluminum and silicon from the soils (Table 1). The Megurie soil contained a greater proportion of citrate-dithionite extractable iron and aluminum compounds and this presumably explains the greater effect of their removal on behaviour. Also with
the Megurie soil the greater the amount extracted the greater was the effect. Other experiments (not reported), in which more severe extractants have been used to remove Fe, Al and Si compounds, indicate that the same conclusion applies to the South Nation soil. In both soils these materials act as thickeners which increase the liquid limit and increase the remoulded shear strength.

It is interesting to note that the yield stress at a given liquidity index for the Na-saturated Megurie soil was observed to vary within narrow limits whereas, with the South Nation soil and the citrate-dithionite extracted Megurie soil there is a great variation in yield stress at constant liquidity index. No explanation for the unexpected results with the latter materials is evident.

Dispersants caused a decrease in the yield stress of the Megurie soil at constant water content and salinity (Fig. 5). At 185% water the yield stress for the natural material lay well above the value for this soil after the dispersant, "Calgon", had been added in sufficient quantity to yield a pore water concentration of 0.5 g/liter, the same concentration as is commonly used when performing grain size analysis. A similar effect was observed with Leda clay (Torrance, 1975).

CONCLUSIONS

The responses of the Megurie soil and the South Nation soil to changes in pore-water chemistry and addition and removal of various materials are remarkably similar, despite the differences in mineralogy. This similarity would not normally be expected since most smectite-dominated soils respond in precisely the opposite manner to imposed chemical changes than do soils dominated by primary minerals, illite and chlorite. As Egashira and Ohtsubo (1981) have demonstrated and as is confirmed by these experiments the smectites in the Ariake Bay marine clay are unusual. The current experiments would seem to eliminate the possibility that citrate-dithionite-extractable iron and aluminum compounds are responsible, since their removal only served to make the Megurie soil less plastic. The response to salinity and ion saturation of the Saga Agricultural Experiment Station paddy soil, which was derived from Ariake Bay alluvium (Egashira and Ohtsubo, 1981), suggests that the weathering that occurred under paddy conditions caused the smectite to exhibit the swelling behaviour normally associated with that mineral. Since an oxidizing environment apparently made this smectite behave "normally", does this imply that the smectites were formed from volcanic ash under reducing conditions and, if so, did that occur before or after sedimentation in Ariake Bay?

The Megurie and South Nation soils both meet the material properties criterion of the general model proposed by Torrance since both are dominated by low-activity minerals, and they also responded in similar manners to the other parameters of the model. Recognition of the Ariake Bay marine clay as a quick clay represents an extension of the spectrum of materials that can exhibit quick clay behaviour to include materials dominated by non-swelling smectites. The puzzling aspect that remains not completely
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explained is why the smectites of Ariake Bay are of low activity and why that activity decreases with leaching. The proposal by Egashira and Ohtsubo (1983) that the low-swelling character is caused by high-iron smectites seems reasonable but needs further investigation. Further clues might be found through investigation of the ultimate source of the sediments which have accumulated in Ariake Bay.

ACKNOWLEDGEMENTS

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