A new class of soils: Fossiliferous soils?

Une nouvelle classe de sols: les sols fossilifères ?

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ABSTRACT: Recent investigations on marine sediments and soils in Japan and South East Asia has shed some light on the potential role of microfossils on geotechnical properties of soils. Observations made on natural deposits and artificial mixtures are used to demonstrate the impact of microfossils, diatoms in particular, on index properties and friction angle of soils. From the results obtained, it is proposed that, in addition to organic and inorganic soils, we should establish a new class: fossilifereous soils.

RÉSUMÉ: Des études récentes sur des sédiments marins et des sols au Japon et en Asie du sud-est nous ont permis d'élucider le rôle potentiel des microfossiles sur les propriétés géotechniques des sols. Des observations faites sur des sol naturels et des mélanges artificiels nous permettent de démontrer l'impact des microfossiles, les diatomées en particulier, sur les propriétés physico-chimiques et sur les paramètres de la résistance au cisaillement, le coefficient de friction en particulier. Ces résultats nous amènent à proposer d'ajouter aux sols organiques et inorganiques, la classe des sols fossilifères.

1 INTRODUCTION

Recent investigations of marine sediments in Japan and South-East Asia has triggered a suite of investigations on the potential role of diatoms on the geotechnical behavior of soils (Tanaka and Locat 1999, Shiwakoti *et al.* 2001). As part of our investigation, it became clear that the geotechnical behavior and index properties of these soils could not be explained using conventional knowledge derived from experience on organic or inorganic soils. In addition, the many classifications proposed for soils and other deposits (Mitchell 1993, Noorany 1989) do not really separate clearly the mechanical and physico-chemical impact of certain microfossils on soil behavior. Geoscientists, however, have long time ago recognized the role of microfossils on some geotechnical properties of marine (*e.g.* Lee 1982, Pittenger *et al.* 1989, Rack and Palmer-Julsen 1992) or lacustrine sediments (Mesri *et al.* 1975, Diaz-Rodriguez *et al.* 1998). In all these studies, some indications were given on the potential impact of these microfossils on strength parameters (*e.g.* cohesion and friction, Mesri *et al.* 1975) but with minimal explanation.

In the geotechnical literature there are many relationships which are based on the plasticity index (Bjerrum 1973). These relationships have been used extensively but were often more difficult to apply in the case of marine sediments, particularly in Japan, and it was recently proposed that such differences are not only due to mineralogy but also to the presence of significant amounts of microfossils (Tanaka and Locat 1998, Tanaka 2000).

In this paper, we introduce the main types of microfossils encountered in soil mechanics, with a particular reference to diatoms (Figure 1d), and we will illustrate how they can influence the physico-chemical and geotechnical properties of soils. We believe that the following results, in addition to those of other researchers (*e.g.* Lee 1982), are convincing enough to propose that we should add, to the main class of soils, *i.e.* inorganic and organic, another class: fossilifereous soils.

2 TYPES AND NATURE OF MICROFOSSILS IN SOILS

Microfossils are micro-remnants (< 1 mm) of either vegetal or animal living species and their evolution (or fate) through diagenetic processes is described by the terms "taphonomy" (Efremov 1940). The microfauna from which are derived the microfossils is vast, but those living in water, and who are of significance from an engineering point of view, can be divided into two simple categories based on the chemical composition of their skeleton: calcareous or siliceous (Figure 1). Calcareous fossils include coccoliths (Fig. 1a) and foraminifera (Fig. 1b) while siliceous fossils include radiolarian (Fig. 1c) and diatoms (Fig. 1d). Except for foram skeletons, when microfossils are found in concentration, by weight, of more than 50%, they constitute oozes (Noorany 1989).

The environments in which these microfossils originate is quite diversified. In general, diatoms oozes are found in surface waters of polar latitudes. Foraminifera would prefer so-called mixed waters of intermediate latitude while radiolarian are quite common at lower latitudes (Kennett 1982). These fossilifereous

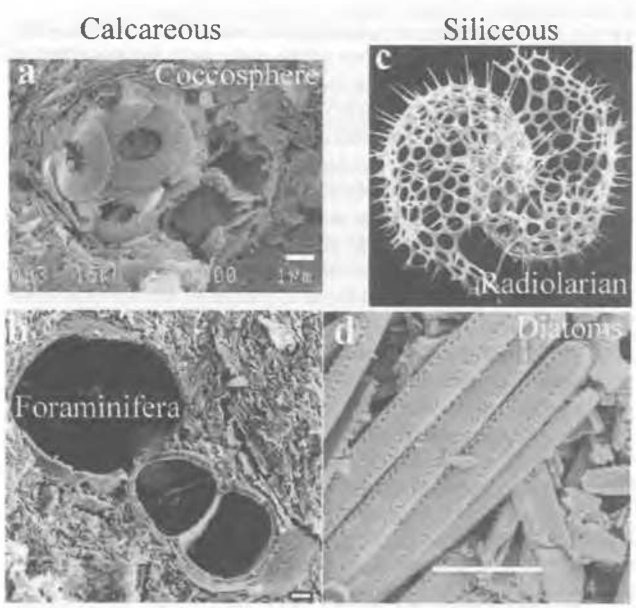

Figure 1. Type of microfossils often found in fossilifereous soils, calcareous: (a) coccosphere (scale bar is 1 μm, sample is from Kobe), (b): foraminifera (scale bar at 10 μm, sample from Bangkok), and siliceous: (c) radiolarian (fossil about 15μm in diameter, photo from K. Takahashi), and (d) pennate diatoms (scale bar at 10 μm, from U.S.A.).

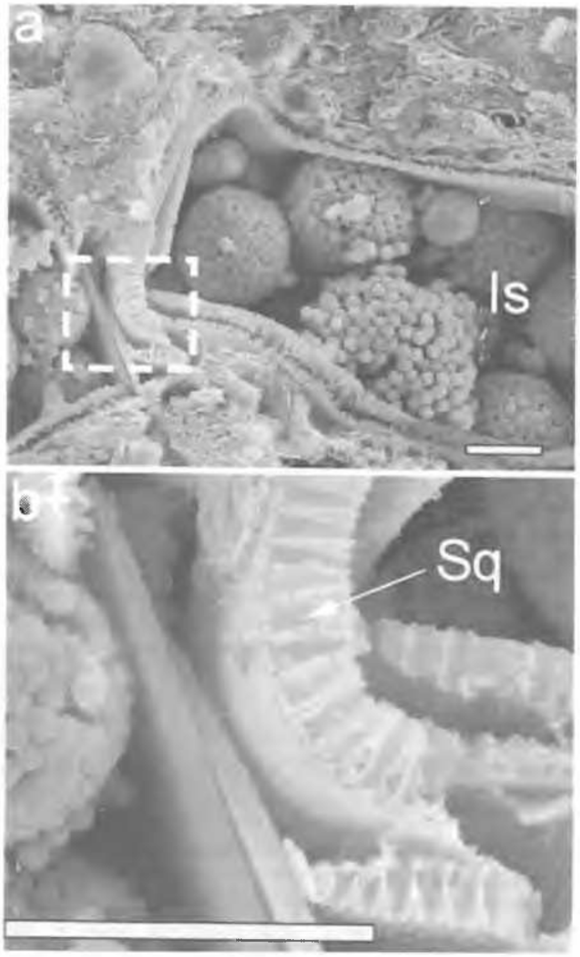

Figure 2. Illustration of intra-skeletal (Is, a) and skeletal (Sq, b) porosity of microfossils. Note the artwork involved in the micro-size skeletal pores seen in the enlargment in (b) and the framboïdal pyrite inside the diatom in (a).

sediments can cover very large areas, for example, there is a large diatom ooze, about 1500km in width, that covers both side of the 60° parallel south of the Pacific Ocean (Reinek and Singh 1975). The vast extent of fossilifereous oozes in the marine environment can explain why most of the early work on geotechnical properties of fossilifereous soils took place as part of the Ocean Drilling Program (DSDP, ODP).

The fate of the microfossils can be quite complex. The skeleton of diatoms and radiolarian consists of amorphous silica (opal) and is very soluble in sea water so that preservation of skeleton is only possible for the largest species. Kennett (1982) indicates that less than 5% of the diatoms skeleton can reach the sea floor without being dissolved. A larger proportions could accumulate if the sedimentary basin is shallower or the sedimentation rate higher.

As it can already be seen from the scanning electron microphotographs images (SEM) in Figure 1, their external and internal structure, porous network and overall shape can play some role on three aspects related to soil behavior: water retention, compressibility and friction. The analysis of their microstructural elements requires the addition of new terms (Figure 2): (1) skeletal (Sq) and (2) intra-skeletal (Is) porosity in addition to the terms intra-aggregate (Ia) and inter-aggregate (Ir, Tanaka and Locat 1999; Locat and Tanaka 2000).

The coccosphere, shown in Figure 1a, consists of an assemblage of calcite micron-size disks called coccoliths. The structure is very compact and the skeletal porosity is negligible and the intra-skeletal porosity is small but probably larger than that of typical aggregate. The strength is quite high and they can resist significant loading stresses without breaking. The one shown in

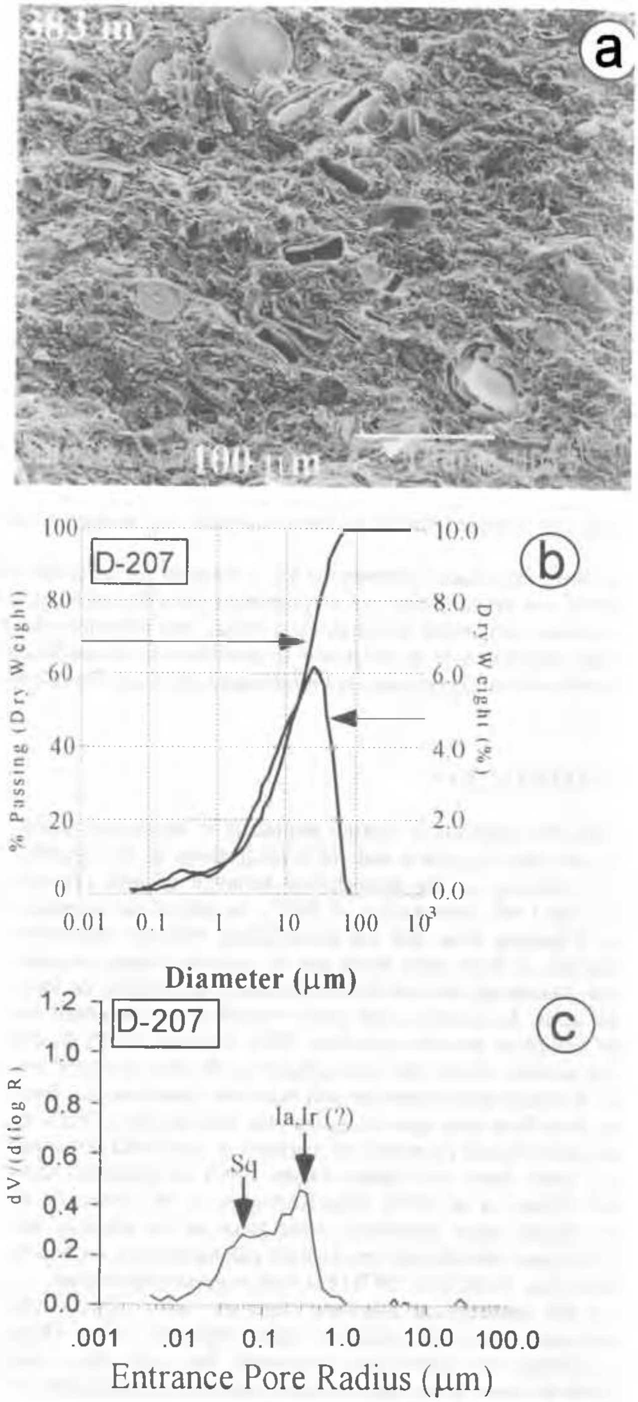

Figure 3. Distribution of diatoms in a consolidated sediment taken at a depth of 383 m at the site of Kansai airport (a), the grain size distribution (b) and the pore size distribution (c) with indications for skeletal porosity (Sq), intra- (Ia) and inter (Ir)-aggregate pores.

Figure 1a is from a drilled site for the futur Kobe airport and comes from a sample taken at a depth of 181 m below the sea bottom.

The foraminifera shown in Figure 1b was taken from a sediment sample collected in Bangkok at a depth of only 8.5 m. It also consists of calcite. These microfossils are quite large compare to the other ones, with a length up to 1 mm. The Skeletal porosity, like for most calcite fossils, is quite limited. The intra-skeletal porosity however is large. Rack and Palmer-Julsen (1992) did recognized that if stresses were high enough to break the foraminifera structure, it would transfer large amounts of water to the soil matrix with its consequence in terms of compressibility and pore pressure development.

The radiolarian shown in Figure 1c is taken from a picture collection of K. Takahashi. Radiolarian consist of silica skeleton which develops into a very light and fragile structure. We have not observed complete radiolarian in our study but we have found many needle-like structure which are believe to be produced when these microfossils are broken. The overall size is quite large (about 10-15 μm). The skeletal porosity is at about 1 μm and the intra-skeletal porosity about 10-15 μm in diameter. Both pore families are very well interconnected. Since this type of microfossil could not resist significant burial stresses, its impact on soil properties , when abundant, would be on the friction angle (ϕ') since their broken pieces would be very sharp and angular.

The diatoms presented in Figure 1d are from a diatomite exploited in the Western part of the United States. There are more than 10 000 different living species of diatoms (Kennett 1982) but they can be simply classified into two categories: pennate (Figure 1d) and centric (Figure 3a). As shown in Figure 2, they can have a large intra-skeletal porosity along with a very well developed skeletal pore network (Fig. 2b). As consolidation takes place, it seems that the clay matrix adjusts around many of these fossils likely by way of some arching phenomena. The presence of pyrite (Fig. 2) can also help to prevent the collapse of the intra-skeletal porosity.

From the above description we can already observe that the particular nature of microfossils make them a microstructural element with unique signature compare to soil mineral particles or organic matter. In the following sections, mostly using diatoms, we will see how these "micro" characteristics can impact on soil behavior.

3 IMPACT ON PHYSICO-CHEMICAL PROPERTIES

Before going into details, we must realize that the surface properties of diatoms have long been recognized by the industry. For example, diatoms are use in making explosive because of their adsorbing capacities (act as a retardant), many types of filter papers are actually made of diatomite (surface properties). The abrasive nature of diatoms is put to work in products like tooth paste (influence on friction angle).

With these observations in mind, we will illustrate the potential impact of microfossil on physico-chemical properties by using results obtained on samples from Osaka Bay (Kansai Airport site, Tanaka and Locat 1999). At this site, diatoms are abundant. At a depth of 383 m below the sea floor, there is a layer which is rich in diatoms (Figure 3). This sample has a water content of 43%, a liquid limit of 117%, a plasticity index of 75%, a clay fraction of 19%, and a liquidity index of 0.08.

As seen in Figure 3a, centric diatoms cover at least 1/3 of the exposed surface. From the SEM picture, we can see that their diameter is about 30 μm and their thickness and intra-skeletal porosity is large with apertures of 30 x 10 μm. Note here that there is no pyrite filling the pore space and that the clay matrix is so compressed that the intra-aggregate pore space has vanished. Still, many large intra-skeletal pores have remained open even under an effective overburden pressure of about 2 MPa!

If we can describe the surface characteristic of a diatom it will be easier to evaluate its impact on physico-chemical properties like specific surface area (*SSA*), water content, and Atterberg's limits.

The grain size distribution of the same sample is given in Figure 3b. The distribution is characterized by a strong mode at about 30μm, which corresponds to the average diameter of the centric diatoms (Fig. 3a). In terms of surface properties, the skeletal porosity is reveal by a mode at an entrance pore radius of about 0.07 μm, as measured with a mercury porosimeter (see also Tanaka and Locat 1999 for more details).

Let us look at the geometry of a centric diatom (Figure 4a) taken from a sample from Kansai airport at a depth of 181m The geometry has been simplified, as shown in Figure 4b, in order to derive an equation to compute the volume of solid of the diatom

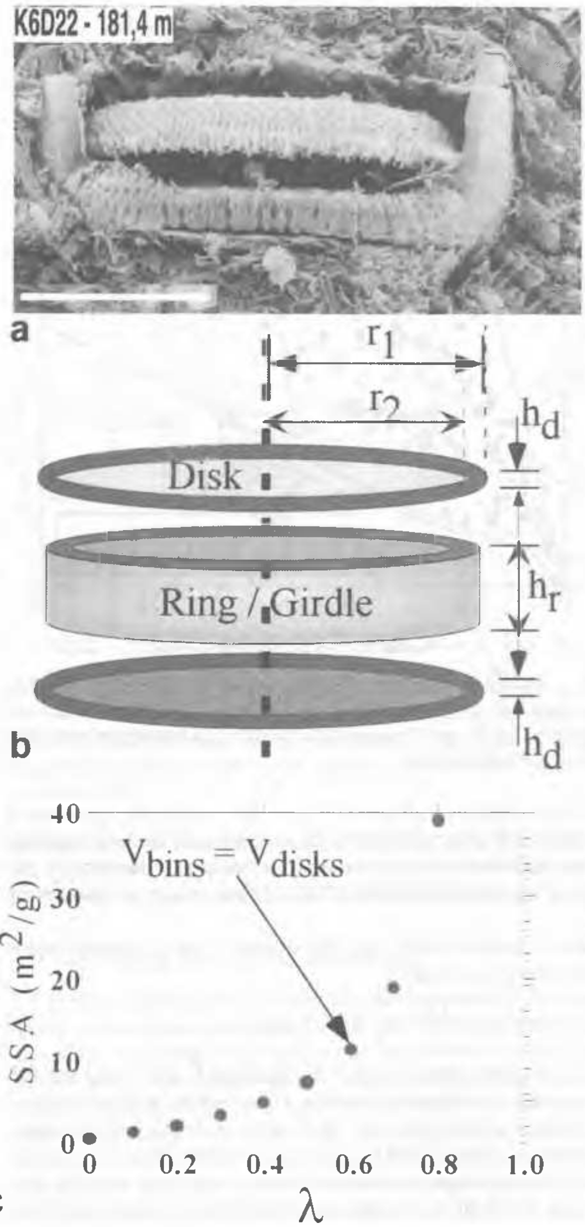

Figure 4. A geometrical description of a centric diatom (a and b) and (c) the relative influence of the skeletal density on the specific surface area (the scale bar in (a) is at 10 μm).

(V_{sf}), the intra-skeletal and skeletal pore volumes so that the specific surface area (*SSA*) could also be evaluated. The constitutive parts of the centric diatom can be described (Fig. 4b) by a ring (or girdle) and two disks, all with a certain diameter and thickness. The skeletal porosity is here consider to be represented by small cylinders of a given diameter (r_c) and depth (l_c, see Figure 2b) and their abundance is given by λ, which is an estimation of their surface distribution relative to the total surface of the disks. The girdle usually has no detectable porosity.

The specific surface area (*SSA*) is given by:

$$SSA = A_t / (\gamma_s \times V_{sf}) \tag{1}$$

where A_t is the total surface and γ_s the unit weight of the diatom (assumed equal to 2.0 g/cm^3). The total area is given by the summation of all the surfaces, including the surface inside the skeletal porosity, so that:

$$A_t = 4\pi r_1 h_d + 4\pi r_1^2 + 2\pi(r_1 + r_2)h_r + 2\pi\left(r_1^2 - r_2^2\right) + n\lambda\pi r_1^2\left(2l_c + r_c\right)/r_c \tag{2}$$

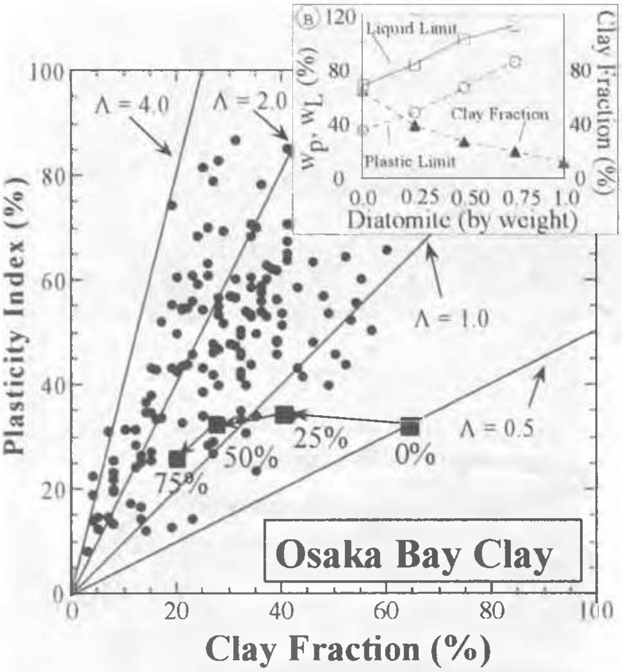

Figure 5. Impact of diatoms on the activity of a kaolin clay. The data from Osaka Bay are given in the background (modified from Tanaka and Locat 1999). In (b) are test results on mixtures of kaolin and diatomite used in the Activity Chart.

with most symbols defined in Figure 4b, except for n, which is the number of disk surfaces with a significant skeletal porosity (or bins) and for l_c and r_c which are respectively the length and radius of the individual bins of the skeletal porosity (see Figure 2).

The volume of solids, for this diatom, can be approximated by the following equation:

$$V_{sf} = 2\pi r_1^2 h_d + \pi\left(r_1^2 - r_2^2\right)h_r - n\lambda\pi r_1^2 l_c \tag{3}$$

So, by using Equation 2 and 3 in Equation 1, and using the following values (estimated from the SEM picture in Figure 4a): r_1 = 12.5 µm, r_2 = 10.5 µm, h_r = 8.0 µm, h_d = 4 µm, l_c = 2.0 µm, r_c = 0.2 µm, n = 4 and λ = 0.6 it gives a value for *SSA* of 11.4 m^2/g! This is in the range of measured specific surface area for diatoms, *i.e.* 10-20 m^2/g. As shown in Figure 4c, the value of *SSA* is very sensitive to the relative density of the skeletal porosity (λ).

Clearly, significant volume of water can be retained inside the diatom microstructure. But how does this effect index properties ? This was explored in an experiment in which mixtures of kaolinite and diatomite were made (see also Tanaka and Locat 1999). The proportion of diatomite was increase from 0% to 100% (dry weight). Then, the mixture were tested for their Atteberg's limits and grain size distribution (see insert (b) in Fig. 5).

By evaluating the impact of increasing addition of diatomite in the mixture on the plastic and liquid limits (Fig. 5b) it appears that they both increase with the same magnitude so that the plasticity index remains more or less constant. In parallel, the clay fraction decreases. So, the activity, as shown in Figure 5, has drastically increased, from about 0.5 (typical for kaolinite) to nearly 2.0 with 75% of diatomite in the mixture. Note that nearly half of the changes in the activity took place with only the addition of 25% of diatomite.

On the other hand, because the water is retained inside the rigid porous network of the diatom skeleton, it does not contribute to the basic index properties; there is a bias. It is possible to estimate the bias if we can compute the relative dry weight of the diatoms (W_{sf}) to that of the dry soil (W_s) in order to compute a corrected water content (w_o) such as:

$$w_0 = w - w_f \tag{4}$$

where w_f is the amount of water retained in the diatoms which can be estimated by the following relationship:

$$w_f = \left(\frac{\gamma_w}{\gamma_{sf}}\right)\alpha\beta \tag{5}$$

where γ_{sf} is the unit weight of the fossil (about 2 g/cm^3) and where:

$$\alpha = \frac{W_{sf}}{W_s} \tag{6}$$

and

$$\beta = \frac{V_{wf}}{V_{sf}} \tag{7}$$

The value of α is estimated by direct observation (counting) or by chemical analysis (Shiwakoti *et al* 2001), and β is computed using the values of Equation 3. So, for the example in Figure 4, we can estimate a value of α at 0.3 and β at 1.9 so that the value of w_f is 28%. This value is close to the actual diatomite content. Therefore, the bias is quite significant! If little change takes place in the geometry of the diatoms until some burial stress, the value of w_f would be nearly constant and its relative importance would increase with depth. In the above example, the *in situ* water content was 43%, so that the corrected water content (or matrix water content) value would close to 15%. To support this analysis we can use the results shown in Figure 5b where, after adding 30% of diatoms (α = 0.3), the liquid and plastic limits also increased by almost 30% which is very close to the above theoretical estimate.

4 IMPACT ON GEOTECHNICAL PROPERTIES

Impact of microfossils on geotechnical properties of soils has been demonstrated, from the point of view of compressibility, by

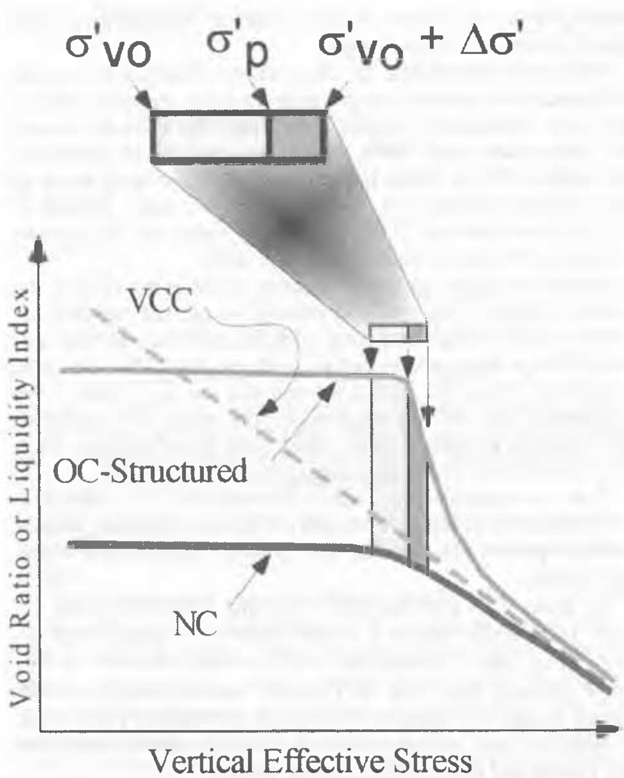

Figure 6. Conceptual view of the potential role of microfossils to explain alternating layer of consolidated and overconsolidated clays at Kansai airport (see also Locat and Tanaka 2000). VCC is the reference virgin compression curve (Bjerrum 1967, Locat and Lefebvre 1986).

Rack *et al.* (1993) and by Tanaka and Locat (1999) and their impact on the shear strength behaviour, including friction, has been detailed by Tanaka (2000) and by Shiwakoti *et al.* (2001).

4.1 *Compressibility*

With the above demonstration of the capacity of microfossils to hold water in a rigid structure, it is not a surprise to find that fossilifereous soils could have very high compression index, even when at great burial depth. Rack *et al.* (1993) found that in some diatomaceous oozes of the North Sea, the compression index (C_c) could be as high as 5.0. For the Kansai airport site, Tanaka and Locat (1999) reported values of C_c as high as 4.7 for a clay sample taken at a depth of 250 m below the sea floor. From these observations, Locat and Tanaka (2001) have proposed a conceptual model illustrating the potential role of microfossil on the consolidation properties of fossilefereous soils (Figure 6). In the case shown in Figure 6, remaining overconsolidation layers (OC) could either contain larger or stronger concentration of microfossils than the normally consolidated layers (NC) for which there was no or little microfossils or they collapse once their yield strength was exceeded by burial. From this model, one would also expect greater compression index for OC layers than for NC layers.

4.2 *Friction angle*

Following the work of Kenney (1959), and of Bjerrum and Simons (1960), it was believe that the friction angle (ϕ') would normally decrease with an increasing plasticity index. Mesri (1975) mentioned that the unique behavior of Mexico City clay, *i.e.* a friction angle at about 40° and a plasticity index of about 300%, was due to the presence of large quantities of diatoms in the soil. From the above observations and those of Mesri (1975), it appears that the presence of significant amounts of diatoms, and likely of other microfossils, can alter the strength parameters, the friction angle in particular.

In order to investigate this in more details, Shiwakoti *et al.* (2001) report test results obtained on kaolin and Singapore clay mixed with increasing amounts of diatomite (Figure 7) and tested in a constant volume shear test apparatus. Kaolin and Singapore clay, before being mixed with diatomite, have their friction angle and plasticity index within the range of other non fossilifereous soils but quite apart from most Japanese soils (Fig. 7). The results obtained for the various mixtures with diatomite show a drastic change in the friction angle for both soil mixtures with only 25% of diatomite. Kaolin friction angle changed from 24° to 34° while Singapore clay went from 22° to nearly 30°. As we have shown above (Fig. 5), the plasticity index did not change significantly up to a concentration in diatomite of 75%. These results show that if a non fossilifereous clay is mixed with diatom, its friction angle move well above the expected trend and join the values observed for Japanese clays. Such result has supported the argument put forward by Tanaka (2000) that many Japanese soils do not follow classical behavior of soils because they can contain significant amount of diatoms. We must remember that most of the classical soil mechanics has been developed on the basis of studies carried out on organic and inorganic soils, not on fossilifereous soils.

5 DISCUSSION

The above presentation has provided some insights on the impact of microfossils on the geotechnical properties of soils in which they are found. When in significant concentration, and the work of Shiwakoti *et al.* (2001) indicates that at about 10% by weight could be the threshold value, they effectively influenced the soil properties. Although their presence has long been recognized from a geological point of view, their geotechnical role had been noted but not always explained. For this reason, we believe that our results have explained some of the discrepancies observed between fossiliferous and non-fossiliferous soils.

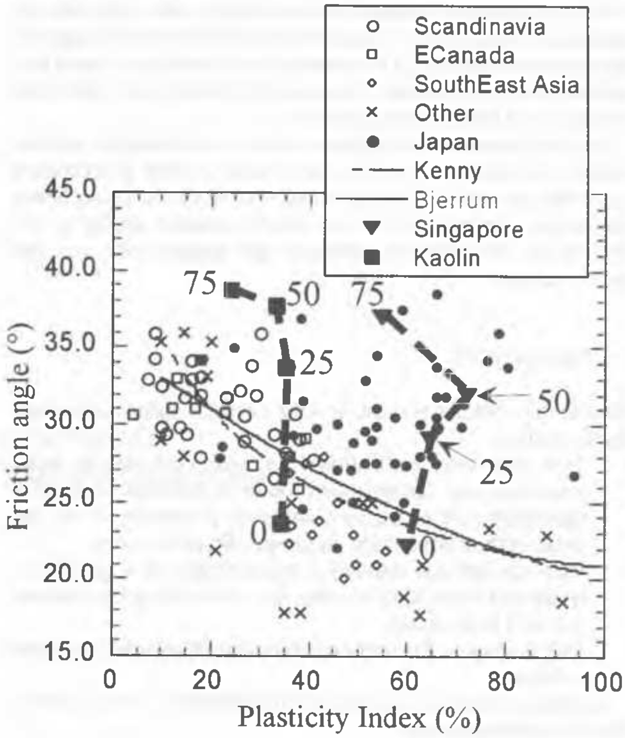

Figure 7. Effect of diatom on the measured friction angle of artificially prepared mixtures of kaolin and Singapore clay (modified after Shiwakoti *et al.* 2001).

5.1 *Measuring microfossil concentration*

One must find a way to evaluate the amounts of diatoms in a given soil in order to decide whether or not to take them into account in evaluating the geotechnical behavior of the soil. For example, from the tests results on many sample from Osaka Bay (Kansai Airport), shown in Figure 5, how much of these tests results could have been influenced by the presence of diatoms ? Shiwakoti *et al.* (2001) have explored this question and proposed a way to have a first estimate of the relative abundance of diatoms in a clay mixture. They propose to use direct counting and then estimate the concentration, by weight, using a calibrated curve obtained from artificial mixtures of kaolin and diatoms. Although this method may be seen as too simple, it did provide positive relationship between the abundance of diatoms and the resulting geotechnical properties. Various methods are available including the use of X-ray diffraction (Bareille *et al.* 1990), infra-red spectroscopy (Frohlich 1989) and chemical analysis (Kamatani and Oku 1999).

5.2 *Fossilifereous soils*

In basic soil mechanics, soil particles are consider either organic or inorganic and this terminology has been often extended to the soil itself, *i.e.* inorganic or organic soils (Lambe and Whitman, 1969). In that sense, microfossils particles are also inorganic. However, the morphological characteristics (including size), porous nature and intrinsic resistance (brittleness) of microfossils particles can be quite different from other inorganic particles. Most inorganic particle of their size (*i.e.* silt), with the exception of kaolinite, are inactive. Diatoms in particular have significant surface properties which are not expected from an inorganic particle 30μm to 100 μm in diameter! In addition, fossilifereous particles, when present in sufficient amount in a soil, will modify significantly both physico-chemical and geotechnical properties to such a point that its behavior departs from what would be expected according to classical soil mechanics. We think that the influence of microfossils is such that their role must be appreciated whenever possible. The ocean floor is covered by fossil rich sediments and, in volume, they could be much more important that any other kind of sub-aerial soils.

All these reasons are invoked to insist on taking into consideration the important role of microfossils on the geotechnical properties of soils. To ensure awareness from the geotechnical community, we believe that we should consider adding a new class of soil, in addition to inorganic and organic soils, *i.e.*: fossilifereous soils.

6 CONCLUSION

Microfossil particles present in soils have the following unique characteristics:

- They trap water and introduce a significant bias on index properties, and diatoms microfossils in particular can play a significant role on physico-chemical properties of soil because of their potentially large specific surface area.
- They can provide delayed compressibility or a sudden increase in compressibility once the yield strength of the microfossil is exceeded.
- They influence the frictional behavior of soils by their size and shape.

For these reasons, we propose to establish a new class of soils: fossilifereous soils.

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