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Indirect estimation of segregation potential based on soil index properties

Évaluation indirecte de potentiel de ségrégation basée sur des propriétés d'index de sol

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ABSTRACT

A new approach to estimate segregation potential values using the frost heave response of two reference soils is presented. The reference characteristics consist of a relationship between segregation potential at zero overburden pressure, specific surface area and average grain size of the fines fraction for two artificial soil mixtures in which the clay mineral is poorly crystallized kaolinite. The prediction of segregation potential values using the reference frost heave characteristics approach is more robust and reliable than other empirical approaches which do not specifically distinguish between clay and nonclay fines.

RÉSUMÉ

On présente une nouvelle approche pour estimer les valeurs du potentiel de ségrégation en utilisant la réponse au soulèvement dû au gel de deux sols de référence. Les caractéristiques de la référence consiste en une relation entre le potentiel de ségrégation à une pression sus-jacente nulle, la surface spécifique et la grosseur moyenne de la fraction des particules fines pour deux mélanges de sols artificiels dans lesquels le minéral argileux est un kaolin faiblement cristallisé. La prédiction des valeurs du potentiel de ségrégation en utilisant l'approche des caractéristiques de soulèvement dû au gel de la référence est moins erratique et plus fiable que les autres approches empiriques qui ne distinguent pas spécifiquement entre l'argile et les particules fines non argileuses.

1 SEGREGATION POTENTIAL OF FINE-GRAINED SOILS FROM SOIL INDEX PROPERTIES

From a phenomenological point of view, frost heave mechanics can be regarded as a problem of impeded drainage in a layered medium to an ice-water interface that exists in the frozen soil at the segregation-freezing front. Konrad and Morgenstern (1980, 1981, 1982) developed a simplified model for water migration in freezing soils and showed that at the onset of formation of the final ice lens in step-freezing tests, i.e. near thermal steady state, the pore-water velocity entering into the unfrozen soil, vu, was proportional to the temperature gradient in the frozen fringe, Grad T_f, provided that the suction at the pore-freezing front was constant.

$$v_u = \frac{P_w - P_u}{d}\overline{K_f} = \left(\frac{P_w - P_u}{T_s}\overline{K_f}\right) GradT_f = SP_o.GradT_f \qquad (1)$$

where P_w is suction at the ice lens,
P_u suction at the frost front,
K_f overall hydraulic conductivity of the frozen fringe
T_s segregation-freezing temperature
d thickness of frozen fringe

The constant of proportionality, i.e. the slope of the linear relationship between vu and Grad T_f, is defined as the segregation potential, SP_o for zero applied overburden pressure.

Konrad (1999) demonstrated that a successful approach for assessing the segregation potential from soil index properties must consider at least the following key factors:

i) grain size distribution and fines content;
ii) clay mineralogy;
iii) soil fabric;
iv) overburden pressure

The analysis of frost heave data on several fine-grained soils confirmed that the segregation potential of saturated soils with no applied surcharge, SP_o, was best related to the average size of the fines fraction (<75μm), d_{50}(FF), its specific surface area, S_s, and the ratio of the material's water content to its liquid limit, w/w_L. The relevancy of this empirical relationship is justified by the fact that frost-susceptibility is controlled by the water movements in capillary channels which can be related, however limited this may be, to an average grain size of the fines fraction and to the amount of adsorbed water, which is associated with the specific surface area. Also, given a soil, it is clear that fabric, hence grain arrangement, influences the capillary channel geometry and therefore the frost-susceptibility. Furthermore, it was also established that soil density needs to be considered in a relative manner in order to cover a wide range of soils. It was thus proposed to use the ratio of water content to liquid limit, w/w_L, as an indicator of relative soil packing. In general, when a soil is sedimented and consolidated under its own weight in a natural environment, w/w_L is about 0.7±0.1. Structured clays, such as Champlain Sea clays, may display w/w_L values much larger than 0.7, as high as 1.3, while destructured clays present w/w_L values close to 0.7.

For w/w_L of 0.7, the best-fit empirical relationship was given as:

$$SP_oS_s = [116 - 75 \log d_{50}(FF)]\ 10^3\ mm^4/(°C.s.g) \qquad (2)$$

where d_{50}(FF) is expressed in μm.

The frost heave response of quarry fines from several locations in the Province of Quebec was studied in the laboratory using one-dimensional step-freezing tests with free access to water. Figure 1 presents this relationship for both fine-grained soils given by Konrad (1999) and the quarry fines. With one exception (basalt fines), the quarry fines have representative points (open circles) that are located below the proposed relationship, which was already a lower bound value for w/wL values close to 0.7. By comparing the specific surface area of each quarry fines sample to the soils given in Konrad (1999) (Figure 2a), it appears that all fine-grained soils used by Konrad (1999) to define the proposed empirical relationship had specific surface areas of the fines fraction (d < 75 μm) larger than 30 m^2/g. The quarry fines, however, had specific surface areas less than 8 m^2/g except for the basalt fines with an S_s value of 12.6 m^2/g.

These data suggest strongly that frost-susceptibility must account for the presence of clay minerals in the soils. This is not surprising considering that the particles of most of the clay minerals are platy whereas nonclay minerals are composed of bulky shaped particles predominantly rock fragments (Mitchell 1993).

The shape of these small particles and their crystal structure influence, in turn, the unfrozen water content when the soil is frozen. As discussed by Konrad (1999), unfrozen water in a frozen soil can be partitioned into capillary water in the pores far from the soil particle surface and adsorbed water that can be considered as strongly influenced by the mineral surfaces. Water mobility in capillary channels is greater than that in the adsorbed water films, as the water molecules are strongly oriented and structured (Hoekstra 1969). As discussed above, frost heave is related to water flow through the frozen fringe, thus through the network of capillary water channels. As different clay minerals have different values of specific surface, the specific surface area of the fines fraction

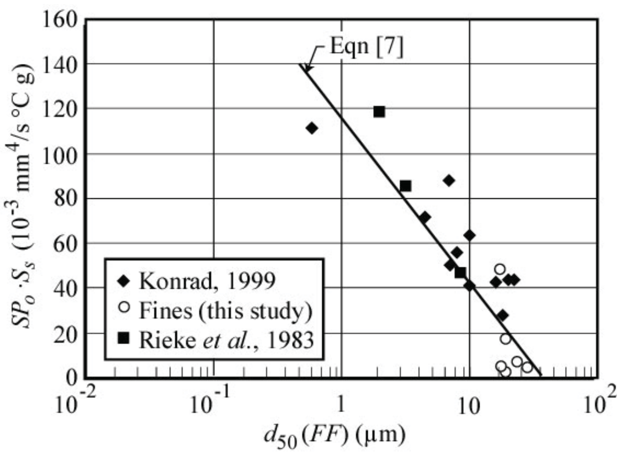

Fig. 1 Comparison of frost heave data from the quarry fines with available data from various soils.

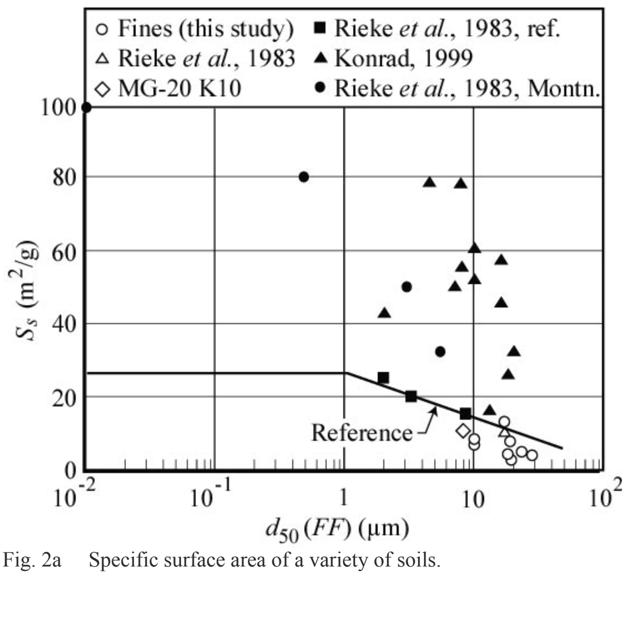

Fig. 2a Specific surface area of a variety of soils.

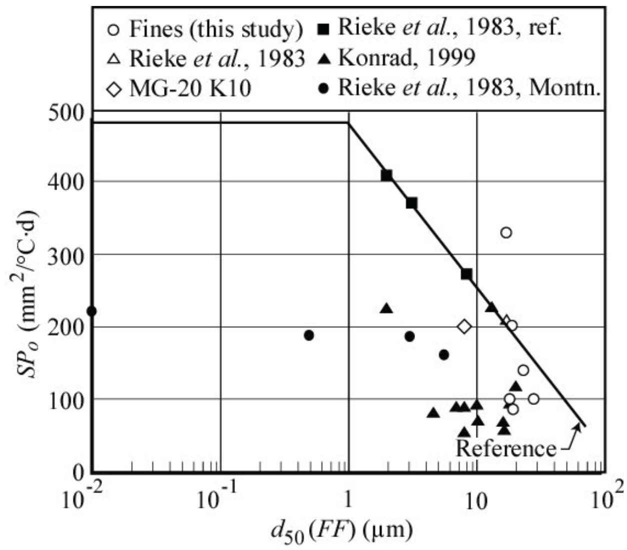

Fig 2b. Segregation Potential of a variety of soils.

can be related to the amount of adsorbed water present in the frozen soil. Increasing adsorbed water content will be associated with increasing values of specific surface. It was thus postulated by Konrad (1999) that for a given value of d_{50}(FF), the amount of capillary water was inversely related to the specific surface and that a consistent relationship between SP_oS_s and d_{50}(FF) should exist in fine-grained soils, which was indeed supported by available data.

The specific surface may also indicate, at least in a qualitative manner, the relative importance of clay minerals in the fines fraction. Data on sand-silt and clay mineral mixtures by Rieke et al. (1983) and on crushed granite- kaolinite clay mixtures (Konrad and Lemieux 2004) show that the specific surface area of fines with 10% kaolinite clay and 90 % granitic fines is 10.5 m^2/g while it is 10 m^2/g in sand–silt mixed with 25% of poorly crystallized kaolinite clay. In granitic fines with kaolinite clay fractions larger than 50%, the specific surface areas are larger than 20 m^2/g. It is thus postulated that fines in which nonclay minerals play a predominant role display generally a specific surface area smaller than about 10 m^2/g. For these soils, there is obviously less adsorbed water and the proposed relationship between segregation potential at zero overburden and index properties established for fine-grained soils in which fines are predominantly clay minerals cannot adequately be used in soils with nonclay fines.

An empirical relationship between segregration potential and index properties for soils with clay and nonclay fines using two reference soils.

A close examination of Rieke et al. (1983) frost heave data on sand/silt and kaolinite mixtures indicates that both specific surface area and average particle size increase with increasing clay mineral content. Although there is thus no clear cut between nonclay and clay fines, it is proposed to define a lower boundary for which the frost heave response is still dominated by the clay minerals in the fines. The data from Rieke et al. (1983) can be used to define this boundary since the fines composition is well known. Two sand-silt-kaolinite clay mixtures: 80Sa-10Si-10K and 80Sa-4Si-16K were choosen as reference soils. For these mixtures, the total fines content is 20% and it is thus appropriate to consider that the mixture's frost heave behaviour is dominated by the fines. Furthermore, it is also clear that with kaolinite clay fractions of respectively 50 and 80%, both mixtures will have a frost- heave response that is closer to soils with clay fines. The reference line is thus taken as a linear relationship between specific surface area and log d_{50}(FF) for d50(FF) values larger than 1 μm. For d_{50}(FF) values smaller than 1μm, the reference specific surface area is set to a constant value of 25.95 m^2/g as illustrated in Figure 2a.

The frost heave response of the reference soils is presented in Figure 2b by the solid line which gives the values of SP_o as a function of average particles size of the fines fraction. As for the reference specific surface area, the reference line for SP_o is also taken as a linear relationship between SP_o and log $d_{50}(FF)$ for $d_{50}(FF)$ values larger than 1 μm. For $d_{50}(FF)$ values smaller than 1 μm, the reference SP_o is set to a constant value of 489 $mm^2/°C.d$.

In summary, the proposed reference characteristics to be used for the analysis of frost heave response of various fine-grained soils can be summarized by the following equations:

for $d_{50}(FF) < 1$ μm: (3)
$S_{sref} = 25.95\ m^2/g$
$SP_{oref} = 489\ mm^2/°C.d$

and

for $d_{50}(FF) > 1$μm: (4)
$S_{sref} = 25.95 - 11.7 \log d_{50}(FF)$
$SP_{oref} = 489 - 232 \log d_{50}(FF)$
with $d_{50}(FF)$ expressed in μm.

Available frost heave data, given in Konrad 2005, were revisited with respect to the reference frost heave characteristics given above. The results of this analysis are summarized on Figure 3 which presents the normalized value of segregation potential, SP_o/SP_{oref}, versus the normalized value of specific surface area, S_s/S_{sref}. As discussed by Konrad (1999), it is important to consider the influence of soil density, i.e. of w/w_L, on frost heave characteristic since it affects particularly unfrozen water content, hydraulic conductivity of unfrozen soil and compressibility. The data presented in Figure 3 are thus separated into four classes:

i) soils with normalized specific surface areas smaller than 1 and with normalized water contents of about 0.7;
ii) soils with normalized specific surface areas smaller than 1 and with normalized water contents larger than 0.8;
iii) soils with normalized specific surface areas greater than 1 and with normalized water contents of about 0.7;
iv) soils with normalized specific surface areas larger than 1 and with normalized water contents larger than 0.8.

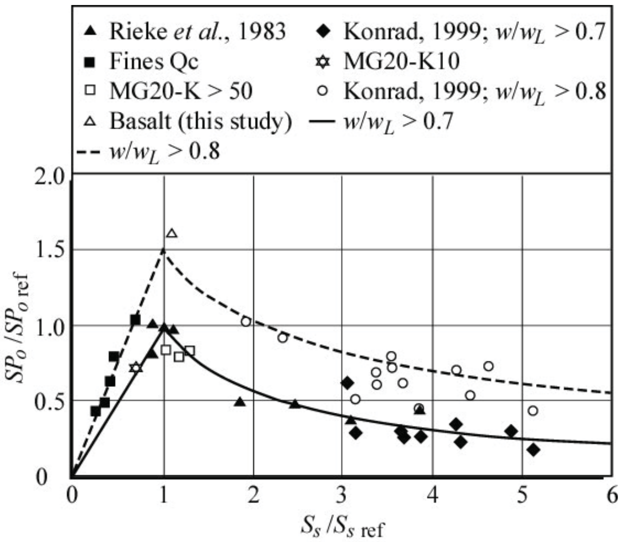

Fig. 3. Normalized segregation potential vs. normalized specific surface area.

Figure 3 establishes clearly that consistent relationships between normalized segregation potential, normalized specific surface area and normalized water content are obtained for all the data, even for nonclay fines. The following empirical relationships are proposed for characterizing the frost heave response of fine-grained soils:

For $S_s/S_{sref} < 1$: (5)

$SP_o/SP_{oref} = S_s/S_{sref}$ if $w/w_L = 0.7 \pm 0.1$
$SP_o/SP_{oref} = 0.08 + 1.42\ S_s/S_{sref}$ if $w/w_L > 0.8$

and

For $Ss/Ssref > 1$: (6)

$SP_o/SP_{oref} = (S_s/S_{sref})^{-0.85}$ if $w/w_L = 0.7 \pm 0.1$
$SP_o/SP_{oref} = 1.5\ (S_s/S_{sref})^{-0.55}$ if $w/w_L > 0.8$

2 CONCLUDING REMARKS

The frost heave response of quarry fines from several locations in the Province of Quebec was studied in the laboratory using one-dimensional step-freezing tests with free access to water. The frost heave response was quantitatively related to the segregation potential parameter defined as the ratio of water intake rate and temperature gradient in the frozen fringe close to thermal steady state. Comparison of the segregation potential values obtained from these laboratory tests with available data on fine-grained soils revealed the importance to include clay mineralogy and overburden effects in any predictive empirical relationship, especially when fines are nonclays. A new approach based on reference frost heave characteristics was thus developed to improve the relationship proposed by Konrad (1999). The reference frost heave characteristics consist of a relationship between segregation potential at zero overburden pressure, specific surface area and average grain size of the fines fraction for two artificial soil mixtures in which the clay mineral is poorly crystallized kaolinite.

The study led to the following results:

- Consistent relationships were obtained between normalized segregation potential, normalized specific surface area and normalized water content for a variety of fine-grained soils with clay and nonclay fines;
- When nonclay fines are predominant, i.e. for normalized specific surface areas less than 1, normalized segregation potential increases linearly with increasing values of normalized specific surface area;
- When the fines consist predominantly of clay minerals, i.e. for normalized specific surface areas greater than 1, normalized segregation potential decreases with increasing values of normalized specific surface area;
- For fine-grained soils with a significant fraction of nonclay fines, the influence of overburden pressure is extremely important and can, at first approximation, be related to the average particles size of the fines fraction.
- The proposed approach based on reference frost heave characteristics has been successfully applied to several well-graded glacial tills in which the fines ranged from nonclays to clays (see Konrad, 2005).
- The prediction of segregation potential values using the reference frost heave characteristics approach is more robust and reliable than the empirical approach proposed by Konrad (1999) which did not specifically distinguish between clay and nonclay fines. Furthermore, the use of normalized values of the key parameters eliminates unrealistic values when the average grain size of the fines are larger than 30 μm.

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