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Microstructure, mineralogy and physical properties: techniques and application to the Pusan Clay

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Abstract: The Pusan Clay is analyzed hereafter from a point of view of mineralogy and microstructure. Results indicate that the Pusan Clay is basically illitic in nature and that the soil microstructure reveals some characteristics which could be responsible for its brittle behavior as observed from sample disturbance. The overall analysis would tend to consider that the Pusan Clay profile analyzed here shows mechanical properties similar to well structured soils or so-called cemented soils.

Introduction

The development of coastal facilities in the Pusan area (Figure 1) has provided an opportunity to investigate the microstructure, mineralogy and physico-chemical properties of the soft sediments of Pusan Harbor. The results reported herein are of a preliminary nature since some tests are still underway. According to Kim (1999), the Pusan Clay deposit is about 30 to 50 meters thick and the sediment originates mostly from the surrounding bedrock which consist of a granodiorite. The tests results reported by Kim (1999) reveal that, from laboratory test, the soil appears underconsolidated while, from *in situ* testing, it appears normally consolidated. With this in mind, the following results will try to bring some ideas or at least some insight into the nature of the Pusan Clay so as to explain or discuss the above observation.

The Pusan Clay Deposit

The Pusan Clay deposit has been investigated in details by Kim (1999) using various sampling techniques. Results from a geotechnical investigation carried out by Tanaka (1999) are shown in Figure 2 to illustrate the changes in the mechanical properties of the sediment. As observed by others (*e.g.* Kim 1999), the clay deposit can be divided into two units: an upper unit (refer to as the Upper Layer) which has a clay content of about 50%, ending at a depth between 15 and 17 metres, and a lower unit (refer to as the Lower Layer) which has a clay content less than 45%. The liquid limit follows the change in grain size but not the plastic limit which remains more or less constant in the two layers. An important observation which has been made before is that the water content profile is nearly constant in each unit as is the liquidity index (close to unity). On the other hand, the undrained shear strength, measured with CPT increases linearly with depth more or less along a Cu/σ'_{vo} between 0.2 and 0.3. However, the undrained shear strength obtained from the vane tests is nearly constant in the Upper Layer while it increases with depth in the Lower Layer in a manner similar to the CPT test results. Finally, the overconsolidation pressure is nearly constant in the Upper Layer while it increases slightly with depth in the lower unit. Such a geotechnical profile is characteristic of what we can find for structured or cemented clays (Locat and Lefebvre 1986).

Methodology

The analyses have been carried out on intact or remolded soil specimens. Unless indicated, all analyses were carried out on bulk samples so as to ensure good correlation between physico-chemical and index properties. Basic index properties were determined at PHRI. Plastic and liquid limits were determined by Casagrande's method as recommended by the Japanese Geotechnical Society. For tests carried out at Laval, BNQ (Bureau de normalisation du Québec) and ASTM standards were used. Physico-chemical tests included: specific surface area (SSA) measured by the Methylene Blue Test (Tran 1977), organic matter content, and cation exchange capacity (CEC). X-ray diffraction analyses (XRD) were performed with Philips and Seimens diffractometers on bulk (random orientation) samples, and on clay fraction of oriented, glycolated and heated (550 °C) sub-samples. Scanning electron microscopic (SEM) investigations were carried out with a JEOL 55 with magnification up to 20 000 and on samples previously freeze-dried in nitrogen. Sample preparation similar to that of Delage and Lefebvre (1984), Lapierre *et al.* (1990) and Locat *et al.* (1996b) was used. Surfaces for SEM observations are cut while sample is still frozen. Therefore, the surface plane is controlled by the ice thus allowing for optimum view of pore network (Delage and Lefebvre 1984). This SEM is also equipped with elemental analyzers (EDAX).

Nature of Pusan Clay

The nature of Pusan Clay has been investigated by means of X-ray diffraction of the clay fraction and EDAX system coupled to the scanning electron microscope. The clay particles of the Pusan Clay were analyzed in various preparation: normal (N, oriented mounts), glycolated (G), and heated (H). As an example, results for sample depth of 5.4 and 21.4 metre are shown in Figure 3. The oriented diffraction data for all samples is given in Figure 4.

The clay mineralogy of the samples analyzed at Laval can be summarized as follows. The main clay mineral is illite with significant amounts of chlorite and vermiculite, traces of kaolinite and detectable amounts of quartz and hornblende. The chlorite is evidenced by a residual peak upon eating (with a little shift towards a lower angle). The vermiculite is revealed by a significant increase in the intensity of the illite peak upon heating at 550°C. The presence of kaolinite can be inferred from the twin peaks near $25°2\theta$. There is no detectable amount of swelling clays. The X-ray diffraction data for all depth tested herein is presented in Figure 4. Results show no significant changes with depth. Apart from the presence of mixed layered minerals, the mineralogy of the Pusan Clay is quite comparable to that of other soil derived from granitic type terrain with a wheathering process leading towards the formation of illite and kalolinite clay minerals rather than smectite (mostly derived from basaltic terrains).

As reported by Kim (1999) the activity of the Pusan Clay varies between 0.75 and 1.25 (Figure 5a). When compared to other soils, Pusan Clay would be close to Singapore clay which is also a non swelling clay but containing more kaolin than illite in the clay fraction (Tanaka *et al.* 1999). The relationship between the Cation Exchange Capacity (CEC) and the plasticity index (I_p) can be used to compare the nature of the Pusan Clay with that of other soft soils (Figure 5b). The Pusan Clay is of relatively low plasticity (less than 40%) and low CEC (15 to 20 meq/100g) and results tend to approach those of sensitive clays from Québec (Canada).

Microstructural Observations of Pusan Clay

The results of microstructural observations of Pusan Clay are presented hereafter (Figure 6). We define the microstructure as follows: the shape, size, nature (in terms of either mineral, organic or fossil remain) and bounding characteristics of the solid phase of a soil (Mitchell 1993). Observations made using the Scanning Electron Microscope (SEM) are very much subjective therefore, some rationale must be applied in order to provide adequate description of the microstructure of the soil. For example, all the SEM pictures shown in Figure 6 are at comparable magnification (see the horizontal bar at 10 μm), with a difference of 400% between the two examples selected for each layer investigated.

In the following we will first introduce the nomenclature of the building blocks and the resulting pore families. Then, we present a series of SEM pictures taken at all depths shown in Figure 2. The analysis is done here in order to compare the Upper and Lower Layers as observed above in trying to find indices leading to some explanation of the observed mechanical behavior noted in the previous sections.

General Observations on the Building Blocks

The building blocks of the microfabric include the following elements (Tanaka and Locat 1999): individual particles (see: e, p and r in Figure 6), aggregates of particles (or flocs, b) and microfossil remains (f). Single particles are often made up of a monomineral grain such as quartz (a), mica (c), pyrite (c, j), or organic debris (j, k). In describing the pore families we consider the following terminology (Tanaka and Locat 1999): inter-aggregate, intra-aggregate, skeletal and intra-skeletal. The first two categories are quite typical of most clayey soils where the pore space exists either between the aggregates and/or particles, or inside the aggregates (Collins and McGown 1974, Delage and Lefebvre 1984). The skeletal pore family represents the pore space occupying the chambers composing the microfossil skeleton (see f in Figure 6) while the interior is called the intra-skeletal pore space.

Fossil remains are not very abundant both those found are mostly part of the diatom family (f, g, h, o, and r). Framboïdal pyrite particles have been found in some places, most of the time inside microfossils (g) or inside organic debris (j, q). The aggregates (or flocs) are often composed of agglomerated (or cemented) clay size particles (usually clay minerals s(d, illite ?) which are bounded by bridges about 2 μm in thickness (b, f).

The pores consist mostly of inter-aggregate (d) and intra-aggregate families with little skeletal and intra-skeletal pores (f, o). We do not observed significant changes in the average inter-aggregate pore diameter which is between 1 and 4 μm. A more adequate description of the pore families will require further investigation by means of mercury intrusion porosimetry (*e.g.* Tanaka and Locat 1999, Lapierre *et al.* 1990).

Observations Along the Soil Profile

Upper Layer

The Upper Layer clay is represented here by 6 samples which are shown in Figure 6a to 6i). The first sample at a depth of 5.4m, presents, at low magnification (a), a well aggregated structure with aggregates about 10 to 40 μm in diameter. Also visible on the same picture are large silt grains. The portion inside the dashed area of (a) is shown in (b) to illustrate the spectacular bounding (bridging) between the aggregates. The sample at 6.4m (c) show a large crystal (biotite or mica, from EDAX analysis) which is well evidenced by the many sheets (a typical phyllosilicate !). An enlargement of the sector shown in (c) is provided in (d) to detail large aggregates composed of finer clay size particles which give them a very angular shape. In the same sample, we can see two framboïdal pyrite grains inside part of a diatom. Sample from a depth of 9.4 m show a large crystal of mica and diatom fossil debris (e and f). The enlarged section (f) shows, in its lower corner, a piece of diatom with very distinct skeletal porosity (chambers). It also presents some very angular aggregates. The sample at a depth of 11.4m contains numerous microfossil remains (about 50 μm long, Figure 6g) which are often filled with framboïdal pyrite. In the enlarged portion, it is possible to see many small bridges linking the various aggregates which appear a little thinner here than in the above samples. The sample analyzed at a depth of 13.4m (i and j) contains visible organic particles and fossil remains. Here, in (j) an organic debris is partly filled with pyrite grains. The last sample of the Upper Layer is from a depth of 15.4m. This sample contains large aggregates, silt grains and organic debris (lower left corner of Figure 6k). Bounding appears less frequent than the upper samples. Still, the particles or aggregates are very angular in shape.

Lower Layer

The Lower Layer is represented here by 3 samples from depth 17.4 to 21.4 (Figure 6m-r). As for the Upper Layer we can observe microfossil remains, particularly abundant in (o), and organic debris also filled with pyrite (q). The most striking difference here is in the views at the larger magnification: the soil samples contain less aggregates but more single silt particles. Bridging is not so well developed.

Therefore, in the search for clues showing differences between upper and Lower Layer the shape and bounding of the aggregates appear quite interesting. If one compare the larger magnification images at each depth, it can be found that the aggregates, at depth from 5.4 to 15.4m, are larger than below that depth and consist mostly of cemented clay size particles with clear bridges between them. On the other hand, from a depth of 17.4 metre, the aggregate are not so frequent and the grains appear mostly composed of single particle with little bridging. Some layer, like at 19.4 metre, showed a higher concentration of microfossils than in the Upper Layer.

Discussion and Conclusion

The above preliminary observations provide some insight into the nature of Pusan Clay. Further analysis will require access to more information on the origin of the sediments and their mode of formation and deposition. Still, considering the interesting debate about the behavior of Pusan Clay we would like to put forward some ideas.

From the data reported by Kim (1999), the Pusan Clay is a normally consolidated deposit which is very sensitive to sampling. On the other hand, it is clear from the result that the Upper Layer has many of the attributes of a "cemented" profile (Locat and Lefebvre 1986) namely: little changes in water content and strength (although CPT values show a linear increase even in this section of the profile). One explanation for this behavior would be that the Upper Layer is composed of a well structured clay with evidences of bridging and potential brittle behavior. From the geotechnical data shown in Figure 2, the depth at which the bonding strength would be overcome is at about 15 metre which corresponds also to the change in the grain size profile.

From the above observations and discussion, we would like to propose the following conclusions, which at this time, must be limited to the specific site investigated:

- The mineralogy of the clay fraction of the Pusan Clay does not show significant changes with depth, and is composed mostly of illite, chlorite and vermiculite with some kaolinite.
- The microstructure of the Upper and Lower Layer is different. The soil of the Upper Layer is mostly composed of well formed angular aggregates bounded to each other by a well develop network of bridges. The soil of the Lower Layer does not contain the same aggregates but is rather composed of a larger proportion of single particles with little aggregation, and much less bridging.
- Microfossils, mostly diatoms, appears more abundant in the Lower Layer.
- SEM observations, which have reveal a well structured soil showing some degree of brittle behavior due to the presence of bridging between aggregates, may be used to explain the sensitivity of the Pusan Clay to sampling.

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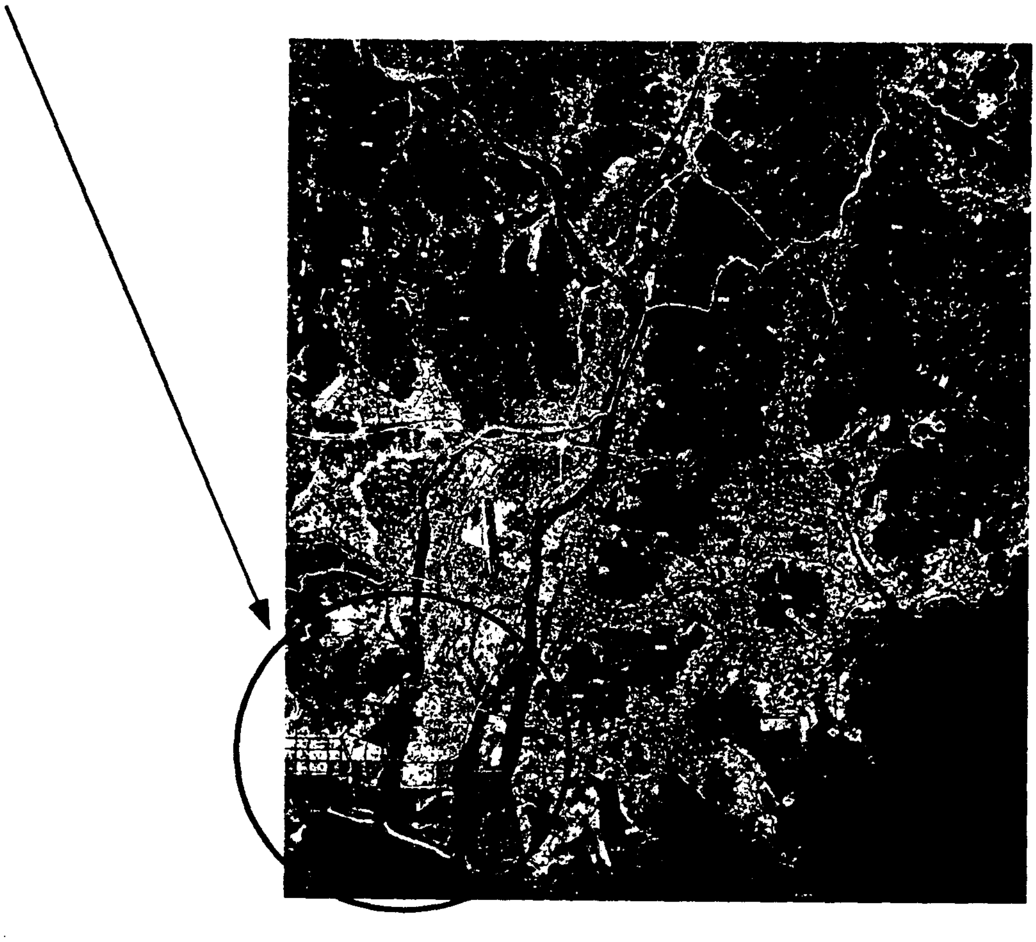
List of Figures



Approximate Location
of the Study Area near Pusan, Korea

Figure 1

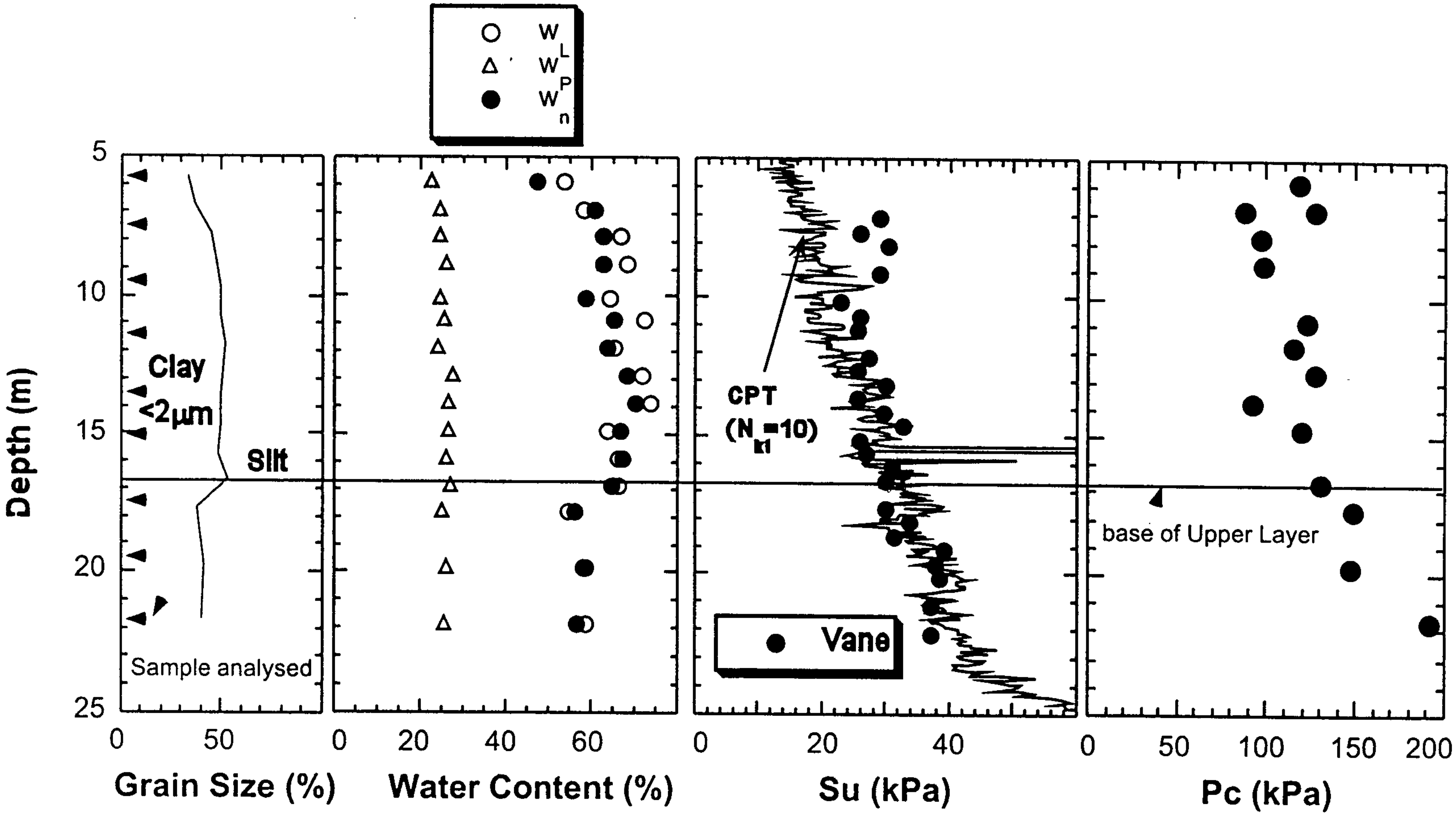
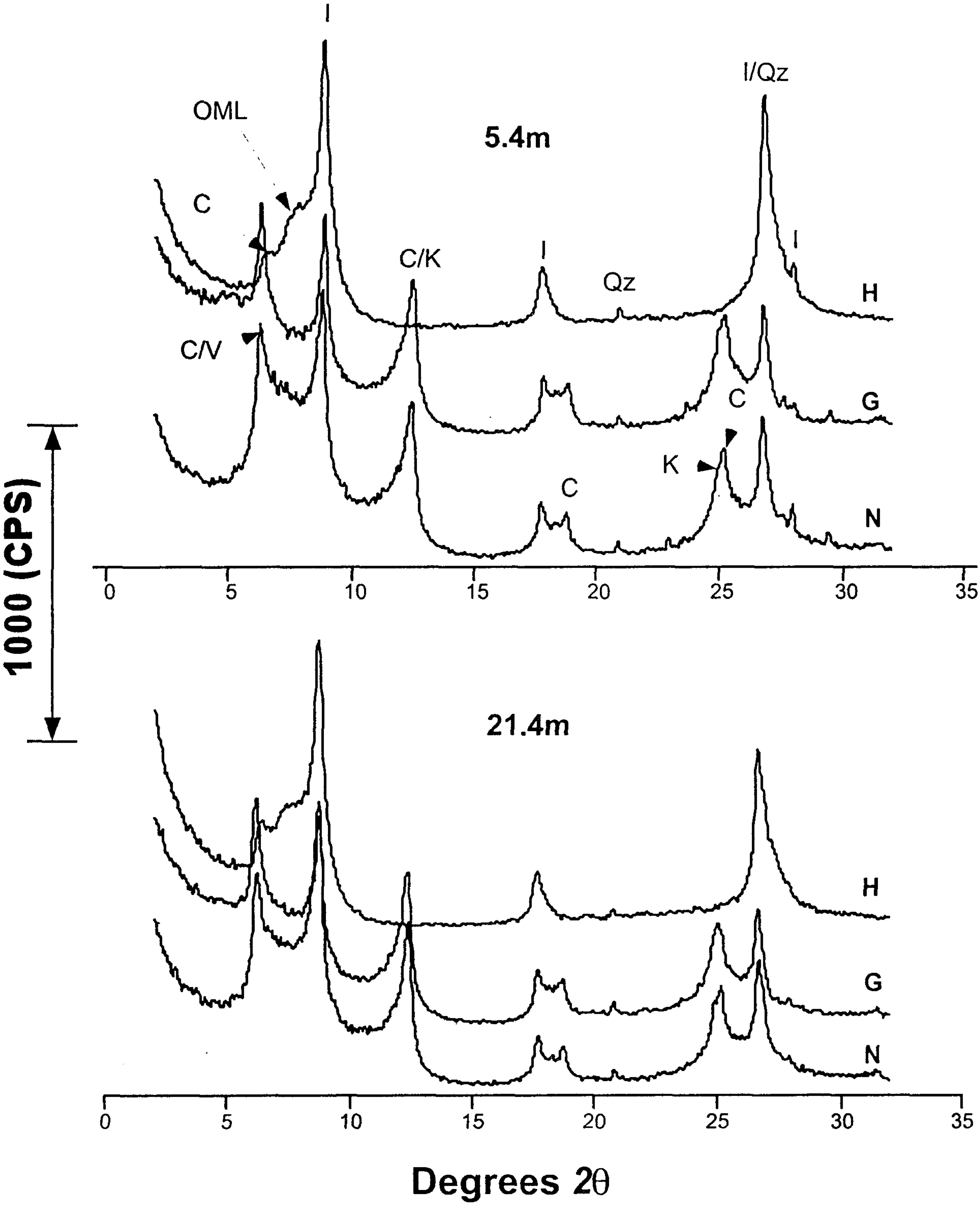


Figure 2. Geotechnical profile of Pusan Clay


5.4m
21.4m
I
I/Qz
OML
C
C/K
I
Qz
I
H
C/V
G
C
K
C
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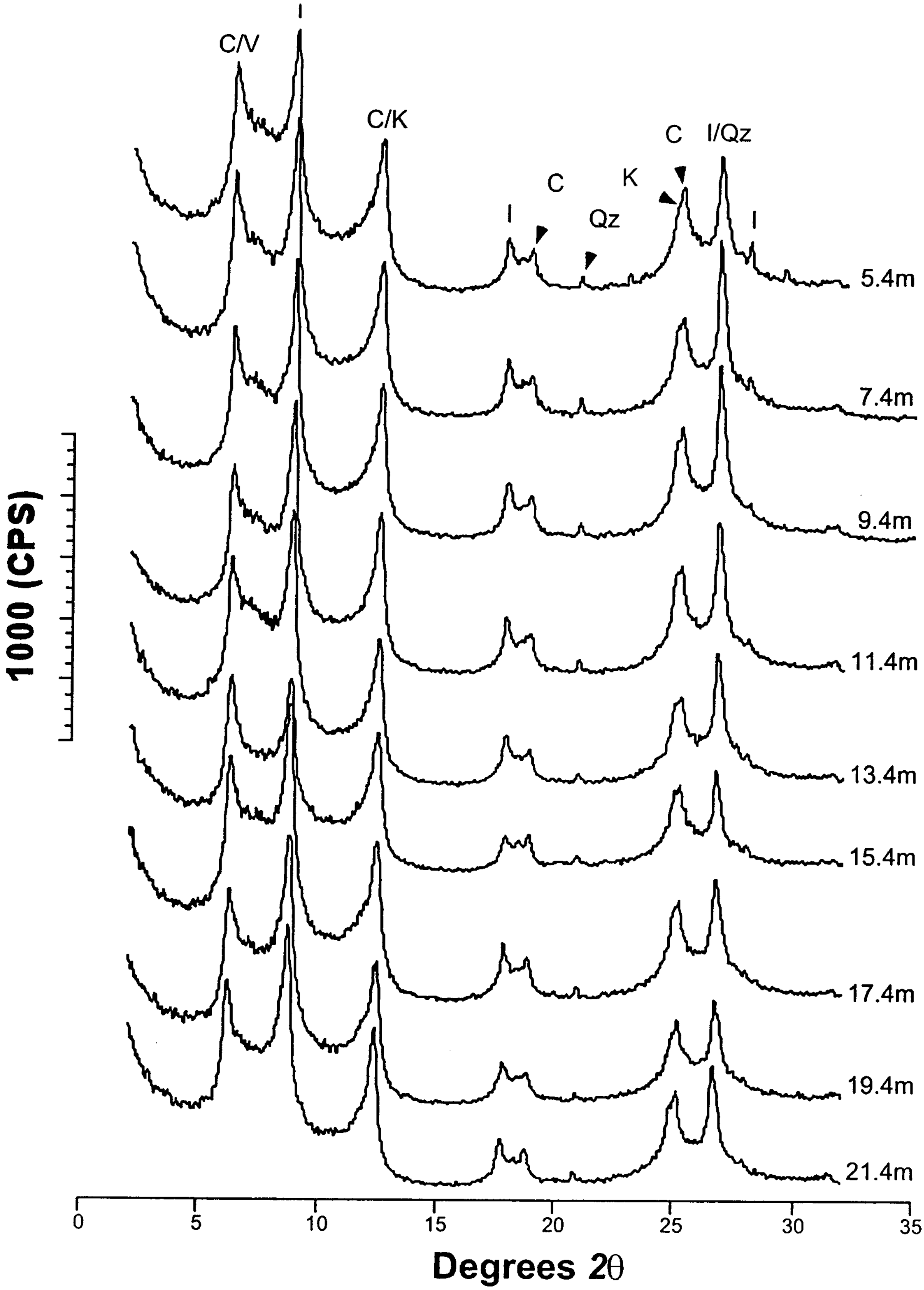
25
30
35
Degrees 2θ

Figure 3



C/V
I
C/K
C
I/Qz
C
K
I
Qz
I
5.4m
7.4m
9.4m
11.4m
13.4m
15.4m
17.4m
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Degrees 2θ

Figure 4.

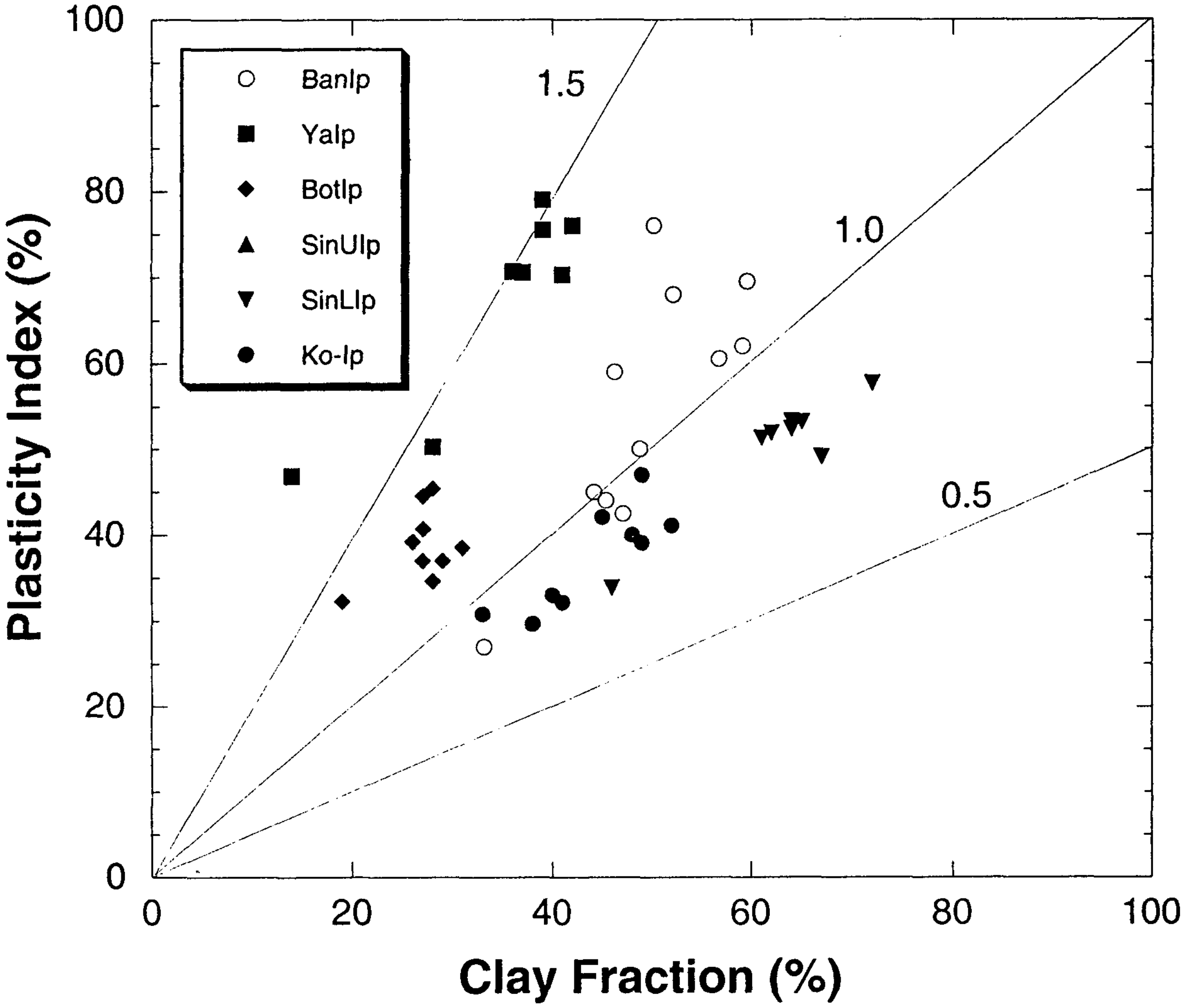

Figure 5a. Activity of Pusan Clay compared to other soils.

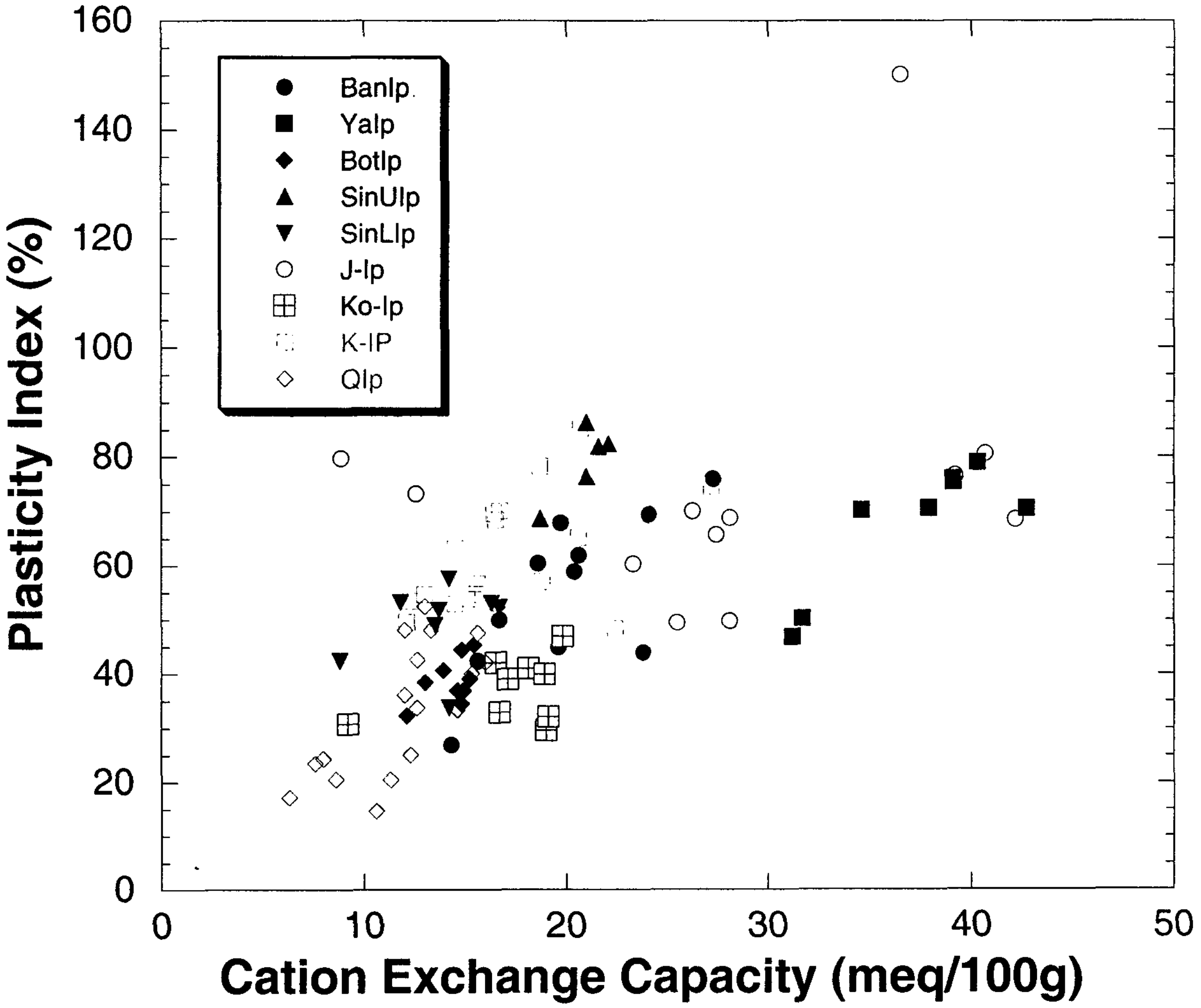

Figure 5b. Phsycio-chemical propreties of Pusan Clay comapred to other soils (Ban: Bangkok; Ya: Yamashita (Japan); Bot: Botkennar; Sin: Singapore; J: Japan clays Ko: Pusan (Korea), Q: Québec clays.

Pusan Clay (5.4, 7.4 and 9.4m)

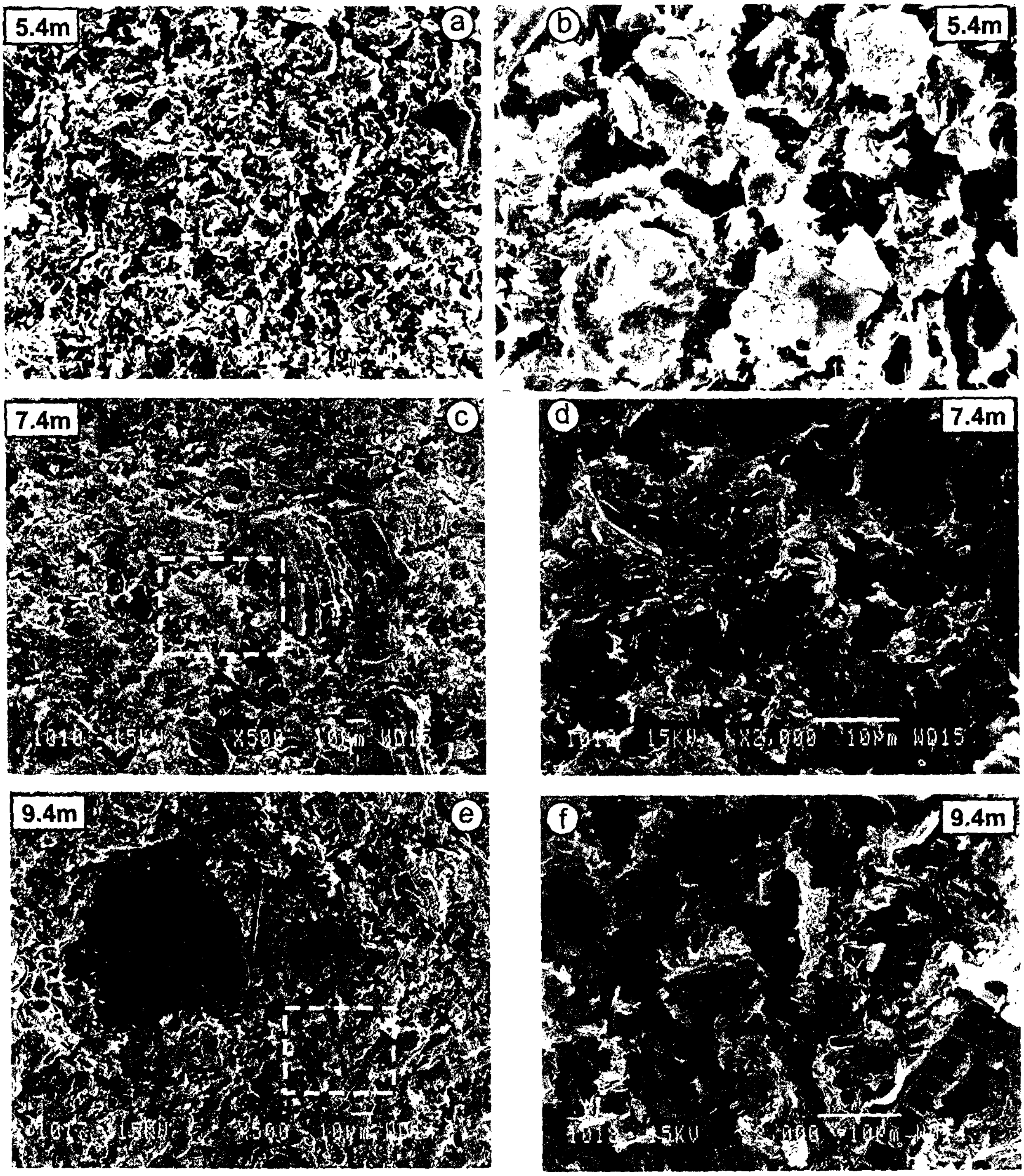

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Figure 6 a to f

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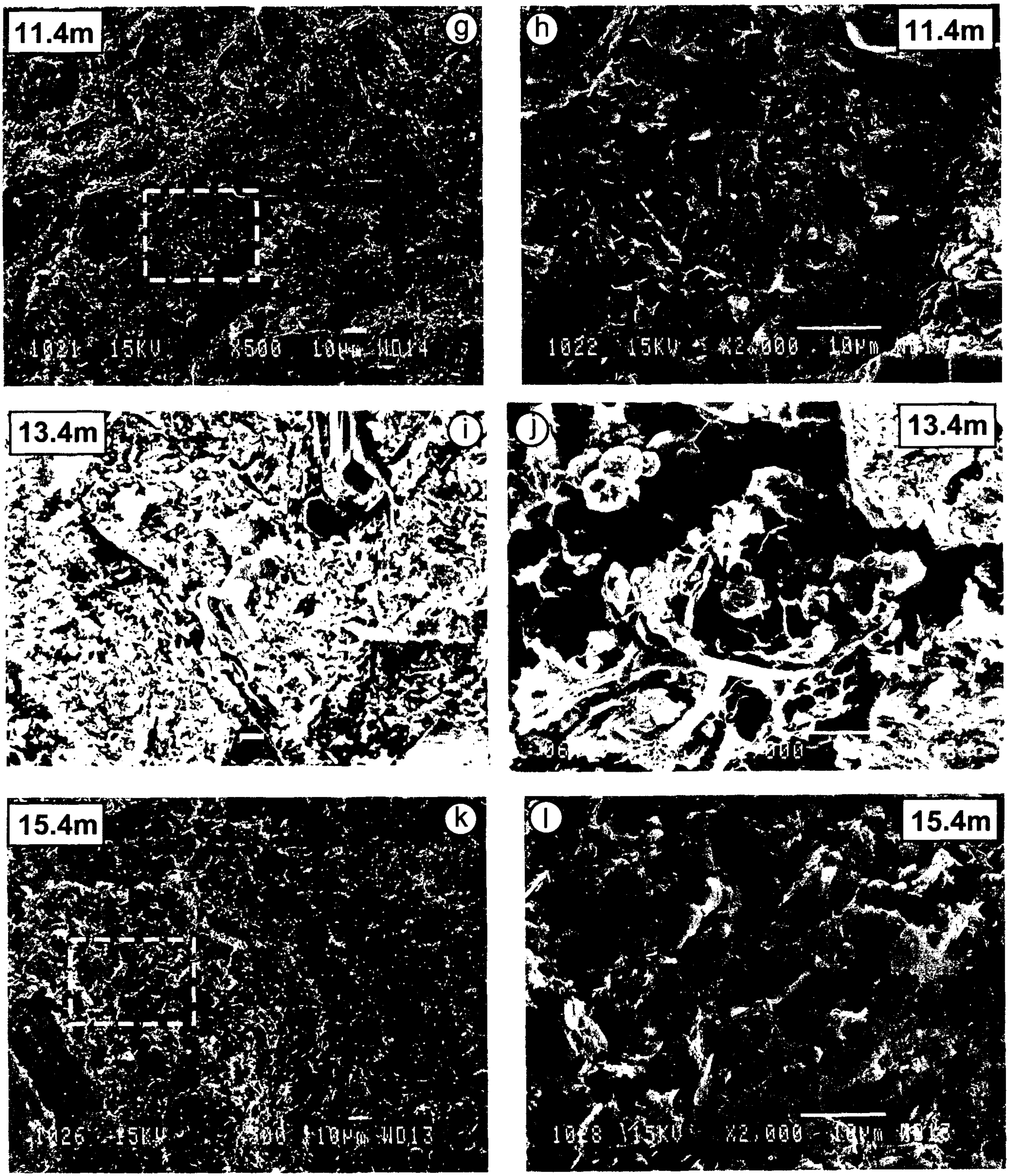
Pusan (11.4, 13.4 and 15.4 m)



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Geotechnical Engineering Division

Figure 6 g-l

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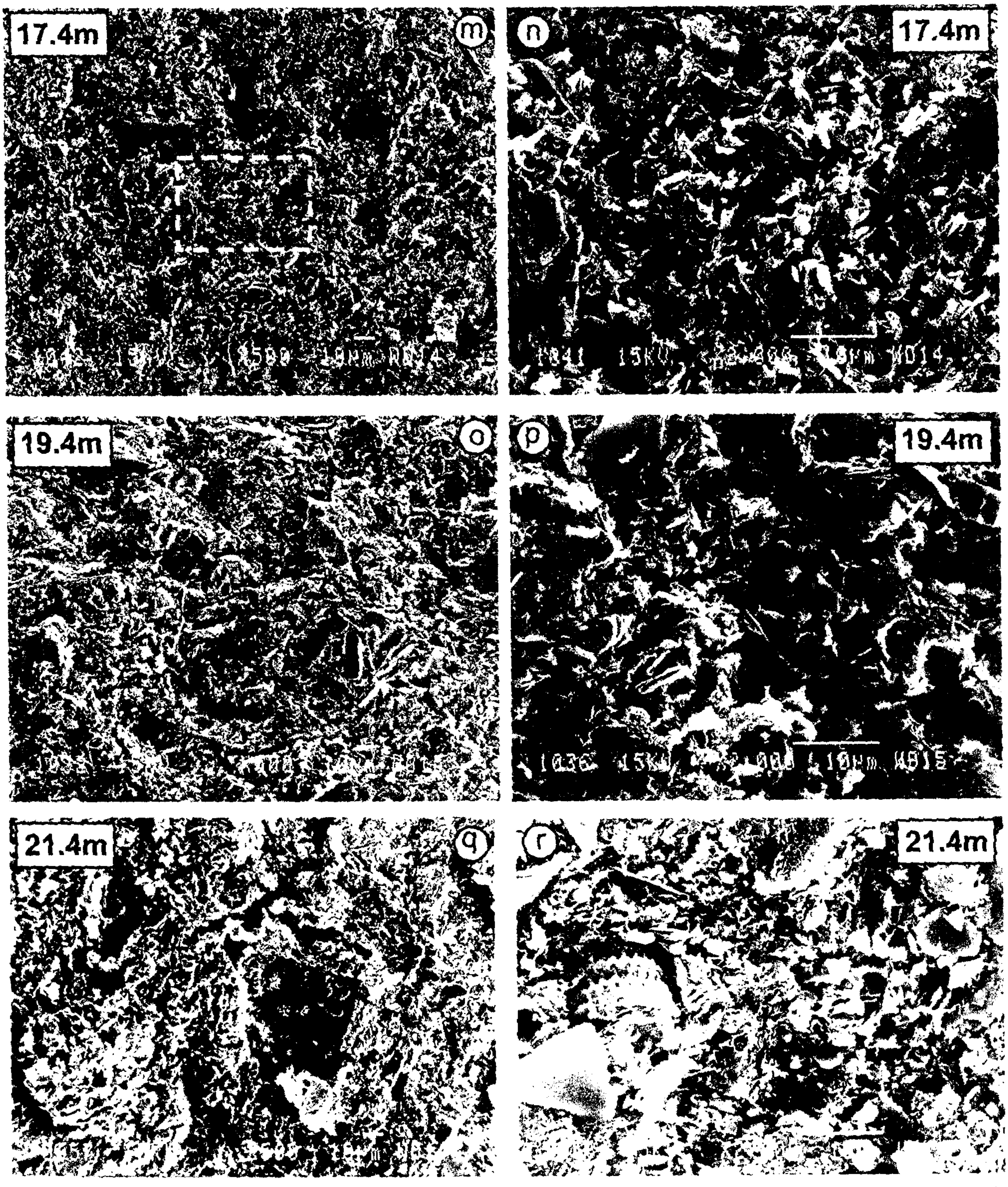
Pusan (17.4, 19.4 and 21.4m)



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