# Expansive soils engineering geological mapping: applied method in clayey soils of Montevideo, Uruguay

MARCOS MUSSO[1] & OSNI PEJON[2]

[1] *Depto. Geotecnia, EESC, Universidade de São Paulo. (e-mail: mmusso@fing.edu.uy) Depto. Geotecncia, FI, Universidad de la República Oriental del Uruguay,*
[2] *Depto. Geotecnia, EESC, Universidade de São Paulo. (e-mail: pejon@sc.usp.br)*

**Abstract:** Expansive clayey soils are widely distributed in different regions of the world and generate losses of thousands of millions of dollars per year, as a consequence of damage in civil buildings. The lack of information about the presence of expansive soils may lead to the mistake in structural foundation design, resulting in one of the factors of damage. Engineering geological mapping is a very useful tool to areas management, but an appropriate methodology does not exist for mapping expansive soils at a medium or large scale.

This research was made on clayey and clayey silt sediments of the Libertad Formation (Uruguay) and applied to a proposal method for expansive soil mapping. The following techniques were used: land evaluation by photo-interpretation and identification of different Landforms to separate homogeneous units, index tests (grain size analysis, Atterberg limits, cationic exchange capacity (CEC) using methylene blue adsorption), clay identification by X-Ray Diffraction (XRD), free swelling and pressure swelling testing of undisturbed and compacted samples (different apparent specific gravity and moisture).

Landform evaluation techniques and cationic exchange capacity analysis was a great aid in guiding the undisturbed sampling for swelling tests. Swelling potentials range from low to high for different soils. Different swelling potentials of soils were determined by association of the information of characterization tests, swelling pressures and Landforms unit from the surface down to 6 metres depth. The Expansive Potential Soil Map of suburban Montevideo city, Uruguay, is an important tool for decision-maker for area management, taking in account the different behaviour of the soils.

**Résumé:** Les sols argileux expansifs sont largement distribués dans les différentes régions du monde et produisent de milliard de dollars de pertes par année par suite de dégâts dans les travaux de Génie Civil. Le manque d'information au sujet de la présence de sols expansifs peut mener à l'erreur dans dessin de les fondation, en résultant en un des facteurs de dégât. La cartographie géotechnique est un outil très utile à gestion de ces type de région, mais une méthodologie appropriée n'existe pas pour dresser une carte des sols expansifs à moyen ou grande échelle.

Cette recherche a été faite sur de sédiments argileux et limon argileux de la Formation Libertad (Uruguay) où a été appliqué la méthode proposé pour la cartographie des sols expansifs. Les techniques ou essais suivantes ont été utilisées: évaluation du terrains par photo interprétation et identification des unités homogènes, les indices physiques du sols, courbe granulométique, limits de Atterberg, capacité d'échange cationique (CEC) par l'essai au bleu de méthylène, identification des argiles par la diffractométrie des rayoins X (XRD), gonflement libre et pression de gonflement sur des échantillons naturelles et qui ont été compacté (masse volumique et teneur en eau variables).

Les techniques de l'évaluation du terrain et de la capacité d'échange cationique ont été demontré etre de grande aide pour guider l'obtention des échantillons naturelles pour les essai de gonflement. Selon ces techniques les sols dans la region sont classifié comme de bas à haut potentiel du gonflement. Le gonglement du sols ont éte determinées par l'association des information de les essais de caractérisation, de pression de gonflement et des unité des terrains, obtenus de la suface jusqu'a 6 m de profondeur. La Carte de Potential de Gonflement du sols de la région suburbaine de Montevideo, Uruguay, est un outil important pour aider la gestion de la région.

**Keywords:** Engineering Geological Mapping, expansive clayey soils, swelling pressure.

## INTRODUCTION

Expansive clayey soils exist in many countries with arid, semi-arid and temperate climates, generating damage of thousands of millions of dollars in civil building every year (Jones and Holtz 1973, Ragozin 1994, Al –Rawas and Qamaruffin 1998). Different factors such as clay size percentage and mineralogy, structure (fabric and dry specific weight) and soil solution environment (ions in solution and degree of ion saturate) influence the clayey soil expansion composition. Other factors are caused by man when the soil is compacted, wet or dried. The studies of some of these factors were used to make engineering geological mapping of expansive soils on small scale in both Spain (Ayala et al. 1986) and the United States of America (Olive et al, 1989). However the traditional methodologies of engineering geological mapping, IAEG (1978), Grant (1972) and Sanejoud (1972), do not have specific suggested methods for expansive soils. It is necessary to develop and improve the methodology of engineering geological mapping of expansive soils at medium and large scales. This methodology should be quick, reliable and effective in identifying expansive soil and quantifying expansive potential. Terrain evaluation techniques such as photo-interpretation should be used to extend expansive properties to different landforms.

This article presents the results of the engineering geological mapping of expansive soils in Montevideo, Uruguay. Expansive soils were identified combining terrain evaluation techniques, index and expansive tests.

# BACKGROUND

Engineering geological mapping is a useful tool in making maps used in civil building projects and area management. The engineering geological map guides more detailed work of soil and rock proprieties. It contains information about geotechnical classification, foundations, water level, hydraulic conductivity and excavatability. However these methodologies do not have suitable routines to map expansive soils. Some research developed in Spain (Ayala et al. 1986) and the USA (Olive, 1989) mapped expansive soil using clay content, clay mineralogy by X Ray Diffraction (XRD), soil classification, free swelling and expansive stress test values of different geologic formations. These studies generated small scale maps (1:100.000) which can be used only as guides to identify expansive soils.

Simple identification tests are necessary to make engineering geological mapping of expansive soils. These tests should be associated with expansive factors, such as clay mineralogy, clay content, structure and moisture content. Swelling tests should be performed on different kinds of soil to show their different expansive potentials.

Remote sensing is another tool that can be used. Separate homogeneous units of Landforms are common in photo-interpretation techniques and similar landforms would have similar properties. When different landforms are identified, it is possible to orient the sampling to characterize the associated soils. If there is a relation between landforms and soil properties, it is possible to extend it and map units with different properties as expansive potential.

Another important aid is to observe the civil building to find damage in houses, highways and pipelines indicating possible expansive soils. Popcorn like structures are common in slopes when expansive clayey soils are exposed to drying and wetting. In non cultivated areas, such soils would generate micro-landforms denominated giligai, which are visible in air photographs.

This study was developed in a sub-urban and rural area of Montevideo, Uruguay (Figure 1). The geology is composed of continental clayey silt soil, clayey soil and loess deposits denominated Libertad formation (Quaternary). This unit was deposited over sandy sediments of the Raigon formation (Pliocene), marls of Fray Bentos formation, granite, gneisses and anfibolite of Montevideo formation (Precambrian) (Preciozzi et al. 1985)

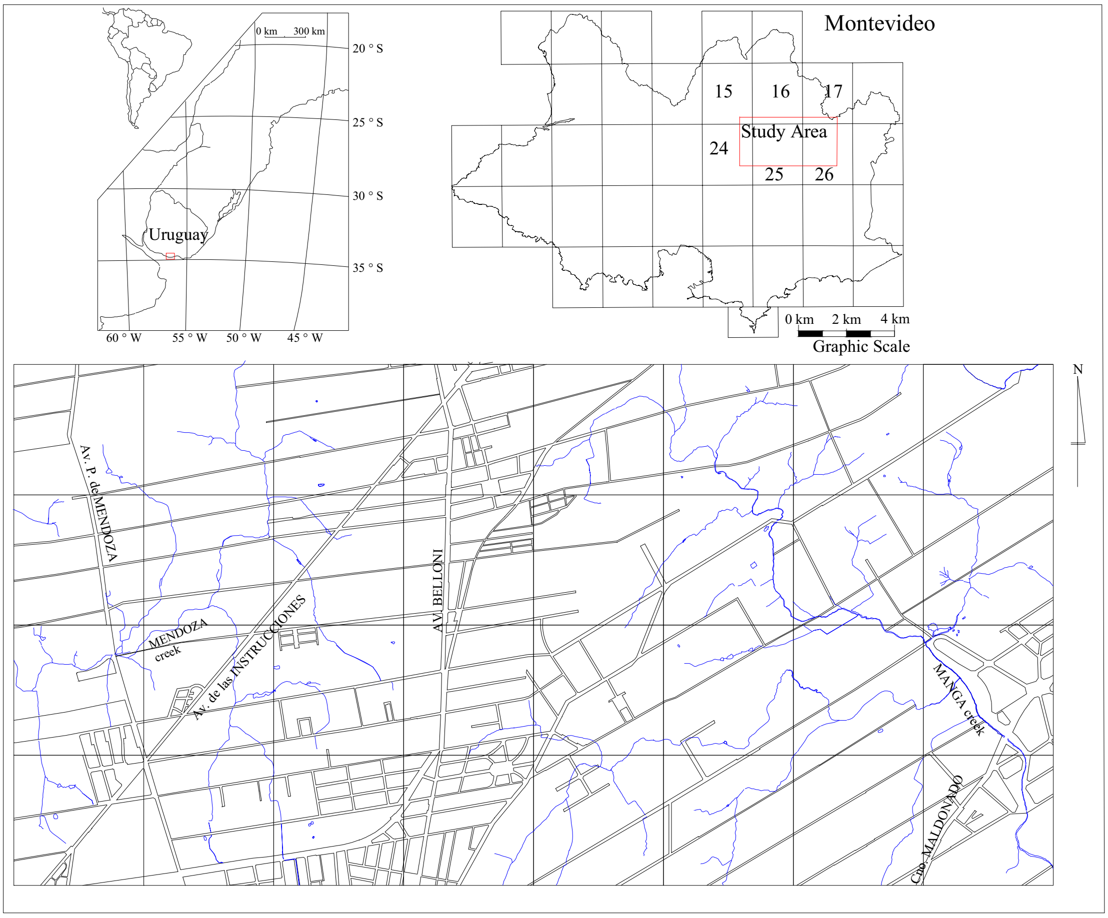



**Figure 1** Study area map of Montevideo, Uruguay

The Libertad formation is composed of fine soil, with a high content of silt and clay and low contents of sand (not higher than 15%). These soils are CL and CH, according to SUCS (Goso et al. 1993, Souza et al 1998). Nahoum et al. (1996) obtained 200 kPa of swelling pressures as the maximum. The admissible tension foundation are 100 to 200 kPa, obtained by standard penetration tests.

# MATERIALS AND METHODS

Different landforms were identified on air photographs (scale 1:10.000) using the method suggested by Lollo (1996). The photo-interpretation was verified with fieldwork and different problems were noted in houses and routes. Dried and popcorn structures were also checked. The different landforms were sampled from the surface to 6 m depth and more than 50 samples were taken. The physical properties of the soil samples were determined using the normal simple test specified in the geotechnical research. The natural water content, specific gravity (Gs), liquid limit (LL) and plasticity index (PI), granulometric size were determined according to Brazilian Standards NBR 6457, 6459, 6508, 7180, 7181, which are similar to ASTM**.**

The cation exchange capacity (CEC) and Blue value (VB) were conducted using blue methylene technique proposed by Lan (1977) and modified by Pejon (1992). The identification of clay mineralogy using X- ray diffraction by Phillips difractometers ( Cu $K\alpha$) was performed according to Brown & Bridley (1980).

Free swell and swell pressure were determined in air-dried undisturbed samples in oedometers. The swell pressures were determined by static compaction remolded samples with different specific weight. The tests were conducted according to Madsen (1999).

# RESULTS AND DISCUSSIONS

The terrain evaluation technique identified 3 Landforms systems (A ,B, C) and Libertad formation was found in the A and B systems. (see attached Expansive Potential Map).

System A has a 6 to 10 % slope and Libertad Formation's thickness is 2 to 6 metres. Granite, gneisses, anfibolite and marls are lithologies in this system. Unit A 1 has a secondary slope of 3 to 6 % and 10 to 20 %, with wavy and plane top and concave-convex and concave-plane slopes. Granite, gneisses, anfibolite and marls are the lithologies presents in this unit. Unit A 2 has secondary slopes of 10 to 20 %. Libertad Formation is at the top, is 3 metres thick and on a 0 to 3 % slope. Granite, gneisses and anfibolite are the litologies present in this unit. Unit A 3 has a secondary slope of 0 to 3 % and 6 to 10 % in similar percentages. The tops of landforms are large and Libertad formation is greater than 6 metres thick.

System B has a 0 to 3 % slope and Libertad Fm's minimum thickness is 4 metres. The precambrian rocks generated increase the slope in the border of the system. Unit B 4 has a slope of 3 to 6 % and 0 to 3 % in similar percentages. Libertad Fm.'s thickness is 4 metres but it decreases to boundaries where precambriam rocks are present. Unit B 5 has an undulated plane and round tops. Loess layers were found 0.3 to 0.5 metres thick, interlaid with silty and clayey soils. Libertad Fm's thickness is 5 metres minimum. The unit B 6 has a plane top and Libertad Fm. is 5 metres thick minimum. This landform is the water shed between Manga and Mendoza creeks. Unit B 7 has two top kinds, one is larger and plane and the other is small and wavy. The slopes are small.

System C has a 0 to 1,5 % slope and the floodplains are composed of recent sediments.

Different problems were found in houses and routes and dried and popcorn structures were observed in slopes when sampled works were performed (Figure 2).

The physical test indicated that Libertad Fm. is composed of fine soils with contents of silt and clay higher than 75 %, in all landforms unit (Figure 3).

a) b) c)

**Figure 2** Pop corn structures (a, b) and damage in building (c)

The plastic limit (PL) values are 14 to 38 %, the liquid limit (LL) values are 29 to 95 % and the plasticity index (PI) values are 14 to 71 %. More than 75 percent of the soils are classified as CH soil according to SUCS, while the rest is CL and MH. All of them are potential expansive soils according to Nelson & Miller (1992).

The CEC values of soils are 10 to 55 com /kg and the VB values are 3.3 to 17. CEC values of clay fraction are 40 to 118 cmol/kg and 80% of the samples have 74 to 118 cmol/kg. Smectites form the greatest part of the clay minerals in the soils and diferent mixtures with illite and kaolinite are present. This analisys is confirmed by XRD (Figure 4). Minerals with 1.4 nm basal spacing in the oriented aggregate method that swell to 1.6 nm under glycol treatment exist. Minerals with 1.0 nm basal spacing were found in the oriented probe and did not swelled under glycol treatment.

The clay mineralogies are different in each landform system. System A has smectite, but no illite. System B has smectite and illite mixtures and sometimes kaolinite.

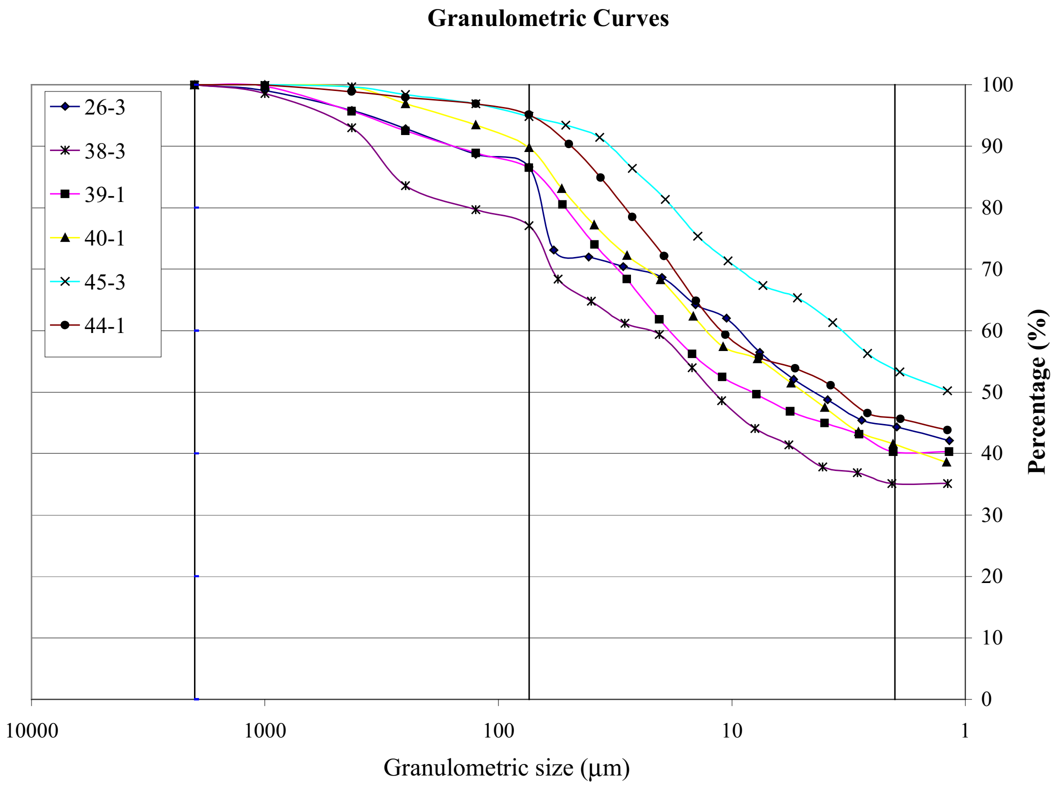



**Figure 3** Granulometric curves. System A 26, 39. System B 38, 40, 44, 45.

In different Landforms (A 2, A 3, B 5, B 6, B 7) undisturbed samples were collected. Free swell and swelling pressure were carried out with these samples. Air-dried samples (moisture between 4 to 10 %) were tested too.

Different swell pressures were determined in samples with similar CEC values, but they had different specific weight or moisture **(**Table 1, 2). Therefore, different samples with CEC values samples were tested to control these variables in order to extend the expansive potential to the landforms (Table 3). The specimens were statically compacted (14; 15.5; 17 kN/m$^3$) with a moisture content of around 15 %.

**Table 1** Free swell air-dried indisturbed samples.

| **Unit** | **Sample** | **CEC (cmol/kg)** | **VB** | **ωini. (%)** | **$\gamma_d$ (kNm$^3$)** | **Sr ini (%)** | **Free swell (%)** |
|---|---|---|---|---|---|---|---|
| A-3 | 26-4 | 43 | 13,7 | 8 | 1,75 | 32 | 27,9 |
| A-3 | 26-3 | 44 | 14,1 | 8 | 1,55 | 26 | 30,3 |
| A-2 | 39-1 | 28 | 8,8 | 7 | 1,61 | 24 | 47,9 |
| B-5 | 40-3 | 45 | 14,4 | 9 | 1,32 | 24 | 31 |
| B-6 | 45-3 | 43 | 14,0 | 8 | 1,84 | 35 | 43,77 |
| B-6 | 45-1 | 35 | 11,0 | 7 | 1,59 | 18 | 29,8 |

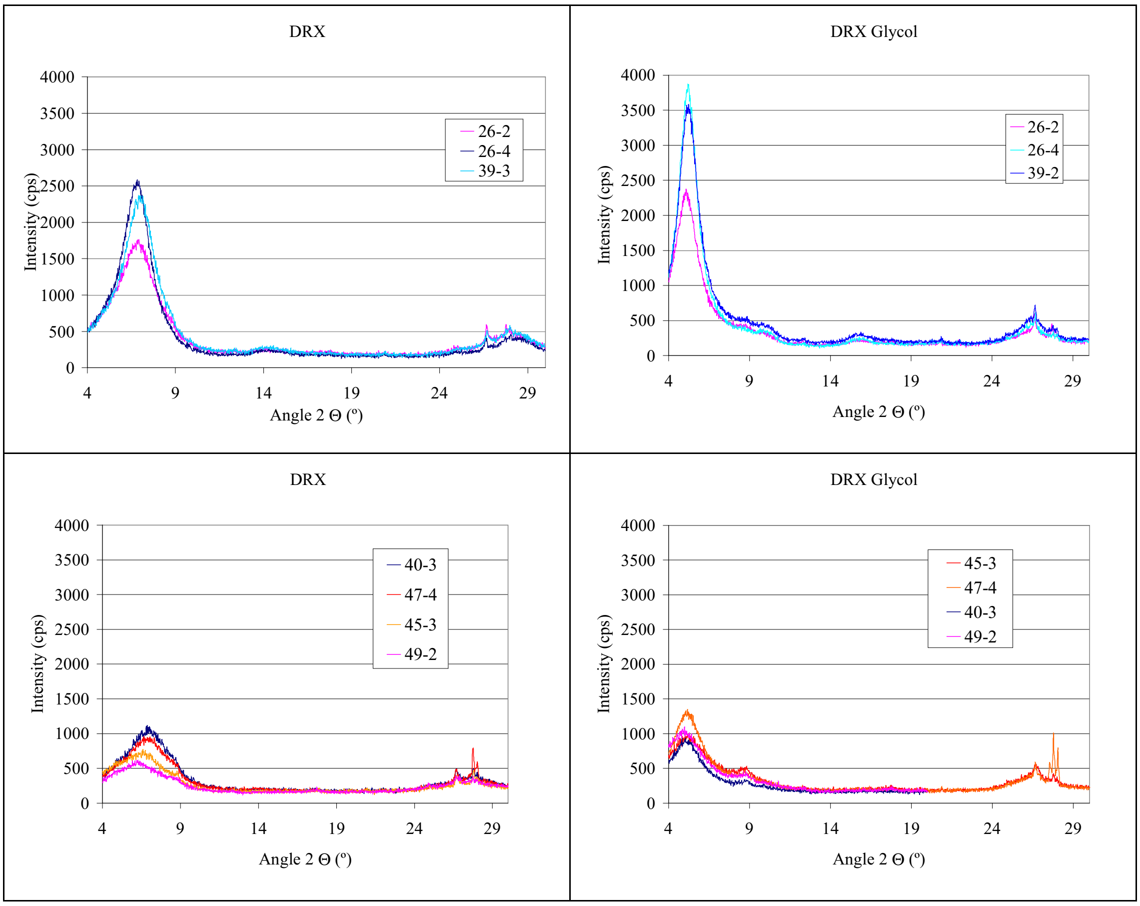



**Figure 4** X Ray Diffraction. System A (26-2, 26-4, 39-3). System B (40-3, 45-3, 47-4, 49-2)

**Table 2** Swell pressure air-dry undisturbed samples

| Unit | Sample | CEC (cmol/kg) | VB | ωini. (%) | $\gamma_d$ (kNm$^3$) | Sr ini (%) | Swell pressure (kPa) |
|---|---|---|---|---|---|---|---|
| A-3 | 26-4 | 43 | 13,7 | 9 | 1,62 | 30 | 139,6 |
| A-3 | 26-3 | 44 | 14,1 | 8 | 1,82 | 33 | 248,9 |
| A-2 | 39-1 | 28 | 8,8 | 6 | 1,67 | 22 | 133,2 |
| B-5 | 40-3 | 45 | 14,4 | 7 | 1,42 | 19 | 99,3 |
| B-7 | 44-1 | 37 | 12,0 | 16 | 1,76 | 56 | 18,7 |
| B-7 | 44-2 | 39 | 12,0 | 4 | 1,65 | 13 | 114,2 |
| B-6 | 45-3 | 43 | 14,0 | 10 | 1,70 | 35 | 476,9 |
| | 47-3 | 38 | 12,0 | 8 | 1,24 | 19 | 18,3 |

**Table 3** Swell pressure undisturbed and compacted samples

| Unit | Sample | CEC (cmol/kg) | VB | Free swell air-dried (%) | Swell pressure (kPa) | Swell pressure compacted samples (kPa) | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | $\gamma_d$ = 14 kN/m$^3$ | $\gamma_d$ = 15,5 kN/m$^3$ | $\gamma_d$ = 17 kN/m$^3$ |
| A-2 | 39-1 | 27,5 | 8,8 | 48 | 133 | 24 kPa | 75 kPa | 218 kPa |
| A-3 | 26-3 | 44 | 14,1 | 30 | 250 | 55 kPa | 201 kPa | 360 kPa |
| B-5 | 40-3 | 45 | 14,4 | 31 | 100 | nd | | |
| B-6 | 45-1 | 35 | 11 | | | nd | 118 kPa | 270 kPa |
| B-6 | 45-3 | 43 | 14 | 30 | 476 | nd | | |
| B-7 | 44-2 | 39 | 12 | | 114 | nd | | |

nd-no data

Different CEC samples generated different swell pressures when the other variables were constant ($\gamma_d$ and $\omega$). When CEC (or VB) increases, the swell pressure increases too. When CEC or VB and $\omega$ are constant, it was observed that the swell pressure grows, if $\gamma_d$ grows. A relationship exists between CEC or VB (representing clay mineralogy) and $\gamma_d$ (representing soil structure): when one of these variables increases the swell pressure increases, too. A similar behavior was observed by Seed et al (1962) in clay mixture samples when compacted in proctor conditions, although using Activity concept (PI/ clay percentage).

Such links may extend expansive potential to other samples using Pereira & Pejon (1999) chart (Figure 5, 6). Four expansive potential levels were defined (Table 4). Since the admissible tensions for foundation are 100 to 200 kPa in Libertad Fm., we have defined 75 kPa as low, 75 to 200 kPa as medium, 200 to 500 as High and greater than 500 as very high expansive potential.

**Table 4** Expansive potential levels

| Swelling pressure (kPa) | Expansive potential |
|---|---|
| < 75 | Low |
| 75-200 | Medium |
| 200-500 | High |
| > 500 | Very High |

System A has low to very high expansive potential values. The greatest part of the samples is in the medium expansive potential field followed by the samples in the high to very high expansive potential field (Figure 5). System B has low to high expansive potential values. The greatest part of the samples is in the medium expansive potential field followed by the samples in the low expansive potential field. Few samples are in the high to very high expansive potential field (Figure 6). These behaviours are in agreement with the swell pressure found for different CECs.

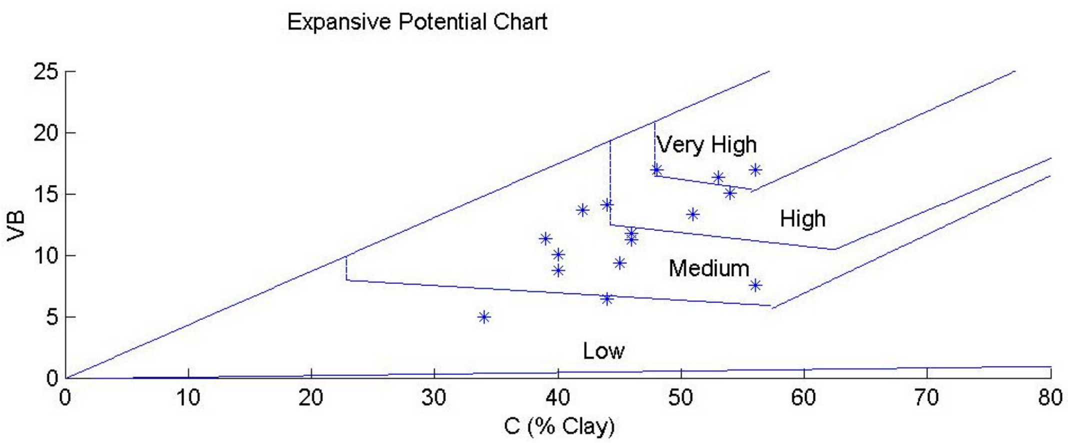



**Figura 5** Expansive potential chart Pereira & Pejon (1999) System A

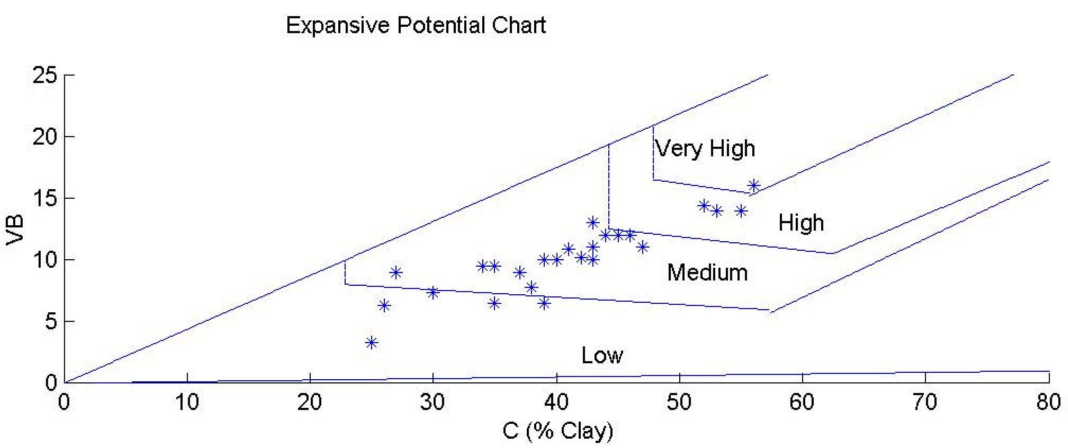



**Figure 6** Expansive potential chart Pereira & Pejon (1999) . System B

## CONCLUSIONS

Landform photo-interpretation technique is a useful tool in identifying geological units and guiding sampling in Libertad Fm., reducing time and test costs.

Blue methylene and XDR techniques allowed the identifying of clay minerals, related to swelling pressure, and allowed the identifying of different expansive potentials. These techniques were combined and were a useful tool in the engineering geology mapping of expansive soils.

Libertad Fm has different expansive potentials from low to very high. The greatest part of the samples showed a medium expansive potential, therefore it could damage houses, pipeline and routes if precautions are not taken.

The Expansive Potential Soil Map of the suburban area of Montevideo city, Uruguay, is an important tool in making decisions about area management, taking into account the different behaviours of the soils.

**Corresponding author:** Mr Marcos Musso, Depto. Geotecnia, EESC, Universidade de São Paulo, Trabalhador Sãocarlense 400, São Carlos, São Paulo, 13566-590, Brazil. Tel: +55 16 33739509. Email: mmusso@fing.edu.uy.

## REFERENCES

AL-RAWAS, A. & QAMARUFFIN, M. (1998) Construction Problems of Engineering Structures Founded on Expansive Soils and Rocks in Northern Oman. *Building and Environment* . **33 (**2-3), 159-171

AL-RAWAS, A. A.(1999) The factors controlling the expansive nature of the soils and rocks of northern Oman. *Engineering Geology* **53**, 327-350.

AYALA, F. J.; GIJON, M. F. OTEO MAZO, C. O. (1986*) Clayey expansive provisory risk map of Spain, 1:1.000.000 scale.* Centro de Estudios Experimentales (CEDEX) & Instituto Geologico y Minero de Espana. (in Spanish)

BROWN, G. & BRIDLEY,G. W. (1980) X-ray Diffaction procedures for clay mineral Identification In. BRINDLEY, G. W. & BROWN, G. eds.(1980*) Cristal structures of clay minerals and their X-ray identification*. Mineralogical Society Monograph Nº 5. London.

DE SOUZA, S; GOSO AGUILAR, C.; HAZARD, D. & NAHOUM, B. (1998) Engineering geological mapping of suburban middle área in Montevideo, 1:20.000 scale. XI Congreso Brasileiro de Mecânica de Solos e Engenharia Geotécnica, Brasilia. 537 – 545. (in Spanish)

GOSO, H.; NAHOUM, B.; BEHAK, L.; DE SOUZA, S. (1993). Engineering geological mapping of suburban área in Montevideo: Pilot model map of Carrasco-Punta Gorda (Montevideo). 7 Engineering Geology Brazilian Congress. Poços das Caldas. 201 - 221 (in Spanish)

GRANT, K (1972) Terrain evaluation. A logical extension of engineering geology. Proceedings of the 1th IAEG Congress, Paris, v2: 971-980.

IAEG (1978) *Engineering Gological Maps: A guide to their preparation*. Paris: Unesco Press. 79p.

JONES, D. E. & HOLTZ, W**.** G. (1973) Expansive soils- the hiden disaster. Civil Engineering, ASCE **43**,(8), 49

LAN, T. N (1977) Soil identification new test: blue methylene test. *Bulletin of Liaison Laboratories des Ponts et Chousses*. **88**, 136-137. (in french)

LOLLO, J. A. (1996) Evaluation terrain technique used in Engineering Gological Maps: applied to Campinas region. Thesis . Escola de Engenharia de São Carlos. Universidade de São Paulo (in Portuguese)

MADSEN, F. T. (co-ordinator) (1999) SUGGESTED METHODS FOR LABORATORY TESTING OF SWELLING ROCKS. INTERNATIONAL SOCIETY FOR ROCKS MECHANICS COMMISSION ON SWELLING ROCKS AND COMMISSION ON TESTING METHODS. *International Journal of Rocks Mechanics and Mining Science* **36**, 291-306.

NAHOUM, B.; PREFUMO, J. E.; GOSO, C.; CHAPUIS, D.; PEYRONEL, S. (1996) Light building foundation problems in expansive soils: Libertad-Dolores Formations studied case. 8 Engineering Geology Brazilian Congress. 215-226. Rio de Janeiro. (in Spanish)

NELSON, J.D. & MILLER, . (1992). *Expansive Soils: problems na practice in foundation and pavement engineering.* New York, John Wiley & Sons, Inc.

OLIVE, W.W.; CHLEBORAD, A F.; FRAHME, C. W.; SCHLOKER, J.; SCHNEIDER, R. R. and SHUSTER,R. L. (1989). *Swelling Clays Maps Of The Conterminous United States*. U. S. Geological Survey Publication. http://www:surevoid.com/surevoi_web/soil_map/co.html (06/10/99)

PEJON, O J. (1992) *Engineering Gological Maps of Piraciaba region–SP (1:100.000 scale): atribute, characterization and methodological aspects studies*. Thesis. Escola de Engenharia de São Carlos. Universidade de São Paulo (in Portuguese)

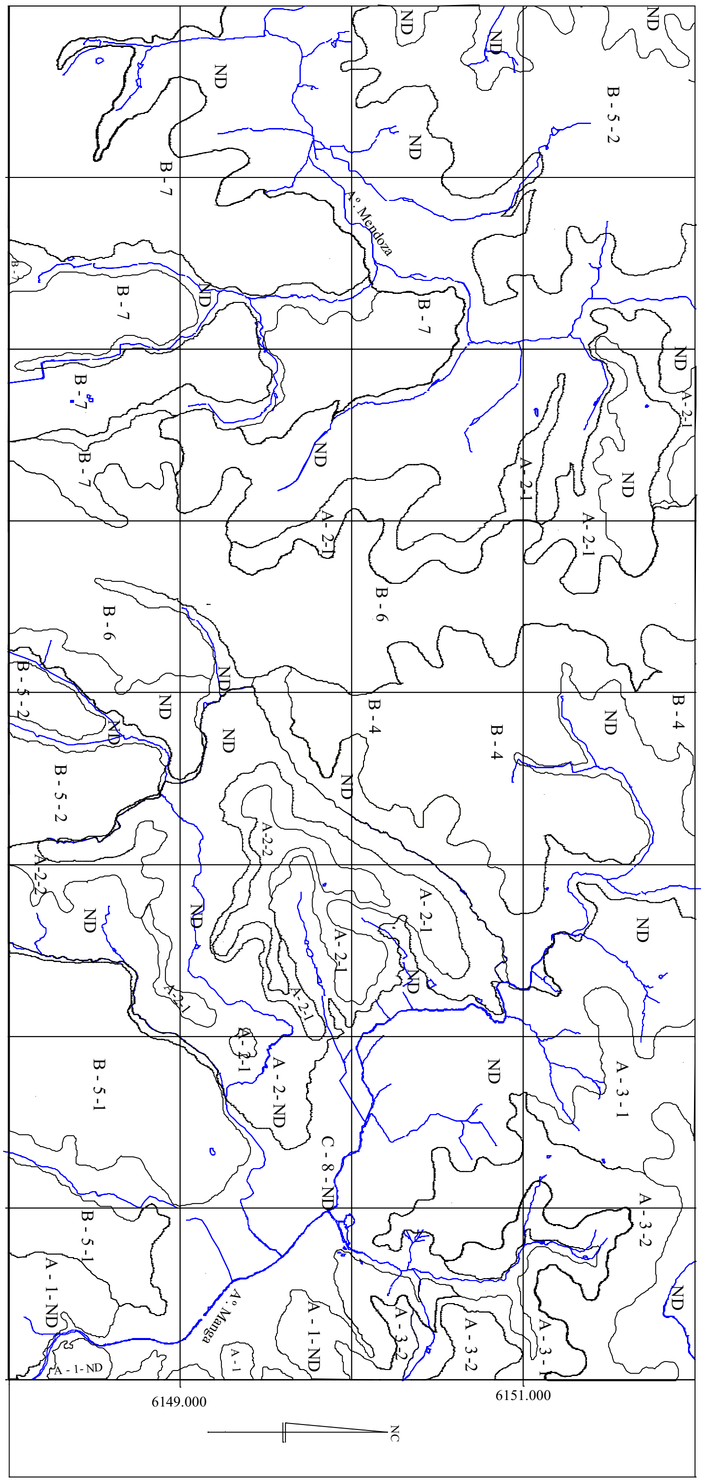
PEREIRA, E. M. & PEJON, O J. (1999) Expansive susceptibility evaluation Alto Iguaçu área -PR-Brazil. XI Panamerican soil mechanics and Getoechnical Engineering Congress, FOZ DE IGUAZU, BRAZIL, 1999. *Anais*. p.255-261. (in Portuguese)

PRECIOZZI, F. ; SPOTURNO, J.; HEINZEN, W.; ROSSI, P. (1985) Geological Map of Uruguay scale 1:500.000. Dirección Nacional de Mineria y Geologia. Ministerio de Industria y Energia. Uruguay. (in Spanish)

RAGOZIN, A L. (1994) *Basic principles of natural hazard risk assessment and management*. 7th International IAEG Congress. p.1277-1286.

SAUJENOUD (1972) *Engineering Gological Maps in France*. Paris. *Bulletin of Liaison Laboratories des Ponts et Chousse. (in French)*

SEED, H. B.; WOORDWARD, R. J. and LUNDGREN, R. (1962) Prediction of swelling potential for compacted clays. *Journal of the Soil Mehanics and Foundations Division ASCE*, **88** (3), 53-87.




Expansive Potential Map of Libertad Fm.

Legend

467.000

SYSTEM UNIT (Element)

A - 3 -(1)

ND - Not avalied Landforms constitute by Granite, Gneisses, Anfibolite, Sedimentary rock, fluvial sediments

469.000

| | |
|---|---|
| < 75 kPa | Low Expansive Potential |
| 75 - 200 kPa | Medium Expansive Potential |
| 200 - 500 kPa | High Expansive Potential |
| > 500 kPa | Very High Expansive Potential |

System A

A-1 not avalied (granite, gneisses, anfibolite, Sedimentary rock)

A-2-1 Low Expansive Potential

A-2-2 Medium to High Expansive Potential

A-3-1 Low to Medium Expansive Potential

A-3-2 Medium to High Expansive Potential

471.000

System B

B-4 Low to Medium Expansive Potential

B-5-1 Medium to Very High Expansive Potential

B-5-2 Medium Expansive Potential

B-6 Medium to High Expansive Potential

B-7 Medium Expansive Potential

473.000

0 m 1000 m 2000 m

Scale 1:10.000