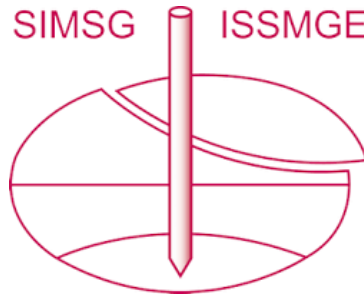


INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING



This paper was downloaded from the Online Library of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). The library is available here:

<https://www.issmge.org/publications/online-library>

This is an open-access database that archives thousands of papers published under the Auspices of the ISSMGE and maintained by the Innovation and Development Committee of ISSMGE.

The paper was published in the proceedings of the 6th International Conference on Geotechnical and Geophysical Site Characterization and was edited by Tamás Huszák, András Mahler and Edina Koch. The conference was originally scheduled to be held in Budapest, Hungary in 2020, but due to the COVID-19 pandemic, it was held online from September 26th to September 29th 2021.

Development of a Rational Methodology for Soil Geotechnical Characterization

A. Boiero

*Amundaray Ingeniería Geotécnica, C.A. /Andrés Bello Catholic University, Caracas, Venezuela,
alvaro.boiero@aig-ca.com.ve*

ABSTRACT: The geotechnical characterization of soils is essential for any geotechnical analysis. Such characterization is a complex process that begins during the subsoil exploration, continues with field and laboratory tests and culminates with the interpretation of the available data and the delimitation of sectors of the studied parcel. The development of a rational methodology for geotechnical characterization (RMGC) was based on discriminant analyzes using available data for 1169 soil samples. These analyzes were performed to differentiate the variable *soil stiffness*. As independent variables, available soil properties in routine geotechnical studies were considered. The validity of the obtained discriminant functions to predict new cases was analyzed, resulting in 81% of new cases correctly classified. A practical application of RMGC in an area of the Araya Peninsula (Venezuela) is presented. *Geotechnical zoning* and *soil behavior* drawings were constructed using geostatistical techniques.

Keywords: geotechnical characterization; soil behavior; geomechanical parameters; geostatistics.

1. Introduction

Civil Engineering and Environmental Engineering include the conception, analysis, design, construction, operation and maintenance of a great diversity of structures, facilities and systems, which are built on, in or with soils and/or rocks. In this way, the properties and behavior of these materials have a great influence on the success, economy and safety of the performed work. To properly deal with the earth materials associated with any project and/or problem, knowledge, understanding, and appreciation of the importance of geology, materials science, materials testing, and mechanics are required [1]. Geotechnical Engineering includes the above, and the subsoil geotechnical characterization is a fundamental step in this process.

However, it is important to note that uncertainty is an important factor present in the entire geotechnical environment. Unlike other Civil Engineering disciplines which deals with designed and manufactured materials (such as steel and concrete, for instance), Geotechnics must deal with a wide variety of different materials originated from complex geological processes, which are normally intermixed and with difficult to determine properties in a precisely way, because they depend on various factors (such as grain-size distribution, mineralogical composition, moisture content, variations in water table depth, history and stress level, among others). Furthermore, usually the available information is limited and imperfect in any geotechnical study [2].

In addition to this uncertain framework, it is worth noting that it is not common in practical Geotechnical Engineering, to carry out rational analysis of available data beyond the application of elementary statistical techniques (basically average and standard deviation), even when over the past five decades significant advances have been made with applications of statistical and probabilistic methods for analyzing soil variability,

as noticed by several authors [2, 3, 4]. This leads to ordinary geotechnical characterization being supported by rough estimates, based on available data and experience in similar geological conditions by the professionals involved in a given study.

On the other hand, it is important to emphasize that the rational characterization of the terrain is fundamental for understanding and determine of the subsoil geomechanical properties, from which estimates of soil strength and deformations due the action of external loads coming from structures and/or equipment are made. These estimates are directly related to the type of foundations to be implemented in a given project, which in turn is intrinsically associated with costs, schedule and general administration of resources in any engineering work.

Taking into account the above, a rational and practical methodology is proposed to characterize the subsoil, in order to identify in a rational way the presence of potentially problematic sectors for the operation of structures and/or equipment. Such methodology is based on the application of geostatistical techniques to field and laboratory data usually available in routine geotechnical studies, and also considers the macroscale soil behavior.

2. Geotechnical characterization

For civil engineers, the materials that make up the earth's crust are arbitrarily classified into two categories: *soil* and *rock*. *Soil* is an accumulation of sediments and other unconsolidated solid particles produced by the mechanical and chemical disintegration of rocks, regardless of whether or not they contain an admixture of organic constituents [5]. *Rock* is a material with a strong internal cohesive and molecular forces which hold its constituent mineral grains together [6]. For civil facilities design, understanding soil behavior is fundamental, since it will experience higher deformations than rocks

under external loads. That is why geotechnical characterization is essential for any project.

Geotechnical characterization is a complex process that begins during the exploration stage of the subsoil, continues with field and laboratory tests carried out with the purpose of estimating certain properties of the soil, and culminates with the interpretation of the available data and the delimitation of sectors of the studied land, considering the strength characteristics of the detected strata, and the expected response of these strata to external loads. Thus, one of the fundamental features of geotechnical characterization includes the zoning of the studied land, in order to identify geologically *homogeneous* units, which can cover different geological ages. Fig. 1 schematically shows the geotechnical characterization process.

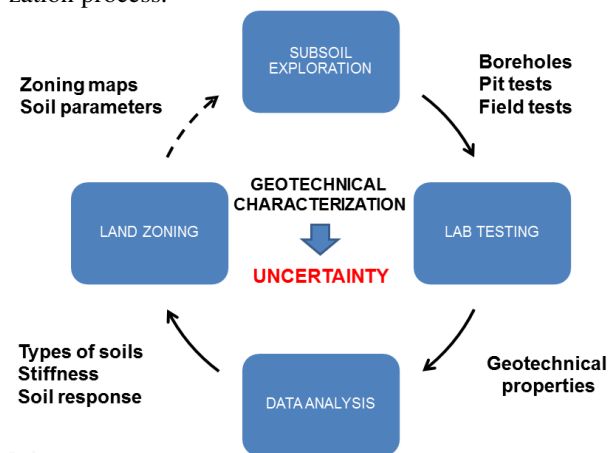


Figure 1. Geotechnical characterization process.

It must be recognized that a soil strata never are truly homogeneous. The soil properties at a site may show large local variations, yet there may be no general trends to the variations, and the average properties may be essentially the same in all portions of the site [7]. This fact is very important, because the analysis of any geotechnical problem requires the adoption of a soil behavior model, which is based on geotechnical parameters that describe the soil behavior under load-deformation conditions. These soil parameters are not known beforehand, so the Geotechnical Engineer must either measure these parameters under controlled laboratory or field conditions, or estimate them from other data [8]. In that way, the geotechnical characterization is completed by assigning representative geomechanical parameters to each sector delimited in the geotechnical zoning. These geomechanical parameters will be used in the geotechnical design of foundations, walls, pavements and earthworks in general, which form part of a project.

3. Soil behavior

The texture of soils, especially of coarse-grained soils, has some relation to their engineering behavior. For fine-grained soils, the presence of water greatly affects their engineering response. Water affects the interaction between mineral grains, and this may affect their *plasticity* (roughly defined as the soil's ability to be molded) and their *cohesiveness* (its ability to stick together). While sands are nonplastic and noncohesive (cohesionless), clays are both plastic and cohesive. Silts

fall between clays and sands: they are fine-grained, yet nonplastic and cohesionless [6].

In general, fine particles fill pore spaces between larger particles, control the permeability of soils, determine whether a given loading condition is drained or undrained, and increase the elastic and degradation threshold strain of soils. Furthermore, a relative small percentage of fines can form stable contacts between coarse grains, providing strength and stiffness to the soil. The Uniform Soil Classification System (USCS) recognizes these observations, clearly separates fines from coarse soils, capture the importance of fines in coarse soils, and even addresses whether those fines are of high or low plasticity [9]. However, it is important to point out that the presence of even a small amount of clay minerals (very small crystalline particles, less than 0.002 mm in size, very active electrochemically) can markedly affect the engineering properties of soil mass. It was recognized that as the amount of clay increases, the behavior of the soil is increasingly governed by the properties of the clay [6, 10, 11]. In that way, as a complement of the information provided by the application of the USCS, understanding the effect of the presence of clay minerals is fundamental to understanding soil behavior.

At that point, it is important to mention that such soils which behavior is strongly affected by the presence of clay minerals, for simplicity are usually called *clays*. However, we really mean *soils that contain enough clay minerals to affect their engineering behavior*. This simplification must be understood, in order to avoid confusion.

The influence of the presence of clay minerals in the soil mass behavior, was extensively studied by several authors in the last four decades. Kenney [12] postulated that residual strength of mixtures of crushed quartz and different clay minerals, are approximately equal to that of the massive mineral when the volume of massive mineral exceeds about 50% of the volume of the mixture. Lupini *et al* [13] mentioned that residual shear behavior changes significantly as the clay content of cohesive soils increases and a change in a shearing mechanism occurs. Skempton [14] indicated for the clayey soils that if the clay fraction is less than 25%, the soil behaves much like a coarse soil (sand or silt). Georgiannou *et al* [15] concluded that up to fraction of 20%, clays do not significantly reduce the angle of shearing resistance of the granular component. Pitman *et al* [16] stated that below 20% fines content, sand dominated behavior is observed. Kumar & Wood [17] found that clay matrix governs the mechanical behavior of clay-gravel mixtures when granular fraction is less than 45%. Vallejo & Mawby [18] reported that shear strength of the sand-clay mixtures would be completely controlled by the sand when fine content is less than 25%. Salgado *et al* [19] found that fines fully control soil response in terms of dilatancy and shear strength beyond 20% of content. Vallejo [20] indicated that coarser grains control the shear strength of gravel-sand mixtures when finer grain concentration is less than 30%. Biscontin *et al* [21] stated that coarse grained particles acting as rigid inclusions in a otherwise clay-water matrix, is a good approximation for fine fractions

higher than 70%; while for very small fractions less than 20% of clay particles, soil behavior is affected only by coarse grains; for 20% to 70% of fine fraction, there is a transition zone, in which the coarse particles are neither in full mutual contact, nor floating in the clay-water matrix.

In order to explain this soil behavior, the *two phase model* was adopted [10]. According to such model, the void ratio of the granular phase (e_g) can be defined as the ratio of volume of the intergranular voids to the volume of granular solids:

$$e_g = \frac{V_v + V_c}{V_g} \quad (1)$$

Where V_v , V_c and V_g are the volume of voids, clay particles and coarse particles (silts, sands or gravels), respectively. Hence, $V_v + V_c$ is the volume of the intergranular spaces. It is assumed in that model that contribution of fines (clay particles) in sustaining the internal forces is secondary if the amount of fines stays within a certain margin. Instead, the coarser grain matrix is dominant in the transfer of contact friction forces. It is also considered that at relatively low fines content, finer grain matrix in the intergranular void spaces would be highly compressible. The exception case is if the fines are located at the contact points of the coarser grain matrix, or they are trapped in the intergranular void spaces in a compacted manner. There is also the possibility for the fines not being present entirely within the pores of coarser grains, but also be lodged between them even at low fine contents, or might form a thin coating, specially if they are highly plastic [11].

Following the two phase model, saturated soils containing a mix of cohesive and granular soils can be idealized as a combination of the two phases: (1) the clay-water phase, referred as the *clay matrix*; and (2) the granular phase. Fig. 2 illustrates the model.

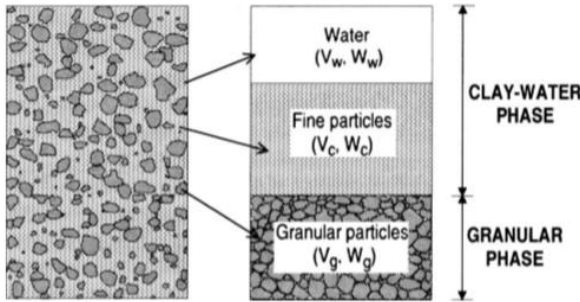


Figure 2. Two-phase conceptual model (Source: modified after [21]).

For most practical purposes, $G_c \approx G_g = G_s$, and the volumetric clay fraction f_c can be approximated by the gravimetric clay fraction FF . The void ratios of the clay-water and granular phases, e_c and e_g respectively, can be determined from the overall void ratio e and the volumetric clay-fraction, according to the following expressions:

$$e_c = \frac{V_w}{V_c} = \frac{e}{f_c} = \frac{G_s \omega}{FF} \quad (2)$$

$$e_g = \frac{V_w + V_c}{V_g} = \frac{e + f_c}{1 - f_c} = \frac{e + FF}{1 - FF} = \frac{G_s \omega + FF}{1 - FF} \quad (3)$$

From Eq. (3), if $e_g \geq 1$, that means that the clay-water phase is greater than the granular phase. In these conditions, the coarser grains behave as rigid inclusions

in the clay-water phase, and provide insignificant contribution to the overall soil behavior, which is only controlled by the clay matrix. Such behavior could be defined as *clay-like behavior*. On the other hand, if the saturated clay fraction is small, the coarser grains are in mutual contact, and the clay matrix is interlocked in the voids of the granular skeleton. In this case, the overall soil behavior is controlled by the granular phase alone, and could be defined as *sand-like behavior*. Boulanger & Idriss [22] summarize the main characteristics of sand-like and clay-like soil behavior. Table 1 shows such features, including additional information regarding textural and other characteristics of soils [6].

Fig. 3 shows relationships between e_g , e_c , ω , and FF . The figure includes information on samples published in the literature [11, 13, 21]. According to this data, it is evident that samples with higher contents of coarse grains present, in general, $e_g < 1$, which could be considered as *sand-like behavior*. It is also observed that samples with FF greater than 20% present values of $e_g > 1$, which could be considered as *clay-like behavior*. In addition, Fig. (3) shows schematical representations of soil fabric for those soil behaviors.

According to the above, from the practical point of view it can be established that for FF equal or greater than 20%, the soils will present a clay-like behavior, while for FF less than 20% the soils will present a sand-like behavior. This limit is generally consistent with what has been published in the literature regarding the influence of clay particles on soil behavior.

Considering the information presented above, it is evident the need to consider the expected behavior of the soil in order to carry out an adequate geotechnical characterization. Such consideration complements the information obtained from the soil classification according to the USCS, particularly in relation to the effect of clay particles on soil behaviour.

4. Statistical and probabilistic methods

Variations of soil properties within a geotechnical medium can be represented by descriptive statistics. Expanding the scope of this approach, it is possible to develop probabilistic models of the spatial variation of the properties of interest by considering them as random variables and fitting a probability density model to histograms obtained from sampling results to describe the random behavior of these variables. It becomes possible to resort to statistical inference, i.e. to the estimation of the general characteristics of the population based on a limited number of samples [23].

The rational methodology for geotechnical characterization was developed considering this framework. Accordingly, this section presents basic theoretical information on statistical discrimination analysis and on *kriging*, two of the techniques used in this work.

Table 1. Textural and other characteristics of soils [6, 22].

Feature	Soil		
	Gravel, sands	Silts	Clays
Grain size	Coarse grained Can see individual grains by eye	Fine grained Cannot see individual grains	Fine grained Cannot see individual grains
Texture / plasticity	Cohesionless Nonplastic Granular	Cohesionless Nonplastic Granular	Cohesive Plastic ---
Effect of water	Relatively unimportant (except for loose, saturated materials under dynamic loads)	Important	Very important
Effect of grain-size distribution	Important	Relatively unimportant	Relatively unimportant
Stress-strain behavior	Strongly dependent on its relative density (D_R) and confining stress		Void ratio highly dependent upon the effective consolidation stress and consolidation stress history
Critical state behavior	The slope of the critical state line in e vs $\log(p')$ space is different from the slope of any virgin consolidation line		The critical state line and virgin consolidation lines are approxi- mately parallel
Sampling and lab testing	Highly susceptible to disturbance using conventional sampling meth- ods Cyclic loading behavior cannot be reliably determined in laboratory		Less susceptible to disturbance from thin-tube sampling Undrained strength (S_u) can be evaluated reliably in laboratory
Field testing	SPT and CPT penetration resistance are reasonably sensitive to varia- tions in D_R Penetration tests can be correlated to various behaviors		CPT penetration resistance di- rectly related to (S_u) SPT provides only a coarse cor- relation with S_u
Characterization	Using <i>in situ</i> penetration tests and semi-empirical correlations		Using lab testing of high quality field samples and <i>in situ</i> testing

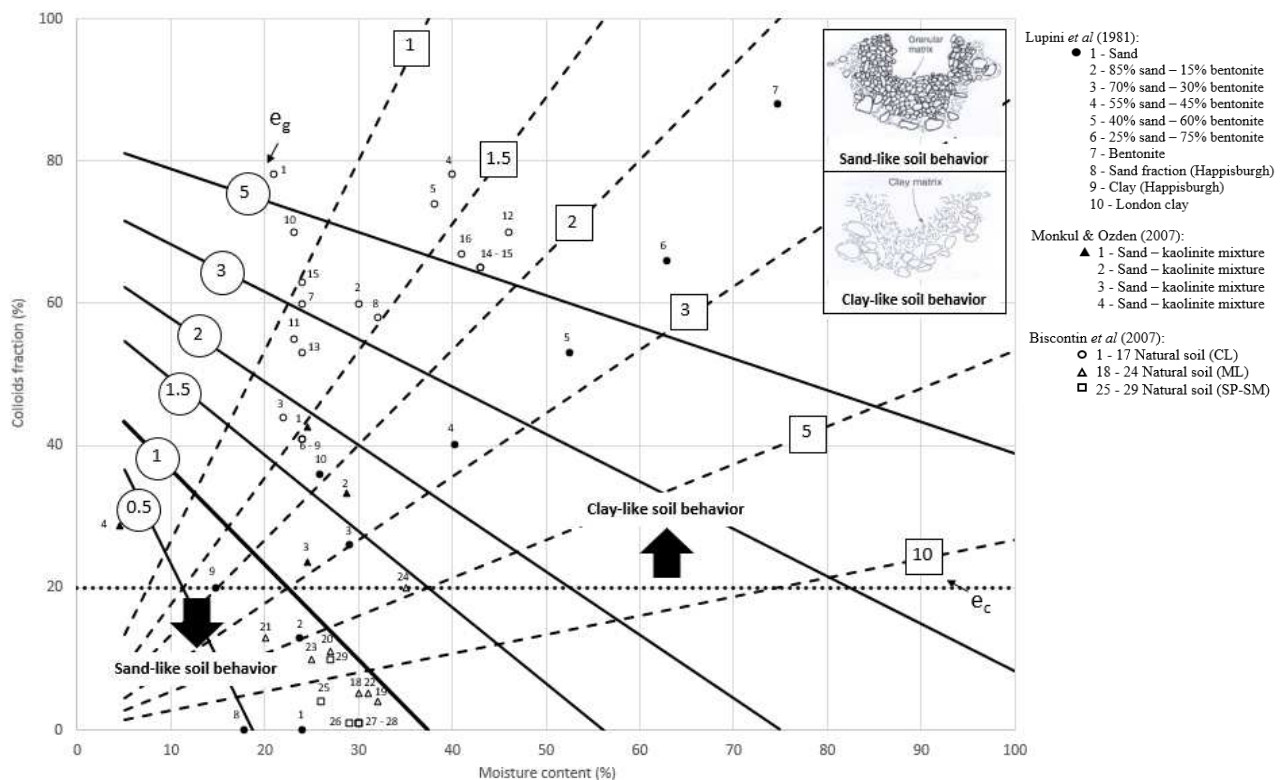


Figure 3. Relationships between e_g , e_c , w and FF (Source: modified after [13]).

4.1. Discriminant analysis

Discriminant analysis is a multivariate statistical technique from which variables that differentiate groups can be identified, as well as establishing how many of these variables are necessary to achieve the best possible classification. The ultimate goal of discriminant analysis is to obtain the linear combination of independent variables that best differentiates groups. Once the discriminant functions have been obtained, they can be used to classify new cases [24]. Discriminant function have the form:

$$D = b_1X_1 + b_2X_2 + \dots + b_nX_n \quad (4)$$

Where $b_1, b_2, \dots, b_n$ are the weights of the independent variables that make the subjects of one of the groups have maximum scores in D , and the subjects of another minimum score.

In order to carry out the discriminant analysis, it is necessary to consider several assumptions, the two most important of which are the following: (1) the matrices of covariances within each group should be approximately equal; and (2) the continuous variables should follow a normal multivariate distribution. However, the above assumptions are not usually verified in practice, because the variables usually do not have normal distributions, and most models assume equality of covariances, which is not always the case [25].

The mathematical model of the discriminant method can be revised in several references [26, 27] and papers [24, 28].

4.2. Kriging

The technique known as *kriging* [29] consists of obtaining linear estimators of minimum variance (*Best Linear Unbiased Estimation* or *BLUE*). Usually, *kriging* is applied considering that the field is wide-sense stationary (constant expected value and autocovariance depending only on the distance between the two points considered). Ordinary *kriging* can be expressed as follow:

$$V^*(X) = \sum_{i=1}^n \lambda_i V_i + [1 - \sum_{i=1}^n \lambda_i] \mu_V \quad (5)$$

Where $V^*(X)$ is the expected value as function of X ; λ_i is a weighting factor; V_i is a value of a function at the point i ; and μ_V is the field's constant expected value.

It is possible to find an unbiased linear estimator with minimal variance that requires no knowledge of the mean μ_V , by imposing the condition:

$$\sum_{i=1}^n \lambda_i = 1 \quad (6)$$

In variogram terms, the ordinary kriging system can be written as follows:

$$\sum_{i=1}^n \lambda_i \gamma_{ij} - \mu = \gamma'_{i0} \quad (7)$$

The condition expressed by Eq.(6) must be met.

The common practice in geostatistics is to calculate the values of the theoretical semivariogram and then, for reasons of calculation efficiency, subtract some constant value from them. The end result is that geostatists eventually solve the equations of ordinary *kriging* in terms of covariances, even when initial calculations are made from semivariograms.

Reference [30] includes detailed information about variograms and ordinary *kriging*.

5. Development of methodology

The rational methodology for geotechnical characterization (RMGC) was developed in four (4) different phases, which are summarized in Fig. 4 including brief information about the scope of each one.

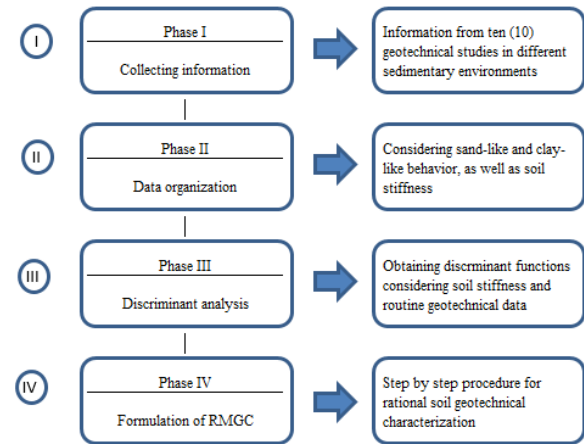


Figure 4. Phases for development of RMGC.

For the development of the RMGC, geotechnical information was available from ten (10) different grounds, located in several areas of Venezuela. Table 2 summarizes relevant information from every geotechnical study.

Table 2. Available geotechnical studies for development of RMGC.

#	Location	Number of boreholes	Depth range (m)	Sedimentary environment
1	Anaco	99	15 – 30	Fluvial
2	Barbacoa	26	14 – 30	Fluvial
3	Santa Inés	30	25 – 30	Fluvial
4	El Palito	80	14 – 30	Coastline
5	El Sitio	30	4 – 30	Fluvial
6	Guanta	23	30 – 40	Coastline
7	Araya	63	15 – 90	Coastline
8	San Joaquín	44	15 – 30	Fluvial
9	San Diego	52	8 – 20	Fluvial
10	Tucupita	29	15 - 20	Delta

From these geotechnical studies, field and laboratory information were available, including records of SPT (*Standard Penetration Test*), and results of moisture content, grain-size distribution, consistency limits, and specific gravity lab tests.

The available data was organized in such a way that it was possible to make the distinction between soils with sand-like behavior and clay-like behavior, considering as a practical criterion the amount of clay particles in the soil. Soil samples with $FF \geq 20\%$ were considered with clay-like soil behavior, while soil samples with $FF < 20\%$ were considered with sand-like soil behavior (see Section 3).

After that, the available data was organized considering the soil stiffness. For this purpose, depending on the soil behavior, the criteria proposed by Schmertmann (1975) for sand-like soils and by Szechy & Varga (1978) for clay-like soils were considered. The first criteria is based on the number of blows recorded during

the performance of the SPT and the relative density of the soils; and the second one is based on the value of the Liquidity Index (LI). These criteria are summarized in Tables 3 and 4. The mentioned tables include assigned values for soil stiffness: 1 to 5 for sand-like soils, and 1 to 3 for clay-like soils.

Table 3. Criteria to estimate soil stiffness for sand-like soils.

N _{SPT} (blows/ft)	Relative density (D _R)	Stiffness (ST)	Assigned value of ST
0 – 4	Very loose	Low	1
4 – 10	Loose		2
10 – 30	Medium	Medium	3
30 – 50	Dense	High	4
> 50	Very dense		5

N_{SPT} = blows/ft recorded during SPT.

Table 4. Criteria to estimate soil stiffness for clay-like soils.

LI (%)	Consistency	Stiffness (ST)	Assigned value of ST
> 0.50	Very soft	Low	1
0.25 – 0.50	Soft		
0.00 – 0.25	Stiff	Medium	2
-0.50 – 0.00	Hard	High	3
< -0.50	Very hard		

LI = Liquidity index = $(\omega - PL) / (LL - PL)$

ω = moisture content; PL = plastic limit; LL = liquid limit.

A total of 1,169 samples were available for this study. Once the available data was discriminated, the number of samples of sand-like soils was 243, while that of clay-like soils was 926. The discriminant analyses were carried out for the groups conformed for sand-like soils and for clay-like soils, in order to obtain discriminant functions for both soil types separately. The software SPSS 19.0.0 (IBM, 2010) was used to perform the analyses. Soil stiffness was selected as dependent variable, considering values between 1 and 5 for sand-like soils, and between 1 and 3 for clay-like soils, as showed in Tables 3 and 4. Soil properties usually determined in routine geotechnical studies were considered as independent variables, such as N_{SPT} , $Pass\#200$, FF , LL , PL , PI , ω , LI and G_s . For each variable used in the analyses, and for each soil stiffness value, statistical techniques were applied to determine the following statistical parameters: average, 95% confidence interval, standard deviation, standard error, and minimum and maximum values. In order to check whether the variables used for the analyses have a normal distribution, the Kolmogorov-Smirnov test was applied. According to this test, if the statistic Z is below 0.05, this means that the analyzed variable does not have a normal distribution. A correlation matrix was elaborated, the KMO index was determined, and the Bartlett sphericity test was carried out, in order to analyze the degree of dependence between the variables. According to these criteria, when the determinant of the correlation matrix is close to 0, the KMO index is greater than 0.7, and Bartlett's test is significant (Sig less than 0.05), the variables would be related to each other. In order to verify whether there are significant differences between the populations of the dependent variable for

the values of the different independent variables, the ANOVA analyses were carried out. This analysis is based on the F statistic, which is distributed according to the F probability model of Fisher-Snedecor. The F statistic is interpreted in such a way that if $Sig < 0.05$ the hypothesis of equality of averages is rejected and it is concluded that not all the compared population averages are equal. Finally, discriminant analyses were carried out to differentiate the stiffness of different soil samples, both for sand-like and clay-like soils. To obtain information on the significance of each quantitative variable in the discriminant function, the step-by-step inclusion strategy was considered. Once the discriminant analysis had been performed for each soil type, the discriminant soil stiffness functions were determined. Table 5 shows relevant information for the performed analyses.

According to the information shown in Table 5, the value of Sig in the Kolmogorov-Smirnov test is less than 0.05 in 75% of the cases for sand-like soils, and 90% of the cases for clay-like soils. Therefore, it can be considered that, in general, the variables used in the analyses do not have a normal distribution. This is in line with previous studies on the statistical distribution of geotechnical parameters [31].

Regarding the dependency between variables, the values of the determinant of the correlation matrix (D), KMO index and Bartlett's sphericity test show that there is some correlation between the variables. However, even when the value of D is close to 0, the coefficients of the correlation matrix generally do not come close to 1, so the existing correlations would not be of good quality. The ANOVA analyses for sand-like behavior samples, showed that the statistic F has a $Sig < 0.05$ for all variables, except for the variable G_s . Therefore, it is concluded that the averages of the distributions of the quantitative variables in each group are not equal, except in the case of variable G_s . For clay-like behavior soil samples, the statistic F has a $Sig < 0.05$ for all variables, except for the variables $Pass\#200$ and LL . So, it is concluded that the averages of the distributions of the quantitative variables in each group are not equal, except in the case of variables $Pass\#200$ and LL . It is important to mention that normality of the variables is a requirement to perform the ANOVA test. However, even though distributions of quantitative variables are not normal in most cases, the ANOVA analysis is valid due to the significant number of samples considered, as well as due to means of each group present significant differences [32]. Table 6 includes the discriminant functions obtained for each case.

In order to analyze the validity of the obtained discriminant functions in relation to their ability to analyze new cases, the classification matrix was constructed for both sand-like and clay-like soils. These matrices made it possible to determine the number of cases well evaluated by the discriminant functions. Tables 7 and 8 show the classification matrices for sand-like and clay-like soils, respectively.

Table 5. Relevant information for performed statistical analyzes.

Figure 1. Soil behavior	Statistical analyses						
	Variables		Normality of variables	Dependency between variables			Population contrast
	Dependent variable	Independent variables	Kolmogorov-Smirnov test	D	KMO test	Bartlett test	ANOVA test
Sand-like	ST	N_{SPT} , $Pass\#200$, FF , LL , PL , PI , ω , LI and G_s	< 0.05 for 75% of cases	3.52×10^{-6}	0.562	$Sig < 0.05$	$Sig < 0.05$ for 90% of cases
Clay-like			< 0.05 for 90% of cases	5.71×10^{-5}	0.550	$Sig < 0.05$	$Sig < 0.05$ for 80% of cases

ST = soil stiffness; N_{SPT} = blows/ft recorded performing SPT; $Pass\#200$ = passes by sieve #200 in a grain-size distribution test; FF = clay fraction; LL = liquid limit; PL = plastic limit; PI = plastic index; ω = moisture content; LI = liquidity index; G_s = specific gravity; D = determinant of the correlation matrix.

Table 6. Discriminant functions for sand-like and clay-like soil behaviors.

Soil behavior	Variables		Discriminant functions
	Dependent variable	Independent variables	
Sand-like	ST	N_{SPT} , $Pass\#200$, PI	$F1 = 0.129(N_{SPT}) - 0.008(Pass\#200) + 0.077(PI) - 3.809$ $F2 = 0.001(N_{SPT}) + 0.044(Pass\#200) + 0.014(PI) - 2.093$
Clay-like		N_{SPT} , $Pass\#200$, LL , PL , PI , ω , LI	$F1 = -0.021(N_{SPT}) + 0.010(Pass\#200) - 0.070(LL) - 0.019(PL) + 0.034(PI) + 0.086(\omega) - 0.013(LI) + 0.605$ $F2 = 0.006(N_{SPT}) - 0.023(Pass\#200) + 0.051(LL) + 0.238(PL) - 0.116(PI) - 0.113(\omega) + 1.228(LI) - 1.019$

ST = soil stiffness; N_{SPT} = blows/ft recorded performing SPT; $Pass\#200$ = passes by sieve #200 in a grain-size distribution test; FF = clay fraction; LL = liquid limit; PL = plastic limit; PI = plastic index; ω = moisture content; LI = liquidity index.

Table 7. Classification matrix for sand-like soils.

Item	Assigned value of ST	Predicted group according discriminant functions					Total
		1	2	3	4	5	
Counting	1	10	10	0	0	0	20
	2	9	22	10	0	0	41
	3	0	2	75	2	0	79
	4	0	0	7	31	1	39
	5	0	0	0	3	61	64
%	1	50.0	50.0	.0	.0	.0	100.0
	2	22.0	53.7	24.4	.0	.0	100.0
	3	.0	2.5	94.9	2.5	.0	100.0
	4	.0	.0	17.9	79.5	2.6	100.0
	5	.0	.0	.0	4.7	95.3	100.0

Correctly classified 81.9% of the original grouped cases.

Table 8. Classification matrix for clay-like soils.

Item	Assigned value of ST	Predicted group according discriminant functions			Total
		1	2	3	
Counting	1	173	11	33	217
	2	2	34	115	151
	3	4	2	556	562
%	1	79.7	5.1	15.2	100.0
	2	1.3	22.5	76.2	100.0
	3	.7	.3	99.0	100.0

Correctly classified 82.3% of the original grouped cases.

Table 7 shows that discriminant functions for sand-like behavior soil samples adequately classify 50% of

the cases with $ST = 1$; 53.7% of the cases with $ST = 2$; 94.9% of the cases with $ST = 3$; 79.5% of the cases with $ST = 4$; and 95.3% of the cases with $ST = 5$; for a total of 81.9% of the cases correctly classified. In the case of clay-like behavior soil samples, Table 8 shows that discriminant functions adequately classify 79.7% of cases with $ST = 1$; 22.5% of cases with $ST = 2$; and 99.5% of cases with $ST = 3$; for a total of 82.3% of cases correctly classified.

According to above, it is possible to affirm that, in general, although the variables under consideration do not meet the normality requirement to carry out the discriminant analyses, they are considered valid for two main reasons: (1) the averages of each stiffness group present significant differences, which allow differentiate them; and (2) the fact that obtained discriminant functions correctly classify more than 81% of the cases.

Finally, it is worth mentioning that due to determined discriminant functions were obtained using data from routine geotechnical studies developed in many different sedimentary environments, these functions are valid for soils located in all types of geological settings. In addition, this statement is supported by the fact that in all geotechnical studies, field and laboratory tests involved in discriminant functions are routinely performed, regardless of the geological environment or the location of the area to be studied (on land or offshore).

6. Formulation of RMGC

The rational methodology for geotechnical characterization (RMGC) is based on the discriminant functions obtained for sand-like and clay-like soils. The results of the performed discriminant analyses will constitute characterization factors: C_1 and C_2 for sand-like soils; and F_1 and F_2 for clay-like soils. Graphs of relationships between those factors were prepared, in order to classified new cases depending on the values of such factors. Those graphs are showed in Fig. 5 and Fig. 6, which include the functions to determine characterization factors.

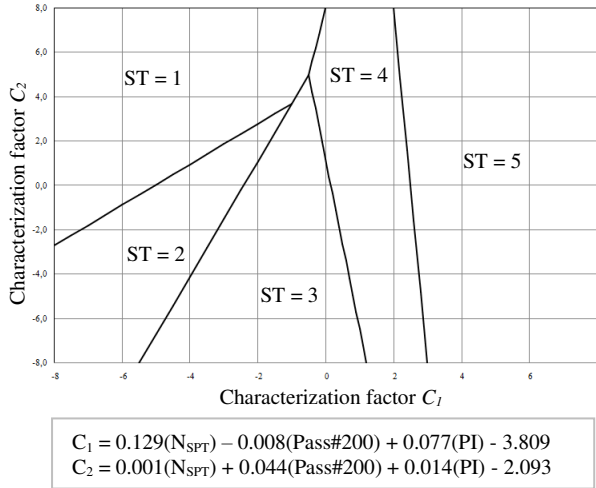


Figure 5. Characterization factors graph for sand-like soils.

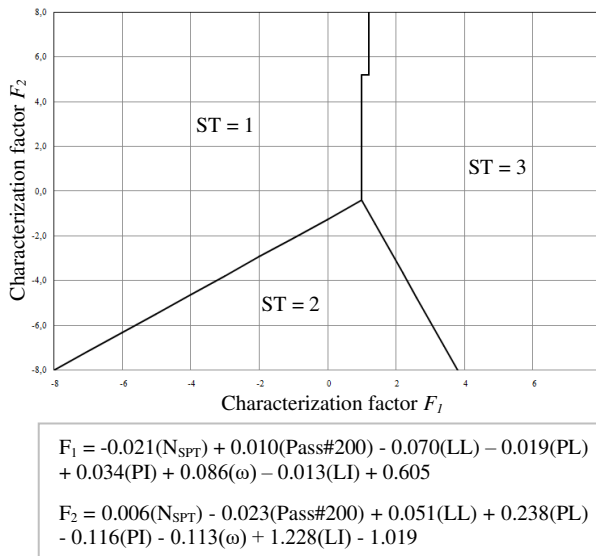


Figure 6. Characterization factors graph for clay-like soils.

Thus, given a soil sample, the values of C_1 and C_2 or F_1 and F_2 (depending on their expected behaviour) are determined. Then, these values are plotted in the graphs shown in Fig. 5 or Fig. 6 (as appropriate) and, depending on the location of the resulted point in the graph, a stiffness value is assigned.

The following is a step-by-step RMGC, based on information available from routine geotechnical studies:

1. Identify the different strata detected in a borehole, and assume that the properties determined in the samples obtained from a given stratum are representative of the entire

stratum (this is a common practice in Geotechnics, since not all samples are tested, but only some representative ones).

2. For each defined strata, consider the following:
 - If the soil has $Pass\#200 \geq 50\%$ (silt or clay), and a grain-size analysis is not available, assume $Pass\#200 = 51\%$.
 - If the soil has $Pass\#200 < 50\%$ (sand or gravel), the FF value is significant when $FF \geq 20\%$. Thus, if a hydrometer test is not available, it is needed to verified that $Pass\#200$ is less than 20%; if this occurs, the effect of the fine fraction is not appreciable in the soil behaviour.
 - If the soil sample is non-plastic (NP), $LL = 1$ and $PL = 0$ must be assumed. These values correspond to soils located in the lower left sector of the Casagrande Charter for fine soils, with little or very low plasticity.
 - For soils in which it was necessary to advance drilling by rotation (very hard or very dense soils), assume a value of $N_{SPT} = 100$ blows/ft.
3. From performed laboratory tests, determine whether the stratum presents a sand-like or clay-like behaviour.
4. Determine soil stiffness for all available soil samples using the characterization factors C_1 and C_2 for sand-like soils, and F_1 and F_2 for clay-like soils.
5. Group the data relating to soil stiffness and soil behaviour as considered appropriate (it can be, for example, meter by meter; or for significant strata detected in the ground, depending on the criteria of the Geotechnical Engineer).
6. Generate the *Geotechnical Zoning Map*, using geostatistics (for instance, *kriging*). For this, any available software in the market can be used. This map will allow to identify sectors of the ground with different stiffness.
7. Generate a *Soil Behavior Map*, also using geostatistics. This map can easily be superimposed on the previous one and thus identify sectors of the ground that present sand-like or clay-like behavior, with its corresponding stiffness.

It is worth mentioning that the application of the proposed methodology requires a carefull reviewing and systematic organization of field and lab data. In addition, it should be noted that the developed methodology constitute a tool that supplement, but does not substitute, traditional interpolation criteria based on geological evidences, and in particular geomorphology and sedimentology.

Using this practical methodology, zoning and soil-behavior maps will be generated, which will allow to make an evaluation of the probability of reaching or exceeding locally some extreme conditions that could be critical for the project under study.

7. Practical application of RMGC

This section will illustrate the application of the RMGC in a practical case. The study area is located in the Northeast of Venezuela, in Sucre State, specifically in the Araya Peninsula, between Punta La Playa and Punta Peñas Negras, close to the towns of El Guamache and Taguapire, in Cruz Salmerón Acosta Municipality. Its limits in UTM coordinates are the following: Northern Limit: 1.177.500, Eastern Limit: 387.000, Southern Limit: 1.176.000, Western Limit: 384.500.

Between 2009 and 2012, geomorphological, surface geological, and geotechnical studies were carried out. In this section, information corresponding to the mentioned studies is included.

From the geological point of view, in the study area the presence of three well-defined geological horizons stands out, represented by sediments of marine origin with a terrestrial influence, recent sediments of Pleistocene age that define the Coche Formation, and, finally, a metamorphic basement constituted mainly by schists and quartzite of the Manicuaire Formation. Fig. 7 shows a view of the geological map of the explored ground.

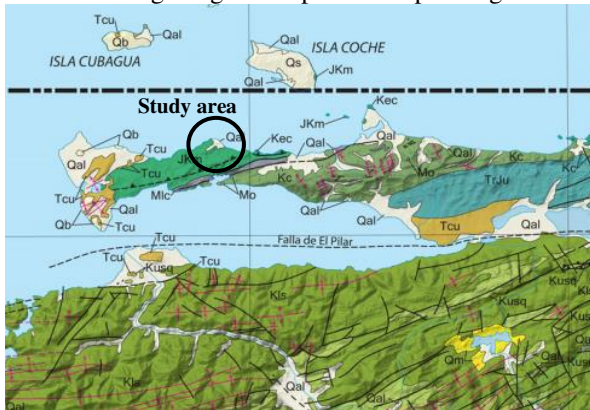


Figure 7. Location of study area. Practical application of RMGC.

Geomorphologically, the project area encompasses two well-defined sectors: a flat sector that constitutes the exit mouth of the creek Playa de Róbalo (that is Róbalo beach); and surrounding elevations that do not exceed 250 meters in height, with rounded shapes. The valley of Playa de Róbalo can be differentiated between the following sectors: (1) continental valley, (2) fluvial-maritime valley, and (3) maritime sector. Fig. 8 shows a photograph of the study area, with approximate location of mentioned sectors.

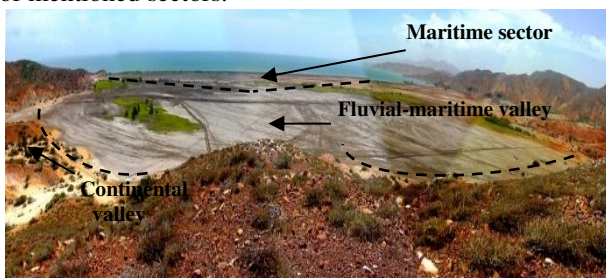


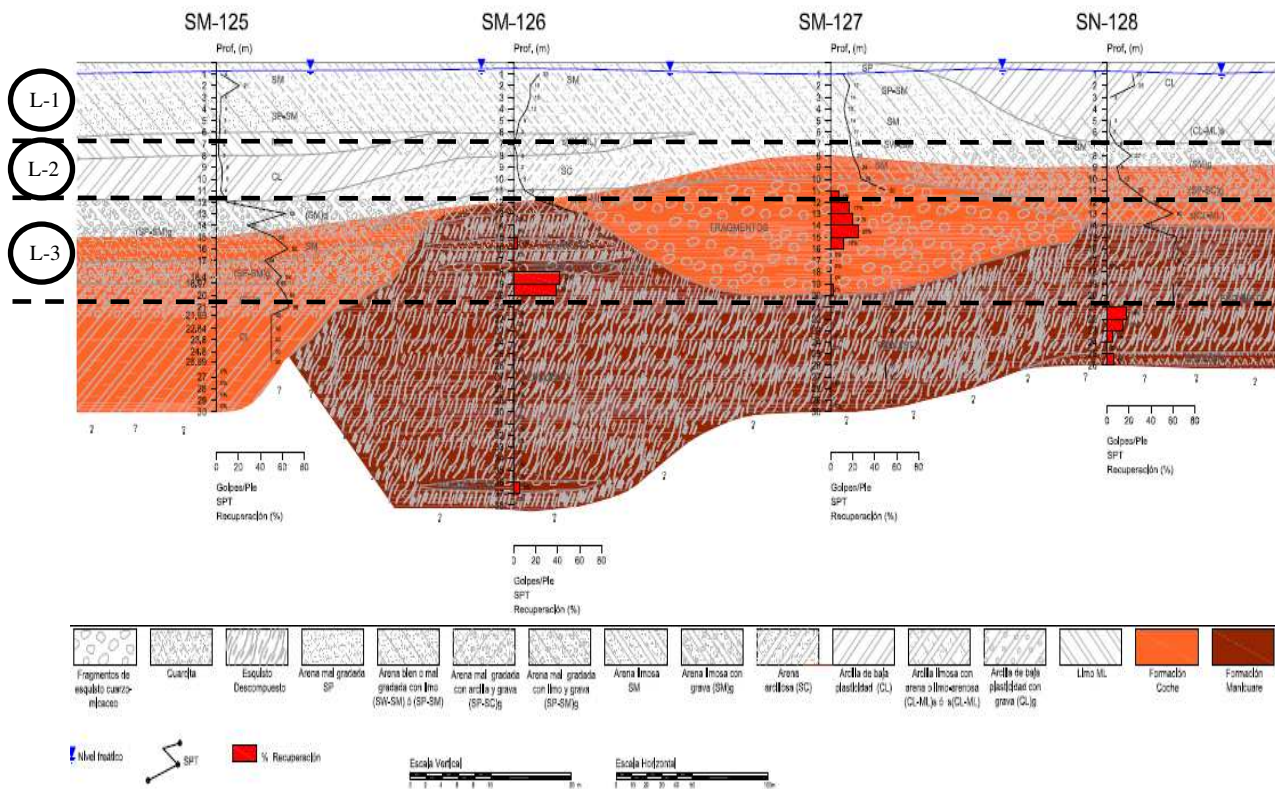
Figure 8. Geomorphology of the study area.

The geotechnical investigation consisted in the execution of 66 boreholes, between 15 m and 90 m of depth. The drillings were performed with sampling at each meter up to the exploration depths. The SPT was recorded when subsoil conditions permitted. In those

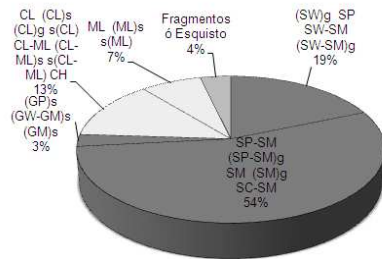
cases in which the detected materials presented very dense compactness, very hard consistencies, or rock characteristics, the drilling advance was carried out by rotation. The laboratory tests performed on samples recovered during exploration included visual classification (ASTM D-2488), natural moisture content (ASTM D-2216), grain-size distribution analysis (ASTM D-422), consistency limits (ASTM D-4318), density (ASTM D-854), and specific gravity (ASTM D-854), in addition to special tests to study the shear resistance and stress-strain characteristics of the detected soils.

As was mentioned before, in the explored subsoil it is evident the presence of three well-defined geological horizons: (1) *Sediments of marine origin with terrestrial influence*. In the first detected horizon there are predominantly granular materials, interspersed by fine materials. The deposition of these sediments occurred in a coastal environment, in which granular sediments would be associated with elongated sandy deposits extending from the area where the river reaches the sea, while strata of fine material could be associated with old coastal lagoons located mainly in the central area of the study ground. (2) *Coche Formation*. Underlying the first horizon, the Pleistocene sediments were detected. Those sediments consisting mainly of clays, generally sandy, with presence of gravel from various rocks and quartz, as well as sandstones and conglomerates, poorly chosen. These sediments were accumulated in a continental environment, by fluvial-torrential processes, which produced alluvial fans. This horizon is observed in almost all the area of study, except the zones near the mountains in which it disappears. (3) *Manicuaire Formation*. This is a metamorphic basement composed of quartz-micaceous schists, micaceous schists, graphite schists and quartzite, characterized by a high degree of deformation presumably related to the processes of subduction, collision and oblique convergence between the Caribbean and South American plates, in addition to the associated post-metamorphic faults and shifts. This metamorphic basement appears in the areas surrounding the mountains and in most of the study area, underlying the Pleistocene sediments of the Coche Formation. However, there are areas in which it appears immediately after the marine sediments.

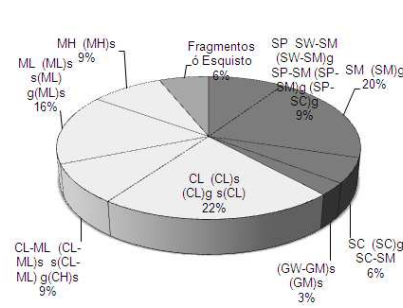
From the point of view of foundation engineering, the materials that are critical for the development of civil works are those most susceptible to deformation under external stresses. Accordingly, in order to describe these materials geotechnically and exemplify the application of the developed methodology, a 21 m depth horizon was considered. Based on the distribution of the materials in such horizon, three layers were defined: layer 1 (L-1), between ground surface and 7 m of depth; layer 2 (L-2), between 7 m and 12 m of depth, and layer 3 (L-3) until 21 m of depth. Fig. 9 summarizes the main information of the considered horizon, including detected soils, N_{SPT} , moisture content and consistency limits values. In addition, in Fig. 9 a representative lithostratigraphic profile of the detected subsoil is included.



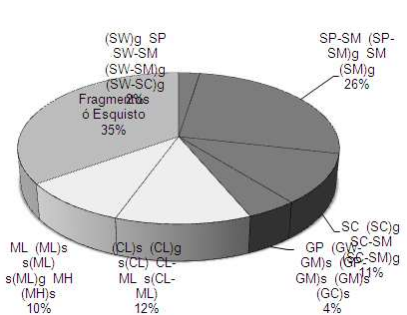
Layer 1 (0 – 7 m)



Layer 2 (7 m – 12 m)



Layer 3 (12 m – 21 m)



Types of soils

Sand = 73.3%	Sand = 35.4%	Sand = 39.3%
Silt = 7.3%	Silt = 25.0%	Silt = 9.6%
Clay = 13.0%	Clay = 30.7%	Clay = 11.8%
Fragments = 3.7%	Fragments = 6.1%	Fragments = 39.4%

General data

$N_{SPT} < 12$ blows/ft (average)	$N_{SPT} < 10$ blows/ft (average)	$N_{SPT} > 50$ blows/ft (average)
$\omega = 15\% - 30\%$ (23% average)	$\omega = 15\% - 75\%$ (34% average)	$\omega = 10\% - 20\%$ (15% average)
LL = 30% (average)	LL = 35% (average)	LL = 23% (average)
PL = 22% (average)	PL = 23% (average)	PL = 18% (average)
PI = 12% (average)	PI = 12% (average)	PI = 5% (average)

Figure 9. Geotechnical information of the study area.

It should be noted that moisture content values are relatively close to PL in L-1 and L-3, while in L-2 these values are close to LL . This fact evidences that L-2 presents high compressibility fines (in approximately 10% of the stratum), represented mainly by high compressibility silt (MH), high compressibility silt with sand (MH)s, and high compressibility clay with sand g(CH)s; with moisture content values higher than LL , which indicates that they are in a consistency similar to a sludge. This is also reflected in the N_{SPT} values recorded during fieldworks.

At the time of executing the fieldwork, the water table was detected at variable depths between 0.30 m and 1.50 m, with an average value of 0.75 m. Such values were obtained from daily measurements taken early in the morning.

The RMGC was used for characterization of layers L-1 to L-3, until 21 m of depth. Step by step procedure presented in Section 6 was implemented. Steps 1 to 4 were applied to every available spreadsheets for the studied land. Figure 10 shows the application of the methodology, taking the borehole SM-01 as an example. Subsequently, by step 5 of the methodology, data was grouped in Layers 1 to 3, as explained above. This is illustrated in Table 9, which includes the information corresponding to all the boreholes executed in the area. The value of column ST corresponds to the average soil stiffness values determined for each metre of layers L-1 to L-3. On the other hand, in column SB is showed the expected soil behavior (S for sand-like soil behavior, and C for clay-like soil behavior). Values of ST and SB were used in steps 6 (*Geotechnical Zoning Map*) and 7 (*Soil Behavior Map*) of the RMGC, respectively.

Steps 6 and 7 of the proposed methodology were developed according to the following sequence, applied separately to layers L-1 to L-3:

- a. Data export to software SURFER 8.0.
- b. Generation of the semivariogram for each layer, using the mentioned software.
- c. Generation of the *Geotechnical Zoning Map* (step 6) and *Soil Behavior Map* (step 7), applying kriging.

Since there is no specific technique for constructing semivariograms (a tool used when *kriging* is applied to analyse the variation of some variable in certain area [30]), different users may consider different semivariograms, which could affect the results obtained for zoning in some way. However, this fact is considered intrinsic to engineering, since the results obtained in a given activity are frequently affected by the particular criterion of the engineer. To select the semivariograms, adjustments were made intuitively using the software SURFER 8.0. Finally, the adjustment between the observed and estimated data was analyzed using the theoretical semivariogram.

Fig. 11, 12 and 13 show the *Geotechnical Zoning Map* and *Soil Behaviour Map* in a superimposed manner for layers L-1, L-2 and L-3, respectively. In those maps it is possible to identify the different sectors of the subsoil considering their stiffness, as well as the expected soil behaviour for the predominant materials in each sector.

From plans showed in Fig. 11 to 13, it is possible to develop a very complete analysis of the subsoil characteristics in the study land. Following, some useful information derived from the application of the RMGC:

- Some geological considerations related to the dip of older stiffer layers and the deposition of recent less rigid layers, could be made. Older layers are located at higher depths in sectors close to the beach line, where greater thicknesses of young sediments were detected.
- A significant change in stiffness is observed in materials below 12 m of depth. Above this depth, sediments of very low to medium stiffness predominate in the explored subsoil, making it susceptible to significant deformations under the action of external loads. Below 12 m and up to the depth analysed, soil stiffness increases appreciably, which shows a change in the sedimentary dynamics of the studied land.
- In L-2 a gradation of coarser to finer sediments is observed from the exit of the Quebrada Playa de Róbal towards the coastline. Likewise, those fine sediments present moisture contents close to LL , a fact which is in keeping with their low stiffness.
- Most of L-1 and L-2 are dominated by materials with the following characteristics: a) water table close to the ground surface; b) soils with sand-like behavior, with very loose to moderately dense compactness (i.e. low stiffness); c) recent sedimentary environment. Such characteristics make these soils susceptible to liquefaction, so it will be necessary to analyse this problem.
- In some sectors of L-2, materials with clay-like behaviour predominate. In those cases, problems related to long-term settlements should be analyzed.
- Taking into account the characteristics of L-1 and L-2 mentioned above, it is possible to glimpse some important aspects for the project, such as: a) the possibility that, in case that the risk of liquefaction is verified, it will be necessary to carry out a subsoil deep improvement; b) the methodology to be used to carry out such improvement (i.e. vibroflotation or dynamic compaction); c) the quality control of the subsoil improvement; d) the expected behavior of the subsoil after being densified; e) definition of modified soil geomechanical parameters for foundation design; f) the impact of these activities on the project's schedule and costs.

The above example shows the importance of a complete and rational geotechnical characterization of a given terrain, since, depending on the potential geotechnical problems of each area, information derived from that characterization will be used to make technical and economic decisions of fundamental importance for the development of the project.

SAMPLE	DEPTH (m)	SAMPLING	N ₆₀ (BLOWS/FT)	VISUAL DESCRIPTION	GRAIN-SIZE DISTRIBUTION (%)					LIMITS			MOISTURE CONTENT (%)	SPECIFIC GRAVITY	LIQUIDITY INDEX	SOIL BEHAVIOR	FACTOR G1 or F1	FACTOR C2 or F2	SOIL STIFFNESS	
					GRAVEL		SAND			PASANTE No. 200	FF	LIQUID LIMIT								PLASTIC LIMIT
					GRUESSA	FINA	GRUESSA	MEDIA	FINA											
1	1	S	4	Fine silty SAND; dark greyish brown color						25		1	5	5,00	S	-3,42	-0,98	2		
2	2	S	6	Silty CLAY; dark greyish brown color						51		32	23	31	0,89	C	3,70	-5,34	1	
3	3	S	7	Fine to medium clayey SAND; gray color; presence of shell fragments				26	35	39		25	16	25	1,00	S	-2,53	-0,24	2	
4	4	S	28	Fine silty SAND, with fine gravel (quartz); gray with red color		2	4	38	43	13	3	1		13	2,67	13,00	S	-0,22	-1,48	3
5	5	S	15			2	4	38	43	13	3	1		13	2,67	13,00	S	-1,90	-1,49	3
6	6	S	12	Silty SAND with gravel (quartz); brown with red color		2	4	38	43	13	3	1		14	2,67	14,00	S	-2,29	-1,50	3
7	7	S	20					10	75	15	3	1		20	2,67	20,00	S	-1,27	-1,40	3
8	8	S	13	Not recovered sample				10	75	15	3	1		22	2,67	22,00	S	-2,18	-1,41	3
9	9	R	100					10	75	15	3	1		15	2,67	15,00	S	9,05	-1,32	5
10	10	S	17	Silty SAND with gravel (quartz); brown with red color	14	19	10	14	28	15	4	1	10	2,72	10,00	S	-1,66	-1,40	3	
11	11	S	13			14	19	10	14	28	15	4	1	8	2,72	8,00	S	-2,18	-1,41	3
12	12	R	100	Conglomerate in metal matrix and cemented metal oxide; dark red color	14	19	10	14	28	15	4	1	8	2,72	8,00	S	9,05	-1,32	5	
13	13	S	65			14	19	10	14	28	15	4	1	9	2,72	9	S	5	1	5
14	14,50	R	100	Fine silty SAND, presence of gravel (quartz); gray with red color; sandy-clay layer at 17 m								1				S	9	-2	5	
15	16	R	100										1				S	9	-2	5
16	17,50	R	100		10	7	19	43	21		1		10	2,72	10	S	9	-1	5	
17	19	R	100		10	7	19	43	21		1		9	2,72	9	S	9	-1	5	

Step 3 (estimated soil behavior.
S = sand-like behavior
C = clay-like behavior)

Step 4 (estimated soil stiffness)

Step 1 (strata in gray and white colors; assumed properties in bold)

Step 2 (assumed properties in bold)

Figure 10. Steps 1 to 4 of RMGC, borehole SM-01.

Table 9. Step 5 of RMGC. Data organization in layers L-1 to L-3.

#	Coordinates		Soil stiffness and expected soil behavior (S = sand-like behavior; C = clay-like behavior)																											
	East	North	Layer 1 (0-7) m										Layer 2 (7-12) m								Layer 3 (12-21) m									
			1	2	3	4	5	6	7	ST	SB	8	9	10	11	12	ST	SB	13	14	15	16	17	18	19	20	21	ST	SB	
1	385.047	1.176.190	2	1	2	3	3	3	3	2	S	3	5	3	3	5	4	S	5	5	5	5	5	5	5	5	5	5	S	
5	385.194	1.176.333	2	2	1	3	3	3	3	2	S	3	3	3	3	3	3	S	3	2	5	3	5	5	3	5	5	4	S	
9	385.585	1.176.371	2	3	4	3	3	2	3	2	S	3	3	3	4	4	3	S	5	5	5	5	5	5	5	5	5	5	S	
10	385.474	1.176.605	2	3	5	2	4	1	2	2	S	1	1	1	2	3	2	S	3	3	3	4	5	5	5	5	5	4	S	
11	385.373	1.176.820	3	3	3	4	4	3	3	3	S	1	1	1	1	3	1	C	3	3	3	3	4	5	4	5	5	3	S	
12	385.258	1.177.065	2	3	3	4	5	5	5	3	S	5	5	5	5	5	5	S	5	5	5	5	5	5	5	5	5	5	S	
14	385.992	1.176.511	3	3	3	3	3	3	3	3	S	5	5	5	5	5	5	S	5	5	5	5	5	5	5	5	5	5	S	
15	385.793	1.176.915	3	3	3	3	3	3	2	2	S	2	2	3	3	1	2	S	1	3	3	3	3	3	4	3	5	3	S	
16	385.688	1.177.128	3	3	3	3	3	2	2	2	S	2	1	1	1	1	1	C	1	3	3	4	4	4	5	4	5	3	S	
17	385.570	1.177.368	3	3	3	3	3	3	3	3	S	3	3	3	3	5	3	S	5	5	5	5	5					5	S	
29	385.112	1.176.923	3	3	3	3	5	5	5	3	S	3	3	5	5	3	4	S	5	5	5	5	5	5	5	5	5	5	S	
30	385.281	1.176.574	3	4	4	3	3	3	3	3	S	3	2	5	5	5	4	S	5	5	5	5	5	5	5	5	5	5	S	
103	385.304	1.177.265	5	5	3	5	5	5	5	4	S	5	5	5	5	5	5	S	5	5	5	5	5	5	5	5	5	5	S	
105	385.384	1.177.144	3	3	3	4	5	5	5	4	S	5	5	5	5	5	5	S	5	5	5	5	5	5	5	5	5	5	S	
106	385.250	1.177.349	3	5	5	5	5	5	5	4	S	5	5	5	5	5	5	S	5	5	5	5	5	5	5	5	5	5	S	
107	385.090	1.177.254	5	5	5	5	4	5	5	4	S	5	5	5	3	3	4	S	5	5	5	5	5	5	5	5	5	5	S	
108	384.856	1.176.547	5	5	5	5	5	5	5	5	S	5	5	5	4	4	4	S	4	4	4	5	5	5	5	5	5	4	S	
109	385.209	1.176.694	1	3	3	3	3	3	3	2	S	4	3	3	3	3	3	S	3	3	3	3	5	3	3	3		3	C	
110	385.347	1.176.131	1	1	3	3	3	3	4	2	S	3	3	5	5	3	4	S	3	3	5							3	C	
111	385.681	1.176.595	1	1	3	3	2	1	1	1	C	1	1	1	3	3	2	C	3	3	3	1	1	3	3	3	3	2	S	
112	386.048	1.176.884	3	3	3	3	3	3	3	3	S	3	1	1	1	1	1	C	1	1	3	3	2	5	5	5	5	3	S	
113	385.476	1.177.108	3	4	3	3	1	1	1	2	S	1	1	1	5	4	2	S	3	3	5	3	3	3	5	5	5	3	S	
114	385.583	1.177.248	3	3	3	3	3	2	1	2	S	1	1	3	3	5	3	S	4	3	3	3	5	5	4	4	3	3	S	
115	385.770	1.177.351	3	3	3	3	3	3	3	3	S	3	3	1	1	1	2	C	1	5	5	5	5	5	5	5	5	4	S	
116	385.827	1.177.254	2	2	2	2	2	3	3	2	S	3	1	1	3	1	2	C	1	1	1	1	1	3	3	3	3	1	C	
117	385.891	1.177.146	3	3	3	3	3	3	3	3	S	3	2	1	2	1	2	C	1	1	1	1	1	3	4	3	3	2	C	
118	385.974	1.177.009	3	3	3	3	3	3	3	3	S	3	1	1	2	2	2	C	1	1	1	1	5	5	5	4	5	3	S	

Table 9. (cont.) Step 5 of RMGC. Data organization in layers L-1 to L-3.

#	Coordinates		Soil stiffness and expected soil behavior (S = sand-like behavior; C = clay-like behavior)																											
	East	North	Layer 1 (0-7) m										Layer 2 (7-12) m								Layer 3 (12-21) m									
			1	2	3	4	5	6	7	ST	SB	8	9	10	11	12	ST	SB	13	14	15	16	17	18	19	20	21	ST	SB	
119	386.121	1.176.769	3	3	3	3	3	3	3	S	1	1	1	1	1	1	C	1	1	1	5	5	5	5	5	5	3	S		
120	386.191	1.176.658	2	2	3	3	3	3	2	S	1	1	1	3	1	1	C	2	3	3	4	3	5	5	5	4	3	S		
121	386.287	1.176.512	3	3	5	3	3	3	1	S	1	2	1	1	1	1	C	1	5	3	3	3	3	3	3	5	3	C		
122	386.401	1.176.370	3	3	3	3	3	3	1	2	S	1	1	1	1	1	C	1	3	5	5	5	5	5	5	5	4	S		
123	386.228	1.176.260	3	3	3	3	3	1	1	2	S	1	1	1	3	3	2	C	3	3	4	3	5	5	5	5	4	S		
124	386.049	1.176.147	3	3	3	3	3	3	2	2	S	2	2	3	3	2	2	S	3	5	5	3	3	3	5	5	5	4	C	
125	386.482	1.176.234	2	3	2	2	2	2	1	2	S	1	1	1	1	1	1	C	5	3	5	5	4	5	5	3	3	4	S	
126	386.318	1.176.131	3	3	3	3	2	2	1	2	S	2	2	2	3	3	2	S	5	5	5	5	5	5	5	5	5	5	S	
127	386.140	1.176.002	3	3	3	3	3	3	3	S	3	3	3	5	5	4	S	5	5	5	5	5	5	5	5	5	5	5	S	
128	385.978	1.175.910	1	1	1	1	2	1	2	1	C	3	3	3	3	4	3	S	5	4	5	5	5	5	5	5	5	4	S	
129	386.266	1.175.911	3	3	3	3	2	2	3	2	S	3	4	5	5	5	4	S	5	5	5	5	5	5	5	5	5	5	S	
130	385.828	1.176.686	3	3	3	2	2	2	2	2	S	2	1	1	3	3	2	C	3	4	4	5	5	5	5	5	5	4	S	
131	385.762	1.176.371	2	3	3	3	3	1	2	2	S	3	3	3	3	4	3	S	4	3	3	4	4	4	5	5	5	4	S	
132	385.803	1.176.167	2	4	3	3	3	3	3	3	S	3	3	5	3	5	4	C	5	5	5	5	5	5	5	5	5	5	S	
133	385.976	1.176.323	3	3	3	3	3	3	3	3	S	3	3	3	4	4	3	S	4	4	3	3	3	3	3	3	5	3	C	
134	386.124	1.176.413	3	2	2	2	2	1	1	1	S	1	3	5	4	5	4	S	5	5	5	5	5	5	5	3	5	4	S	
135	385.508	1.176.227	1	5	1	3	3	3	3	2	S	3	3	3	5	5	4	S	5	5	5	5	5	5	5	5	5	5	S	
136	385.853	1.176.449	3	3	3	3	3	3	3	3	S	3	3	3	5	5	4	S	5	5	5	5	5	5	5	5	5	5	S	
137	386.066	1.176.591	3	3	3	3	3	3	2	2	S	1	1	1	3	5	2	C	5	5	5	5	5	5	5	5	5	5	S	
138	385.949	1.176.615	3	3	3	3	3	3	1	2	S	1	1	3	3	3	2	C	3	5	5	5	5	5	5	5	5	4	S	
139	385.883	1.176.786	3	3	3	3	3	3	1	2	S	1	1	1	1	1	1	C	3	5	5	5	5	5	5	5	5	4	S	
140	385.364	1.176.456	1	1	4	3	3	3	2	2	S	2	2	2	2	3	2	S	2	3	3	5	5	5	3	4	5	3	S	
141	385.591	1.176.815	3	3	3	3	3	1	1	2	S	1	1	1	1	2	1	C	2	2	2	3	2	2	5	4	3	2	S	
142	385.519	1.176.937	2	3	3	3	3	3	2	2	S	1	1	1	1	1	1	C	1	3	2	2	3	3	3	3	3	2	S	

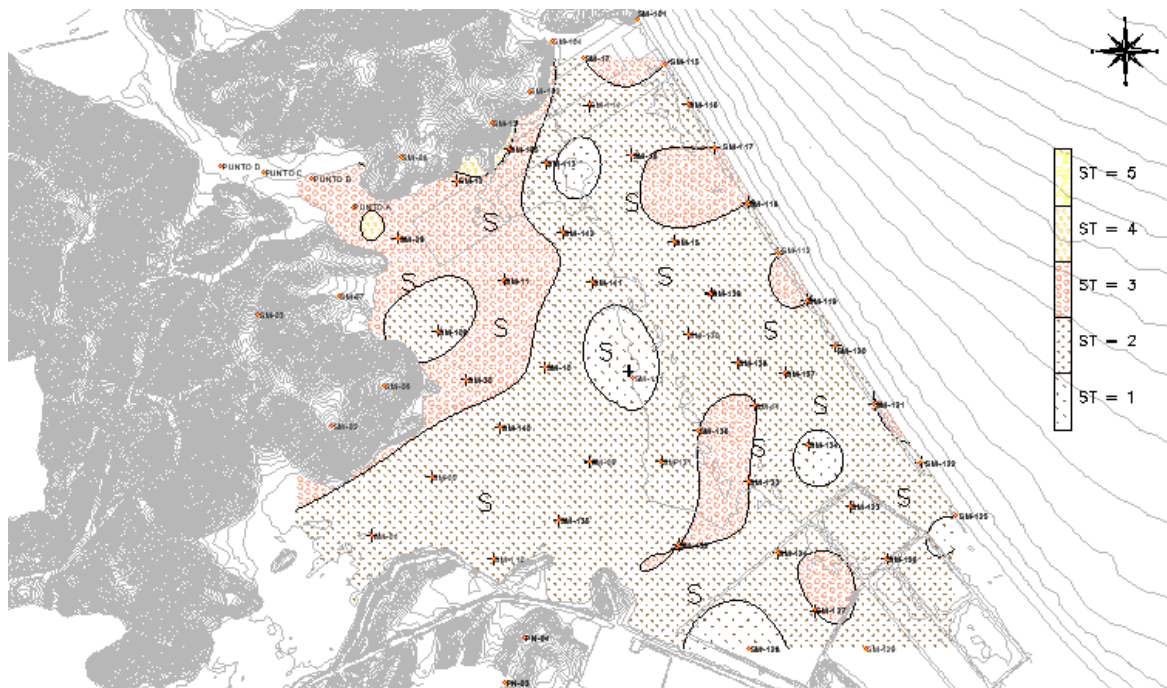


Figure 11. Steps 6 and 7 of RMGC, zoning and soil behavior maps, L-1. Note: S = sand-like behavior; C = clay-like behavior.

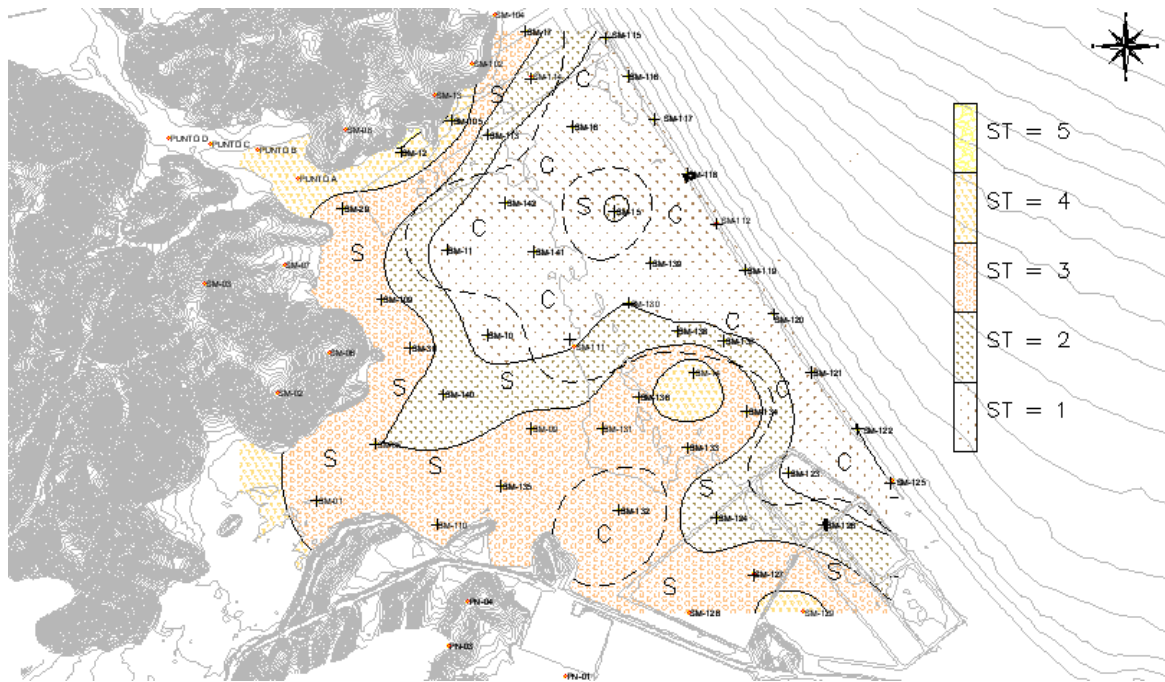


Figure 12. Steps 6 and 7 of RMGC, zoning and soil behavior maps, L-2. Note: S = sand-like behavior; C = clay-like behavior.

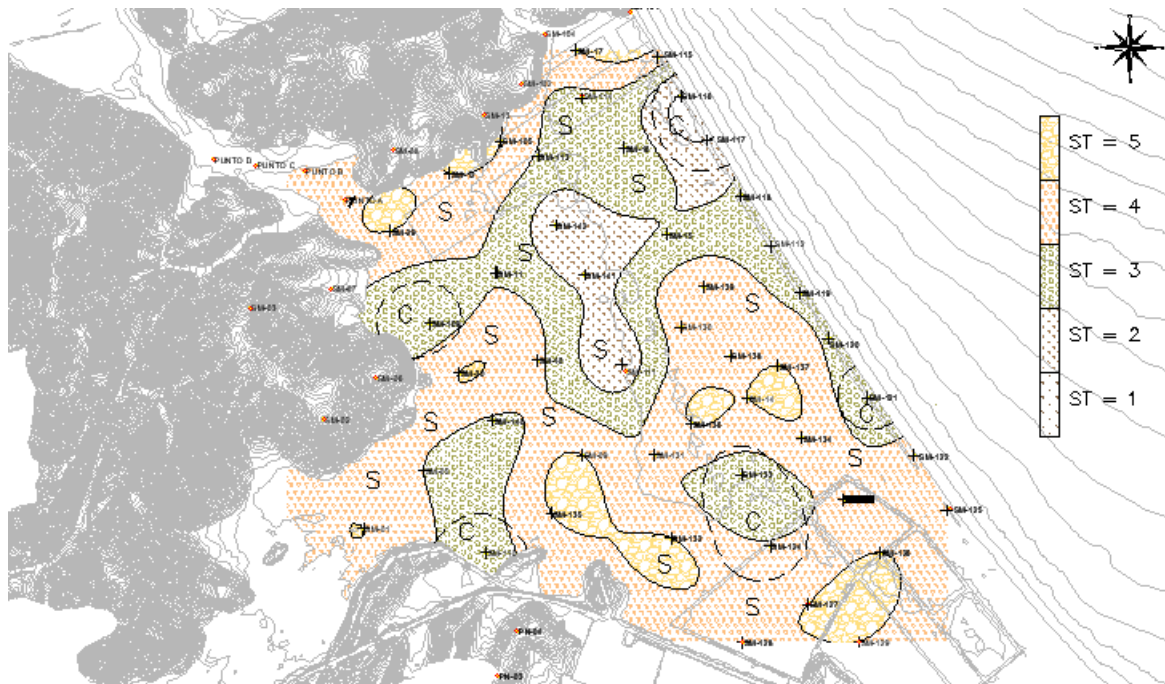


Figure 13. Steps 6 and 7 of RMGC, zoning and soil behavior maps, L-3. Note: S = sand-like behavior; C = clay-like behavior.

8. Conclusions

Geotechnical characterization is a complex process that includes data collection in field and laboratory, and its subsequent interpretation for the delimitation of sectors of a given ground, considering the resistance characteristics of the detected strata and the expected response of these strata to external loading.

The developed RMGC considers the use of available information in routine geotechnical studies limited data to carry out the geotechnical zoning of a given land, also considering the expected geomechanical behavior of the sediments that constitute it. Taking into consideration several investigations during the last four decades,

as practical criteria it can be established that for FF equal or greater than 20%, the soils will present a clay-like behavior, while for FF less than 20% the soils will present a sand-like behavior.

The main advantage of the RMGC application is that it considers, in addition to the soil stiffness, the expected soil behavior. Likewise, since its use intrinsically contains the use of geostatistical techniques, the distribution of soil stiffness and behavior in a given ground constitute a very robust estimate, based on continuous functions that explain the behavior of each variable in the different directions of space. In addition, this technique makes it possible to analyses the variability of the

estimate, that is, the degree of uncertainty (in the form of variance or standard deviation).

The proposed methodology was applied in a practical case in this work, specifically in the characterization of a terrain located in Punta La Playa, on the Northern side of the Araya Peninsula, Sucre State, Venezuela. From the performed analyses, the direct association of the stiffness of the different detected sediments with the location of geological formations and with potential geotechnical problems in the studied land is evident.

The application of the proposed RMGC in a practical case makes it possible to appreciate the importance of carrying out a complete and rational geotechnical characterization, since, depending on the potential geotechnical problems of each parcel, the information derived from this characterization will be used to make technical and economic decisions of vital importance for the development of a project.

References

- [1] Mitchell, J. & Soga, K. "Fundamentals of soil behavior", 3rd ed., John Wiley & Sons, New Jersey, USA, 2005.
- [2] Bourdeau P. & Amundaray J.I. "Non-parametric simulation of geotechnical variability", *Geotechnique*, 55, pp. 95-108, 2005.
- [3] Baecher, G. & Christian, J. "Reliability and statistics in geotechnical engineering". John Wiley & Sons, USA, 2003.
- [4] Shit *et al* (2016) Shit, P., Bhunia, G. & Maiti, R. "Modeling earth systems and environment". Springer International Publishing, Vol. 2, 2016. <https://doi.org/10.1007/s40808-016-0160-4>.
- [5] Terzaghi, K. "Theoretical soil mechanics", 1st ed., John Wiley & Sons, New York, USA, 1943.
- [6] Holtz, R., Kovacs, W. & Sheahan, T. "An introduction to geotechnical engineering", 2nd ed., Pearson, USA, 2011.
- [7] Taylor, D. "Fundamentals of soil mechanics", 1st ed., John Wiley & Sons, New York, USA, 1948.
- [8] Kulhawy, F. & Mayne, P. "Manual on estimating soil properties for foundation design", prepared by Cornell University Geotechnical Engineering Group, Hollister Hall, New York, USA, 1990.
- [9] Santamarina, J., Klein, K., Wang, Y. & Prencke, E. "Specific surface: determination and relevance", *Canadian Geotechnical Journal*, 39, pp. 233-241, 2002.
- [10] Mitchell, J. "Fundamentals of soil behavior", 1st ed., John Wiley & Sons, Inc., New York, USA, 1976.
- [11] Monkul, M. & Ozden, G. "Compressional behavior of clayey sand and transition fines content", *Engineering Geology*, 89, pp. 195-205, 2007.
- [12] Kenney, T. "Residual strength of mineral mixtures", In: *Proceedings 9th International Conference on Soil Mechanics and Foundation Engineering*, Tokyo, Japan, 1, pp. 155-160, 1977.
- [13] Lupini, J., Skinner, A. & Vaughan, P. "The drained residual strength of cohesive soils", *Geotechnique*, 31, pp. 181-212, 1981.
- [14] Skempton, A. "Residual strength of clays in landslides, folded strata and the laboratory", *Geotechnique*, 35, pp. 3-18, 1985.
- [15] Georgiannou, V., Burland, J. & Hight, D. "The undrained behavior of clayey sands in triaxial compression and extension", *Geotechnique*, 40, pp. 431-449, 1990.
- [16] Pitman, T., Robertson, P. & Sego, D. "Influence of fines on the collapse of loose sands", *Canadian Geotechnical Journal*, 31, pp. 728-739, 1994.
- [17] Kumar, G. & Wood, M. "Fall cone and compression tests on clay-gravel mixtures", *Geotechnique*, 49, pp. 727-739, 1999.
- [18] Vallejo, L. & Mawby, R. "Porosity influence on the shear strength of granular material-clay mixtures", *Engineering Geology*, 58, pp. 125-136, 2000.
- [19] Salgado, R., Bandini, P. & Krim, A. "Shear strength and stiffness of silty sand", *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE 126, pp. 451-462, 2000.
- [20] Vallejo, L. "Interpretation of the limits in shear strength in binary granular mixtures", *Canadian Geotechnical Journal*, 38, pp. 1097-1104, 2001.
- [21] Biscontin, G., Simonetta, C. Pestana, J. & Simonini, M. "Unified compression model for Venice Lagoon natural silts", *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, pp. 932-942, 2007.
- [22] Boulanger, R. & Idriss, I. "Evaluating the potential for liquefaction or cyclic failure of silts and clays", Report No. UCD/CGM-04-01, Center for Geotechnical Modeling, Department of Civil & Environmental Engineering, College of Engineering, University of California at Davis, California, USA, 2004.
- [23] Auvinet, G. "Geotechnical Engineering in Spatially Variable Soft Soils", In: *The 9th Arthur Casagrande Lecture - Proceedings XVI Panamerican Conference on Soil Mechanics and Geotechnical Engineering*, Cancun, Mexico, 1, pp. 13-107, 2019.
- [24] De La Fuente, S. "Análisis discriminante (Discriminant analysis)", Faculty of Economics and Business Studies, Universidad Autónoma de Madrid, Madrid, España, 2011.
- [25] Eisenbeis, R. "Pitfalls in the application of discriminant analysis in bussiness and economics", *The Journal of Finance*, 32, pp. 875-900, 1977.
- [26] De la Garza García, J. "Análisis estadístico multivariante: un enfoque teórico y práctico (Multivariate statistical analysis: a theoretical and practical approach)", 1st ed., Editorial McGraw-Hill, Madrid, España, 2013.
- [27] Peña, D. "Análisis de datos multivariantes (Multivariate data analysis)", 1st ed., Golden Phoenix, Madrid, España, 2002.
- [28] Torrado, M. "Análisis discriminante mediante SPSS (Discriminant analysis through SPSS)", *Revista d'Innovació i Recerca en Educaió*, Universitat de Barcelona, Vol. 6, 2, pp. 150-166, 2013.
- [29] Matheron, G. "Les variables généralisées et leur estimation (Generalized variables and their estimation)", Masson et Cie, France, 1965.
- [30] Isaaks, E. & Srivastava, R. "An introduction to applied geostatistics", 1st ed., Oxford University Press, New York, USA, 1989.
- [31] Al Dianty, M., Yahaya, A. & Ahmad, F. "Probability distribution of engineering properties of soils at telecommunication sites in Indonesia", *International Journal of Scientific Research in Knowledge*, 2, pp. 143-150, 2014.
- [32] "SPSS Statistics brief guide", prepared by IBM, USA, 2010.