ANALYSIS OF SOIL COMPACTNESS OF THE URBAN AREA OF BAURU / SÃO PAULO STATE USING STANDARD PENETRATION TESTS AND SEISMIC REFRACTION

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ABSTRACT – This study was done to determine compactness of soil strata in the urban area of Bauru, central São Paulo State using standard penetration test (SPT) and seismic refraction methods. Frequency distribution within boreholes was measured every meter to a depth of 30 meters. The geometric mean of standard penetration test values was computed every meter. A biplot graph showing the relationship of SPT with depth indicates soil stratification. In addition, five sections of seismic refraction values, which also indicate the compactness of soil strata, were obtained. A comparison of the two methods shows significant correlation between the results obtained from each.
Keywords: SPT, seismic refraction, compactness, soil stratification.

RESUMO – *J.R. Sturaro, P.M.B. Landim, W. Malagutti Filho, J.C. Dourado - Análise da compacidade do solo na área urbana de Bauru/ Estado de São Paulo utilizando Ensaios de Penetração Padronizado e sísmica de refração*. Este estudo foi feito para determinar os estratos de compacidade do solo na área urbana de Bauru, parte central do Estado de São Paulo, utilizando os ensaios de penetração padronizada (SPT) e de sísmica de refração. Foi realizada a distribuição de frequência do SPT para cada metro perfurado, até a profundidade de 30 metros, e calculada a média geométrica para cada metro perfurado. Estabeleceu-se um gráfico de dispersão entre a profundidade e o SPT médio, que refletiu a estratificação do solo. Em paralelo, foram efetuadas cinco seções de sísmica de refração. Os resultados foram comparados em uma tabela final e apresentaram boa similaridade.
Palavras-chave: SPT, Sísmica de refração, Compacidade, Estratificação do solo.

INTRODUCTION

Soil compactness results from mechanically increasing the density of soil. In construction, this is a significant part of the building process. If performed improperly, settling of the soil could occur and result in unnecessary maintenance costs or structure failure. Almost all types of building sites and construction projects utilize mechanical compactness techniques. From an engineering geology viewpoint, soil compactness properties can be correlated with other geotechnical variables, which are part of every type of engineering project.

The compactness of sandy soils measured through simple recognition drilling by standard penetration test (SPT). Although widely criticized in the face of poorly constrained operational characteristics, SPT is widely used in Brazil to assess soil strength. Although soil resistance is an important measurement, few studies have focused on its mapping and spatial distribution in Brazil. Among the such studies are Sturaro and Landim (1996) and Mendes and Lorandi (2008).

The importance of knowing the behavior of soil is crucial to the success of construction projects. This study illustrates a way to obtain data on strata compactness from simple recognition drilling and makes a comparison with results from shallow seismic refraction surveys. Data in this case study come from the urbanized area of the city of Bauru, located in the central region of São Paulo State/Brazil.

METHODOLOGY

The work was based on the use of two techniques: statistical, using linear regression analysis, and geophysical, applying seismic refraction.

Standard Penetration Test (SPT)

According to the ABGE (1990), SPT is an in-situ dynamic penetration test designed to provide information on the geotechnical engineering properties of soil.

The test uses a thick-walled sample tube with an outside diameter of 50 mm, an inside diameter of 35 mm, and a length of about 650 mm. The tube is driven into the ground at the bottom of a borehole by blows from a slide hammer with a weight of 65 kg falling through a distance of 760 mm. The tube is driven 150 mm into the ground, and then the number of blows needed for the tube to penetrate each 150 mm, up to a depth of 450 mm, is recorded. Each segment is measured with reference to chalk marks made on the drilling rod at 150 mm intervals. The value of the resistance to penetration is the number of blows required for crimping the end of the sampler 30 cm. The blow count provides an indication of the density of the ground, and it is used in many empirical geotechnical engineering formulae.

The main purpose of the test is to provide an indication of the relative density of granular deposits, such as sands and gravels, from which it is virtually impossible to obtain undisturbed samples. The great merits of the test and the main reasons for its widespread use, is that it is simple and inexpensive. The soil-strength parameters that can be inferred are approximate, but they may give a useful guide in ground conditions where it may not be possible to obtain borehole samples of adequate quality, such as in strata characterized by gravels, sands, silts, clay containing sand or gravel, or weak rock. The usefulness of SPT results depends on the soil type, with fine-grained sands giving the most useful results. Despite its many flaws, it is usual practice to correlate SPT results with soil properties relevant for geotechnical engineering design. Because SPT results are often the only test results available, the use of direct correlations has become common practice in Brazil.

Seismic Refraction

Seismic refraction is a geophysical method used in the fields of engineering geology, geotechnical engineering, and exploration geophysics. It is performed using seismographs and/or geophones in an array and with an energy source. The seismic refraction method utilizes the refraction of seismic waves on geologic layers and rock or soil units to characterize the subsurface geologic conditions and geologic structure. The methods depend on the fact that seismic waves have differing velocities in different types of soil or rock. In addition, the waves are refracted when they cross the boundary between different types (or conditions) of soil or rock. The methods enable the determination of general soil types and the approximate depth to strata boundaries or bedrock.

The technique artificially generates waves on the surface and records the elapsed time after they have traveled through the ground. Elastic waves can be generated by various source, including explosives or falling weights, either free or forced. The amount of energy required for the source depends on the depth of the study: a deeper target needs more energy. In the case of shallow tests, such as in the current study, we can use less powerful wave sources, as hammer impacts.

Geophones record the waves on the surface by transforming the mechanical energy of seismic waves into electrical energy, thus allowing later interpretation. Generally, multichannel equipment is connected to several geophones arranged in line. This arrangement enables faster and with greater precision.

In this research the technique was carried out in 5 sections, using 24 geophones spaced 5 meters each one. The seismic waves were generated using explosives, in 5 different shot points: 2 external and 3 internal to the geophones array.

The records of the waves are used to determine propagation times of the waves refracted and to reconstruct their paths. Interpretation techniques allow determination of various types of subsurface geological structures.

Linear Regression Analysis

A linear equation is appropriate to analyze the correlation between the two variables if, in a dispersion diagram, they plot in an approximately linear relationship. A simple linear model can then be used to predict the occurrence of one variable with respect to the other.

When a significant linear correlation exists, the relationship between the variables can be quantified using linear regression analysis. The coefficient of determination, R^2, is used to check the variation in y explained by x.

CASE STUDY

The study area is the urban region of the city of Bauru, which is located in the western plateau of São Paulo State, as shown in Figure 1. The studies related to geotechnical mapping and geostatistical analysis made in this region are part of the doctoral thesis of Sturaro (1994) and are published in Sturaro and Landim (1996).

In the study area for each of the civil engineering projects, data have been obtained from soil tests and underground sampling used in foundation design and geotechnical characterization. SPT values for each point are an average of 172 values. Their location, as well as the location of the seismic refraction tests, are shown in Figure 2.

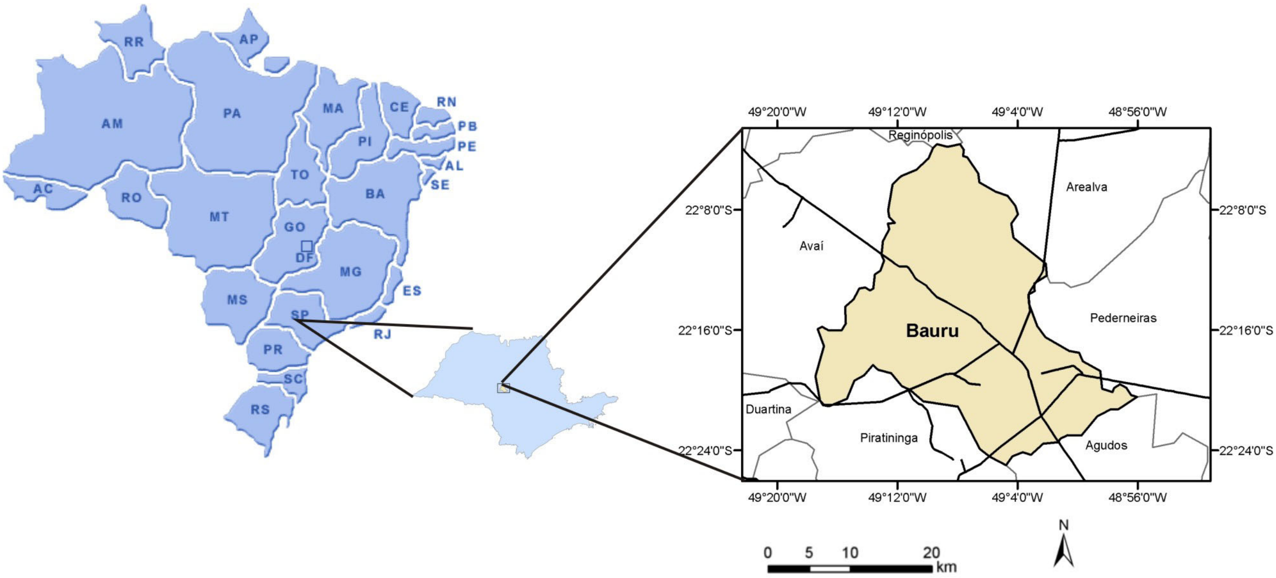

FIGURE 1. Location of study area.

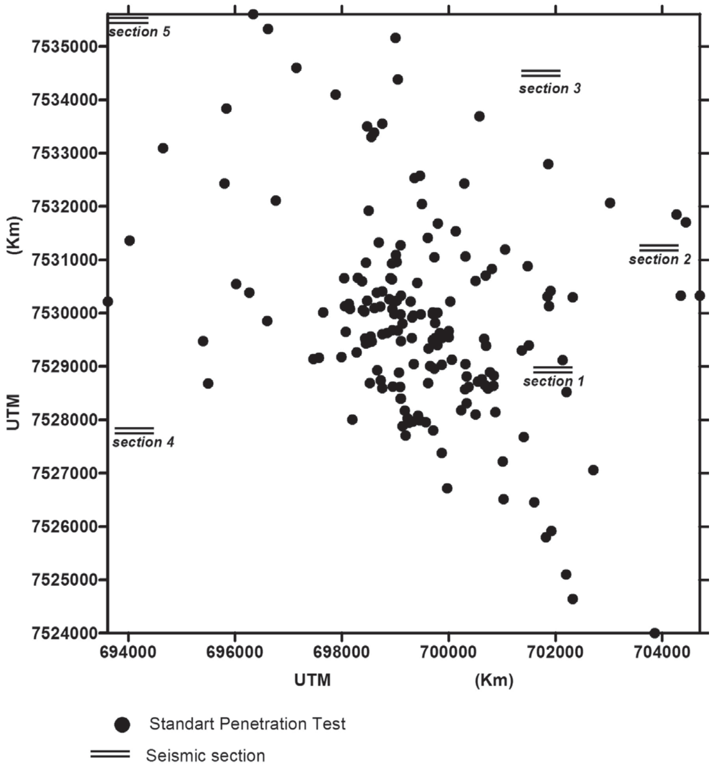

FIGURE 2. Location map of SPT points and seismic sections.

Soil Characteristics

According to studies conducted by IPT (1991), in the region of the Bauru River and its tributaries in the study area, hillsides to near the bottoms of valleys are covered by soils with characteristics of Oxisols. A detailed analysis of the soil revealed a sequence made by a biphasic sandy horizon, with a maximum thickness of 20 cm, rising gradually to a sandy soil with low clay content, red color, and micro aggregate structure. With increasing depth, the soil becomes a little more clayey while retaining its color and structure. Upon reaching depths of about 10 to 15 meters, the soil gradually becomes less clayey, and the contribution of material from the underlying rock becomes more evident.

Linear Regression Analysis

Linear regression analysis was used to verify the relationship between SPT and depth. The SPT geometric mean was correlated with the appropriate depth level. The geometric mean was used because of the positive skewness of the distribution of the variable frequency SPT, which is typical for lognormal distribution, as shown in Figure 3.

As shown in Figure 4, the value of the correlation coefficient *r* was 0.93, and the distribution of points is very close to being linear. The value of the coefficient of determination, R^2, was 0.865. Therefore, in the linear model, depth accounts for 86% of the behavior of the SPT.

A least-squares analysis shows inflection points in the line. These inflection points are probably related to changes in compactness in depth. Visually, the graph can be divided in four segments , as shown in Figure 4 and the hypothesis is that they represent the main layers of the subsoil, in terms of compactness average.

Seismic Sections

Seismic sections with iso-velocity values of seismic rays are shown in Figure 5. The seismic sections were calculated using the tomographic inversion method, that involves the establishment of an initial velocity model, which is interactively modified based on the travel times measured.The software Seismager/2D, that was used, has an algorithm for minimizing the differences of times using the least squares nonlinear method.

The analysis revealed the presence of three to four layers of soil compactness in the region. Typically, the second stratum is represented by a more developed soil, consisting of fine sandy clay with low compactness. The increase of wave velocity in this stratum can be attributed to increased levels of soil moisture. From the third layer and below, the data indicate a less-developed, fine sand-silt-clay soil. This soil type was found in nearby mechanical drilling. At the bottom of the section, near the top of the bedrock, sudden changes of velocity of the refracted waves occur, causing a blind zone.

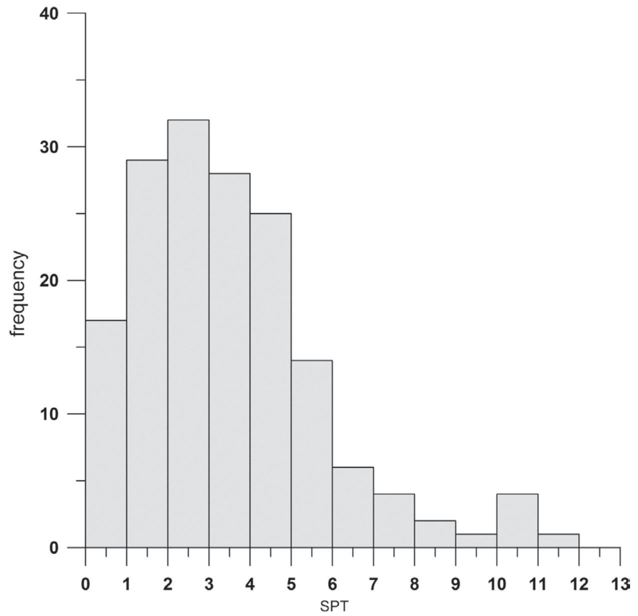

FIGURE 3. Typical SPT histogram.

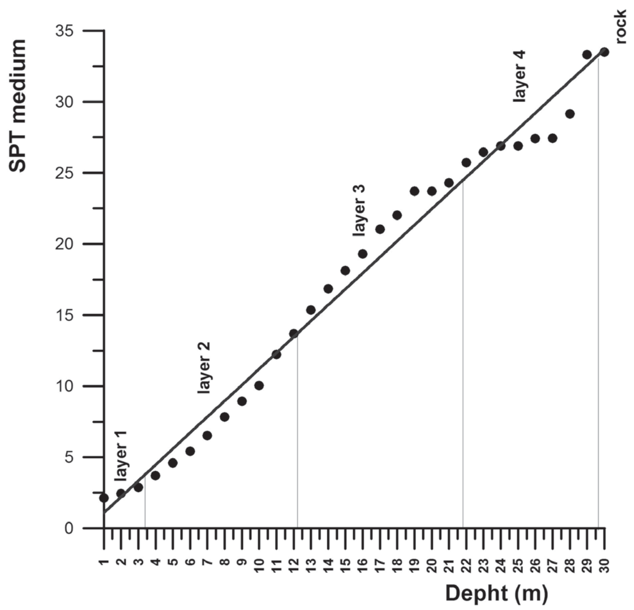

FIGURE 4. Correlation between SPT medium and depth.

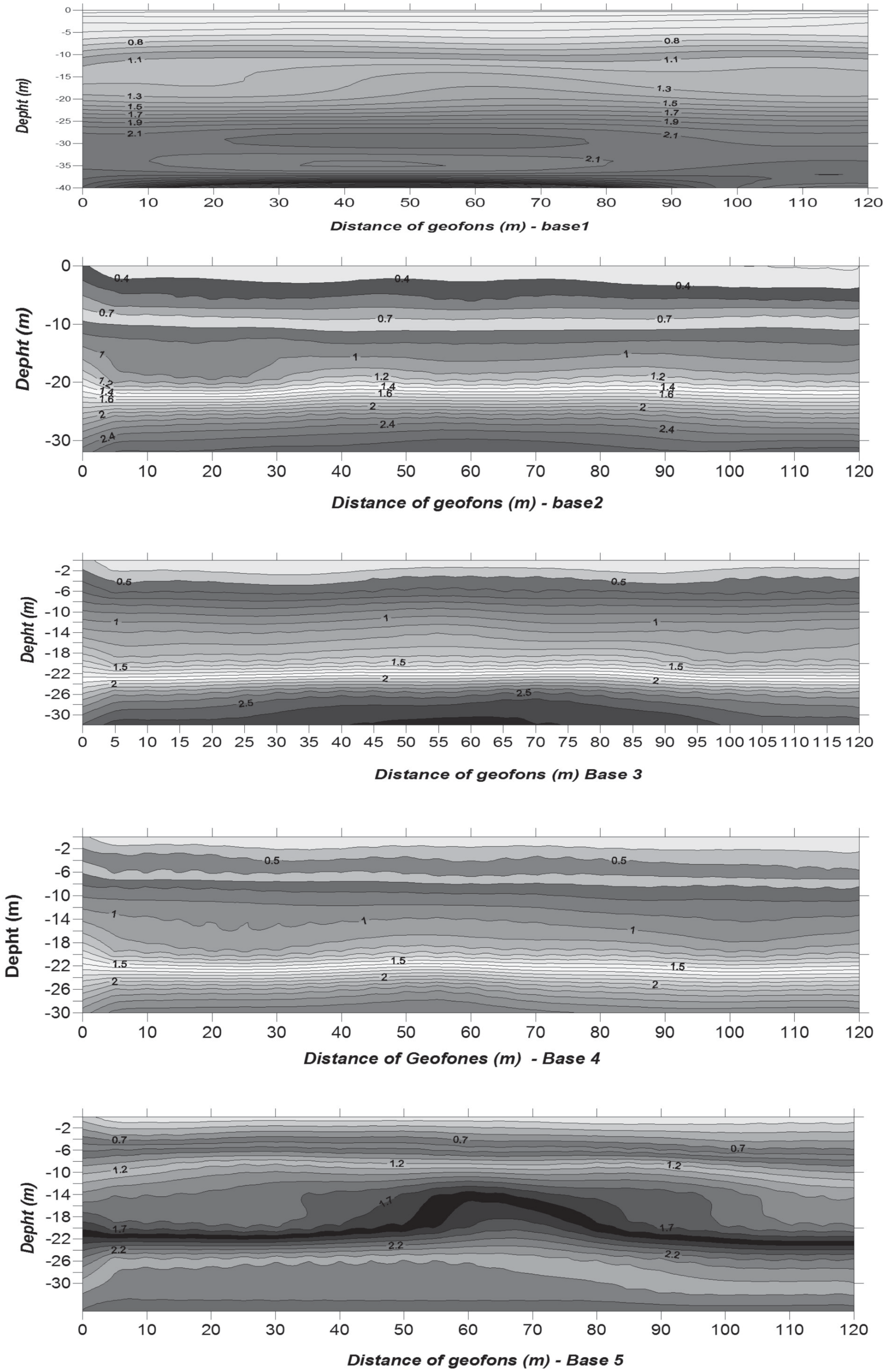

FIGURE 5. Seismic sections showing, in detail, the increase in wave velocity with depth.

Each one of the five vertical sections is made using a regularly spaced mesh of wave velocity values. Thus, it is possible to calculate a mean section from all the sections.

As a result of the trend of increasing wave velocity with depth, the mean section was interpolated by kriging in the presence of drift in the vertical direction. Simple kriging was used to compute the first-degree trend residuals, and the estimated values were added to the trend values (Goovaerts, 1997). The geostatistical treatment was based on Deutsch and Journel (1992) and Pannatier (1996). The program SURFER, version 8 (2002), was used to compute and draw the mean seismic section, which is shown in Figure 6.

Another view, this one in the ZY plane, is shown in Figure 7. In this vertical section, changes in wave velocities indicative of seismic strata can be observed more clearly.

The second derivative was calculated to identify changes with depth in the mean seismic section. This calculation identifies the rate of change in slope along the vertical direction. The second derivative test may be used to determine the concavity of a function, as well as a function's inflection points. At points on a graph where the concavity changes direction vertically, the second derivative is equal to zero. These inflection points can be a useful tool for determining the division of layers (Figure 8).

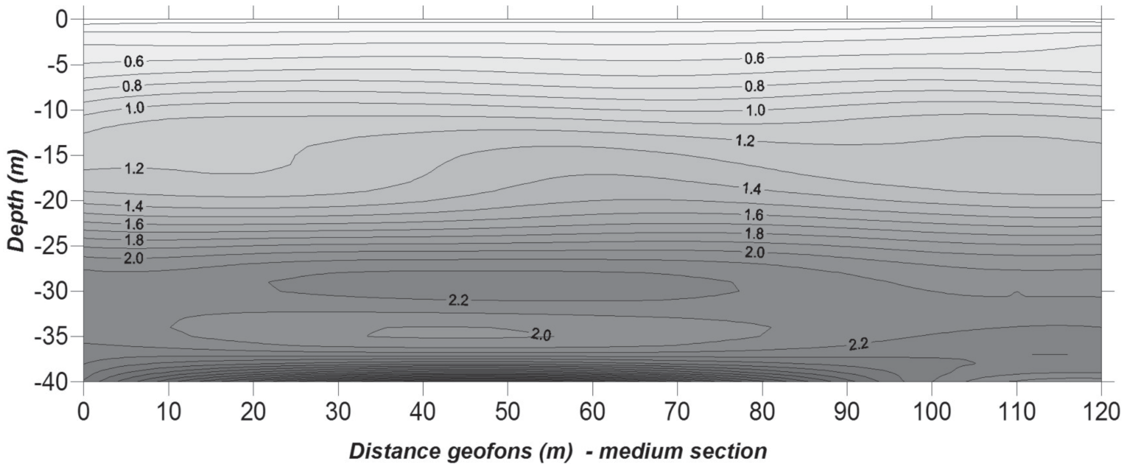

FIGURE 6. Mean seismic section showing velocities.

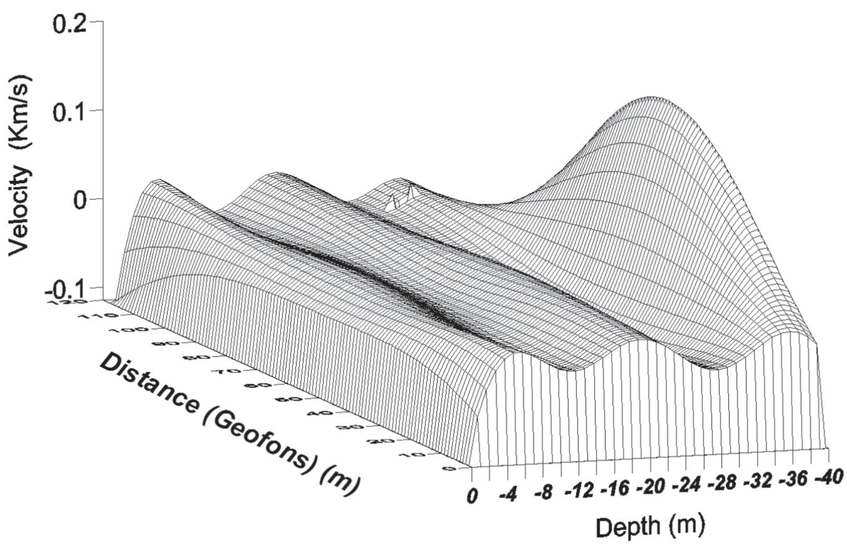

FIGURE 7. Perspective view of the mean seismic section.

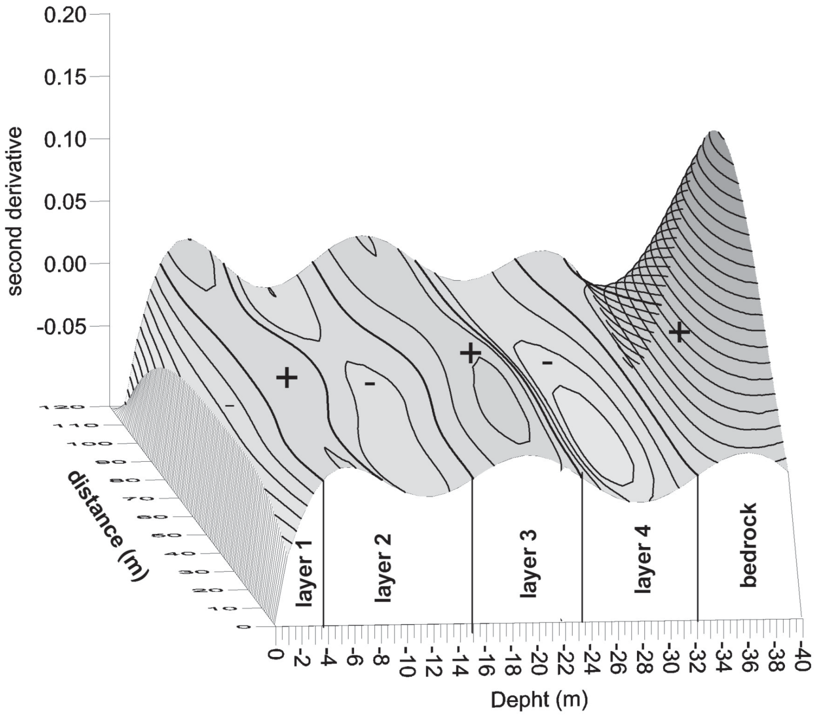

FIGURE 8. Perspective view of the second derivative of the mean section and delimitation of the hypothetical thickness of compactness, where the iso-value curve of the second derivative is zero.

Comparison of Methods

The graph represented in the Figure 4 illustrates the variation of the medium SPT (geometric mean) for each depth. Changes in the growth rate of the SPT related to the depth (inflection point) are interpreted by the authors as contacts between the layers. Thus the soil was stratified throughout the study region.

The graph in Figure 8 constitutes the arithmetic mean for each grid point considering the five vertical seismic sections, which has identical configuration in the distribution of points of velocity.

Based on the interpretation of the two graphs, which defined the soil stratification, a comparison between the two methods was carried out (Table 1).

The Table 1 presents a comparison between the two methods used to define the amount of soil compactness. An equivalence in the methods is evident; the number of layers is equal, and there is a clear relationship in the magnitude of the values, even at the top of the bedrock at the bottom of the section. These results are significant, because there were only 5 seismic tests, but there were 172 SPT values.

TABLE 1. Soil layer compaction - comparision between the two methods.

Layer	Depth (m)		Thickness (m)	
	SPT	Seismic Section	SPT	Seismic Section
1	3.4	3.8	3,4	3.8
2	12.4	15.0	9,0	11.2
3	21.9	22.0	9,5	7.0
4	30.0	32.0	8,0	10.0
bedrock	30.0	32.0	–	–

CONCLUSION

The technique of seismic refraction is a very efficient geophysical test to determine compactness of the soil. A comparison of results obtained using seismic refraction data and SPT values to delineate the depth and compactness of layers showed that using SPT values is a reasonable alternative that gives results consistent with seismic refraction methods.

The use of a mean seismic section, interpolated by kriging with drift and with delineation of seismic strata using the second derivative, is a procedure that can provide significant support for the interpretation of geophysical data. A more definitive study could be made by using a regular grid for SPT values on a regular mesh of seismic refraction profiles.

Both techniques indicated four layers and the top of the bedrock quite well. Note, however, the differences in thickness of the layers, which can be attributed to the more localized character of the geophysical method, even when worked on a mean section, while the profile of SPT values is made up of an average of the whole study area. In addition, the geometric mean has a statistical confidence interval, with values for a given level of confidence that can establish a range involving the values determined by the seismic refraction.

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