Comparative Study of the spatial variability of shear strength parameter from different test methods

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ABSTRACT: Spatial variability of geotechnical properties of particular soil layers is a common phenomenon. Various properties may also have dissimilar variation which in addition to the difference arising from differing test methods surmounts to a technical challenge when it comes to the determination of the design parameters. However, it is common practice to simply state the range of the measured parameters from various tests and then present a deterministic mean value, whereas evaluation of the probabilistic weighted mean values is more appropriate. In order to arrive at a systematic evaluation procedure, in this article the shear strength parameter (Su) determined from a number of different in-situ as well as laboratory tests on particular soil layers are considered.

1 INTRODUCTION

Applications of probabilistic methods in geotechnical engineering have increased remarkably in recent years. Many engineers are concerned about what these developments mean and how they can be applied with confidence. Geotechnical engineers and geologists deal with materials whose properties and spatial distribution are poorly known and with problems in which loads and resistances are often coupled. Historically, the geotechnical profession has dealt with uncertainty on important projects by using the '*observational*' approach; this is quite compatible with reliability-based methods (G. B. Baecher & J. T. Christian 2003).

Because of natural inherent complexity of soil properties, it is not surprising that the physical properties of soils vary from place to place within resulting deposits. The scatter observed in soil data comes both from this spatial variability and from errors in testing. Each of these exhibits a distinct statistical signature, which can be used to draw conclusions about the character of a soil deposit and about the quality of testing. Means and standard deviations can be used to describe the variability in a set of soil property data.

Table 1 shows coefficient of variation range for different parameters after Phoon & Kulhawy 1996. The important thing to note in

Table 1 is how large are the reported coefficients of variations of soil property measurements. Most are tens of percent. These are useful measures, but they combine data in ways that mask spatial information. Describing the variation of soil properties in space requires additional tools. Spatial variation in a soil deposit can be characterized in detail, but only with a great number of observations, which normally are not available. We have to find a way that helps us to choose value of the required parameter among different limited number of tests performed on the site. This can be done through statistical study of different tests together.

2 STUDIED FIELD

The case studied here is an industrial state 472 m × 374 m in Asalooyeh port in the south of Iran. To reach the desired elevation a layer of almost 2 meter embankment was executed. For geotechnical studies 40 boreholes were drilled with depths from 20 m to 80 m borehole locations are shown in

Figure 1. During drilling procedure different in-situ tests such as SPT, field vane test (FVT), pressuremeter (PMT), down-hole and cross-hole tests were performed and in different layers of soil disturbed and undisturbed samples were acquired. Total test numbers peformed in boreholes were 645 SPT tests, 323 FVT tests and 30 pressuremeter tests and 1877 disturbed and 321 undisturbed samples were taken from boreholes. Although some layers and zones of coarse materials could be found, dominant classification of site soil was low plasticity silt (ML) and somehow clay (CL).

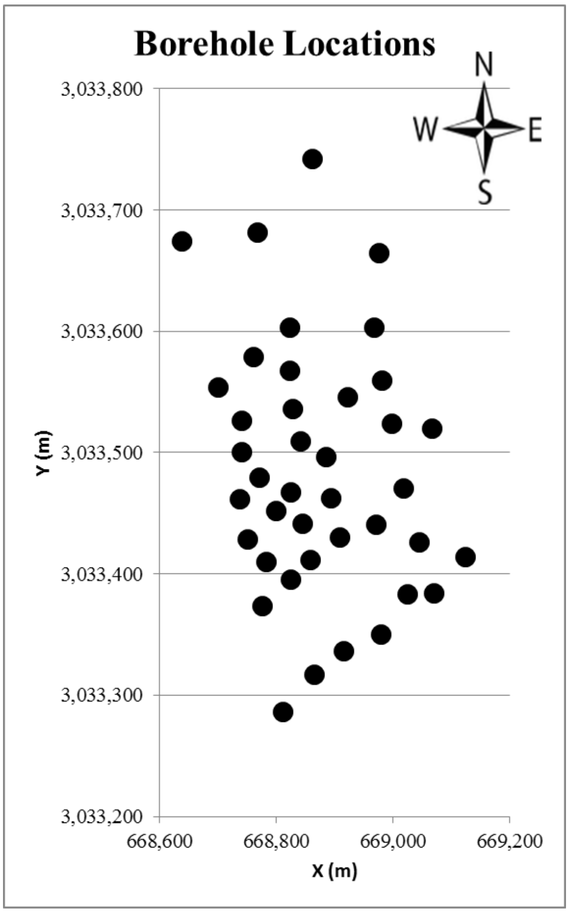

Figure 1 Borehole Locations

2.1 *Choosing parameter*

As the aim of the project was to find a way to compare and study different test result with each other, a parameter must be chosen which can be calculated from the most different tests performed on the site. Because of the dominant site soil classification is fne grained soil; it seems to be suitable to concentrate on the undrained *shear strength (Su)* which can be calculated form SPT, FVT, Pressuremeter and laboratory tests among those performed on the site.

3 ESTIMATING S_U

3.1 *SPT relations for Su*

A summary of the existing correlations between q_u with N_{SPT} are presented in Table 2. Besides the correlations expressing qu in terms of N_{SPT}, a number of other researchers considered the correlation between undrained shear strength (Su) with N_{SPT}. It is worth mentioning that by assuming full saturation of the sample in unconfined compression test the failure envelope may be taken to be parallel to σ_n axis (i.e. ϕ_u=0) and thus undrained cohesion or shear strength is equal to $q_u/2$.

Table 1, Coefficient of variation for some common field measurements (Phoon & Kulhawy, 1996)

Test type	Property	Soil type	Mean	Units	COV (%)
CPT	q_T	clay	0.5 – 2.5	MN/m^2	< 20
	q_c	clay	0.5 – 2	MN/m^2	20 – 40
	q_c	sand	0.5 – 3	MN/m^2	20 – 60
	s_u	clay	5 – 400	KN/m^2	10 – 40
SPT	N	clay & sand	10 – 70	blows/ft	25 – 50
DMT	A reading	clay	100 – 400	KN/m^2	10 – 35
	A reading	sand	60 – 1300	KN/m^2	20 – 50
	B reading	clay	500 – 880	KN/m^2	10 – 35
	B reading	sand	350 – 2400	KN/m^2	20 – 50
	I_D	sand	1 – 8		20 – 60
	K_D	sand	2 – 30		20 – 60
	E_D	sand	10 – 50	MN/m^2	15 – 65
PMT	P_L	clay	400 – 2800	KN/m^2	10 – 30
	P_L	sand	1600 – 3500	KN/m^2	20 – 50
Lab index	E_{PMT}	sand	5 – 15	MN/m^2	15 – 65
	w_n	clay & silt	13 – 100	%	8 – 30
	w_L	clay & silt	30 – 90	%	6 – 30
	w_P	clay & silt	15 – 15	%	6 – 30

However, contrary to the implication by its name, the SPT is not completely standardized (Clayton, 1995; Sivrikaya and Toğrol, 2006) and its results are affected by many factors such as test equipment, drilling procedure, as well as soil types and conditions. This fact has brought about the need for correction of test results. McGregor and Duncan (1998) have presented the most comprehensive equation for N_{SPT} correction;

$$N_{60} = (C_B C_C C_R C_{BF} C_S C_A C_E) \times N_{field} \quad (1)$$

Where:

- C_B borehole diameter correction factor,
- C_C hammer cushion correction factor,
- C_R rod length correction factor,
- C_{BF} blow count frequency correction factor,
- C_S liner correction factor,
- C_A anvil correction factor,
- C_E energy correction factor.

Table 2 Correlations between qu and SPT–N for various fine-grained soils (F. Kalantary et al. 2009)

Author(s)	Soil types	q_u (kPa)
Terzaghi & Peck (1967)	Fine-grained soil	12.5 N
Sanglerat (1972)	Clay	25 N
	Silty Clay	20 N
Schmertmann (1975)	High PI clay	25 N
	Medium PI clay	15 N
	Low PI clay	7.5 N
Nixon (1982)	Clay	24 N
Kuhawy & Mayne (1990)	Fine-grained soil	$58\ N^{0.72}$
Sivrikaya & Toğrol (2006)	High plastic clay	$9.5\ N_{field}$
		$13.63\ N_{60}$
	Low plastic clay	$6.7\ N_{field}$
		$9.86\ N_{60}$
	Clay	$8.66\ N_{field}$
		$12.38\ N_{60}$
	Fine-grained soil	$8.64\ N_{field}$
		$12.36\ N_{60}$

3.2 *FVT relations for Su*

Field vane test procedure allows evaluation of the undrained shear strength; equation 2 shows a general formula for deriving the shear strength from a vane shear test:

$$S_u = \frac{n+3}{D+Hb(n+3)}\frac{2T}{\pi D^2} \qquad (2)$$

Where n = non uniform shear strength distribution factor; b = anisotropy factor; D & H = width and height of the vane respectively. Equation 2 considers a non-uniform shear strength distribution along the top and bottom shear surface, soil anisotropy and any geometrical H/D ratio. The standard method of interpretation of the vane tests assumes uniform shear strength on failure surfaces (n = 0) and isotropic shear strength of the soil (b = 1) in rectangular vane of H/D = 2, leading to the following text book expression which is derived from equation 2 (F. Schnaid 2009):

$$S_u = \frac{6T_m}{7\pi D^3} \qquad (3)$$

Where Su = undrained shear strength from the vane and T_m = maximum value of measured torque.

3.3 *PMT relations for Su*

There are several different methods for estimating shear strength from pressuremeter tests. One of them is for the loading analysis that Gibson and Anderson (1961) method assumes the soil to behave as an elastic –perfect plastic Tresca material. The analytical solution for the cavity expansion in the plastic stage of an infinitely long cylindrical cavity was derived was derived above as:

$$p = \sigma_{h0} + s_u\left[1 + \ln\left(\frac{G}{s_u}\right) + \ln\left(\frac{\Delta V}{V}\right)\right] \qquad (4)$$

Where p is the total pressuremeter pressure, σ_0 the is-situ horizontal stress; the undrained shear strength and G the shear modulus. The volumetric strain is:

$$\frac{\Delta V}{V} = \frac{a^2 - a_0^2}{a^2} \qquad (5)$$

In other words the test results can be represented as shown in Figure 2 and the slope of the plastic portion is equal to the undrained shear strength of the soil.

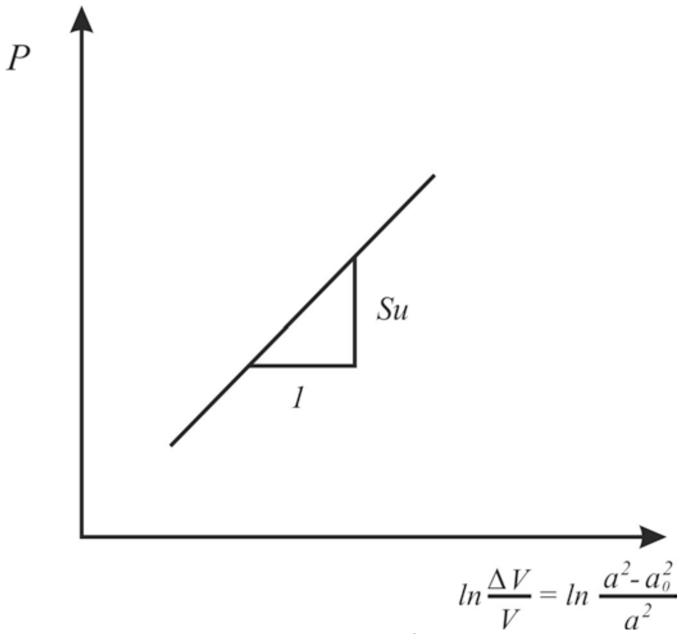

Figure 2 Graphical representation of the loading analysis of pressuremetr tests is clay (after Gibson & Anderson 1961)

3.4 *Laboratory Tests*

From triaxial UU tests S_u can be calculated as $q_u/2$. In other laboratory tests such as triaxial CD test or direct shear test which would provide both cohesion and friction angle, maximum shear strength is counted as S_u, as shown in Equation 4:

$$\tau_{max} = \sigma'_n \times \tan(\phi') + C \qquad (4)$$

4 SUMMARY STATISTICS OF RESULTS

Initially the summary statistics of different S_u results estimated from different tests is reviewed separately to obtain an overall understanding of each test in each layer.

It must be mentioned that S_u calculated from PMT test's results were not in the natural range for these soil materials, so they were omitted and just statistics of other test's results are shown in Table 3 to Table 7.

For calculating S_u from SPT tests Equation 5 is used:

$S_u = 4.5 \times N_{corrected}$ (5)

The vane blade used for testing had the geometric ratio H/D = 2 and diameter D = 45 mm.

Table 3 Summary statistics for different tests in depths between 1 m - 10 m

	S_u (SPT) kPa	S_u (FVT) kPa	S_u (Lab) kPa
Mean	95.22	89.61	69.36
Standard Error	9.19	6.35	3.03
Median	89.60	85.33	69.05
Standard Deviation	48.65	33.61	19.66
Sample Variance	2366.86	1129.49	386.49
Kurtosis	-0.50	1.78	1.35
Skewness	0.52	0.92	0.04
Range	179.44	161.68	105.57
Minimum	26.46	29.94	23.01
Maximum	205.90	191.62	128.58
Sum	2666.30	2509.05	2912.92
Count	28	28.00	42

Table 4 Summary statistics for different tests in depths between 10 m - 15 m

	S_u (SPT) kPa	S_u (FVT) kPa	S_u (Lab) kPa
Mean	81.94	89.57	86.87
Standard Error	7.26	6.28	6.61
Median	75.82	77.85	92.57
Standard Deviation	42.95	37.16	31.71
Sample Variance	1844.53	1380.75	1005.51
Kurtosis	-0.70	2.60	-0.62
Skewness	0.54	1.73	-0.62
Range	150.22	155.69	103.55
Minimum	18.95	53.89	30.41
Maximum	169.18	209.59	133.96
Sum	2867.87	3134.82	1998.11
Count	35	35	86.87

Table 5 Summary statistics for different tests in depths between 15 m - 20 m

	S_u (SPT) kPa	S_u (FVT) kPa	S_u (Lab) kPa
Mean	99.95	90.27	113.65
Standard Error	8.01	3.50	11.12
Median	100.15	91.32	129.99
Standard Deviation	50.64	22.16	55.61
Sample Variance	2564.60	491.24	3092.20
Kurtosis	1.40	-0.48	-0.77
Skewness	1.02	-0.06	-0.60
Range	229.15	89.82	177.53
Minimum	30.18	41.92	19.62
Maximum	259.33	131.74	197.15
Sum	3997.84	3610.88	2841.26
Count	40	40	25

Table 6 Summary statistics for different tests in depths between 20 m - 30 m

	S_u (SPT) kPa	S_u (FVT) kPa	S_u (Lab) kPa
Mean	110.22	109.35	164.39
Standard Error	8.04	5.23	10.37
Median	90.27	101.80	171.35
Standard Deviation	55.69	36.20	68.78
Sample Variance	3101.28	1310.74	4730.33
Kurtosis	3.44	0.05	-0.56
Skewness	1.62	0.69	-0.40
Range	288.76	155.69	262.50
Minimum	32.17	44.91	36.30
Maximum	320.92	191.62	128.58
Sum	5290.57	2509.05	2912.92
Count	48	28.00	42

Table 7 Summary statistics for different tests in depths between 30 m - 40 m

	Su (SPT) kPa	Su (FVT) kPa	Su (Lab) kPa
Mean	100.86	107.59	200.69
Standard Error	6.49	6.70	15.20
Median	101.75	101.80	215.57
Standard Deviation	36.13	37.31	89.94
Sample Variance	1305.50	1391.87	8088.94
Kurtosis	-0.45	-0.34	-0.39
Skewness	0.50	0.36	-0.74
Range	138.30	152.70	317.07
Minimum	45.09	32.94	16.68
Maximum	183.39	185.63	333.75
Sum	3126.64	3335.42	7024.28
Count	31	31	35

5 VARIOGRAM ANALYSIS

The variogram (or semi-variogram) is a graph relating the variance of the difference in value of a variable at pairs of sample points to the separation distance between those pairs. It is highly used in geostatistical analysis and especially for the Kriging interpolating method. Here we use it to characterize spatial variability between our SPT test results. The variogram 2γ is usually defined as the expected value of the squared difference

$$2\gamma = E\left[\left\{z(x_i) - z(x_j)\right\}^2\right] = Var\left[z(x_i) - z(x_j)\right]$$

Now, with N(h) representing the number of pairs separated by lag h (plus or minus the lag tolerance), the semivariance can be computed for lag h as

$$\gamma = \frac{1}{2N(h)}\sum_{i=1}^{N(h)}[z(x_i + h) - z(x_i)]^2$$

At first to identify if the results or better to say the soil characteristics are isotropic in each layer variogram in 4 different direction of 0°, 45°, 90° and 135° with tolerance of ±22.5° were calculated. As there were no considerable changes in different direction, soil layers were considered as isotropic and the variogram with lag h of just separated by distance and not considering its direction is studied here.

5.1 *Fitting model to experimental variograms*

In this study spherical model is used to model the experimental variograms. This model has three components, sill, range and nugget which can show us some information about the variability of data. A brief explanation and their interpretation can be written as

Range: as the separation distance h increases, less correlation is expected, and hence and increase in the variogram. At some point, this increase flattens off. The distance which the variogram flattens off is termed the range. It can show somehow the range of influence of data on each other.

Sill: the level which the variogram flattens of is termed the sill. It is often close to the sample data variance.

Nugget: In theory the semivariogram value at the origin (0 lag) should be zero. If it is significantly different from zero for lags very close to zero, then this semivariogram value is referred to as the nugget. The nugget represents variability at distances smaller than the typical sample spacing, including measurement error.

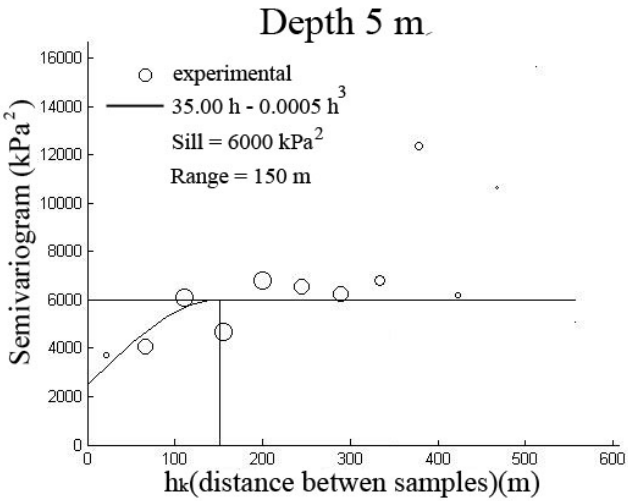

Figure 3 Semivariogram in Depth of 5 meter

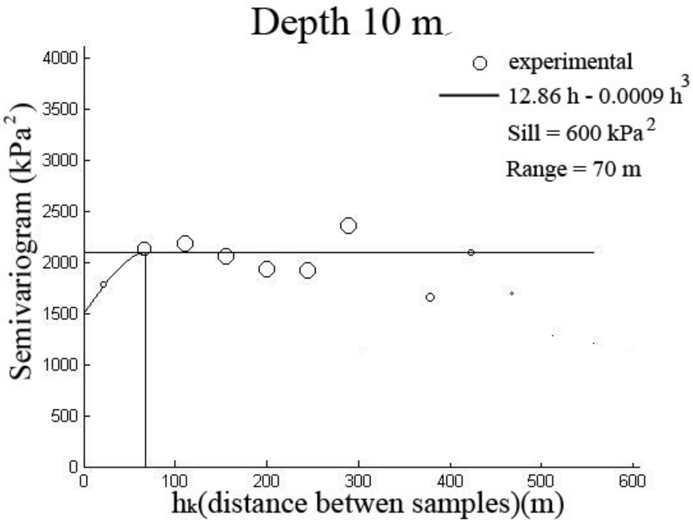

Figure 4 Semivariogram in Depth of 10 meter

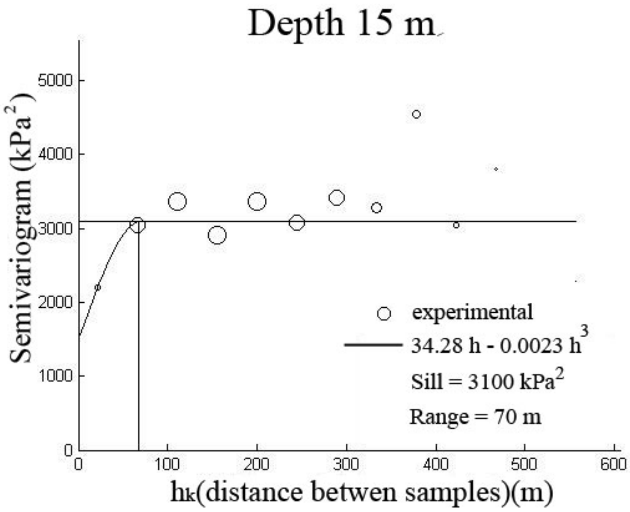

Figure 5Semivariogram in Depth of 15 meter

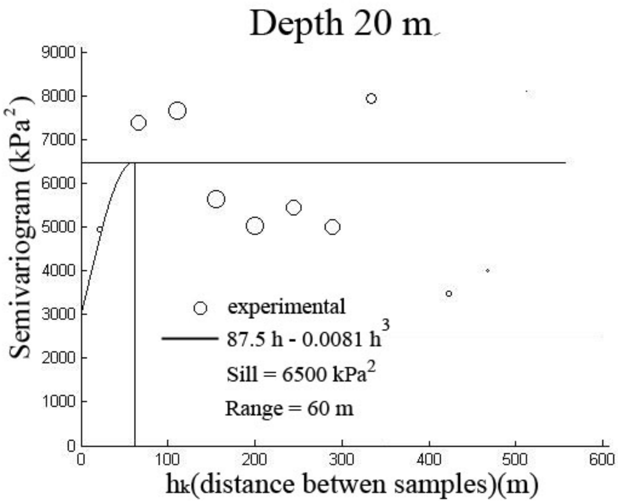

Figure 6 Semivariogram in Depth of 20 meter

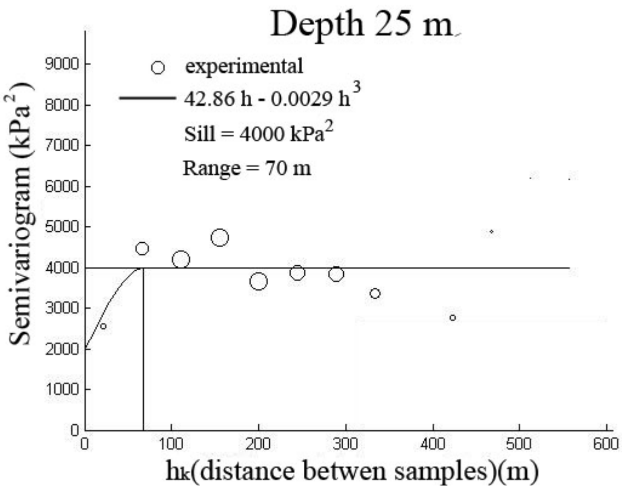

Figure 7 Semivariogram in Depth of 25 meter

It should be noted that size of points in each graph is related directly to the number of pairs which has distance h (in a range we chosen around h), or N(h). for each h, the more the N(h) the bigger the point is graph is. It can help to understand which points can be more important and which odd points can be neglected as their size is too small.

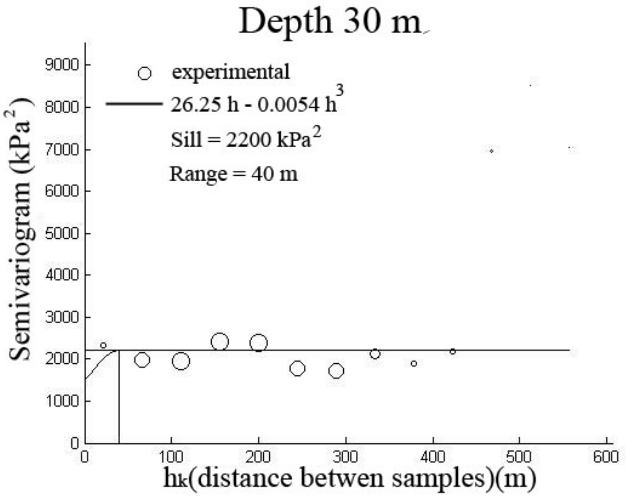

Figure 8 Semivariogram in Depth of 30 meter

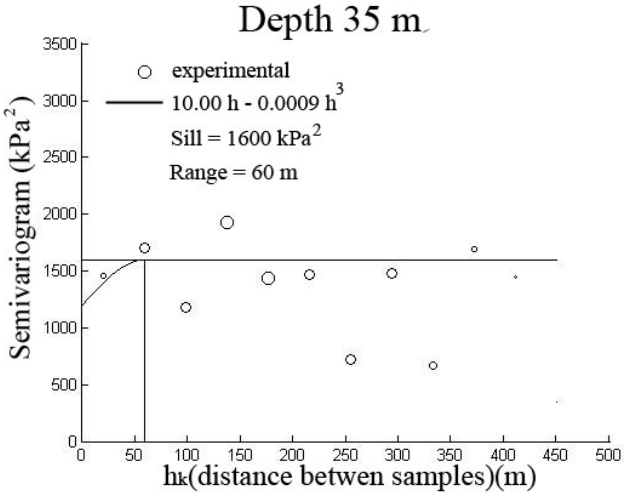

Figure 9 Semivariogram in Depth of 35 meter

5.2 *Interpreting Variograms*

According to definition of sill, range and nugget some characteristics of SPT results can be interpreted form the variograms shown in Figure 3 to Figure 9. However it cannot be very exact but they even show a rough estimation about how the tests were conducted appropriate or how much the result may be reliable.

As it is seen in Figure 3, the sill in variogram graph for layer in depth of 5 meter (test executed in depth of 2.5 meter to 7.5 meter) is relatively higher than same parameter in depth of 10 or 15 meter. It can show more variability in low depth and near the surface soil characteristics. However it may be because of the test errors but because of the behavior we know about the near surface layers of soil this higher sill in comparison with next layers can be justified. as borehole logs shows soil in layers with depth of 10 and 15 meters is almost homogeneous and almost all the samples are ML, but in layers with less depth more percentage of sand and even gravel is seen, as some of samples are SM or GM. This variability is soil type is another reason can justify high sill or equivalently high sample variance in depth of 5 meter. In Figure 4 and Figure 5 variogram of tests result in layers of 10 and 15 are shown. These layers are almost homogeneous and soil type is mostly ML. as it is expected variograms are almost the same, with close sill, range and nugget. The lower sill shows less variability and maybe more reliability in results. After these two layers variogram of test results in depth of 20 meter, a sudden change in trend of varigrams through the layers is seen. The results show relatively high variability and experimental variogram points are not forming any desired trend which a common variogram model can be fitted on them. Instead of reaching a constant level by increasing lags semivariance values increase then suddenly decrease.it must be noted that soil type in this layer is almost the same as layers in depth of 10 and 15. We cannot judge and decide whether the results are reliable or not with just this graph, but this helps us to find there is a problem here and we must find why variogram of these tests data does not follow the trend most of other varigrams of soil data have. To find the reasons lead to this we must do some more exact investigation. Again in layer of 25 meter depth variogram behaves almost like preceding one in 10 and 15 meter depths. However its sill is a little higher than what we have in depths of 10 and 15 meter but it is not significant. Next layers we consider are variograms of layers in depths 30 and 35. In these layers changes in soil type can be seen. In previous layers up to depth of 25 meter, mainly silty soil formed the layers but after that increase of clay percentage and more CL and CL-ML soils are observed among soil samples. Decrease of sill is seen in these two layer's variograms. It may be inherent characteristics of clayey soils but for being sure about this theory, lots of more investigations are needed.

6 SUMMARY

As mentioned before, spatial variability in geotechnics is results of so many different reasons. To obtain a physical property of a specified soil like undrained shear strength, some steps are needed to be done. There are different types of tests which Su can be obtained from. Each test may have different results in different soils and different results in comparison with other tests. During the tests, human errors, test's equipment and other error sources may affect test's results. After taking initial results of any test, like N_{SPT}, there are different equations to obtain Su or any other parameter needed. Each one of these different factors would lead to a high variability of results. Apart from error sources, spatial variability is a soil inherent characteristic. Using variograms cannot specify all factors have affected test results and complete map of spatial variability of soil but can show more information about essential statistics of soil test's results. By knowing statistics like mean, variance etc… a rough view about variability in soil test result's data can be reached but by considering variograms which show variation of data in relation with distance (considering direction or not) between sample points can help to gain more information about results and reliability of them. As it is explained in section 5, nugget, sill and range are three factors of model fitted to the experimental variogram may show tests' precision in comparison with other tests in other layers and if the variability of results are in acceptable range or not. For instance by calculating variogram parameters for a large sets of SPT results, nugget to ratio would be a suitable dimensionless variable for comparing the dispersion of different data sets with each other. Furthermore if the database would be large enough, putting all the nugget to sill ratios together would lead to a good criteria of normal and acceptable dispersion of test's results in different soil types.

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