A Case Study of the Measurement of the Spatial Correlation Length of Soil Parameters Using SPT and CPT Field Tests Data

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Abstract. The Hoor-Al-Azim wetland is situated in the southwest of Iran and the southeast of Iraq, in the Middle East. Various industrial projects have been implemented in this region, and major projects are planned for the future. Therefore, geotechnical investigation of this area is crucial to understand its geology and geotechnics. It is necessary to determine the type and number of investigation tests required for this purpose. The water depth in Hoor-Al-Azim varies, but it is usually about 3-4 m. To facilitate access, some access road embankments have been constructed, and more will be implemented in the future. However, the slope stability of these embankments is uncertain due to the lack of reliable geotechnical properties. Hence, reliability analysis of trenches and slopes is needed.

The Random fields technique is one of the reliability analysis methods that can be employed. The spatial correlation length is a key parameter in this technique, and it can be calculated in several ways. Geotechnical site data analysis can provide the required information, which can be used in different geotechnical designs, such as slope stability analysis. Geotechnical data is usually derived from in-situ tests like CPT and SPT. While the comparison of SPT and CPT has been investigated in different aspects, evaluating and comparing the spatial correlation length obtained from these tests at the same site has not been discussed in technical literature. Therefore, in this article, geotechnical data obtained from the results of SPT and CPT tests at several sites in Hoor-Al-Azim has been investigated using Vanmarcke's expeditive method (VXP). In general, the distance of CPT data is shorter than SPT data, resulting in less calculation of the spatial correlation length and more variability. The article also proposes some suggestions for the distance of boreholes by calculating the horizontal spatial correlation length.

Keywords: Slope stability · Data uncertainty · Reliability analysis · Random field · Spatial correlation length · SPT · and CPT field tests

1 Introduction

Random field theory has been increasingly utilized to model soil variability and reduce uncertainty in soil properties [1]. A random field is characterized by its mean, variance, and spatial correlation length (SCL), which is a measure of distance within which soil

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properties exhibit a strong correlation [2]. In practice, the SCL should be estimated from a population of observations [3], and various methods have been developed to characterize this parameter from soil data. The first correlation concept and the definition of the SCL were introduced by Vanmarcke [4]. However, literature on calculating the SCL of soils based on real data is limited [5–8], and mainly refers to the Cone Penetration Test (CPT) and Standard Penetration Test (SPT) data, as they yield a large amount of closely spaced data [9, 10].

The geotechnical site investigation data are often inadequate for evaluating soil statistical parameters like SCL, as they are planned without considering the soil's inherently variable nature [11]. Although SPT and CPT have been compared and evaluated in various aspects, the technical literature has not discussed evaluating and comparing the spatial correlation length obtained from these tests at the same site. Therefore, in this article, geotechnical data obtained from the results of SPT and CPT at several sites in the Hoor-Al-Azim have been investigated using Vanmarcke's expeditive method (VXP).

1.1 Hoor-Al-Azim Wetland

The Hoor-Al-Azim wetland is situated in the southwestern region of Iran, in the Khuzestan province near the border between Iran and Iraq. This area is home to the Azadegan and Yadavaran fields, and various types of infrastructure are planned to be constructed here, including storage tanks with circular foundations, pipelines, pipe racks, buildings (such as substations, control buildings, camps, etc.), different types of mechanical facilities, and roads. As some parts of the site require excavation that may reach depths of 2.0 to 3.0 m below the natural ground surface, ensuring a stable excavation slope is crucial. A comprehensive study of the soil strata has been conducted to obtain detailed information. The geographic proximity and geology of the area are presented in Figs. 1 and 2, respectively.

1.2 Geotechnical Investigation

To determine the soil properties of the Hoor-Al-Azim region, a geotechnical investigation was conducted to obtain the necessary parameters for the detailed design of the project. The investigation involved field exploration, laboratory testing, and engineering analysis. In-situ tests, specifically the electrical piezocone penetration (CPTu) and Standard Penetration Test (SPT), were performed during field studies.

During the investigation, it was observed that the water elevation was at a depth of about 3.0 to 4.6 m from the ground surface. Soil layers above the groundwater surface were mainly composed of silty clay with sand, silty sand, or sandy silt with clay. These layers were stiff or dense in dry conditions, but if they continued below the water table, they would become soft to medium stiff or loose to medium dense. Generally, it was observed that the upper soil layers from the groundwater surface to a depth of about 15 to 20 m were soft to stiff in clay and loose to medium dense in sandy or silt layers. Beyond that depth, the soil layers changed from very stiff to hard in clay and from dense to very dense in sand or silt.

Fig. 1. Geographic proximity of the area in Iran map

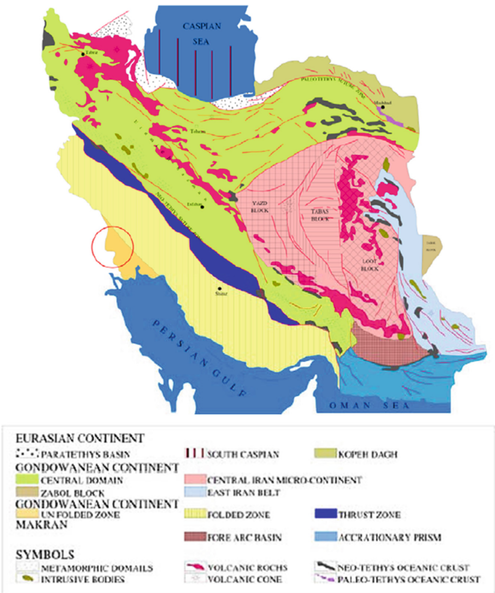


Fig. 2. Geological of the area in Iran map

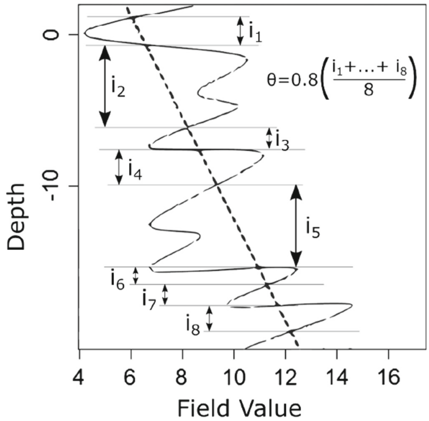


Fig. 3. Illustration of the Vanmarcke's expeditive method for calculation of SCL

2 Method of Determining SCL

The correlation concept and the definition of the scale of fluctuation were first introduced by Vanmarcke. Since then, various techniques have been developed to model the heterogeneity of soil properties as random fields using Vanmarcke's theory [12].

This study aims to calculate and compare the spatial correlation length based on the results of SPT and CPT data obtained from the Azadegan and Yadavaran fields in the Hoor-Al-Azim wetland. Vanmarcke's expeditive method was employed for this purpose.

2.1 Vanmarcke's Expeditive Method

Vanmarcke proposed a simple method for approximating the spatial correlation length of stochastic processes, which is known as Vanmarcke's expeditive method. This method involves averaging the distances between the consecutive intersections of the overall profile and the trend line of a given profile. The spatial correlation length can then be estimated as 80% of this average distance, using Eq. (1). Figure 3 illustrates how to calculate the spatial correlation length using this method.

$$\theta = \sqrt{\frac{2}{\pi}}\overline{d} \cong 0.8\overline{d} \tag{1}$$

3 Characteristics of Studied Sites

3.1 Areas

A geotechnical investigation was conducted at the Azadegan and Yadavaran field sites, as shown in Fig. 4. Basic studies were conducted in several areas, including well pads, the CAMP, warehouse, drilling storage, and Kushk manifold. The well pads are located in the Azadegan field, while the other areas are in the Yadavaran field, as indicated in Fig. 5.

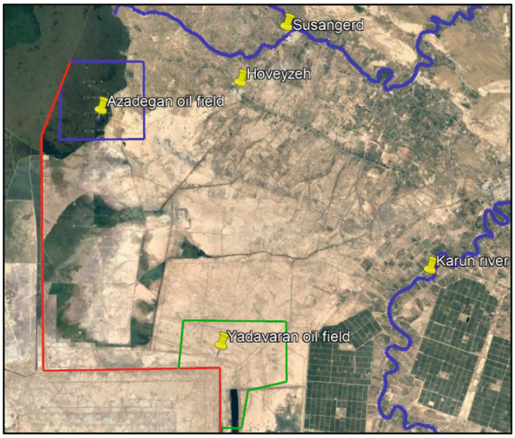
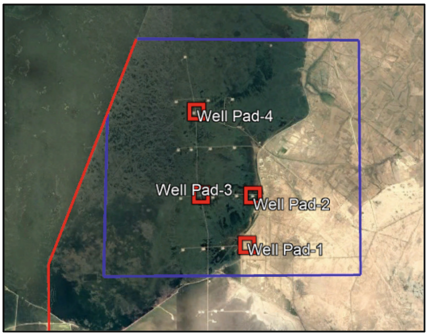


Fig. 4. The situated of the studied sites



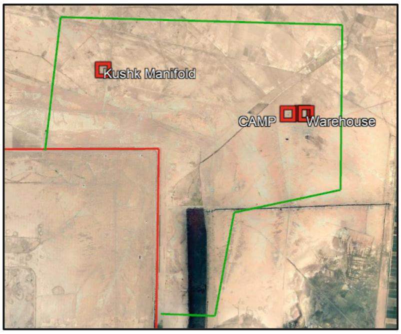


Fig. 5. The situated of the studied areas. Left: Azadegan and right: Yadavaran fields

3.2 Field Tests

Several exploratory boreholes were drilled using the continuous coring method as part of the geotechnical investigation. Standard penetration testing (SPT) was performed in the boreholes to evaluate the mechanical properties of the sub-surface layers. The SPT results were extracted from the borehole logs, with the frequency of testing being every 1 or 1.5 meters. In addition, ten static cone penetration tests were performed near the boreholes on the natural ground in the fields. CPTu tests were performed to complete the depth of the boreholes Continuously, and data on qc, fs, pore pressure, speed, and inclination were recorded automatically at every 2 cm of penetration using a data logger linked to a laptop computer. These data were corrected for zero-value readings at the top of the boreholes and other cone factors. The subsurface soil and its physical properties were investigated through field exploration and laboratory testing, and the program is presented in detail in the logs of boring.

SPT test. In the SPT test, the number of blows of a 64.0 kg hammer falling freely from a height of 76.0 cm to cause 30.0 cm penetration of a split spoon sampler, with

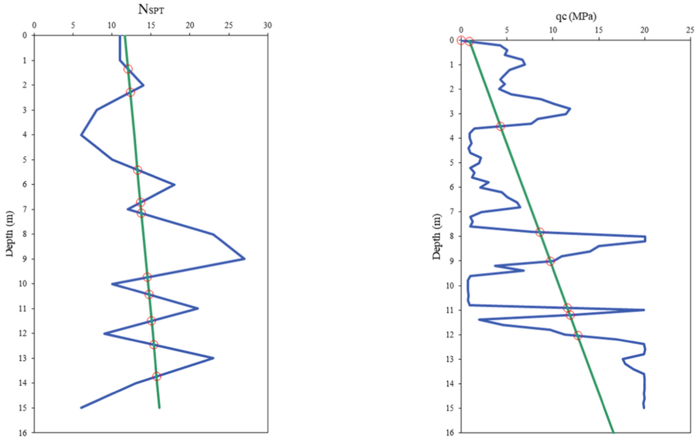


Fig. 6. Variation of field data versus depth in one of the different boreholes. Left: SPT blows and right: q_c values of CPT test

3.8 cm internal and 5.0 cm external diameters, is recorded. The blow numbers are an indication of the relative density of granular and consistency of cohesive soil layers. The borehole logs provide blow numbers for six consecutive 75mm penetrations of the spoon sampler, and the final SPT test result is the sum of the blow numbers for the last four 75mm penetrations. Figure 6 shows variations of the field SPT blows versus depth in one of the different boreholes.

CPTu test. The CPTu tests were conducted following the ASTM D5778 standards. In this test, the hydraulic jacks provide the driving force, with a maximum capacity of 10 tons for the cone and the hydraulic system. The hydraulic system is designed to push the rods at a constant speed between 1.5-2.5 cm/s. Figure 6 shows an example of the variation of “qc” with depth for one of the different CPTu boreholes.

4 Results and Discussion

The coordinates of SPT and CPTu boreholes in different sites are presented in Tables 1 and 2. The specifications related to the field tests, including depth, data intervals used for calculating the spatial correlation length, and the resulting spatial correlation length are listed in Tables 3 and 4 (Figs. 7 and 8)

The spatial correlation length obtained from the CPT test was generally smaller compared to the value obtained from the SPT results, with one exception where the difference in value between the coefficient of variation of the SPT and CPT data was very high. This could be due to the difference in the data intervals between the two tests, which are much smaller in the CPT. Increasing the sampling intervals increases the spatial correlation length, while increasing the spatial correlation length in the random field model increases the probability of failure in geotechnical structures [11].

In the Yadavaran site, the SCL obtained from SPT and CPT results were more similar than in the Azadegan site. Generally, the coefficient of variation of SPT data was much lower than the coefficient of variation of CPT data. On average, this value was equal

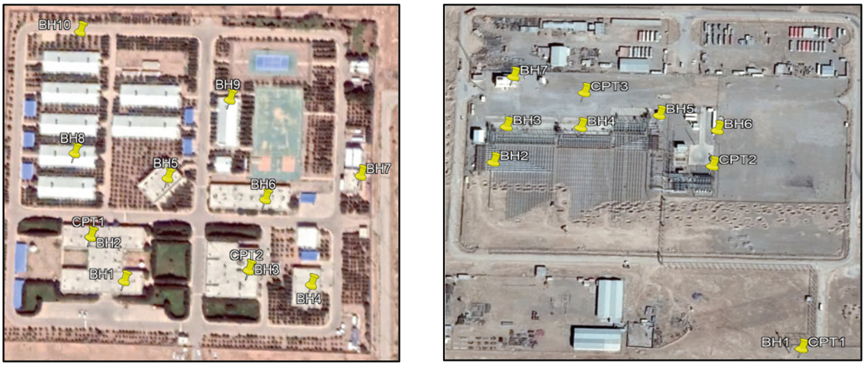


Fig. 7. CPTu and SPT boreholes location in CAMP and Kushk manifold areas

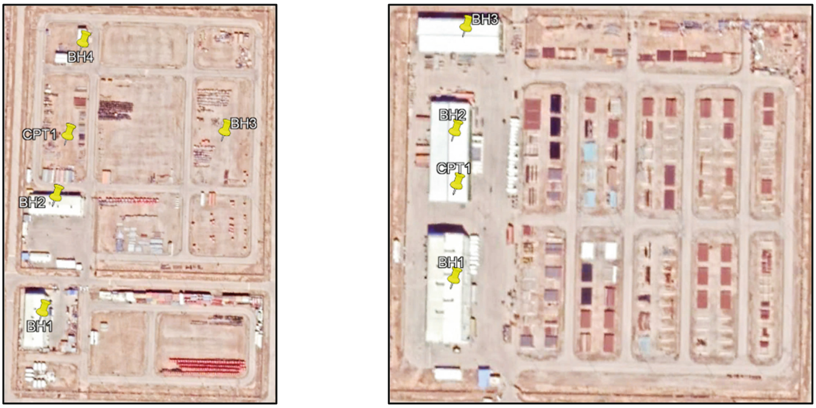


Fig. 8. CPTu and SPT boreholes location in warehouse and drilling storage

to 40% in the SPT test and 70% in the CPT results. The inherent variability of SPT measurements is reported in Phoon, Kulhawy, and Grigoriu (1995) with a COV value in the range of 25-49% in sandy and silty soils, whereas this value is 37-57% in clayey soils. For CPT measurements, the COV value is in the range of 10-81% in sandy soils, whereas this value is 5-40% in silty clay soils [13]. Also, the coefficient of variation of the spatial correlation length based on SPT and CPT results was equal to 37.6%.

5 Horizontal Spatial Correlation Length

In the current study, the topography of the project area is nearly flat. Therefore, Vanmark's method was used to calculate the horizontal spatial correlation length, as illustrated in Fig. 9. In areas with three or more boreholes, one borehole was selected as the index borehole, and its horizontal distances from the others were measured. The average SPT results obtained during the previous step of vertical spatial correlation were used as data. The calculation of the horizontal spatial correlation length provided recommendations

Table 1. Coordinates of CPTu and SPT boreholes location in Azadegan field site

Site	Area	Boreholes	UTM	
			X	Y
Azadegan field	Well pad-1	BH-1	767726	3477670
		CPTu-1	near BH-1	
	Well pad-2	BH-2	768058	3480825
		CPTu-2	near BH-2	
	Well pad-3	BH-3	764808	3480823
		CPTu-3	near BH-3	
	Well pad-4	BH-4	764500	3486000
		CPTu-4	near BH-4	

Table 2. Spatial correlation length of CPTu and SPT boreholes in Azadegan field site

Site	Area	Boreholes	Depth (m)	Data intervals (m)	COV (%)	θ (m)	Average
Azadegan field	Well pad-1	BH-1	12	1.5	42	4.8	BH = 3.4 m
		CPTu-1	20	0.2	77	1.4	
	Well pad-2	BH-2	12	1.5	24	2.0	
		CPTu-2	20	0.2	66	3.5	
	Well pad-3	BH-3	12	1.5	52	3.8	CPTu = 2.2
		CPTu-3	20	0.2	57	1.8	
	Well pad-4	BH-4	12	1.5	78	3.1	
		CPTu-4	20	0.2	54	2	

for the distances and number of boreholes required for geotechnical investigations. The results of the horizontal spatial correlation length are presented in Table 5.

Table 3. Coordinates of CPTu and SPT boreholes location in Yadavaran field site

Site	Area	Boreholes	UTM	
			X	Y
Yadavarn field	CAMP	BH-1	225637	3435146
		BH-2	225612	3435180
		BH-3	225732	3435152
		BH-4	225779	3435140
		BH-5	225672	3435223
		BH-6	225746	3435205
		BH-7	225819	3435221
		BH-8	225601	3435244
		BH-9	225721	3435281
		BH-10	225607	3435337
		CPTu-1	near BH-2	
		CPTu-2	near BH-3	
	warehouse	BH-1	226884	3434974
		BH-2	226899	3435086
		BH-3	227067	3435146
		BH-4	226929	3435238
		CPTu-1	226912	3435146
	drilling storage	BH-1	226608	3435112
		BH-2	226612	3435214
		BH-3	226622	3435286
		CPTu-1	226612	3435177
	Kushk manifold	BH-1	785712	3437733
		BH-2	785371	3437975
		BH-3	785383	3438024
		BH-4	785464	3438025
		BH-5	785549	3438044
		BH-6	785613	3438025
		BH-7	785388	3438093
		CPTu-1	near BH-1	
		CPTu-2	785609	3437976
		CPTu-3	785466	3438073

Table 4. Spatial correlation length of CPTu and SPT boreholes in Yadavaran field site

Site	Area	Boreholes	Depth (m)	Data intervals (m)	COV (%)	θ (m)	Average
Yadavarn field	CAMP	BH-1	15	1	56	1.9	1.9
		BH-2			73	1.6	
		BH-3			56	3.0	
		BH-4			65	1.9	
		BH-5			60	1.5	
		BH-6			63	2.9	
		BH-7			46	1.1	
		BH-8			43	1.8	
		BH-9			43	1.5	
		BH-10			58	1.7	
		CPTu-1	15	0.2	76	1.5	1.6
		CPTu-2	25		70	1.7	
	warehouse	BH-1	15	1.5	54	1.7	2.7
		BH-2			22	3.2	
		BH-3			47	3.2	
		BH-4			28	2.9	
		CPTu-1		0.2	66	1.4	1.4
	drilling storage	BH-1	15	1.5	22	2.2	2.3
		BH-2			23	2.2	
		BH-3			28	2.5	
		CPTu-1		0.2	70	2.2	2.2
	Kushk manifold	BH-1	25	1.5	28	2.1	2.9
		BH-2	15		21	3.5	
		BH-3			21	2.6	
		BH-4			27	1.9	
		BH-5			42	4.1	
		BH-6			51	3.8	
		BH-7			30	2.3	

(*continued*)

Table 4. (*continued*)

Site	Area	Boreholes	Depth (m)	Data intervals (m)	COV (%)	θ (m)	Average
		CPTu-1	25	0.2	64	1.1	1.1
		CPTu-2	15		97	1.2	
		CPTu-3			79	1.1	

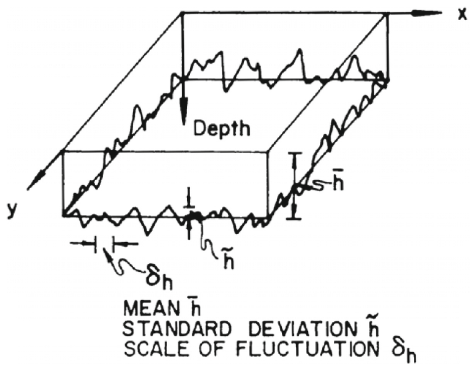


Fig. 9. Parameters of randomly varying depth to rock [4]

Table 5. Horizontal spatial correlation length of SPT boreholes in Yadavaran field site

Site	Area	Field test	Horizontal spatial correlation length (m)
Yadavarn field	drilling storage	SPT	92
	Kushk manifold		64

6 Conclusion

The random fields technique is a powerful method for reliability analysis that relies on the spatial correlation length, a key parameter that can be obtained from geotechnical site data analysis. Geotechnical data is mainly derived from in-situ tests, such as CPT and SPT, which have been compared and evaluated in various aspects. However, the literature lacks discussion on evaluating and comparing the spatial correlation length acquired from these tests at the same site. This study focuses on calculating and comparing the spatial correlation length based on SPT and CPT field test data results in the Azadegan and Yadavaran field sites situated in the Hoor-Al-Azim wetland. Vanmarcke's expeditive method (VXP) was used to investigate geotechnical data obtained from the results of SPT and CPT tests at several sites in the Hoor-Al-Azim. Furthermore, this study suggests borehole distances using the calculation of the horizontal spatial correlation length. The obtained results are summarized as follows:

1. The spatial correlation length obtained from the CPT test results is generally smaller compared to that based on the SPT results. This could be due to the difference in data intervals between the two tests, which were much smaller in the CPT. The SPT and CPT test data had frequencies of every 1 or 1.5 m and 0.2 m, respectively.
2. The coefficient of variation of SPT data was much lower than that of CPT data, with an average value of 40% in the SPT test and 70% in the CPT results. Where the difference in value between the coefficient of variation of SPT and CPT data was very high, the spatial correlation length obtained from the SPT test was smaller compared to that based on the CPT results.
3. The spatial correlation length based on the SPT data was about 1.5 to 2 times the distance of the data, while in the CPT, this number was between 5 to 10 times the data intervals.
4. The coefficient of variation of the spatial correlation length based on both SPT and CPT results were equal.
5. When the borehole depth and sample intervals were more similar between the SPT and CPT tests, the spatial correlation length was less different.
6. Based on the horizontal spatial correlation length, it is suggested that the distance between boreholes be about 60 to 100 m. If the distance between boreholes is greater than this value, it is recommended to add a third borehole.

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