Comparative Evaluation of Cone Penetration Test Data for Estimating the Bearing Capacity of Pile Foundations in Sandy Soils of Sanur, Bali

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ABSTRACT

Accurate estimation of foundation bearing capacity is a fundamental aspect of geotechnical engineering design, directly influencing the safety, serviceability, and cost-efficiency of structural systems. Among various in-situ testing methods, the Cone Penetration Test (CPT) has gained widespread application due to its efficiency, reliability, and ability to provide continuous soil profiling. However, despite its advantages, CPT data may exhibit considerable variability even within relatively small areas, especially in sandy soil conditions commonly found in coastal regions. Such variability can lead to significant differences in estimated bearing capacities, posing challenges in foundation design decision-making.

This study presents a comparative analysis of CPT data collected from several locations within the Sanur area of Denpasar, Bali, Indonesia. The selected sites are geologically characterized by predominantly sandy deposits with minimal cohesive content. The ultimate bearing capacity of shallow foundations was estimated using Terzaghi's classical bearing capacity theory, assuming a foundation depth of 6 meters for consistency across all test points.

The results reveal that the calculated single pile bearing capacity ranges from 10.22 to 13.42 kN with 0.30-meter diameter and 6-meter depth. Coefficient of Variation (CoV) values support this finding, with qc exhibiting moderate to high variability (15%–62%) and fs showing lower variability (7%–17%). These CoV values are consistent with established ranges for sandy coastal soils and align with findings from previous studies. This moderate degree of variation reflects the influence of local subsurface heterogeneity, even in seemingly uniform sandy strata. The study highlights the necessity of integrating statistical evaluation of geotechnical parameters into design procedures, especially in environments where small-scale soil variability can affect structural performance.

The findings provide practical insights for geotechnical engineers and practitioners, emphasizing the importance of multiple CPT soundings and spatial analysis when developing foundation design criteria in similar coastal environments.

Keyword: Pile, Cone Penetration Test, Coefficient of Variation

INTRODUCTION

Sanur is one of the rapidly developing coastal areas in Denpasar City, Bali. Its popularity as an international tourist destination has driven extensive infrastructure development, including the construction of hotels, villas, restaurants, and other supporting facilities. This surge in construction activity necessitates reliable geotechnical investigations, particularly in foundation planning, to ensure the stability and safety of structures (I Made Sudjana et al., 2019; Putra, 2022).

In geotechnical practice across Bali, the Cone Penetration Test (CPT) has become the primary method for subsurface investigation. This method is widely employed due to its rapid execution, efficiency, and ability to provide continuous soil profile data. CPT produces key parameters such as cone tip resistance (q_c) and sleeve friction (f_s), which can be used to estimate soil bearing capacity through various empirical approaches. The use of CPT is especially common in projects across Sanur due to its practicality, particularly in sandy soils typical of coastal environments. However, CPT test results often exhibit significant variability, even between closely spaced locations. This variability may arise from natural soil heterogeneity, depositional conditions, groundwater fluctuations, and other local disturbances. Such uncertainties can impact the reliability of bearing capacity estimations if not properly accounted for. Therefore, statistical approaches are needed to understand the extent of variation and its influence on design outcomes (Basoka, 2020; Dharmayasa & Utami, 2018; Satriyo et al., 2020).

One of the most commonly used statistical parameters to quantify data variability is the Coefficient of Variation (CoV), defined as the ratio of the standard deviation to the mean of a dataset. The CoV reflects the degree of data dispersion relative to its central value. In the context of CPT data, the CoV of qc values provides an indication of the heterogeneity of subsurface conditions at a given site. A high CoV value indicates significant uncertainty, which must be carefully considered in foundation design particularly when a deterministic approach is still being used. Previous studies have reported CoV values for qc ranging between 0.1 to 0.8, depending on the soil type and geological setting. These values illustrate the extent to which data variability can affect the final bearing capacity calculations. By incorporating CoV into the design process, engineers can evaluate the need for higher safety factors or consider probabilistic approaches, which are increasingly adopted in modern geotechnical engineering (Bong & Stuedlein, 2017; Mert & Yazici, 2021; Phoon & Kulhawy, 1999).

The soil conditions in Sanur are generally composed of sandy layers formed through coastal sedimentation. Although these soils may appear relatively uniform at first glance, there are often substantial local variations. These differences are attributed to changes in sediment structure, tidal influences, groundwater level fluctuations, and other environmental factors. As such, despite the widespread use of CPT, careful interpretation of the data must account for these local variations to ensure accurate foundation design. This study aims to evaluate the variability of foundation bearing capacity derived from CPT data in the Sanur area of Bali. The primary objective is to analyze the bearing capacity of single footings at a depth of 6 meters using Terzaghi's classical method, based on qc values obtained from multiple CPT locations. The analysis results are used to determine the mean bearing capacity, standard deviation, and the corresponding CoV. Through this approach, the study seeks to provide a clearer understanding of the range of foundation bearing capacities in the region and the extent to which uncertainty should be incorporated into the design process. The main contribution of this research lies in presenting a quantitative characterization of the distribution of foundation bearing capacity values based on actual CPT data from Sanur. This information will benefit planners and civil engineering practitioners in making more accurate, efficient, and safe design decisions. Moreover, the study reinforces the importance of applying statistical analysis in geotechnical data interpretation and promotes the use of risk-informed design approaches that are better suited to naturally variable ground conditions.

Cone Penetration Test

Based on the Cone Penetration Test (CPT), the allowable bearing capacity of a pile can be estimated using an empirical approach that considers two primary components: end bearing resistance and shaft friction. The formula used for this estimation is as follows(Schmertmann, 1978):

$$Q = (q_c . Ab)/F1 + (JHP . O)/F2 \qquad \text{Eq. 1}$$

Where:

1. q_c = cone tip resistance obtained from CPT readings, typically averaged over a zone approximately ±1 pile diameter above and below the pile tip. This parameter represents the soil strength directly beneath the base of the pile.
2. Ab = cross-sectional area of the pile base, calculated based on the pile's geometry.
3. F1 = factor of safety for end bearing; a value of 3 is commonly used in practice to account for uncertainties in subsurface conditions and interpretation of CPT data.

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4. JHP = total shaft resistance (frictional resistance) developed along the pile shaft. This is typically derived from the sleeve friction measurements in CPT data or estimated from cone resistance using empirical correlations, depending on the soil type.
5. O = perimeter of the pile cross section, used to calculate the shaft surface area that contributes to the frictional resistance.
6. F2= factor of safety for shaft friction; typically taken as 5 due to the higher variability and uncertainty associated with this component, particularly related to installation effects and soil

This method represents a simplified yet practical approach commonly used in pile foundation design, particularly for sandy soils where CPT is the preferred in-situ test method. The end bearing component reflects the capacity directly beneath the pile tip, whereas the shaft friction is developed through the interaction between the pile surface and surrounding soil along the embedded length. The use of different safety factors for end bearing and shaft friction reflects the relative confidence in these components. End bearing is generally more reliable and less affected by construction methods, while shaft resistance is more sensitive to stratigraphic variation and installation disturbances. This approach is especially beneficial in locations like coastal areas of Bali, including Sanur, where CPT is frequently employed due to its efficiency and ability to provide continuous soil profiling. With minimal disturbance and faster execution, CPT offers a reliable dataset for estimating pile capacity when combined with appropriate safety considerations.

Coefficient of Variation

Ideally, the selection of resistance factors in foundation design should be based on the degree of variability present in the geotechnical parameters at a given site. When site-specific data are limited or unavailable, making statistical analysis unfeasible, generalized estimates of the coefficient of variation (CoV) for common soil properties can serve as first-order approximations. Even when sufficient site data exist for direct statistical evaluation, a more robust characterization of geotechnical variability can be obtained by combining local measurements with prior knowledge through Bayesian updating techniques. (Phoon & Kulhawy, 1999).

From the past literature, it has been observed that many researchers have proposed CoV values for various geotechnical input parameters as shown in Table 1. These parameters are often represented using probability distribution functions to reflect natural variability. The most commonly employed distributions include those with exponential characteristics such as the Normal, Lognormal, Exponential, and Gamma distributions as well as non-exponential forms like the Beta distribution. These models help quantify uncertainty and allow for probabilistic approaches to be incorporated into the design process (Kumar Baidya et al., 2017).

Table 1. Coefficient of Variation (CoV) for geotechnical properties and in-situ tests (Kumar Baidya et al., 2017)

Property or in-situ test results	Coefficient of Variation (*COV*)	Source
Unit Weight (γ)	3-7%	Harr (1984), Kulhawy (1992)
Buoyant Unit weight (γ_b)	0-10%	Lacasse and Nadim (1997), Duncan (2000)
Effective Stress Friction Angle (φ')	2-13%	Harr (1984), Kulhawy (1992)
Undrained Cohesion (c) for clay	20-50%	Lumb (1974), Singh (1971)
Undrained Cohesion (c) for sand	25-30%	Lumb (1974)
Undrained Shear Strength (S_u)	13-40%	Harr (1984), Kulhawy (1992), Lacasse and Nadim (1997), Duncan (2000)
Undrained Strength Ratio (S_u/σ'_v)	5-15%	Lacasse and Nadim (1997), Duncan (2000)
Compression Index (C_c)	10-37%	Harr (1984), Kulhawy (1992), Duncan (2000)
Coefficient of Consolidation (c_v)	33-68%	Duncan (2000)
Coefficient of permeability of partly saturated clay (k)	130-240%	Harr (1984), Benson *et al.* (1993)
SPT blow count (N)	15-45%	Harr (1984), Kulhawy (1992)

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The development of typical CoV benchmarks for soil parameters plays a key role in helping engineers understand the expected range of variability associated with commonly used geotechnical properties. Such benchmarks also assist in identifying atypical variabilities that may signal unusual subsurface conditions requiring special attention. However, it is important to note that many of the statistical values reported in the literature are derived from total variability analyses that often assume soil uniformity across the study area an assumption that may not reflect the true heterogeneity of the subsurface conditions (Phoon & Kulhawy, 1999). The coefficient of variation can be calculated using the following equation.

$$CoV = \frac{\sigma}{\mu} \quad \text{Eq. 2}$$

RESULTS AND DISCUSSION

This comparative analysis utilizes four CPT (Cone Penetration Test) datasets collected from various locations within the Sanur area, Denpasar, Bali. These data sets were selected based on their proximity and geological similarity, representing typical subsoil conditions found in this coastal region. The CPT results provide a continuous profile of cone tip resistance (q_c) and sleeve friction (f_s), which are essential for evaluating the bearing capacity of foundation systems. The specific details and summary of each dataset, including test depth and stratigraphic characteristics, are presented in Table 2. These data form the basis for assessing the variability of soil resistance values and estimating the allowable bearing capacity of single piles under uniform depth assumptions.

Table 2. The calculation of bearing capacity pile foundation

Location	Depth	q_c (kg/cm^2)	f_s (kg/cm)	Diameter (ton)				
				D25	D30	D35	D40	D45
DPS_01	0.2	18	4	3.01	4.31	5.86	7.64	9.65
DPS_01	0.4	16	8	2.74	3.92	5.30	6.90	8.70
DPS_01	0.6	12	14	2.18	3.09	4.15	5.38	6.75
DPS_01	0.8	18	22	3.29	4.65	6.25	8.09	10.16
DPS_01	1	24	28	4.36	6.18	8.31	10.75	13.51
DPS_01	1.2	22	36	4.16	5.86	7.84	10.11	12.67
DPS_01	1.4	81	44	13.94	19.90	26.93	35.02	44.16
DPS_01	1.6	68.625	54	12.07	17.18	23.18	30.09	37.89
DPS_01	1.8	68	66	12.16	17.26	23.25	30.13	37.90
DPS_01	2	51	76	9.53	13.44	18.02	23.26	29.17
DPS_01	2.2	63	86	11.65	16.46	22.08	28.54	35.81
DPS_01	2.4	61.75	98	11.64	16.39	21.95	28.31	35.49
DPS_01	2.6	76	112	14.19	20.01	26.82	34.63	43.44
DPS_01	2.8	73	128	13.95	19.60	26.21	33.78	42.30
DPS_01	3	57.625	140	11.62	16.21	21.55	27.64	34.49
DPS_01	3.2	49	150	10.37	14.37	19.00	24.28	30.20
DPS_01	3.4	44	164	9.77	13.45	17.71	22.54	27.95

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DPS_01	3.6	55	180	11.82	16.34	21.59	27.55	34.23
DPS_01	3.8	35	198	8.83	11.97	15.57	19.63	24.14
DPS_01	4	45.875	214	10.86	14.84	19.41	24.58	30.36
DPS_01	4.2	63	226	13.85	19.09	25.16	32.05	39.77
DPS_01	4.4	46	242	11.32	15.39	20.06	25.34	31.21
DPS_01	4.6	32	258	9.28	12.40	15.93	19.88	24.25
DPS_01	4.8	33	276	9.73	12.97	16.64	20.75	25.29
DPS_01	5	25.25	284	8.59	11.30	14.34	17.71	21.41
DPS_01	5.2	26	294	8.87	11.66	14.80	18.27	22.09
DPS_01	5.4	18	302	7.69	9.93	12.41	15.12	18.07
DPS_01	5.6	23	310	8.63	11.26	14.19	17.42	20.95
DPS_01	5.8	15	320	7.48	9.56	11.84	14.32	16.99
DPS_02	6	17	330	7.96	10.22	12.70	15.41	18.33
DPS_02	0.4	18	10	3.10	4.43	5.99	7.79	9.82
DPS_02	0.6	9	16	1.72	2.42	3.24	4.17	5.22
DPS_02	0.8	14	20	2.60	3.67	4.93	6.36	7.98
DPS_02	1	22	24	3.97	5.63	7.58	9.81	12.34
DPS_02	1.2	26	30	4.72	6.69	8.99	11.64	14.62
DPS_02	1.4	27	38	5.01	7.07	9.49	12.26	15.38
DPS_02	1.6	56.375	46	9.94	14.14	19.08	24.76	31.17
DPS_02	1.8	69	56	12.16	17.30	23.35	30.29	38.14
DPS_02	2	67.75	68	12.15	17.24	23.21	30.07	37.82
DPS_02	2.2	63	78	11.53	16.31	21.91	28.34	35.59
DPS_02	2.4	51	88	9.72	13.67	18.28	23.56	29.51
DPS_02	2.6	55	96	10.50	14.76	19.74	25.44	31.86
DPS_02	2.8	76	108	14.12	19.93	26.74	34.53	43.32
DPS_02	3	61.25	120	11.90	16.69	22.27	28.66	35.85
DPS_02	3.2	77	130	14.63	20.58	27.54	35.50	44.47
DPS_02	3.4	62	142	12.37	17.28	22.99	29.52	36.87
DPS_02	3.6	53	156	11.12	15.42	20.42	26.11	32.49
DPS_02	3.8	42	172	9.57	13.13	17.24	21.90	27.12
DPS_02	4	49.625	190	11.10	15.27	20.08	25.55	31.66
DPS_02	4.2	43	206	10.27	14.01	18.31	23.18	28.61
DPS_02	4.4	60	224	13.33	18.35	24.16	30.75	38.12
DPS_02	4.6	63	240	14.07	19.36	25.47	32.40	40.16

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DPS_02	4.8	43	258	11.08	14.99	19.45	24.48	30.08
DPS_02	5	34.625	274	9.96	13.32	17.12	21.38	26.09
DPS_02	5.2	36	290	10.44	13.94	17.91	22.36	27.27
DPS_02	5.4	36	302	10.63	14.17	18.18	22.66	27.61
DPS_02	5.6	23	314	8.69	11.33	14.27	17.52	21.06
DPS_02	5.8	22	324	8.68	11.29	14.17	17.35	20.81
DPS_02	6	18	332	8.16	10.49	13.07	15.88	18.92
DPS_05	0.2	13	4	2.19	3.14	4.25	5.54	7.00
DPS_05	0.4	17	10	2.94	4.19	5.67	7.37	9.29
DPS_05	0.6	11	16	2.05	2.89	3.88	5.01	6.28
DPS_05	0.8	13	22	2.47	3.48	4.65	6.00	7.51
DPS_05	1	29	28	5.18	7.36	9.91	12.84	16.16
DPS_05	1.2	49	34	8.55	12.18	16.45	21.37	26.92
DPS_05	1.4	56	42	9.82	13.98	18.87	24.50	30.86
DPS_05	1.6	37	52	6.87	9.69	13.00	16.80	21.07
DPS_05	1.8	31	60	6.01	8.43	11.26	14.49	18.12
DPS_05	2	28	68	5.65	7.88	10.47	13.43	16.76
DPS_05	2.2	50	78	9.40	13.24	17.74	22.89	28.70
DPS_05	2.4	43.75	86	8.51	11.92	15.91	20.48	25.61
DPS_05	2.6	78	94	14.23	20.14	27.07	35.02	43.99
DPS_05	2.8	45	104	8.99	12.56	16.71	21.45	26.78
DPS_05	3	19	112	4.87	6.58	8.55	10.77	13.23
DPS_05	3.2	22	118	5.45	7.40	9.65	12.17	14.99
DPS_05	3.4	48	126	9.83	13.68	18.16	23.26	28.99
DPS_05	3.6	62	136	12.27	17.16	22.86	29.37	36.70
DPS_05	3.8	76	148	14.75	20.69	27.61	35.54	44.45
DPS_05	4	75	158	14.75	20.64	27.51	35.37	44.21
DPS_05	4.2	77	168	15.23	21.30	28.37	36.46	45.55
DPS_05	4.4	51	176	11.10	15.33	20.22	25.77	32.00
DPS_05	4.6	68	184	14.01	19.48	25.84	33.09	41.23
DPS_05	4.8	77	194	15.64	21.79	28.95	37.11	46.28
DPS_05	5	51.5	206	11.66	16.01	21.04	26.74	33.11
DPS_05	5.2	47	216	11.08	15.14	19.81	25.10	31.01
DPS_05	5.4	28	224	8.10	10.81	13.90	17.35	21.17
DPS_05	5.6	30	232	8.55	11.44	14.72	18.39	22.45

DPS_05	5.8	26	240	8.02	10.64	13.61	16.91	20.56
DPS_05	6	37	250	9.98	13.42	17.36	21.77	26.67
DPS_06	0.2	12	4	2.03	2.90	3.93	5.12	6.47
DPS_06	0.4	18	10	3.10	4.43	5.99	7.79	9.82
DPS_06	0.6	8	18	1.59	2.22	2.96	3.80	4.75
DPS_06	0.8	25	28	4.53	6.42	8.63	11.17	14.04
DPS_06	1	30.5	36	5.55	7.86	10.57	13.67	17.18
DPS_06	1.2	36	44	6.58	9.31	12.51	16.18	20.32
DPS_06	1.4	27	54	5.26	7.38	9.84	12.66	15.83
DPS_06	1.6	39	66	7.41	10.43	13.95	17.99	22.53
DPS_06	1.8	37	76	7.24	10.15	13.53	17.40	21.75
DPS_06	2	28	86	5.93	8.21	10.87	13.88	17.27
DPS_06	2.2	54	94	10.31	14.49	19.38	24.97	31.27
DPS_06	2.4	41.375	104	8.40	11.70	15.55	19.93	24.86
DPS_06	2.6	56	116	10.98	15.37	20.50	26.36	32.95
DPS_06	2.8	43	126	9.01	12.50	16.55	21.17	26.35
DPS_06	3	17	134	4.88	6.53	8.39	10.48	12.79
DPS_06	3.2	20	142	5.50	7.39	9.53	11.94	14.61
DPS_06	3.4	46	152	9.91	13.70	18.09	23.08	28.67
DPS_06	3.6	58	164	12.06	16.75	22.20	28.40	35.37
DPS_06	3.8	67	174	13.69	19.06	25.30	32.42	40.42
DPS_06	4	72.375	182	14.69	20.47	27.20	34.87	43.49
DPS_06	4.2	47	192	10.70	14.69	19.29	24.50	30.33
DPS_06	4.4	76	204	15.63	21.74	28.85	36.94	46.04
DPS_06	4.6	75	214	15.63	21.69	28.74	36.78	45.79
DPS_06	4.8	91	226	18.43	25.69	34.14	43.78	54.61
DPS_06	5	52.75	240	12.39	16.94	22.18	28.11	34.73
DPS_06	5.2	34	252	9.52	12.75	16.44	20.56	25.14
DPS_06	5.4	24	260	8.01	10.55	13.41	16.58	20.06
DPS_06	5.6	35	270	9.96	13.33	17.15	21.44	26.18
DPS_06	5.8	48	278	12.21	16.54	21.50	27.08	33.29
DPS_06	6	27	288	8.94	11.78	14.98	18.54	22.45

As illustrated in Figure 2, noticeable differences can be observed in the estimated bearing capacities among the test locations. At a depth of 6.00 meters, the allowable bearing capacity of the single pile foundations varies significantly, ranging from approximately 10.22 to 13.42 tons. This wide range reflects the inherent variability of subsurface conditions within the study area, even within a relatively confined geographic zone. The variation

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may be attributed to differences in soil stratigraphy, cone resistance (q_c) values, and the degree of soil compaction or saturation. Such findings highlight the importance of site-specific investigations and reinforce the need to account for spatial variability in geotechnical design.

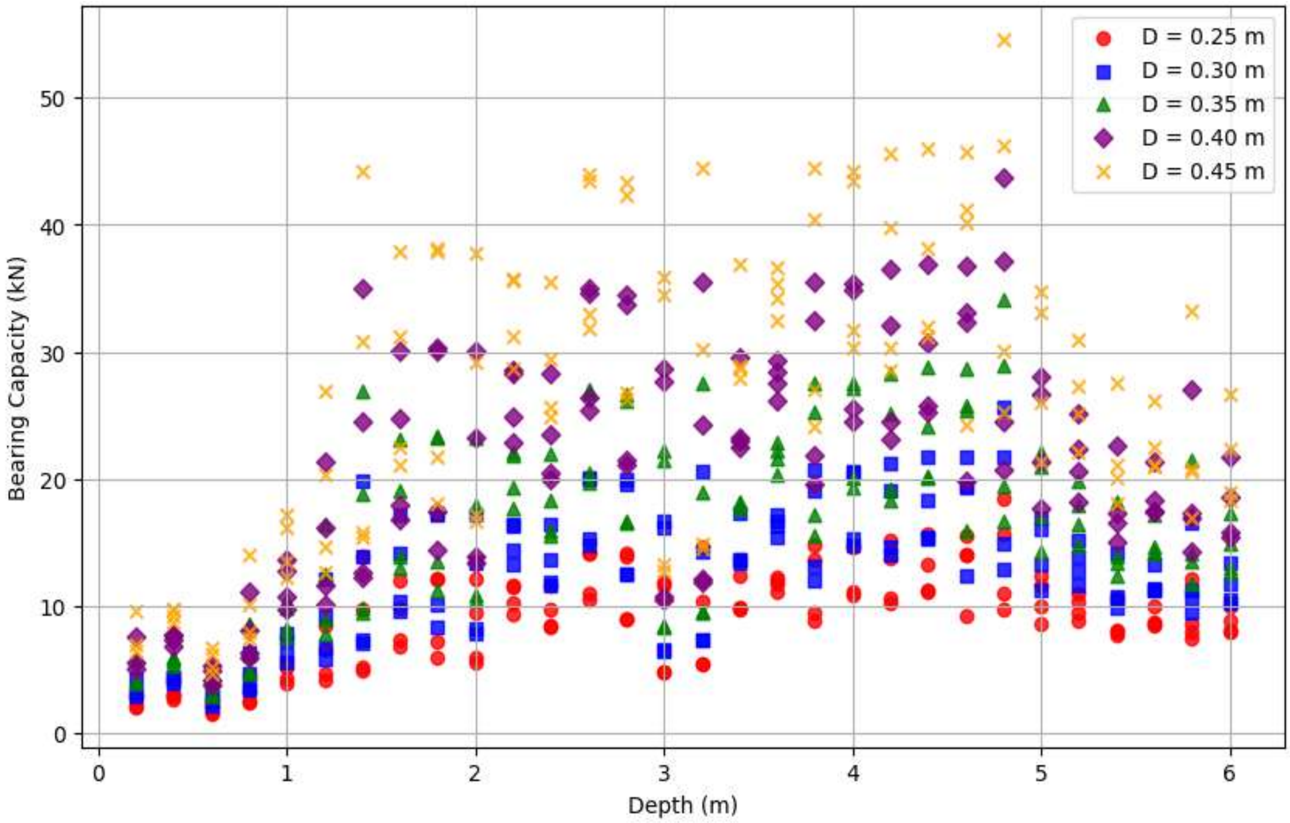

Figure 1. Single Pile Bearing Capacity vs Depth

Next, the Coefficient of Variation (CoV) values for both cone tip resistance (q_c) and sleeve friction (f_s) at each depth and CPT location are presented in Table 3 and Table 4, the CoV for q_c ranges from approximately 15% to 62%, while the CoV for f_s falls within the range of 7% to 17%. These values indicate a moderate to high level of variability in the cone resistance, and a relatively lower variability in sleeve friction. When compared to the reference ranges provided earlier in Table 1, it can be observed that the obtained CoV values in Table 3 and Table 4 remain within the expected bounds reported in previous literature. This confirms that the soil variability observed in the Sanur area is consistent with typical patterns for sandy coastal soils, where heterogeneity in stratification and material composition is common. These CoV values also highlight the need for careful interpretation in the design phase, as variations in q_c and f_s can significantly influence the calculated bearing capacity and, consequently, the safety and performance of the foundation system.

Table 3 Coefficient of Variation cone tip resistance (q_c)

Depth (meter)	**q_c (kg/cm^2)**				**Standard Deviation**	**Mean**	**Coefficient of variation (CoV)**
	DPS_01	**DPS_02**	**DPS_05**	**DPS_06**			
1	24.0	22.0	29.0	30.5	4.03	26.4	15%
2	51.0	67.8	28.0	28.0	19.36	43.7	44%
3	57.6	61.3	19.0	17.0	23.98	38.7	62%
4	45.9	49.6	75.0	72.4	15.09	60.7	25%
5	25.3	34.6	51.5	52.8	13.38	41.0	33%
6	17.0	18.0	37.0	27.0	9.32	24.8	38%

Table 4 Coefficient of Variation sleeve friction (f_s)

Depth (meter)	Total f_s (kg/cm)				Standard Deviation	Mean	Coefficient of variation (CoV)
	DPS_01	DPS_02	DPS_05	DPS_06			
1	28.0	24.0	28.0	36.0	2.31	26.7	9%
2	76.0	68.0	68.0	86.0	4.62	70.7	7%
3	140.0	120.0	112.0	134.0	14.42	124.0	12%
4	214.0	190.0	158.0	182.0	28.10	187.3	15%
5	284.0	274.0	206.0	240.0	42.44	254.7	17%
6	330.0	332.0	250.0	288.0	46.78	304.0	15%

The high coefficient of variation (CoV) in cone resistance (q_c) noted in CPT data signifies considerable spatial variability in subsurface conditions, which has essential ramifications for foundation construction. This heterogeneity might diminish confidence in predicted bearing capabilities, requiring more conservative safety margins to avert probable failure mechanisms including differential settlement or localized bearing failure. This complicates settlement predictions, as varying soil stiffness from fluctuating qc values can result in unequal deformation under load. Furthermore, the CPT data utilized in this analysis and typically in several parts of Indonesia originates from manual CPT testing as shown in Figure 1, wherein cone penetration is facilitated by human power rather than mechanical apparatus. This manual technique provides more uncertainty due to irregular loading rates, probable misalignment, and operator variability, hence exacerbating data scatter. Consequently, designers must either implement elevated safety factors or utilize reliability-based design methodologies that explicitly consider statistical and procedural uncertainties. Integrating such heterogeneity into design promotes safety and performance while facilitating better informed and optimized engineering decisions.

Figure 2. Ilustration of manual cone penetration test using manpower

CONCLUSIONS

The analysis of CPT data from the Sanur area reveals significant variability in the estimated allowable bearing capacity of single pile foundations at a depth of 6.00 meters, ranging from approximately 10.22 to 13.42 tons. This variation reflects the heterogeneous nature of the subsurface conditions, even within a limited geographic region. Contributing factors include differences in soil stratigraphy, cone resistance (qc), and degrees of soil compaction or saturation. Furthermore, the calculated Coefficient of Variation (CoV) values support this finding, with qc exhibiting moderate to high variability (15%–62%) and fs showing lower variability (7%–17%). These CoV values are consistent with established ranges for sandy coastal soils and align with findings from previous studies. Notably, part of this variability can also be attributed to the testing method itself, as the CPTs used in this analysis and generally across Indonesia are typically conducted manually using manpower to drive the cone into the soil. This manual approach introduces additional uncertainty due to inconsistent penetration force, operator technique, and potential misalignment. Overall, these results emphasize the importance of conducting site-specific investigations and considering spatial and procedural variability in geotechnical design. Accounting for these factors is crucial for achieving more accurate bearing capacity estimations and ensuring the safety and reliability of foundation systems in coastal environments like Sanur.

To enhance practical application in similar coastal environments, engineers should consider key design strategies based on the observed variability in CPT data. Owing to the intrinsic heterogeneity of coastal soils and the additional uncertainty associated with manual CPT testing methods, site investigations should include multiple test locations to more effectively capture spatial variability. Statistical methodologies, such as using characteristic values informed by the coefficient of variation (CoV) or applying reliability-based design approaches, can improve the accuracy and efficiency of foundation design. When feasible, manual CPT data should be corroborated with more consistent methods, such as mechanical CPT or borehole sampling. Additionally, adopting conservative design parameters, anticipating potential differential settlement, and implementing ground improvement strategies in areas with significant variability are essential practices to ensure the safety and long-term performance of foundation systems in coastal environments.

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