Comparison of Bearing Capacity of Shallow and Deep Foundations Based on Sondir (DCPT) Data: A Case Study of Office Building Rehabilitation in Medan City

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Abstract

Foundation design requires accurate knowledge of subsurface soil bearing capacity, particularly for building rehabilitation projects where structural loads may change. This study evaluates and compares the bearing capacity of shallow and deep foundations based on Dutch Cone Penetrometer Test (Sondir/DCPT) data collected during the rehabilitation of the BKKBN Regional Office Building on Jl. Gn. Krakatau, Medan, North Sumatra. Two sondir points (S-1 and S-2) were tested using a 2.5-ton capacity cone penetrometer following ASTM D3441 procedures, reaching maximum depths of 5.40 m and 4.60 m with cone resistance (CR) values of 209 kg/cm² and 205 kg/cm², respectively, both classified as very dense soil. Shallow foundation bearing capacity was calculated using the general Meyerhof approach (Qa = CR/40) for footing widths ranging from 125×125 cm² to 200×200 cm², while deep foundation bearing capacity was calculated using the De Beer method for driven piles and bored piles with diameters of 20-60 cm. The results show that at a depth of 3.00 m, the allowable bearing capacity of a 200×200 cm² shallow footing reaches 82,000 kg (S-1) and 61,000 kg (S-2), while a single driven pile of 40 cm diameter at the maximum tested depth provides 94,082.77 kg (S-1) and 92,156.91 kg (S-2), consistently 7-8% higher than a bored pile of the same diameter due to soil densification during pile driving. The comparison indicates that shallow foundations are technically adequate for this project given the shallow occurrence of very dense soil, while deep foundations remain preferable where higher loads, groundwater interference, or long-term settlement control are governing design considerations.

Keywords: *Bearing Capacity, Sondir (DCPT), Shallow Foundation, Deep Foundation, Medan*

Introduction

A foundation is the structural element that transfers all loads from a building, including dead load, live load, and dynamic load, directly to the supporting soil layer beneath it. Before a foundation can be properly designed, the bearing capacity and characteristics of the underlying soil must first be determined through a soil investigation (soil investigation/geotechnical survey). One of the most widely used field methods in Indonesia for shallow-to-medium depth soil investigation is the Dutch Cone Penetrometer Test, commonly referred to as Sondir or DCPT (Dutch Cone Penetration Test), which measures cone resistance (CR) and total skin friction (TSF) at every 20 cm interval of penetration.

This research is based on a soil investigation report for the rehabilitation of the BKKBN (National Population and Family Planning Board) Regional Office Building of North Sumatra Province, located on Jl. Gn. Krakatau, Kelurahan Pulo Brayan Darat II, Kecamatan Medan Timur, Kota Medan. Two sondir points (S-1 and S-2) were tested to a target depth of 20.00 m using a 2.5-ton capacity sondir apparatus, but both points were terminated earlier once the cone resistance exceeded 200 kg/cm², indicating a very dense soil layer had been reached. In practice, engineers are frequently confronted with the decision of whether a shallow foundation (footing) is technically sufficient, or whether a deep foundation (driven pile or bored pile) is required. This decision directly affects construction cost, schedule, and long-term structural performance, particularly for rehabilitation projects where the existing building layout constrains foundation options. Therefore, this study aims to compare the allowable bearing capacity of shallow foundations calculated using the Meyerhof approach against the allowable bearing capacity of deep foundations (driven pile and bored pile) calculated using the De Beer approach, both derived from the same sondir dataset, in order to provide practical guidance for foundation selection in similar soil conditions in Medan City.

Literature Review

2.1 Cone Penetration Test (Sondir/DCPT)

The Dutch Cone Penetrometer Test (Sondir/DCPT) is a field test procedure used to obtain the cone resistance (CR) and skin friction resistance of soil layers by pushing a biconus cone into the ground at a constant rate. The test procedure generally follows the Standard Test Method for Mechanical Cone Penetration Testing of Soil [1], and in Indonesia is also standardized under SNI 2827:2008 [9]. Sulistianto and Rus [2] applied Sondir (CPT) alongside Standard Penetration Test (SPT) data to determine the depth of hard soil layers and to guide foundation-type recommendations for an industrial storage facility in Samboja, Kutai Kartanegara, concluding that pile or bored pile foundations were recommended once the design load exceeded the shallow soil's bearing capacity. Similarly, Anggreana, Elizar, and Pratama [3] used sondir data at two testing points to classify soil density and recommend short driven piles at one point and bored piles at another point where harder soil was found at greater depth, demonstrating that sondir-based bearing capacity analysis can vary significantly even within a single project site.

2.2 Shallow Foundation Bearing Capacity

Shallow foundations (footings) are typically used when a soil layer with adequate bearing capacity is found at a relatively shallow depth. Based on the Meyerhof approach derived from sondir results, the allowable bearing capacity, disregarding footing width, is generally simplified as Qa = CR/40, where Qa is the allowable bearing capacity for a settlement of 2.54 cm (kg/cm²) and CR is the cone resistance (kg/cm²). Fauzi and Ikhya [4] analyzed the influence of hard-soil depth and footing width on the bearing capacity of continuous shallow foundations using PLAXIS 2D, concluding that wider footings increase bearing capacity but are also more sensitive to the depth of the groundwater table. Muda [5] compared sondir-based bearing capacity with laboratory-derived values, finding that shallow foundation capacities obtained from sondir data were generally lower and more conservative than laboratory-based calculations. Ahmad [6] compared the L'Heminier and Meyerhof methods for shallow foundation design based on two sondir points and found that both methods yielded sufficient bearing capacity where hard soil occurred within 2.6-2.8 m depth, allowing the use of shallow foundations for cost and schedule efficiency.

2.3 Deep Foundation Bearing Capacity

Deep foundations, such as driven piles and bored piles, are used when the soil layer with adequate bearing capacity lies beyond the practical depth of shallow footings, or when the structural load exceeds the shallow foundation's allowable capacity. The De Beer method, derived directly from sondir data [10], calculates the allowable bearing capacity of a driven pile as Qa = (CR.F)/3 + (TSF.O)/5, and for a bored pile as Qa = (CR.F)/3, where F is the cross-sectional area of the pile and O is the perimeter of the pile section. The absence of the skin-friction term in the bored-pile formula reflects the reduced shaft resistance typically observed in drilled piles, where the surrounding soil is disturbed during excavation rather than densified as in pile driving. Mardianti, Nuklirullah, and Dwina [7] applied the Aoki-De Alencar and Schmertmann-Nottingham methods on sondir data for a hospital building project in Jambi and obtained allowable single-pile bearing capacities ranging from 63 to 200 tons depending on pile grouping. Nugraha and Harahap [8], studying a project in Medan Tembung, Medan City, compared the Meyerhof and Aoki-De Alencar methods for driven piles based on combined CPT and SPT data and found that the Meyerhof method consistently produced higher single-pile capacities than the Aoki-De Alencar method, underscoring the importance of method selection alongside raw field data when comparing foundation alternatives.

Research Methodology

3.1 Location and Field Data

The soil investigation was conducted at the rehabilitation site of the BKKBN Regional Office Building of North Sumatra Province, located on Jl. Gn. Krakatau, Kelurahan Pulo Brayan Darat II, Kecamatan Medan Timur, Kota Medan, Provinsi Sumatera Utara. Two sondir/DCPT points (S-1 and S-2) were tested using a light sondir apparatus with a capacity of 2.5 tons, in accordance with [1] and [9]. At each 20 cm interval, the total resistance (TR) and cone resistance (CR) were recorded, from which the friction resistance (FR = TR - CR), skin friction (SF = FR × 20/10), total skin friction (TSF = ΣSF), and local skin friction (LSF = FR/10) were derived.

3.2 Shallow Foundation Bearing Capacity Formula

The allowable bearing capacity of a shallow (spread) foundation, disregarding footing width, is calculated using:

Qa = CR / 40

where Qa is the allowable bearing capacity for 2.54 cm settlement (kg/cm^2) and CR is cone resistance (kg/cm^2). This value is then multiplied by the footing area to obtain the total allowable load (kg) for footing sizes of 125×125, 150×150, 175×175, and 200×200 cm^2.

3.3 Deep Foundation Bearing Capacity Formula (De Beer Method)

The allowable bearing capacity of a driven pile is calculated using:

$Qa = (CR \cdot F)/3 + (TSF \cdot O)/5$

while the allowable bearing capacity of a bored pile is calculated using:

$Qa = (CR \cdot F)/3$

where Qa is the pile bearing capacity (kg), CR is cone resistance (kg/cm^2), TSF is total skin friction (kg/cm), F is the pile cross-sectional area (cm^2), and O is the pile perimeter (cm). Both formulas incorporate safety factors of 3 (end bearing) and 5 (skin friction), consistent with common Indonesian geotechnical practice for sondir-based pile design [10].

3.4 Comparative Analysis Procedure

The comparison between shallow and deep foundation bearing capacity was carried out by (1) tabulating the allowable bearing capacity of shallow footings at depths of 0-3.00 m, the practical depth range for shallow foundation application; (2) tabulating the allowable bearing capacity of driven piles and bored piles at 30 cm and 40 cm diameter across the full tested sondir depth; and (3) comparing the resulting values at equivalent depths to identify the depth at which each foundation type becomes governing, both technically and in terms of relative capacity gain per unit depth.

Results

3.1 Soil Investigation Summary

The soil investigation results at both sondir points indicate a soil profile that becomes progressively denser with depth, reaching the "very dense" classification ($CR \geq 200$ kg/cm^2) before the planned 20.00 m depth was reached, as summarized in Table 1.

Table 1. Summary of Sondir/DCPT Results

Parameter	S-1	S-2
Planned depth (m)	20.00	20.00
Groundwater level/GWL (m)	-4.10	-4.00
Maximum depth achieved (m)	5.40	4.60
Maximum cone resistance, CR (kg/cm^2)	209	205
Total skin friction, TSF (kg/cm)	262	252
Soil density classification	Very dense	Very dense

3.2 Shallow Foundation Bearing Capacity

Using the formula Qa = CR/40, the allowable bearing capacity of shallow footings at depths of 1.00, 2.00, and 3.00 m is presented in Table 2 (point S-1) and Table 3 (point S-2).

Table 2. Shallow Foundation Bearing Capacity - S-1 (kg)

Depth (m)	CR (kg/cm^2)	125×125 cm^2	150×150 cm^2	175×175 cm^2	200×200 cm^2
1.00	12	4,687.50	6,750.00	9,187.50	12,000.00

Depth (m)	CR (kg/cm²)	125×125 cm²	150×150 cm²	175×175 cm²	200×200 cm²
2.00	21	8,203.13	11,812.50	16,078.13	21,000.00
3.00	82	32,031.25	46,125.00	62,781.25	82,000.00

Table 3. Shallow Foundation Bearing Capacity - S-2 (kg)

Depth (m)	CR (kg/cm²)	125×125 cm²	150×150 cm²	175×175 cm²	200×200 cm²
1.00	15	5,859.38	8,437.50	11,484.38	15,000.00
2.00	68	26,562.50	38,250.00	52,062.50	68,000.00
3.00	61	23,828.13	34,312.50	46,703.13	61,000.00

It is noteworthy that at point S-2, the bearing capacity value decreases from 68,000 kg at 2.00 m to 61,000 kg at 3.00 m for the 200×200 cm² footing, which reflects a locally softer lens within the soil profile rather than a continuously increasing trend, consistent with the fluctuating CR values recorded in the field data.

3.3 Deep Foundation Bearing Capacity (Driven Pile vs. Bored Pile)

The allowable bearing capacity of driven piles and bored piles at 30 cm and 40 cm diameter, calculated with the De Beer method across the full sondir depth, is presented in Table 4 (S-1) and Table 5 (S-2).

Table 4. Deep Foundation Bearing Capacity - S-1 (kg)

Depth (m)	CR	TSF	Pile 30cm	Pile 40cm	Bore 30cm	Bore 40cm
1.00	12	12	3,052.08	5,325.44	2,826.00	5,024.00
2.00	21	34	5,586.06	9,646.08	4,945.50	8,792.00
3.00	82	74	20,705.16	36,189.55	19,311.00	34,330.67
4.00	77	130	20,582.70	35,502.93	18,133.50	32,237.33
5.00	177	220	45,828.30	79,630.40	41,683.50	74,104.00
5.40 (max)	209	262	54,155.58	94,082.77	49,219.50	87,501.33

Table 5. Deep Foundation Bearing Capacity - S-2 (kg)

Depth (m)	CR	TSF	Pile 30cm	Pile 40cm	Bore 30cm	Bore 40cm
1.00	15	12	3,758.58	6,581.44	3,532.50	6,280.00
2.00	68	48	16,918.32	29,675.09	16,014.00	28,469.33
3.00	61	112	16,475.58	28,352.11	14,365.50	25,538.67
4.00	137	186	35,767.74	62,029.65	32,263.50	57,357.33

Depth (m)	CR	TSF	Pile 30cm	Pile 40cm	Bore 30cm	Bore 40cm
4.60 (max)	205	252	53,025.18	92,156.91	48,277.50	85,826.67

At equal diameter, the driven pile consistently produces a higher allowable bearing capacity than the bored pile, by approximately 7-8% at maximum tested depth (e.g., 94,082.77 kg vs. 87,501.33 kg at 40 cm diameter, S-1). This difference is attributed to the absence of the skin-friction term in the bored-pile formula, reflecting soil disturbance during the drilling process compared to the densification effect of pile driving.

3.4 Comparison of Shallow and Deep Foundation Bearing Capacity

Table 6 compares the allowable bearing capacity of a 200×200 cm² shallow footing against a single 40 cm diameter driven pile and a 40 cm diameter bored pile, at depths where both foundation types can be technically evaluated using the available sondir data.

Table 6. Comparison of Shallow Footing (200x200 cm²) vs. 40 cm Diameter Piles (kg)

Point	Depth (m)	Shallow Footing	Driven Pile	Bored Pile
S-1	1.00	12,000.00	5,325.44	5,024.00
S-1	2.00	21,000.00	9,646.08	8,792.00
S-1	3.00	82,000.00	36,189.55	34,330.67
S-2	1.00	15,000.00	6,581.44	6,280.00
S-2	2.00	68,000.00	29,675.09	28,469.33
S-2	3.00	61,000.00	28,352.11	25,538.67

At the same depth, the shallow footing (200×200 cm² = 40,000 cm² contact area) provides a substantially higher total allowable load than a single 40 cm diameter pile, since its bearing area is far larger. However, this comparison is only valid when a competent bearing layer is available at shallow depth without excessive settlement risk. Since both sondir points at this site reach the "very dense" classification (CR ≥ 200 kg/cm²) within 4.60-5.40 m, and the groundwater table lies at approximately 4.00-4.10 m, shallow foundations founded above or just at the groundwater level are technically adequate for typical low-to-medium rise office building loads. Deep foundations, on the other hand, remain the preferred option where: (a) design loads exceed the capacity that can be economically provided by enlarging footing dimensions, (b) differential settlement must be minimized across an existing structure being rehabilitated, or (c) the excavation for shallow footings would be complicated by the shallow groundwater table. In the context of this rehabilitation project, where the existing footprint and adjacent structure limit large excavation, a combination of moderately sized shallow footings founded at 2.00-3.00 m depth—above the governing very dense layer—offers an economical and technically sound solution, while deep foundation alternatives (driven pile or bored pile) should be reserved for portions of the structure subjected to higher concentrated loads.

Conclusion

Based on the sondir (DCPT) data collected at two points (S-1 and S-2) during the soil investigation for the rehabilitation of the BKKBN Regional Office Building in Medan, both points reach a very dense soil classification (CR ≥ 200 kg/cm²) at relatively shallow depths of 5.40 m and 4.60 m, respectively. The allowable bearing capacity of shallow foundations, calculated using the Meyerhof approach (Qa = CR/40), reaches 82,000 kg (S-1) and 61,000-68,000 kg (S-2) for a 200×200 cm² footing at 2.00-3.00 m depth, while the allowable bearing capacity of a single 40 cm diameter driven pile calculated using the De Beer method reaches 94,082.77 kg (S-1) and 92,156.91 kg (S-2) at maximum tested depth. Driven piles consistently outperform bored piles of the same diameter by 7-8%, attributable to soil densification during driving versus soil disturbance during drilling. Given the shallow depth of very dense soil at this site, shallow foundations are technically adequate for typical office building loads and offer a more economical and time-efficient solution than deep foundations, provided that footings are founded above or at the groundwater level and settlement is properly controlled. Deep foundations remain necessary where higher concentrated loads, differential settlement control, or site-specific construction constraints govern the design. These findings are consistent with previous sondir-based studies conducted in Medan and other regions of Indonesia [2]-[8], which similarly emphasize that foundation-type selection should be based on a site-specific comparison of shallow and deep foundation bearing capacity rather than a default preference for either type.

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