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# REVIEW STUDY OF FOUNDATION STRUCTURE OF BELAWAN MEDAN CRANE ELECTRIFICATION SUBSTATION BUILDING REGARDING BEARING CAPACITY AND SETTLEMENT

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**Abstract**

This study aims to evaluate the foundation structure of the Crane Electrification Substation building in Belawan, Medan, against the soil bearing capacity and foundation settlement. The study was conducted through literature studies, field surveys, and structural analysis using SAP2000 software. The evaluation includes the pile bearing capacity, pile group efficiency, and analysis of single and group pile settlement. The results of the analysis show that the pile cap configuration with 8 piles provides the best performance with a total settlement of 65 mm, still within the tolerance limit as an "isolated foundation". While the configuration with 6 piles shows a settlement of 84 mm, which exceeds the limit without tie beams, but is still acceptable if the foundation is considered a "raft" system with tie beam support. This study emphasizes the importance of choosing the right foundation configuration to ensure the stability and safety of the structure.

**Keywords:** Pile Foundation, Soil Bearing Capacity, Foundation Settlement, Pile Cap

## Introduction

The lowest portion of a building that is directly connected to the ground is the foundation. The foundation of a building serves to support the weight of the superstructure above it (Kuswaya & Ma'arif, 2020). The foundation must also be carefully planned and constructed in order to provide a strong building. The lowest portion of a building is the foundation, which is connected to the earth. In the building structure, the foundation functions to carry the load of the building above it (Ginting et al., 2019; Simanjuntak & Lubis, 2024). To produce a sturdy building, the foundation must also be planned and done very carefully (Haziri et al., 2019). The soil's carrying capacity and settling must be taken into account while planning the foundation. Total settlement, in which every component of the foundation collapses simultaneously, and differential settlement, in which only a portion of the foundation collapses or tilts, are typically considered when discussing settlement. This can cause problems for the structure it supports (Megananda et al., 2020). The pile settlement is strongly influenced by the size of the pile, the concrete quality of the pile, the value of the tip bearing capacity and the friction of the pile due to the soil (Prabowo et al., 2019), and the mechanical parameters of the soil. A long pile decline will have the risk of increasing its decline due to the frictional resistance of the soil to the pile increasing due to depth (Ramadani, 2020). That the settlement of a building foundation point will produce a difference in settlement between foundation points, and limit the value between 50 – 75 mm depending on the soil type is a requirement that the settlement of a foundation point is still acceptable for a building foundation system (Prima et al., 2022; Sari et al., 2025). Soil is a major element in any construction project, both as a medium for supporting structural loads and as a construction material itself (Sohn et al., 2014). Soil characteristics greatly affect the stability and strength of the structure, therefore understanding the physical properties of soil is very important (Rinda et al, 2020). Soil in natural conditions is formed from mineral grains that have undergone physical and chemical weathering (Syahputra & Suzanti, 2023).

The main components of soil consist of air, water and solid particles (Setiawan et al., 2020). The composition and proportion of these three determine the technical properties of the soil (Dananjaya et al., 2022). Saturated conditions occur when all pores are filled with water, while soil containing both water and air is called partially saturated. Soil is considered dry when its water content is zero (Mugiono et al., 2020; Priambodo, 2020). Soil strength is influenced by the arrangement of soil layers and structures (Januar & Agung, 2023). The more heterogeneous the structure, the more complex the foundation planning required (Marpaung et al., 2022). Some important factors to consider in soil strength investigations include (Mina et al., 2019). Depth and thickness of the soil layer, permissible soil stress, hydrological conditions of the soil layer (Haziri et al., 2019). Soil settlement and displacement due to loads, heavy equipment vibration, and changes in moisture content must be anticipated in foundation planning to stay within tolerance limits (Djarwanti et al., 2015). Soil investigations are conducted to determine the type of soil layer, moisture content, water table, and other technical values required for foundation design (Luo & Li, 2019). The results of field and laboratory investigations usually include: Soil layer type at several depths (Ria Bela et al., 2024), SPT (Standard Penetration Test, conus tip resistance and sticking resistance (sondir results) values (Nurul Fadilah et al., 2018). The lower structure consists of elements embedded in the ground, such as foundations and pile caps (Lim et al., 2021). Deep foundations are used when the hard soil layer lies deep below the surface (Chen et al., 2022). A commonly used type of deep foundation is pile foundation (Campione, 2024). Pile foundations have a significant length and a relatively small diameter (Saputra, 2021). These foundations are used when shallow soils are unable to bear the weight of the structure (Azizi et al., 2020). The main function of the foundation is to transmit the load of the structure to the subgrade (Muluk et al., 2020). The foundation must be able to withstand: dead load live load, horizontal load, earthquake load, wind load, water lift, moment and torque (Hasibuan et al., 2021). Foundation design is strongly influenced by the type of soil and the magnitude of the working load (Yingka, 2012).

This study focuses on evaluating the foundation structure of the Crane Electrification Substation at Belawan Port, Medan. The construction of this electrification substation is very important to support container crane operations at the port, so the stability of the foundation is a crucial factor for the smooth distribution of logistics. The soil conditions in the Belawan area are dominated by soft clay layers with a relatively shallow water table, which has the potential to cause significant subsidence. Therefore, this study aims to evaluate the bearing capacity and subsidence of the planned pile foundation, as well as to compare several pile cap configurations to obtain the safest and most effective design (Sinar et al., 2020).

## Research Methods

This research methodology is designed to provide a systematic description of the stages and approaches used in the study (Novita et al., 2019). The research was carried out through a series of activities that included field data collection as a representation of actual conditions (Wismantaraharjo et al., 2020), as well as data analysis to obtain results that are valid and relevant to the study objectives (Alhabsyi et al., 2025). This research consists of several main stages as follows (Ningrum & Pandulu, 2020). Literature Study: initial activities in the form of a review of relevant literature to strengthen the theoretical basis and research direction (Tian et al., 2024). Data Collection the data collected includes field data and data related to the object of study (Pratama et al., 2019). Data Analysis: the data that has been obtained is analyzed using structural analysis methods that are in accordance with the needs of the study (Suroso & Tjitradi, 2020). The research site was conducted in the area planned as the project site, as shown in Figure 1.

Figure 1. Review Study Location

This research was conducted through several structured stages. The first stage was a literature study to strengthen the theoretical basis regarding soil bearing capacity and pile foundation settlement. The second stage was a field survey, which included collecting soil data through sounding tests and Standard Penetration Tests (SPT) to obtain technical soil parameters. The third stage was processing soil data to determine the bearing capacity of a single pile based on skin friction and end resistance. The fourth stage was modeling the foundation structure using SAP2000 software to analyze the interaction between columns and foundations. The fifth stage is the evaluation of pile bearing capacity in groups and settlement analysis using the Vesic method. The final stage is the comparison of the analysis results for each pile cap configuration (5, 6, and 8 piles) so that the configuration that is most suitable for the soil conditions in Belawan can be determined.

Data collected through field surveys were systematically compiled and analyzed (Ojedokun et al, 2012). Data collection and presentation procedures are carried out with attention to accuracy and consistency, so that the information produced can provide a strong basis for the planning process (Sari et al., 2019).

## Research Results and Discussion

### Structural Analysis

The three-dimensional model was formed based on the architectural and structural plans, using a finite element approach (Haeri & Fathi, 2015). The structure was modeled as a special moment bearing frame system (SRPMK) according to Santoso & Hartono (2020).

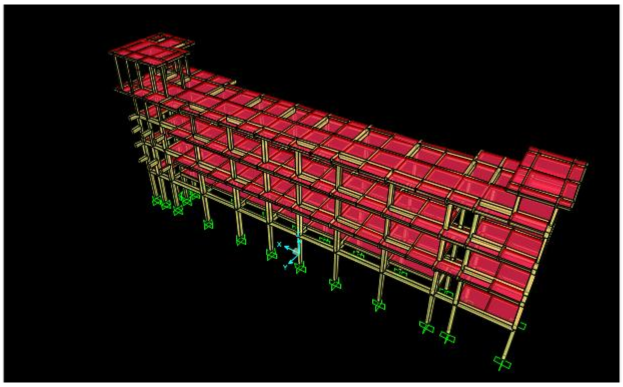

Figure 2. Structure Modeling

Analyzed loads include:

a) Dead loads and additional loads (SDL) such as ceramics, specs, waterproofing, and floor coverings.
b) Live load according to space function (corridor, public space, service area, etc.).
c) Lateral load (earthquake) using location parameters in Lumajang:
   - Ss = 0.8487g
   - S1 = 0.4005g
   - Seismic Design Category = D
   - R = 8 (SRPMK)
   - Cd = 5.5
   - $\Omega_0$ = 3

### Column and Foundation Interaction

Column Interaction Diagram

The analysis was performed on column K1 with concrete grade fc'=25 MPa and reinforcing steel grade fy = 400 MPa. The interaction diagram was obtained from the modeling results in SAP2000 (Ramadani, 2020).

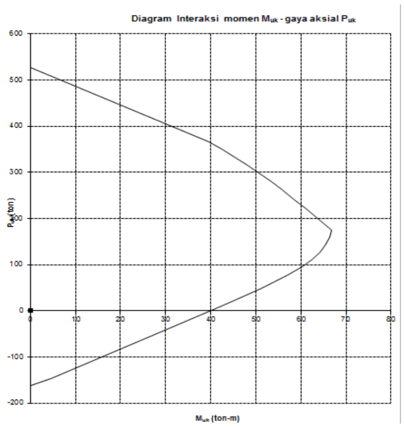

Figure 3. Column Interaction Diagram $K_1$

**Pile Support Analysis**

In order to evaluate the bearing capacity of the piles, it is first necessary to determine the safety factor used in the calculation. The selection of the safety factor depends on the type of structure and the quality of field control during construction. As shown in Table 1, different values are applied for monumental, permanent, and temporary structures, with higher factors required when the level of control is poor. These values provide the basis for calculating the allowable pile capacity in this study.

Table 1. Recommended safety factor

| **Structure Classification** | **Safety Factor** | | | |
|---|---|---|---|---|
| | **Good Control** | **Normal Control** | **Poor Control** | **Very Poor Control** |
| Monumental | 2.3 | 3 | 3.5 | 4 |
| Permanent | 3 | 2.5 | 2.8 | 3.4 |
| Temporary | 1.4 | 2 | 2.3 | 2.8 |

Based on material strength,
Cross- sectional area

$$A = \frac{\pi D^2}{4} = \frac{\pi(0.4)^2}{4} = 0.1256\ m^2 \cdots (1)$$

Axial capacity of materials

$$P = A \cdot f_c = 0.1256 \cdot 8.33 \cdot 10^6 = 1.049\ kN \cdots (2)$$

Based on SPT data

$$q_p = 400\left(\frac{N_1+N_2}{2}\right) = 400 \cdot 19.5 = 7{,}800\ kN/m^2 \cdots (3)$$

End bearing:

$$Q_p = A_p \cdot q_p = 0.1256 \cdot 7{,}800 = 979.68\ kN \cdots (4)$$

Blanket friction:

$$Q_s = \tau \cdot P \cdot L = 0.2N \cdot p \cdot L = 655.63\ kN \cdots (5)$$

Ultimate bearing capacity:

$$Q_{ult} = Q_p + Q_s = 1635.31\ kN \cdots (6)$$

With safety factor (FS = 3):

$$P_{allow} = \frac{Q_{ult}}{3} = 545.10\ kN \cdots (7)$$

**PileCap Design Evaluation**

Studies were conducted on three pile count options for the PC1 pilecap: 5, 6, and 8 pilings (Wismantaraharjo et al., 2020). The load distribution results and pile group efficiencies were calculated using the

$$Eg = 1 - 0.205\,.\,\theta\ with\ \theta = arctan\ arctan\ \left(\frac{m}{n}\right) \cdots (8)$$

For 6 poles (m = 3, n = 2):

$\theta = arctan\ arctan\ (1.5) = 56.31$° Eg = 0.761 … (9)

**Pole Drop Analysis**

The pile settlement analysis aims to evaluate the magnitude of vertical deformation that occurs due to the applied structural loads on the foundation. The calculation was carried out using the Vesic method, which considers settlement at the pile tip, settlement along the pile shaft, as well as the contribution of the surrounding soft soil layers. This analysis is critical to ensure that the total settlement remains within the permissible tolerance limits for safe foundation performance.

Pole bar drop:

$$S_1 = \frac{(Q_{wp} + \xi Q_{ws})L}{A_p E_p} \ldots (10)$$

Settlement at the pile tip (vesic method):

$$S_2 = \frac{q_{wp} D}{E_s}(1 - \mu_s^2) I_{wp} \ldots (11)$$

$$q_{wp} = \frac{Q_{wp}}{A_p} \ldots (12)$$

$$S_2 = \frac{Q_{wp} C_p}{D q_p} \ldots (13)$$

Decline along the blanket:

$$S_3 = \left(\frac{Q_{ws}}{pL}\right)\frac{D}{E_s}(1 - \mu_s^2) I_{ws} \ldots (14)$$

Results:

The foundation used in the analysis consists of spun piles with a diameter of 40 cm and a length of 50 m. These piles have a concrete strength of fc' = 50 MPa with an axial capacity calculated based on SPT data collected in the field. The pile caps analyzed have varying dimensions: 240 × 220 × 80 cm for a 5-pile configuration, 320 × 200 × 80 cm for a 6-pile configuration, and 440 × 200 × 80 cm for an 8-pile configuration. The pile cap concrete uses a quality of fc' = 25

MPa. The foundation safety factor is determined according to the permanent building classification, namely FS = 3.

**Column Force Ratio Evaluation**

The analysis of pile settlement is conducted to estimate the total vertical displacement that may occur due to applied structural loads. The calculation considers both settlement at the pile tip and along the shaft using the Vesic method. The results are then compared with the allowable settlement limits, generally ranging between 50–75 mm depending on soil conditions. The following section presents the calculation outcomes for each pile group configuration and highlights whether the observed settlement values remain within acceptable limits.

The force distribution on the pilecap is checked with the control:

$$P_{max} < Q_{all}$$

Table 2. Pile Cap Analysis

| Configuration | Pile Cap Dimensions (cm) | Number of Poles | Single Settlement (mm) | Group Settlement (mm) | Description |
|---|---|---|---|---|---|
| **5 Poles** | 240 x 220 x 80 | 5 | - | - | Not OK |
| **6 Poles** | 320 x 200 x 80 | 6 | 37.70 | 84 | Not OK (Without tiebeam) |
| **8 Poles** | 440 x 200 x 80 | 8 | 28.87 | 65 | OK |

Results:

Option 6 piles is safe in terms of column force, but attention needs to be paid to the settlement aspect of the foundation, as the settlement exceeds the limit if no tie beam is used. The 5-pile option does not meet the structural requirements. The 8-post option is the safest and most conservative option, ideal in terms of force and foundation settlement. This evaluation is very important in foundation design because if the compressive force of the column exceeds the pile capacity, structural failure of the lower element (foundation) may occur before the superstructure.

The analysis results show that the 5-column configuration does not meet the requirements because the stress-to-support ratio exceeds the permissible limit. The 6-column configuration is able to withstand the load with a stress ratio of < 1, but results in a settlement of 84 mm, which exceeds the tolerance limit of 75 mm if the foundation is considered an isolated foundation. This condition is still acceptable if the pile cap is connected to a tie beam so that it functions similarly to a raft system. Meanwhile, the 8-pile configuration provides the best performance with a total settlement of 65 mm, which is still within the tolerance limit. These results indicate that increasing the number of piles improves load distribution and reduces the amount of foundation settlement. Given the soft soil conditions typical of Belawan, an 8-pile configuration is recommended as it provides greater security against the risk of differential settlement. Furthermore, these results are consistent with the theory of pile group efficiency, whereby a greater number of piles can improve stability despite the consequence of higher construction costs. Therefore, the final design choice needs to consider the balance between technical aspects (bearing capacity, settlement, structural safety) and economic aspects (pile number efficiency).

## Conclusion

Based on the results and discussion that have been determined, the following conclusions can be drawn: The bearing capacity of a single spun pile D40cm, with Wika specifications, so that the allowable bearing capacity is close to the plan, the depth is L = 50m. PC1 plan size 240cm x220cm thick 80cm with 5 poles, the ratio of the stress suffered by the poles in a group to the allowable bearing stress is greater than one, namely 1.1 at the time of the earthquake plan. Study PC1 size 320cm x 200cm thick 80cm with 6 piles, the ratio of the stress suffered by the piles in a group to the allowable bearing stress was less than one, i.e. 0.68 at the time of the earthquake, but the settlement of the group piles of 84mm exceeded that required when the foundation system is still considered "isolated foundation", i.e. 75mm. The study with PC1 with 8 piles, size PC1 = 440cm x 200cm thick 80cm, the ratio of the stress suffered by the piles in a group to the allowable bearing stress was less than one, i.e. 0.5 or not exceeding the allowable, at the time of the plan earthquake, also the group pile settlement of 65 mm did not exceed the required for the foundation to still be considered an "isolated foundation", i.e. 75 mm. This study evaluated the bearing capacity and foundation settlement of the Crane Electrification Substation project at Belawan Port, taking into account the local soil conditions, which are predominantly soft clay. The analysis results show that the pile cap configuration with 8 piles is the safest option, with a settlement of 65 mm that is still within the tolerance limit. A 6-pile configuration is still possible if supported by a tie beam, while a 5-pile configuration does not meet the requirements. The results of this study emphasize the importance of considering local soil conditions and selecting the appropriate foundation configuration to ensure the stability and safety of the structure.

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