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Zonation of Soil Bearing Capacity from Cone Penetration Test Data: Case Study in Padang

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Abstract*—This study aims to map the zonation of soil bearing capacity in Padang City, covering five districts —Koto Tangah, Padang Barat, Nanggalo, Padang Timur, and Padang Selatan —comprising a total of 12 test points. The data were obtained from Cone Penetration Test (CPT) results, which were subsequently analysed to determine the ultimate bearing capacity of the soil, the safety factor of foundations against load eccentricity, and settlement at several test points. The analytical approach focused on assessing vertical bearing capacities, comparing estimated working loads with calculated ultimate bearing capacities, and determining settlement under representative design load conditions. From 12 test points distributed across the five districts, the results indicate that all locations exhibit safety factors significantly above the minimum requirement (FS > 3), suggesting that the ground has excellent capacity to sustain structural loads. In addition, the observed settlements are small, ranging from 0.8 mm to 6.4 mm, and remain well below the commonly accepted tolerance for foundation settlement (25–50 mm). These results support the notion that the subsurface layers in these areas are stable and do not pose a significant risk of foundation settlement. Therefore, the soil conditions at all test points can be categorised as safe, stable, and suitable to support the assumed design load of 100 kN, regardless of whether pile foundations or shallow foundations are used. The resulting soil bearing capacity zonation map is expected to serve as a practical reference for foundation planning, assisting engineers and planners in selecting appropriate foundation systems, and supporting sustainable infrastructure development in Padang City in a safer, more effective, and efficient manner.

***Keywords*—Soil bearing capacity; cone penetration test; geotechnics; natural disasters.**

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I. INTRODUCTION

Infrastructure development in Padang has experienced rapid growth in line with economic advancement and improvements in the quality of life over the past few years [1]. The increasing number of infrastructure projects has significantly influenced the city's diverse geological conditions, including the potential risks of natural disasters such as earthquakes, landslides, and flooding. Geologically, this region exhibits high soil heterogeneity across different locations. Furthermore, Padang's position at the convergence of three major tectonic plates makes it one of the most seismically vulnerable areas in Indonesia [2], as demonstrated by the large earthquake in 2009 [3], which caused widespread damage to infrastructure [4].

This reality directly affects soil conditions in infrastructure development, particularly in foundation construction [5]. In the context of building foundation planning, soil bearing capacity is a critical parameter that determines the safety and stability of structures and serves as a fundamental basis for sustainable infrastructure planning [6], [7]. Determining this parameter requires reliable in-situ testing methods that can provide accurate representations of subsurface conditions. The Cone Penetration Test (CPT) is one such method that has proven to be effective and efficient in evaluating soil characteristics in detail [8], [9]. For instance, it provides data on cone tip resistance (qc), sleeve friction (fs), and friction ratio, which are essential for calculating the bearing capacity of both shallow and deep foundations. Additionally, CPT data can be used as a preventive measure to identify soil layers susceptible to liquefaction.

In this regard, Padang City faces a high risk of soil liquefaction, yet the application of CPT methods remains limited [10]. Despite the elevated liquefaction potential, the comprehensive use of CPT for mapping soil bearing capacity remains relatively scarce. The absence of soil-bearing capacity zonation maps integrated with Geographic Information Systems (GIS) [11] further undermines the precision and adaptability of foundation planning to local conditions. This paper highlights the urgency of conducting research to analyze soil bearing capacity in Padang City, utilizing 12 CPT data points distributed across five districts, which are considered representative of the region's geotechnical conditions. The findings of this study are expected to establish a geotechnical database and soil bearing capacity zonation, which will serve as valuable references for planning, designing, and constructing infrastructure that is resilient to potential natural disasters in the area.

II. Materials and Methods

In this study, soil data were obtained from testing activities conducted during infrastructure development projects in Padang City, including buildings, roads, and bridges, using the Cone Penetration Test (CPT) method. The data were collected from the Public Works Department, with testing points distributed across 12 locations in five districts of Padang City. The instruments employed in this research included the Geo 5 application and ArcGIS, which were utilized for data analysis.

The CPT results were used to obtain values of cone resistance (qc), sleeve friction (fs), and the friction ratio (FR), calculated using the following equation:

$$fs: (JP - qc) \times A/B \quad (1)$$

$$FR: (qc/fs) \times 100 \quad (2)$$

Where:

qc : cone resistance value
A : reading interval (20 cm)
JP : number of resistance readings
fs : sleeve friction value
B : equipment factor

The CPT test results at each testing point are presented graphically and analyzed based on cone resistance (qc) and sleeve friction (fs) values. In the case of a shallow foundation with a width B, the bearing capacity (Qu) below a vertical and centered load is obtained by the following general relation (Terzaghi's superposition principle):

$$Qu = cNc + q\,(Nq - 1) + \frac{1}{2}\gamma B N\gamma$$

Where :

Qu : bearing capacity (per unit length)
γ : unit weight of the soil
q : vertical surcharge lateral to the foundation
c : soil cohesion; and
Nγ, Nc and Nq are the bearing capacity factors

Meanwhile, for deep foundations,

$$Qtotal = Qs + Qp$$

Where:

Qtotal : Total bearing capacity (kN)
Qs : Shaft resistance along the side of the pile (kN)
Qp : Point resistance at the tip of the pile (kN)

III. Results and Discussion

The geotechnical analysis of soil bearing capacity using CPT data in Padang City is illustrated in the following discussion. This analysis encompasses several districts in Padang City, including Koto Tangah, Padang Barat, Nanggalo, Padang Timur, and Padang Selatan, with a total of 12 testing points strategically distributed across these areas. The explanation is as follows:

A. Koto Tangah District

Points 1 and 2 utilize deep foundations with a pile diameter of 0.3 meters and a depth of 10 meters, respectively. Points 1 and 2 of this test are located in the Koto Tangah District, and the analysis results obtained using Geo5 software are presented below.

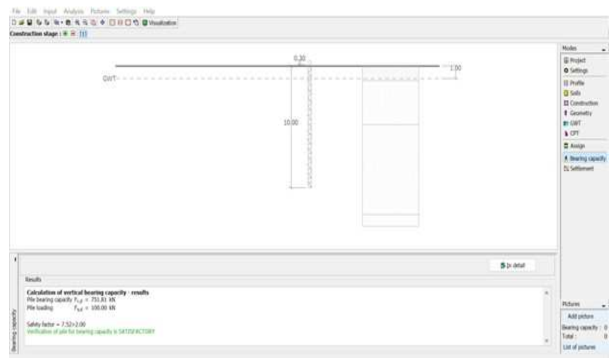

Fig. 1 Bearing Capacity of Point 1

The analysis of soil bearing capacity at Point 1 indicates that the ultimate pile capacity reaches 751,81 kN with a design load of 100,00 kN. This value represents a safety factor of 7.35, which significantly exceeds the minimum requirement (≥ 2.0). Accordingly, it can be concluded that the soil conditions at this location exhibit a very high bearing capacity. The magnitude of this capacity suggests the presence of dense to very dense soil layers, or even hard strata at the pile tip depth, which contribute predominantly to end resistance, along with additional support from shaft resistance [12], [13]. Thus, point 1 can be categorised as a zone with very high soil bearing capacity and substantial potential for the development of heavy structures in Koto Tangah District. Nevertheless, this considerable capacity value still requires further verification through comparative data such as Standard Penetration Test (SPT) or bore log results, as well as settlement analysis, to ensure that the resulting zonation is truly representative.

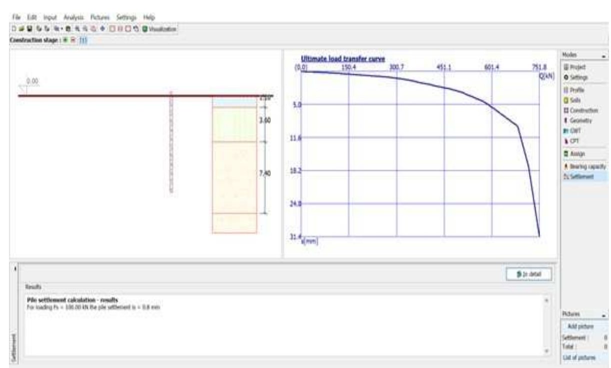

Fig. 2 Settlement Point 1

The settlement analysis at Point 1, as illustrated by Figure 2, shows that under a design load of 100 kN, the pile settlement is only 0,8 mm. This value is significantly smaller than the allowable settlement range for single piles in building structures, which is 10 mm–25 mm. Thus, within the working load range, the deformation response is very stiff. The load–settlement curve (ultimate load transfer) indicates an ultimate pile capacity of approximately 750 kN at settlements exceeding 30 mm [14]. Consequently, the safety factor against the design load is about 7,5. In the service load zone (≤100–200 kN), the curve remains nearly linear, indicating that soil deformation around Point 1 is minimal and the vertical bearing capacity is highly reliable. From a serviceability perspective, the settlement of 0.8 mm is negligible and unlikely to induce differential settlement that would compromise the stability or performance of superstructures. Based on this analysis, the geotechnical zonation at Point 1 may be classified as very high bearing capacity and very low settlement, making it highly suitable for supporting heavy structures in Koto Tangah District. Nevertheless, to avoid potential overestimation of bearing capacity due to limitations in numerical modelling assumptions or uncertainties in soil parameter correlations, field verification through Static Load Testing (SLT) and cross-validation with Cone Penetration Test (CPT) data and laboratory soil testing remain necessary [15]. Furthermore, if pile foundations are to be implemented in the form of pile groups, additional analyses of group effects are required [16], long-term consolidation, and the potential for negative skin friction (downdrag) caused by embankment loads [17] must be comprehensively considered to ensure the reliability and safety of the foundation system.

The subsequent discussion concerns Point 2, which is also located in Koto Tangah District, and presents the results and explanations as follows.

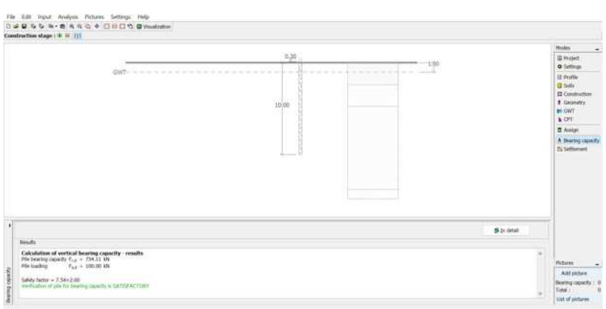

Fig. 3 Bearing Capacity of Point 2

The calculation of soil bearing capacity at Point 2 shows that the ultimate capacity reaches approximately 754,1 kN, while the applied design load is only 100,00 kN. This value yields an actual safety factor of 7.54, which is far greater than the minimum general requirement of 2.0; thus, in terms of the ultimate limit state, the pile condition can be considered highly safe. Even when applying a conservative safety factor, the allowable pile capacity remains in the range of 250–300 kN, meaning that the working load of 100 kN utilises less than 40% of the permissible capacity.

In addition, if the foundation is to be used as a pile group, further evaluations of group effects, long-term consolidation, and the possibility of negative skin friction due to embankment loads or soil settlement around the piles must be comprehensively addressed [18]. Overall, these results suggest that pile foundations at Point 2 are suitable for supporting heavy structures in the Koto Tangah District.

In addition to examining the bearing capacity at Point 2, the settlement analysis was also conducted, with the results presented as follows.

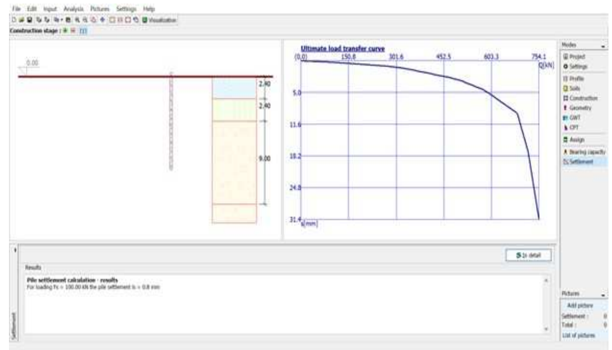

Fig 4 Settlement of Point 2

The load settlement curve presented in the figure exhibits a pattern similar to that observed in the previous results. In the initial stage, the relationship between load and settlement is linear, indicating that the soil surrounding the pile remains in an elastic condition [18]. As the load increases, the curve begins to bend and flatten, reaching the ultimate capacity of approximately 754,1 kN at a settlement of more than 30 mm. Under the design load of 100 kN, the pile settlement is only 0,8 mm, which is significantly smaller than the allowable settlement range for single piles in building structures, generally within 10–25 mm. This demonstrates that soil deformation around the pile is very low; hence, from a serviceability perspective, the pile is very safe and unlikely to cause differential settlements that could adversely affect the superstructure.

Moreover, with an actual safety factor exceeding 7,5, the pile's bearing capacity is considerably higher than the applied design load. This condition further supports classifying this site as having very high bearing capacity and very low settlement, making it suitable for the construction of heavy structures. Nevertheless, these numerical analysis results require validation through Static Load Testing (SLT) and comparison with other geotechnical data, such as CPT or laboratory soil testing, to ensure consistency. Furthermore, if the foundation is applied in the form of a pile group, additional considerations, including group effects, long-term consolidation, and the potential for negative skin friction due to embankment loads, must also be taken into account [19].

B. Padang Barat District

The next district is Padang Barat, represented by Points 3 and 4. Point 3 uses a shallow foundation with dimensions of 1.5 x 1.5 m, and Point 4 uses a deep foundation with a pole diameter of 0.3 m and a depth of 10 m. The explanations regarding soil bearing capacity and settlement analysis are presented as follows.

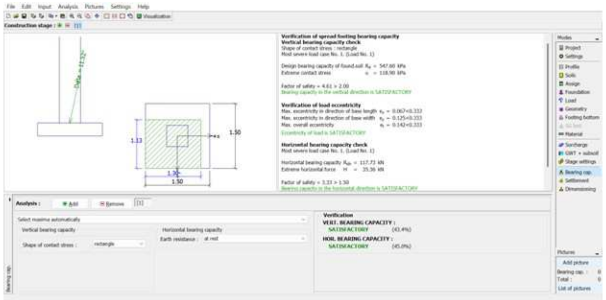

Fig. 5 Bearing Capacity of Point 3

The analysis results indicate that the soil bearing capacity at Point 3 is relatively high and safe to support the design load. The design bearing capacity was 547,60 kPa, while the maximum contact pressure at the foundation base was only about 118,90 kPa. This is a vertical safety factor of 4,61, which is well above the general minimum requirement of 2,0. The utilization level of the soil capacity is only about 43%, indicating that, in terms of vertical bearing capacity, the foundation conditions are very safe.

The eccentricity check also shows compliance, with the eccentricity value remaining within the foundation kern, ensuring that the stress distribution at the foundation base is entirely compressive, without the risk of tensile stresses. For horizontal bearing capacity, the value obtained is 117.73 kN, while the applied horizontal load is only about 35.36 kN. This results in a horizontal safety factor of 3,33, which exceeds the minimum requirement of 1,5. Accordingly, the 1,50 m × 1,50 m footing foundation analyzed at Point 3 provides sufficient safety against both vertical and horizontal loads.

From an engineering perspective, the relatively large safety margins offer opportunities for design optimization, for instance by adjusting the foundation size or depth to improve cost efficiency, while still adhering to technical requirements. Nevertheless, further evaluations of settlement, groundwater fluctuation effects, and the potential for differential settlement between foundation points remain necessary to ensure long-term service performance. Overall, the soil conditions at Point 3 are characterized by good bearing capacity and are capable of providing a safe foundation for the superstructure. The analysis is subsequently extended to the settlement results at Point 3, as presented below.

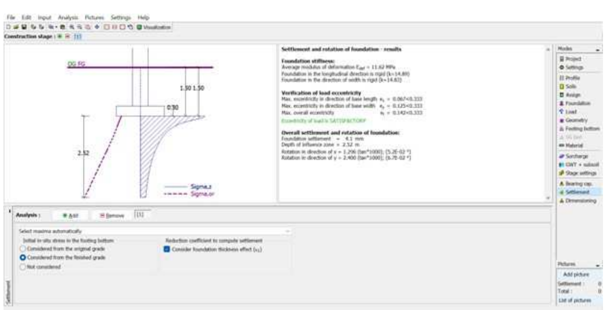

Fig. 6 Settlement of Point 3

The calculation results show that the total settlement of the foundation at Point 3 is 4,1 mm, with the influence zone depth reaching 2,52 m below the foundation base. This value is considered very small, as the commonly accepted settlement tolerance for shallow foundations in ordinary building structures ranges from 25 to 50 mm. Thus, the foundation is safe at this point from excessive settlement.

In addition, the load eccentricity analysis indicates that the values of ex, ey, and the total eccentricity remain below the limits of L/6 and B/6. This implies that the resultant load remains within the foundation kern, ensuring uniform soil stress distribution without generating tensile stresses. In terms of foundation rotation, the maximum recorded rotation is only 0.067°, which is very small and does not significantly affect the stability or functionality of the superstructure.

Therefore, it can be concluded that the foundation at Point 3 is safe against settlement and rotation issues and is capable of sustaining the applied loads in accordance with the design. The following location in Padang Barat District is designated as Point 4, with the analysis results presented as follows.

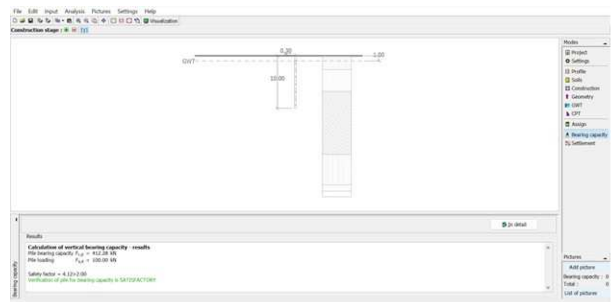

Fig. 7 Bearing Capacity of Point 4

Based on the analysis of the vertical pile bearing capacity at the observed point, the ultimate capacity (Fu,d) was determined to be 412,28 kN, with a design working load (Fs,d) of 100,00 kN. The resulting safety factor is 4,12, which is greater than the commonly required minimum value of 2,0. This indicates that the soil bearing capacity at this location remains highly adequate to sustain the design load applied to the pile. This condition also demonstrates that the applied load utilizes only about 24% of the pile's ultimate capacity, meaning that the pile is still in a safe condition and far from reaching its failure limit.

Additionally, the verification results confirm that the pile meets the bearing capacity requirements (satisfactory). Therefore, it can be concluded that the soil bearing capacity at this point is relatively good, and the pile foundation can safely and reliably support the planned structural load.

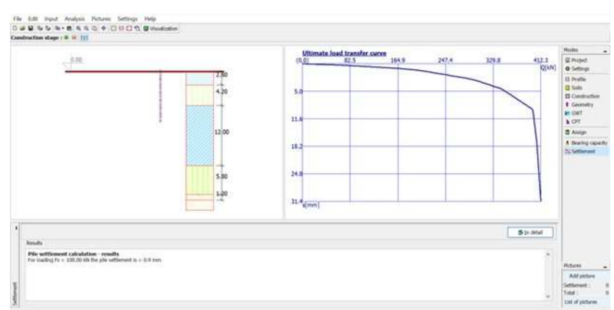

Fig. 8 Settlement of Point 4

Based on the pile settlement analysis, under the design loading condition of 100 kN, the resulting settlement is only 0,9 mm. This value is considerably smaller than the allowable settlement limit for a single pile foundation, which is typically around 25 mm for serviceability requirements in building structures. The load–settlement curve further illustrates that, even at the ultimate load of 412,3 kN, the corresponding settlement is only 31 mm. This indicates that the pile still has a significant reserve capacity before reaching failure.

Therefore, it can be concluded that the settlement of the pile under the design load at this point falls within a safe and satisfactory range and does not pose any issues regarding the stability or serviceability performance of the supported structure.

C. *Nanggalo District*

The subsequent analysis focuses on the points located in Nanggalo District, represented by Points 5 and 6. Points 5 and 6 utilise deep foundations with a pile diameter of 0.3 meters and a depth of 10 meters, respectively. The explanations regarding their soil bearing capacity and settlement behavior are as follows.

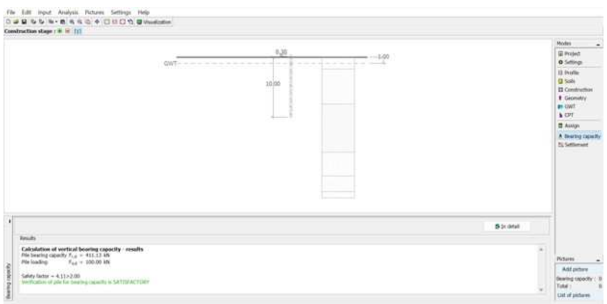

Fig. 9 Bearing Capacity of Point 5

Based on the analysis at Point 5, the ultimate pile bearing capacity (Fu,d) was obtained as 411,13 kN, with the design load (Fs,d) of 100.00 kN. This calculation yields a factor of safety of 4,11, which is significantly higher than the commonly required minimum standard of 2.0. This condition indicates that the pile at Point 5 possesses more than adequate bearing capacity to support the intended structural loads. The applied load corresponds to only about 24% of the pile's ultimate capacity, confirming that the pile remains in a safe state with a considerable reserve capacity. Software verification further affirms that the pile at Point 5 satisfies the bearing capacity requirements (satisfactory). Therefore, it can be concluded that the soil bearing capacity at Point 5 is very favorable, and the pile foundation at this location is capable of operating stably and reliably to sustain the building loads above it.

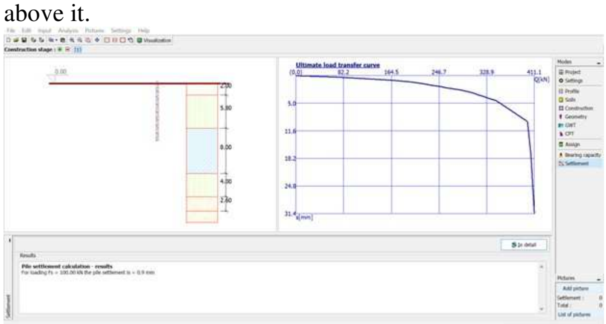

Fig.10 Settlement of Point 5

Based on the settlement analysis of the pile at Point 5, under the design load of 100 kN, the resulting settlement was only 0,9 mm. This value is minimal and well below the allowable settlement limit for a single pile foundation, which is typically around 25 mm according to general serviceability criteria. The load–settlement curve further indicates that when the ultimate pile capacity of approximately 411,1 kN is reached, the corresponding settlement is only about 31 mm. This finding demonstrates that the pile retains a substantial reserve capacity. Under working load conditions, the deformation is negligible, posing no significant effect on the stability or serviceability of the supported structure. Therefore, it can be concluded that the settlement at Point 5 is classified as very safe and satisfactory, confirming the suitability of the pile foundation at this location for supporting the planned building loads.

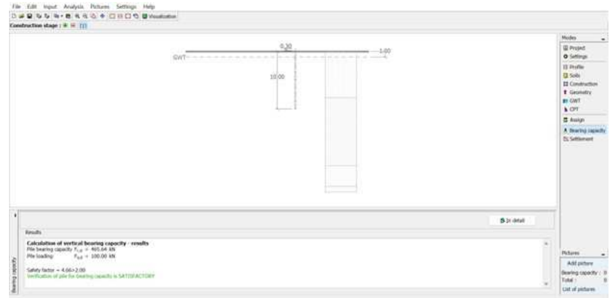

Fig. 11 Bearing Capacity of Point 6

At Point 6, the analysis of soil bearing capacity indicates that the ultimate pile capacity is 465,64 kN under a design load of 100 kN, resulting in a safety factor of 4,66 (>2.0). This means that the working load mobilizes only about 21,5% of the ultimate capacity (100/465,64), reflecting a substantial reserve capacity and operating conditions far from the failure limit. Compared with the previous point (~412 kN), the higher capacity at Point 6 suggests the presence of stronger or thicker supporting soil layers at the pile's working depth. The software verification classified the result as 'Satisfactory,' confirming that, in terms of soil bearing capacity, the pile foundation at this point is safe and reliable to support the planned structural loads, with a very low risk of shear or base failure under service conditions.

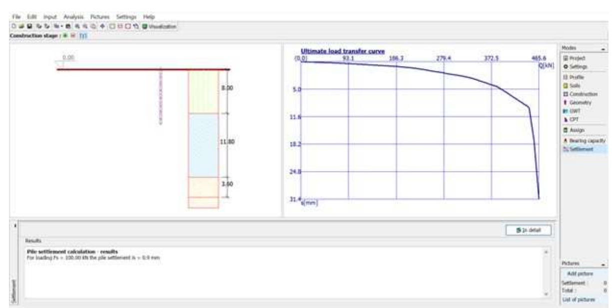

Fig. 12 Settlement of Point 6

Based on the settlement analysis at Point 6, under the design load of 100 kN, the pile settlement is only 0,9 mm. The load–settlement curve demonstrates a stiff response within the service load range and exhibits a sharp increase in deformation only as it approaches the ultimate capacity of approximately 465,6 kN, corresponding to a settlement of about 31 mm. This indicates that, under the operational load of 100 kN (≈22% of Qu), the deformation remains very small and well below the commonly adopted serviceability limit for single piles (≤25 mm). Accordingly, the settlement at Point 6 is classified as safe and highly satisfactory, posing no risk to the performance or comfort of the supported structure. It is consistent with the bearing capacity results that demonstrate a substantial reserve capacity.

D. Padang Timur District

The subsequent analysis concerns the locations situated in Padang Timur District, represented by Points 8 and 9. Theses point use shallow foundations with dimensions of 1.5 x 1.5 meters. The explanations for both soil bearing capacity and settlement behavior are as follows.

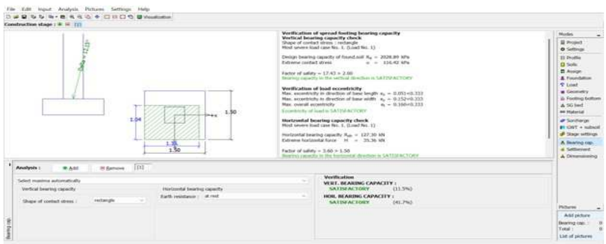

Fig. 13 Bearing Capacity of Point 7

Based on the verification of bearing capacity at Point 7, the calculated design vertical bearing capacity of the foundation soil was Rd ≈ 2028,89 kPa, while the extreme contact pressure was only 116,42 kPa. This results in a very large vertical safety factor of 17,43 (> 2.0). Such a condition indicates very low vertical capacity utilization (≈ 11,5%), meaning the applied vertical load is far below the soil's resistance. Load eccentricity checks also meet the requirements: the maximum eccentricities along the length and width (e_x = 0,051; e_γ = 0,152) as well as the total eccentricity (e_0 = 0,160) are all less than 0,333, which confirms that the contact pressure distribution remains within the safe zone, without partial base uplift. For the horizontal condition, the computed lateral resistance was Rh ≈ 127.30 kN, whereas the extreme horizontal load to be resisted was H = 35.36 kN, resulting in a lateral safety factor of ≈ 3.60 (> 1.5), which is also satisfactory.

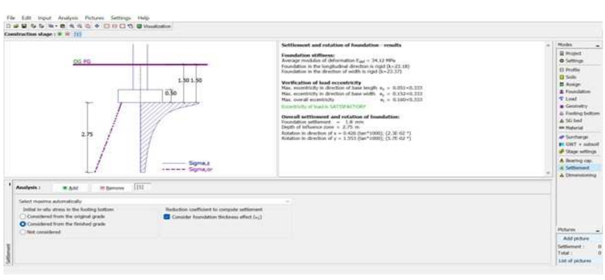

Fig.14 Settlement of Point 7

Overall, the verification demonstrates satisfactory performance in both vertical and horizontal bearing capacity; the shallow foundation at this point possesses substantial reserve capacity and a negligible risk of shear failure or excessive contact pressure. A practical recommendation is that, despite the very high safety factor, settlement analysis and surface pressure distribution should still be assessed at the detailed design stage (including consolidation checks for saturated clay layers) to ensure that serviceability, in addition to strength, is fully satisfied.

Subsequently, based on the settlement analysis at Point 7, the foundation demonstrates excellent service performance, with an average deformation modulus of E_{def} ≈ 34,12 MPa, an influence depth of 2,75 m, and a total settlement of only 1,8 mm, which is negligible compared to common serviceability limits. Load eccentricity checks are also satisfied (e_x = 0,051; e_γ = 0,152; e_0 = 0,160, all < 0,333), ensuring that the base contact pressure distribution remains within the safe zone without partial base uplift. Measured foundation rotations are very small, with tan·1000 = 0,426 in the x-direction (≈0,02–0,03°) and tan·1000 = 1,553 in the y-direction (≈0,05–0,06°), which do not indicate any risk of structural tilting under service loads. Overall, in terms of serviceability and foundation stiffness, the conditions at Point 7 are satisfactory: settlement and rotation are minimal and will not compromise structural performance provided that no significant changes in loading or subsurface conditions occur. Nevertheless, during construction, it is recommended to conduct field monitoring of settlement and rotation (e.g., using in-situ settlement plates or leveling) and to verify subsurface profiles (particularly the presence of saturated clay layers) to ensure that field behavior is consistent with design assumptions.

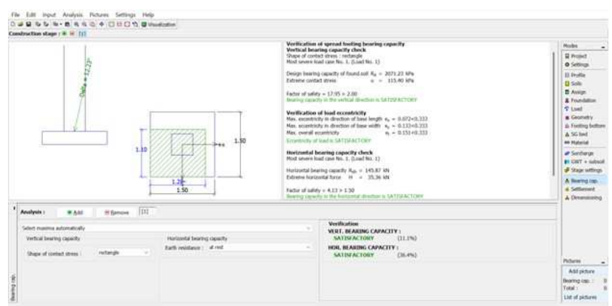

Fig. 15 Bearing Capacity of Point 8

The calculation results indicate that at Point 8, the foundation exhibits a highly adequate soil bearing capacity in both vertical and horizontal directions. The maximum contact stress of 115,40 kPa is far below the allowable soil capacity (2071,23 kPa), yielding a safety factor of 17,95, indicating that the foundation is extremely safe against the risk of soil shear failure or excessive settlement due to capacity exceedance. In terms of load eccentricity, the values of e_x, e_γ, and the total eccentricity are all within the B/6 and L/6 limits. This confirms that the resultant load remains within the foundation's kern, thereby ensuring uniform stress distribution without inducing tensile stresses at the base.

This condition is critical to guarantee that the foundation performs stably without significant torsional effects. Regarding horizontal resistance, the analysis shows that the applied horizontal load (35,36 kN) is far lower than the soil's lateral resistance capacity (145,87 kN). With a safety factor of 4,13, the condition is considered highly safe, ensuring that the foundation can resist lateral actions such as earthquake forces, wind loads, or earth pressures.

Overall, the soil bearing capacity analysis at Point 8 demonstrates that the foundation is in a safe and stable condition with respect to vertical loads, eccentricity, and horizontal actions. Therefore, the foundation at this location can be relied upon to support the structure without risk of bearing capacity failure.

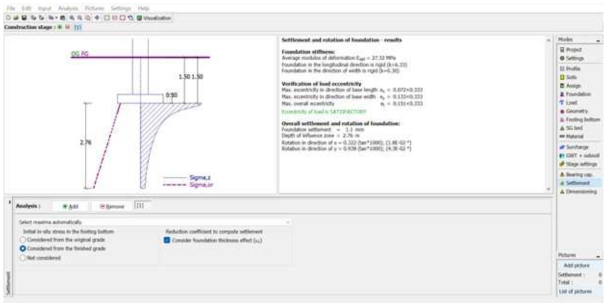

Fig. 16 Settlement of Point 8

At Point 8, the calculated settlement of 1,1 mm is far below the allowable settlement limits for shallow foundations in building structures (typically 25–50 mm). Thus, with respect to the serviceability limit state, the foundation at Point 8 can be considered highly safe, with negligible risk of inducing harmful differential settlements. The deformation modulus (Edef = 27,32 MPa) indicates relatively stiff soil behavior, consistent with the observed small settlement and rotation (≤ 0,054°). The eccentricity check confirms that the load resultant remains within the kern, ensuring that the stress distribution at the foundation base remains entirely compressive without the risk of tensile stresses. The depth of the influence zone, approximately 2,76 m, suggests that the soil layers governing the deformation are relatively shallow; therefore, variations in moisture content or fluctuations in the groundwater table within this depth should be carefully monitored during long-term operation. Overall, the foundation deformation at Point 8 meets serviceability requirements with a wide safety margin. For design completeness, it is recommended to verify compressibility parameters through correlations with CPT/boring data and laboratory tests, and to check consistency between points to minimize the risk of non-uniform settlement across the structure.

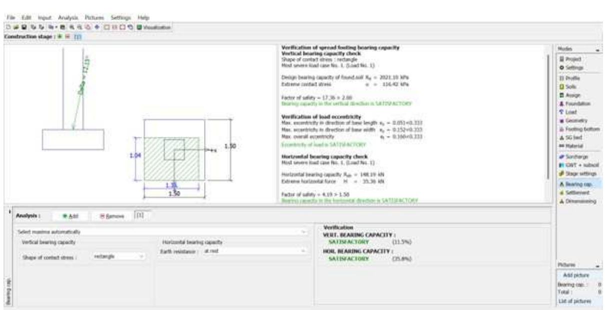

Fig. 17 Bearing Capacity of Point 9

Subsequent analysis at Point 9 indicates that the foundation possesses a very large margin of safety against soil bearing capacity failure under both vertical and lateral loading. The maximum contact stress (116,42 kPa) is far below the allowable soil bearing capacity (2021,10 kPa), such that the foundation is classified as highly safe with respect to the ultimate limit state, with a vertical factor of safety of approximately 17,4. The load eccentricities also remain within the foundation's kern, ensuring that the base stress distribution is entirely compressive and free of tensile zones, which is favorable for foundation stability. Regarding lateral resistance, the horizontal capacity is also adequate, with a safety factor of ≈4,2 and a utilization ratio of less than 25%, indicating strong resistance to horizontal forces such as wind, seismic loading, and soil displacement.

From a practical standpoint, this large safety margin provides opportunities for design optimization (e.g., reductions in footing dimensions or embedment depth) when cost efficiency is desired, though any modification must be supported by technical verification. Beyond the strength aspect, a serviceability analysis (settlement evaluation) remains necessary, as the present calculation does not yet include settlement values. Settlement must be computed and compared against structural tolerance limits to avoid detrimental differential settlement [20]. Finally, field verification through Static Load Testing (SLT), as well as correlation with CPT/boring data and laboratory testing, is strongly recommended to confirm soil parameters and to ensure that the bearing capacity has not been overestimated.

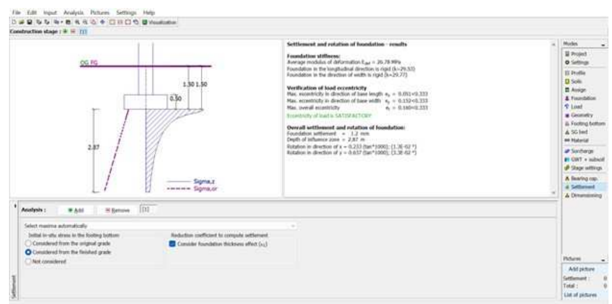

Fig. 18 Settlement of Point 9

The calculation results indicate that the foundation at Point 9 undergoes a total settlement of 1,2 mm, which is considered very small compared to the allowable limits typically adopted for buildings (generally 25–50 mm for conventional structures). The soil deformation modulus (26,78 MPa) is relatively high, suggesting that the soil layer beneath the foundation is sufficiently stiff and can effectively distribute loads. The load eccentricities (0,051–0,160) remain well below the limit of one-sixth of the foundation width (0,333), thereby ensuring that the stress distribution beneath the foundation is entirely compressive without the occurrence of tensile stresses. This condition supports both the foundation's safety and long-term performance.

The depth of influence, estimated at 2,87 m, indicates that the stress zone induced by the foundation is relatively shallow, meaning that the load does not significantly affect the deeper soil layers [21]. The measured foundation rotations are also minimal (0,013°–0,033°), implying no risk of tilting or differential instability of the foundation. Therefore, the foundation settlement at Point 9 can be classified as safe, meeting the serviceability limit state (SLS) criteria and posing no potential for structural damage to the superstructure [22]. Nonetheless, attention should still be given to long-term consolidation, particularly if soft clay layers exist beneath the zone of influence, through continuous monitoring of soil investigation data and time settlement analysis.

E. Padang Selatan District

The subsequent analysis focuses on the points located in Padang Selatan District, represented by Points 10, 11, and 12. Points 10, 11, and 12 use shallow foundations with dimensions of 1.5 x 1.5 meters. The explanations provided regarding their soil bearing capacity and settlement behavior are as follows.

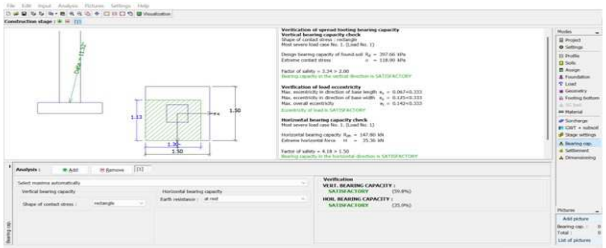

Fig. 19 Bearing Capacity of Point 10

The calculation results at Point 10 indicate that the foundation with dimensions of 1,5 m × 1,5 m has an ultimate bearing capacity of 397,66 kPa, while the maximum applied load generates a contact pressure of only 118,90 kPa. With a factor of safety of 3,34, the foundation can be considered highly secure against shear failure of the supporting soil. The relatively large safety margin also provides additional tolerance for potential variations in soil properties or increases in applied loads.

In terms of load eccentricity, the eccentricity values in the x-direction (0,067) and y-direction (0,125) are significantly lower than one-sixth of the foundation width (0,333). Consequently, the stress distribution at the foundation base remains entirely compressive, without the occurrence of tensile stresses. This condition confirms that the resultant load lies within the foundation kern, thereby ensuring overall stability.

Furthermore, for lateral loading, the foundation exhibits a horizontal resistance capacity of 147,80 kN, compared to the applied horizontal load of only 35,36 kN. The resulting safety factor of 4,18 (>1,5) indicates that the foundation is sufficiently rigid to resist lateral forces without risk of sliding or displacement. Therefore, it can be concluded that the foundation at Point 10 demonstrates safe soil-bearing performance under both vertical and horizontal loading, with load eccentricity within permissible limits, and that it ensures reliable structural stability.

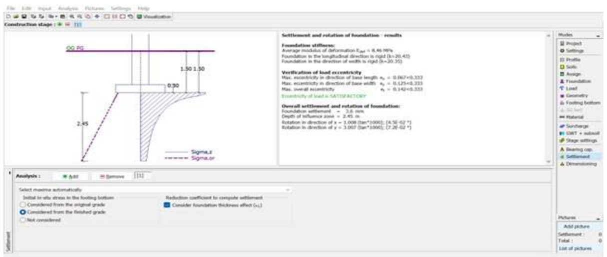

Fig. 20 Settlement of Point 10

The settlement analysis at Point 10 indicates a total foundation settlement of 3,6 mm, with an influence zone extending to approximately 2,45 m beneath the footing base. The average soil deformation modulus (E_{def}) = 8,46 MPa, while the foundation stiffness is classified as rigid in both directions ($k_x \approx 20{,}43$; $k_y \approx 20{,}35$). The load eccentricities remain within the kern (e_x= 0,067; e_y = 0,125; e_t= 0,142 < 1/6), ensuring that the stress distribution at the footing base is fully compressive. Foundation rotations are negligible, with values of approximately 0,045° in the x-direction and 0,072° in the y-direction. The computed settlement of 3.6 mm is significantly below the conventional serviceability limit for shallow foundations in building structures (≈25–50 mm), thereby confirming that the foundation performance at Point 10 is serviceable and safe. The relatively lower value of E_{def} indicates that the local soil is more compressible than at stiffer locations. Consequently, in the final design stage, attention should be given to potential differential settlement between points, long-term consolidation effects (if clayey strata are present), and possible fluctuations of the groundwater table. Overall, the foundation's deformation response at Point 10 is satisfactory for the design load, with a comfortable margin of safety against serviceability issues.

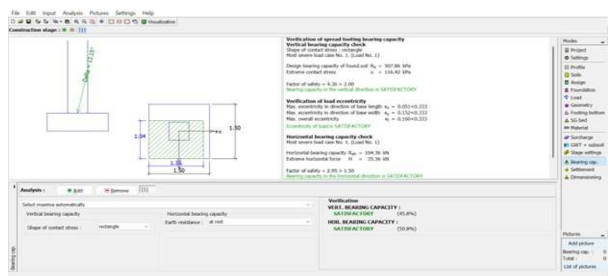

Fig. 21 Bearing Capacity of Point 11

The verification results at Point 11 demonstrate that the foundation possesses adequate capacity in both vertical and horizontal directions. The factor of safety under vertical loading reaches 4,36, indicating that the working stress remains far below the allowable soil bearing capacity. This confirms that the soil conditions at Point 11 are sufficiently strong to safely sustain the applied structural loads. The small eccentricities (e.g., ex, ey, et), all well below the 1/6 foundation dimension limit, ensure a uniform stress distribution across the foundation base, eliminating tensile stresses. Such a condition is critical for maintaining stability and preventing foundation tilting.

In terms of lateral stability, the shear demand induced by horizontal loads is substantially lower than the available soil resistance, with a factor of safety of 2,95. This indicates that the foundation remains secure against sliding and horizontal displacement. Overall, the foundation at Point 11 can be considered highly safe in relation to vertical bearing capacity, load eccentricity, and lateral stability. Nevertheless, the relatively high safety factors also suggest potential opportunities for foundation optimization, such as reducing footing dimensions or improving material efficiency, should economic considerations become a design priority, without compromising structural safety

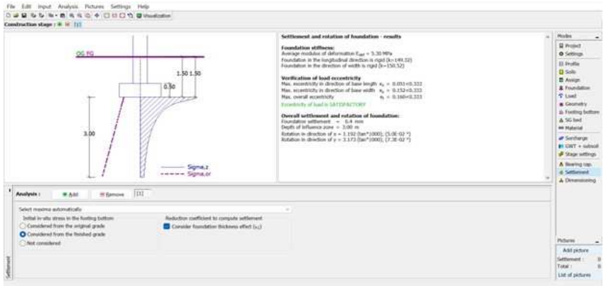

Fig. 22 Settlement of Point 11

The settlement analysis at Point 11 indicates that the soil at this location has a moderate deformation modulus of 5,30 MPa, providing adequate stiffness to support the foundation. The computed total settlement of 6,4 mm is well within the permissible limit specified in foundation design standards (commonly 25–50 mm for shallow foundations), thereby classifying the response as safe. Foundation rotation is also negligible, ensuring that no structural instability or serviceability issues will arise in the superstructure. Furthermore, the eccentricity values remain within the foundation's kern, confirming that the applied loads are uniformly distributed and do not induce excessive stress concentrations at the base.

Accordingly, the foundation at Point 11 is deemed secure against both total and differential settlements, with minimal risk of tilting or cracking in the supported structure. From a serviceability perspective, the foundation's performance fully satisfies the SLS requirements, ensuring the long-term safety and functionality of the superstructure.

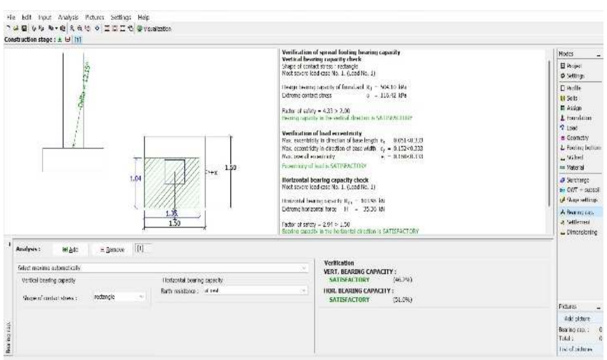

Fig. 23 Bearing Capacity of Point 12

The working stress at the foundation base (116,42 kPa) is only about 23% of the allowable soil bearing capacity (116,42/504,10 ≈ 0,23), indicating a large vertical safety margin and a negligible risk of mechanical failure due to soil capacity limitations. The load eccentricity remains within the foundation's kern, ensuring that the stress distribution forms a full trapezoid without tensile zones, thereby preserving footing stability and minimizing torsional risk.

In terms of horizontal resistance, the lateral capacity utilization is approximately 34% (35,36/103,98 ≈ 0,34), indicating sufficient resistance against lateral forces such as wind, earthquakes, or soil movement. Practically, this means that the foundation at Point 12 is safe with respect to both the ultimate limit state (ULS) and lateral loading conditions. However, before finalizing the design, the following verifications are recommended (1) serviceability verification, including settlement calculations and/or static load testing (SLT), (2) validation of soil parameters using CPT/boring data and laboratory testing to minimize the possibility of overestimating soil capacity, (3) if a group foundation configuration is to be applied, evaluation of group effects, long-term consolidation, and potential negative skin friction (downdrag) due to fill loads should be conducted [23], [24]. By carrying out these verification steps, the design can be further optimized (e.g., more efficient footing dimensions) without compromising structural safety.

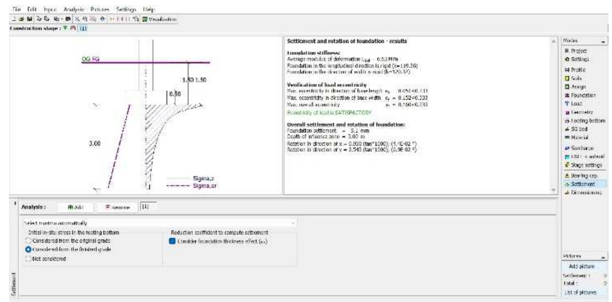

Fig. 24 Settlement of Point 12

Based on the analysis results, the foundation at Point 12 experiences a total settlement of 5.1 mm. This value is relatively small and remains well below the commonly accepted threshold for shallow footings, which ranges between 25 mm and 50 mm [25]. This indicates that, in terms of the serviceability limit state (SLS), the foundation remains safe and does not induce excessive deformation in the superstructure. The load eccentricities (e_x, e_y, e_t,) are all less than 0,333, confirming that the applied loads are still within the kern of the foundation. Consequently, the stress distribution at the foundation base remains uniform in compression (without generating tensile stresses), thereby avoiding the risk of partial contact loss. The foundation rotations in both the x and y directions are also very small (each less than 0,1°), demonstrating that foundation stability is well maintained and that no significant tilting occurs due to eccentric loading.

Overall, the foundation condition at Point 12 is considered safe with respect to settlement. The applied loads remain within acceptable tolerances for soil deformation, both vertically and rotationally. Nonetheless, attention should still be given to the potential for long-term consolidation settlement, particularly if compressible clay layers are present, as well as to the effects of group foundation interaction if the system is applied in clusters.

IV. Conclusion

This study successfully the zonation of soil bearing capacity in Padang City based on Cone Penetration Test (CPT) data collected from five districts, namely Koto Tangah, Padang Barat, Nanggalo, Padang Timur and Padang Selatan. The analysis revealed variations in ultimate bearing capacity values across test locations, which are influenced by local geotechnical conditions. Overall, areas with denser and well consolidated soil layers exhibited higher bearing capacities compared to zones dominated by soft clay or loose sand deposits. The resulting zonation can serve as an initial reference for foundation planning and infrastructure development in Padang City, ensuring designs are more adaptive to the local soil characteristics.

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