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Assessment of the load-bearing capacity of foundation soil composed of layers of compacted rock blocks

Avaliação da capacidade de carga de terreno de fundação formado por camadas de blocos de rocha compactados

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Abstract: This article presents an evaluation of the load-bearing capacity of a layer of compacted rock blocks, using shear strength parameters obtained through the GSI geomechanical classification system. This approach allows for estimating the load-bearing capacity of the soil-foundation system by applying established theoretical methods. The behavior of the rock material was assessed through a plate load test, and the results indicated that the assumption of treating the compacted rock block layer as a rock mass yielded a load-bearing capacity consistent with that determined from the plate load test. Furthermore, the geotechnical parameters derived from the back-analysis of field test results aligned well with those obtained via the application of the GSI system. Therefore, utilizing geomechanical classification systems is shown to be a viable methodology for designing shallow foundations on layers of rock blocks.

Keywords: Load-Bearing Capacity; Geomechanical Classification; Plate Load Test.

Resumo: No presente artigo é apresentada a avaliação da capacidade de carga de uma camada de blocos de rocha compactados, cujos parâmetros de resistência ao cisalhamento foram obtidos a partir do emprego do sistema de classificação geomecânica GSI, permitindo a estimativa da capacidade de carga do sistema solo-fundação pelo uso de métodos teóricos consagrados. A avaliação do comportamento do material rochoso foi feita a partir da realização de ensaio de placa. Os resultados obtidos indicaram que a hipótese da consideração da camada de blocos rochosos compactados como um maciço rochoso levou a uma capacidade de carga compatível com aquela obtida no ensaio de placa realizado. Além disto, os parâmetros geotécnicos do material resultantes da retroanálise dos resultados do ensaio de campo foram compatíveis com aqueles obtidos na aplicação do sistema GSI. Portanto, o emprego dos sistemas de classificação geomecânica apresenta-se como uma metodologia viável a ser empregada no projeto de fundações rasas assentes sobre camadas de blocos rochosos.

Palavras-chave: Capacidade de Carga; Classificação Geomecânica; Ensaio de Placa.

1. Introduction

The choice between shallow and deep foundations directly relates to the soil's bearing capacity at varying depths. When soils at shallow depths exhibit good bearing capacity, shallow (or direct) foundations become the most suitable solution (TEIXEIRA & GODOY, 1998; SILVA, 2023). Otherwise, it is necessary to resort to deep foundations or improve the geotechnical properties of the soils in the superficial layers (FREITAS, 2016; PEREIRA, 2018). Numerous techniques can be adopted for soil improvement, such as replacing existing material with soil-cement, compacted soil, or other materials, provided these alternatives demonstrate better mechanical characteristics.

For instance, soil-cement can be an effective method, where adding a binder to the soil significantly enhances the cohesive intercept of the material's shear strength. This effect arises from mixing soil with cement followed by compaction, which leads to enhanced mechanical properties (OLIVEIRA, 2011; OLIVEIRA, 2018; RICARTE, 2021). According to Carneiro et al. (2019), compaction improves the geotechnical properties of the soil through mechanical energy application, thereby increasing shear strength while reducing permeability and compressibility. However, both methods necessitate detailed preliminary studies, including the proper selection of borrow materials, compaction tests, and, in the case of soil-cement, the correct mix design, highlighting the complexity of implementing these techniques.

An alternative approach for shallow foundation projects involves replacing low-strength and highly deformable soils with a material formed from interlocked and compacted rock blocks. This technique is believed to create a layer with high shear strength and low deformability, which are desirable characteristics for shallow foundation installations.

To evaluate the bearing capacity of compacted or cemented soils, laboratory tests can define the cohesive intercept and friction angle of their shear strength, or field tests like the Standard Penetration Test (SPT) and Cone Penetration Test (CPT) can be employed (CINTRA, AOKI & ALBIERO, 2011; VELLOSO & LOPES, 2011). However, due to the nature and dimensions of rock blocks, determining their shear strength parameters through testing presents challenges. Tests like SPT and CPT are impractical for rocky materials due to their impenetrability, and laboratory equipment necessary for large-scale testing is limited and costly.

Given the absence of established methods for determining the bearing capacity of soils comprising compacted rock block layers, it's reasonable to assume that this material, a blend of rock blocks and cyclopean concrete, resembles a highly fractured rock mass. According to Hoek and Marinos (2000), such a rock mass displays numerous randomly distributed sets of discontinuities, with compact fillings and angular fragments. Under these conditions, the material's shear strength parameters and deformability properties can be estimated utilizing geomechanical classification systems from Rock Mechanics, such as the Geological Strength Index (GSI) proposed by Hoek et al. (2002), along with knowledge of the intact rock properties of the constituent material.

Thus, this study evaluates the bearing capacity of a layer of compacted rock blocks, with shear strength parameters obtained through the GSI geomechanical classification system. This approach enabled estimating the soil foundation system's bearing capacity using well-established theoretical methods. The behavior of the rocky material was assessed through a plate load test and a numerical back-analysis of the results, aiming to validate the methodology employed to estimate the soil foundation system's bearing capacity in terrains composed of compacted rock blocks.

2. Materials and methods

2.1 Site description

The study was conducted at Residencial Brisas do Parque, located on Rua Professor Jacinto Botelho, Block 15, Lots 1 to 12, in the Guararapes neighborhood of Fortaleza, Ceará, Brazil. The site characterization was based on two borehole tests (SM) between October and November 2023. All procedures followed the recommendations of the Brazilian standard NBR 6484 (ABNT, 2020).

The results are presented in geotechnical-geological profiles, illustrating the stratification of the soil layers based on boreholes SM-01 and SM-03. Figure 1 displays the site's stratigraphy as determined from the borehole data, highlighting the three identified layers: silty-sandy clay with soft consistency, silty-sandy clay with hard consistency, and conglomeratic sandstone.

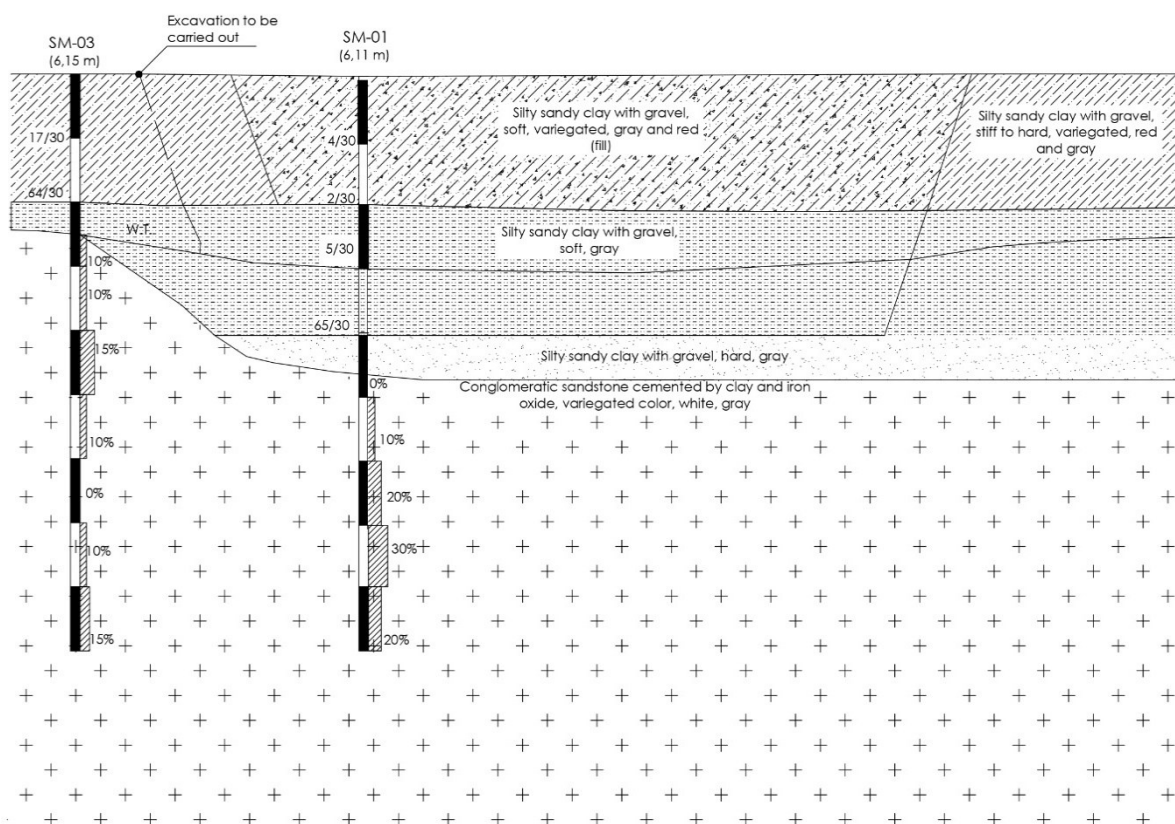


Figure 1 – Soil profile in the study area.
Source: Authors (2024).

Based on the borehole results, it was found that the allowable bearing pressure of 500 kPa, as specified in the design, was not achieved at the planned foundation level of 4.04 m. According to Décourt (1992), the allowable bearing pressure obtained was only 50 kPa due to the presence of a soft silty-sandy clay layer with gravel located between depths of 4.11 m and 2.11 m.

Therefore, the possibility of ground improvement was considered by removing the silty-sandy clay layer and subsequently replacing it with a compacted mixture composed of approximately 75% pedra rachão (crushed stone) – with particle sizes ranging from 76 mm to 250 mm – and 25% cyclopean concrete. This mixture intends to achieve a material with high frictional resistance due to the interlocking of granite rock blocks and significant cohesion provided by the Portland cement in the concrete. As a result, the goal is to produce a material capable of sustaining the design bearing pressure for the foundation soil.

2.2 Estimation of rock layer properties

Due to the inability to conduct laboratory and field tests on the mixture of rock blocks and concrete, its shear strength properties were estimated by applying geomechanical classification concepts from the field of Rock Mechanics. The mixture was deemed representative of a highly fractured rock mass. In this context, the crushed stone particles (pedra rachão) are analogous to a fracturing pattern characterized by numerous randomly distributed discontinuities. Simultaneously, the concrete component provides cohesion similar to that found in rock masses, attributed to the interparticle bonding forces between the minerals.

This study employed the geomechanical classification system proposed by Hoek et al. (2002), known as the Geological Strength Index (GSI). This study utilized the geomechanical classification system proposed by Hoek et al. (2002), known as the Geological Strength Index (GSI). Based on this methodology, GSI values were estimated according to the fracturing pattern of the material and the quality of discontinuities between rock blocks. Additionally, values were

defined for the uniaxial compressive strength (σ_c), the material constant of the intact rock (m_i), which includes the crushed stone particles, and the disturbance factor (D). With these parameters established for the compacted mixture, estimating the cohesion and friction angle parameters of the material's shear strength was possible. These parameters were then used to determine the bearing capacity of foundations on rock masses through established theoretical approaches, such as those proposed by Brinch-Hansen (1961), Meyerhof (1963), and Vésic (1975).

According to NBR 6122 (ABNT, 2020), the bearing capacity of foundations may be estimated using theoretical methods, enabling a grounded analysis based on soil conditions and foundation characteristics, such as geometry and embedment depth. In this study, the bearing capacity of the soil-foundation system was estimated by considering the settlement of a 45 cm diameter circular plate resting on the compacted rock block layer.

2.3 Direct load test

The plate load test, conducted in accordance with NBR 6489 (ABNT, 2019), enables the definition of the pressure–settlement curve of the soil, simulating the loads transmitted by shallow foundation elements such as isolated footings. A circular steel plate with a minimum diameter of 30 cm is used, placed at the base level of the footing. The test continues until the applied pressure reaches twice the allowable bearing pressure for the soil or until the specified maximum settlement is reached. The type of loading may vary depending on the purpose and design of the foundation and can be rapid, slow, cyclic, or mixed (Monteiro et al., 2017; Albuquerque & Silva, 2023).

In the present study, the behavior of the in situ compacted rock block layer was evaluated through a slow-loading plate load test, following the specifications of NBR 6489 (ABNT, 2019). Settlements were obtained by averaging the values measured by dial gauges (deflectometers) attached to a plate with an area of 1,590.43 cm² (diameter of 45 cm). Figure 2 shows the plate used in the test and the arrangement of deflectometers employed to measure settlements.



Figure 2 – Circular steel plate used in the load test.
Source: Authors (2024).

The loads were applied using a 50 tf capacity hydraulic jack, with a Doosan DX225LCA backhoe loader weighing approximately 21,500 kg and serving as the reaction system.

The load test was conducted on a compacted rock layer approximately 0.89 m thick. This thickness is less than the estimated depth of the stress bulb generated by the plate loading during the test. According to Cintra, Aoki, and Albiero (2011), the stress bulb depth for rectangular footings can be estimated as 3B (three times the foundation base width), at which the stress reduces to 10% of its initial value.

The plate load test was performed in 10 loading stages, with pressure increments of 100 kPa, reaching a maximum pressure of 1000 kPa. The unloading process was performed in 4 stages, with pressure reductions of 250 kPa at each stage. Loads were maintained until displacement stabilization (slow loading test) in all phases.

During the loading phase, measurements were taken at intervals of 0 min, 1 min, 2 min, 4 min, 8 min, 15 min, and 30 min to monitor settlement stabilization. The final loading stage lasted at least 12 hours, provided there was no failure of the ground. During unloading, measurements followed the same time intervals, with an additional reading taken 30 minutes after full load removal to detect any residual settlement. This process was repeated during the loading phase, ensuring consistency in measurements for settlement monitoring.

2.4 Back analysis of the plate load test

The back-analysis of the plate load test was conducted to determine the geotechnical-geological parameters of the compacted rock block layer and to compare them with the values obtained using the GSI geomechanical classification system proposed by Hoek et al. (2002). This methodology allows for evaluating a material's behavior based on its response to loading applied during a field test. The results from the plate load test were back-analyzed using RS2 software (by Rocscience), employing the finite element method (FEM) to solve the governing equations. The materials were assumed to exhibit a perfectly elastic-plastic Mohr-Coulomb behavior in the numerical back-analysis. In this material model, total strain is decomposed into two components: elastic strain, which is recoverable, and plastic strain, which is permanent.

Regarding modeling and finite element mesh discretization (Figure 3), RS2 provides a standard option for automatic mesh generation. Boundary conditions were defined by constraining the lateral edges from moving horizontally (x-axis). Additionally, all nodes at the base of the soil layer were fixed, preventing any displacement.

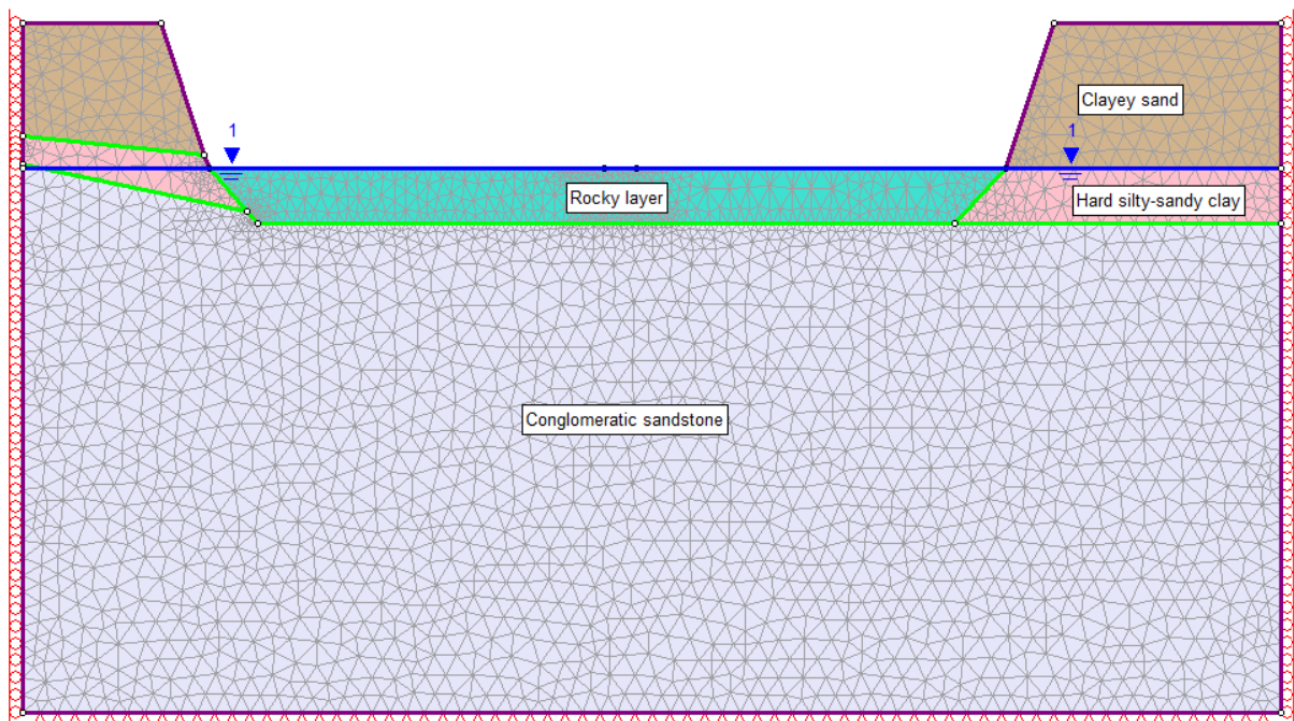


Figure 3 – Finite element mesh and boundary conditions utilized in the numerical modeling with RS2 software.

Source: Authors (2024).

3. Results and discussion

3.1 Estimation of shear strength parameters using geomechanical classification

For the bearing capacity analysis, the foundation material, a compacted rock block mixture, was initially treated as a highly fractured rock mass, with an estimated GSI of 15%, indicative of numerous randomly distributed discontinuities among the crushed stone particles. Unlike other classification systems, Hoek et al. (2002) do not categorize rock mass quality classes based on GSI values.

The uniaxial compressive strength (σ_{ci}) was estimated at 50 MPa, based on field observations using a geological hammer, where the rock particles required more than one blow to fracture. This justifies the assigned strength value, which, according to ABGE Standard 109/2024 (ABGE, 2024), corresponds to category R4. The m_i parameter, representing the shear strength of the intact rock, was estimated at 15, characterizing the material as sandstone or quartzite, as per Hoek & Brown (1980). This value is consistent with data provided by RocLab software (Rocscience), derived from global case studies.

The disturbance factor (D)—necessary to estimate cohesion and friction angle using the Hoek et al. (2002) methodology—was set at 0, assuming the fracture pattern of the compacted rock layer remains unchanged after compaction. This is akin to excavation in a rock mass without explosives, leading to minimal disturbance.

The values of cohesion (c) and friction angle (ϕ) obtained using the Hoek et al. (2002) approach, based on the criteria outlined above, were 1390 kPa and 23° , respectively. However, due to uncertainty in the estimated cohesion, a safety factor of 10 was applied, reducing the cohesion value to 139 kPa. Considering the uncertainties related to the rock mass properties, this safety factor was adopted and proved suitable when analyzing the results presented below. The unit weight of the material, accounting for the nature of fragmented rock composites, was estimated at approximately 20 kN/m³.

3.2 In-situ plate load test

The results of the plate load tests (Table 1) revealed the settlement behavior of the ground under various levels of applied pressure. Initially, with an applied pressure of 95 kPa, the observed settlement was -0.12 mm. As the pressure increased to 984 kPa, the maximum settlement reached -2.68 mm. After unloading, a residual settlement of -1.85 mm was recorded, indicating that a significant portion of the total deformation was plastic; thus, modeling the material as perfectly elastic-plastic in the back-analysis proved appropriate.

The results demonstrated that the observed settlement remained within acceptable limits under the maximum applied pressure during the plate test. According to Terzaghi et al. (1996), residential buildings can tolerate maximum absolute settlements of up to 25 mm.

Figure 4 presents the pressure vs. settlement curve obtained during the plate load test. Based on the in situ results shown in Figure 4, the relationship between the applied pressure and the resulting settlement was approximately linear up to the maximum applied load, indicating no signs of failure under drained conditions.

The bearing capacity estimated through extrapolating the plate load test results using the Van der Veen (1953) method was 2000 kPa. This method provided a satisfactory fit to the experimental data obtained, as shown in Figure 4.

Table 1 – Results of the in-situ plate load test (slow loading).

Pressure (kPa)	Settlement (mm)
0	0
95	-0,12
194	-0,32
293	-0,59
391	-0,87
490	-1,20
588	-1,48
687	-1,63
786	-1,91
885	-2,23
984	-2,68
736	-2,48
490	-2,37
243	-2,20
4	-1,85

Source: Authors (2024).

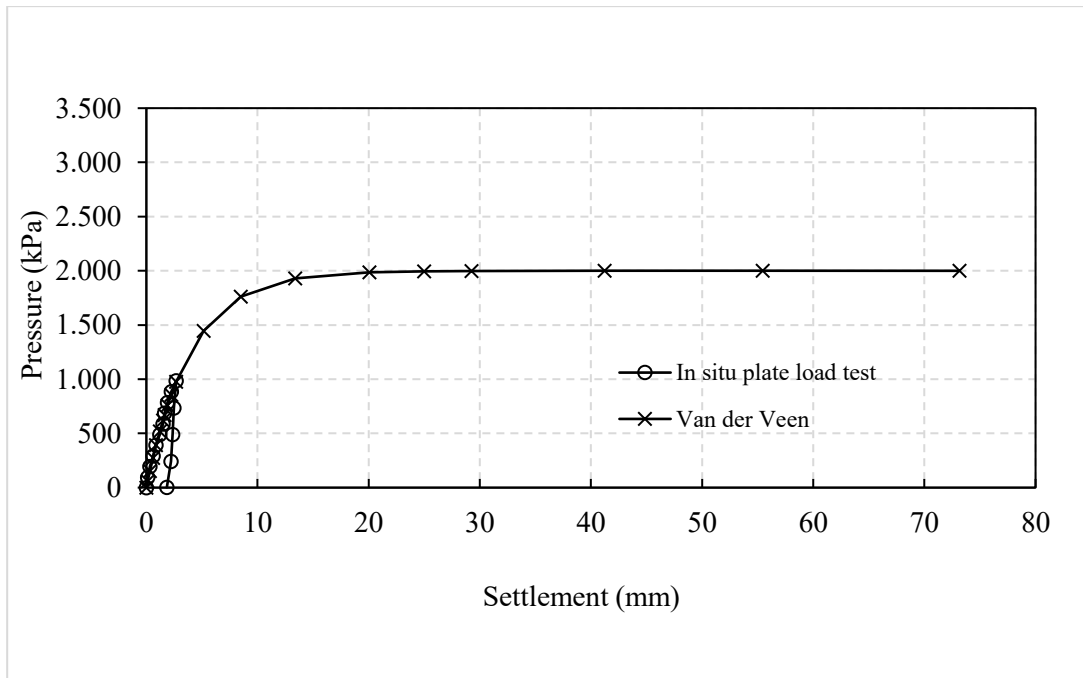


Figure 4 – Pressure vs. settlement curve from the plate load test and extrapolation using Van der Veen (1953).
Source: Authors (2024).

3.3 Back analysis of the plate load test

Figure 5 presents the comparison between the pressure versus settlement curves obtained from the plate load test and the back-analysis, from which the geotechnical-geological properties listed in Table 2 were derived. Initially, the results show a satisfactory fit between the outcomes of the back-analysis and the data from the plate load test. When comparing the maximum pressure values, the difference between the two methods is minimal—only 1.63%. The settlement obtained in the back-analysis was 0.06 mm greater than that observed experimentally, which, from an experimental standpoint, is considered negligible. The difference in residual settlement was slightly higher, with the back-analysis yielding a value 0.27 mm lower than the test. These discrepancies are deemed acceptable, considering that numerical analysis may not capture all real ground conditions, along with the inherent variability in experimental procedures.

In this context, the criteria for peak shear strength—cohesion and friction angle—are considered, reflecting the initial conditions of the soil as shown in Table 2. These criteria are compared with the values of the rock layer obtained through geomechanical classification. The results indicate a satisfactory agreement between the estimated shear strength parameters for the compacted rock block layer, based on the GSI geomechanical classification system, and the values obtained from the back-analysis of the plate load test. This suggests that the methodology applied in this study for estimating the shear strength properties of compacted rock block layers for shallow foundation settlements has proven effective.

In this case, it is important to note that a safety factor of 10 was applied to the cohesive parameter obtained through geomechanical classification. This reduction was deemed appropriate, considering that the mineral skeleton formed by the compacted rock blocks does not exhibit the same cohesive forces between minerals as those found in a natural rock mass. Additionally, the significant cohesion value obtained in the back-analysis can be attributed to the presence of a cementing agent—specifically, the Portland cement used in the concrete mixture added to the rock blocks.

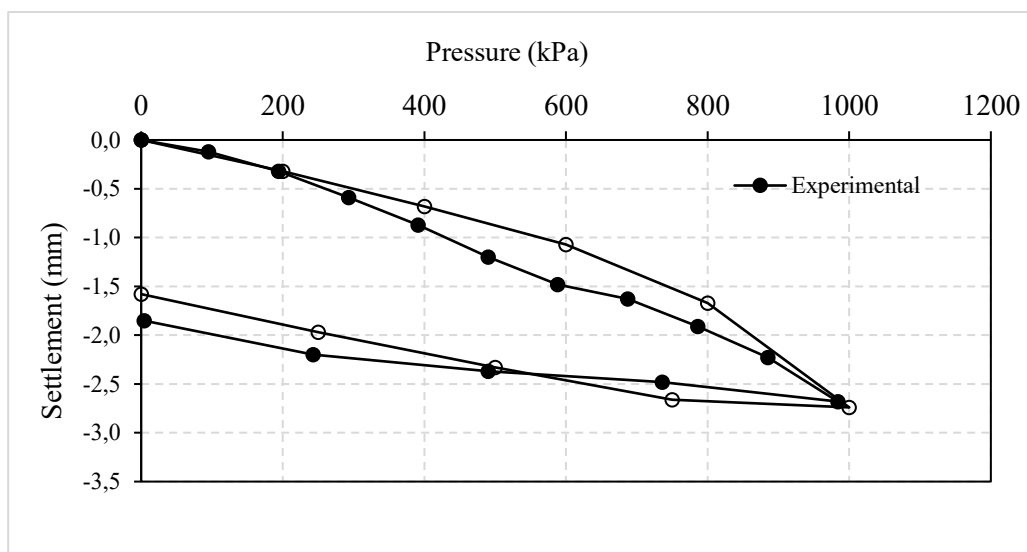


Figure 5 – Comparison of pressure versus settlement curves obtained from the plate load and back-analysis. Source: Authors (2024).

Table 2 – Parameters of strength and deformability derived from the back-analysis of the plate load test.

Material	Specific weight (kN/m ³)	Young's modulus (kPa)	Poisson's ratio	Friction angle (°)	Cohesion (kPa)
Clayey sand	19	20000	0,35	12,4	79,7
Silty-sandy clay	21	20000	0,35	12,4	79,7
Rock layer	19	468000	0,49	23,0	110,0

Conglomeratic sandstone	22	468000	0,49	20,0	40,0
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Source: Authors (2024).

3.4 Evaluation of the load-bearing capacity of the rock layer

Figure 6 presents the pressure versus settlement curves derived from the plate load test, the results from its extrapolation using the Van der Veen method (1953), which indicated a bearing capacity of 2000 kPa, and the curve obtained from the numerical modeling of the in situ test (back-analysis). It is important to note that, once the geotechnical-geological parameters of the foundation soil materials are established through the back-analysis of the plate load test results, it becomes feasible to define a pressure versus settlement curve for various loading levels, as shown in Figure 6.

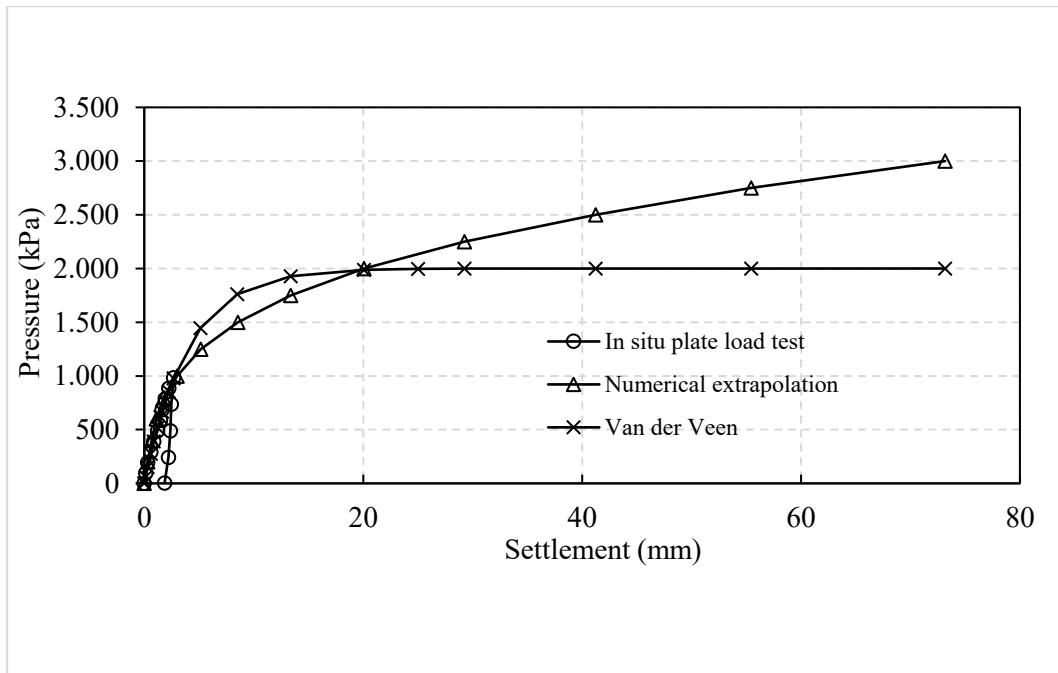


Figure 6 – Comparison of the load test curves, Van der Veen (1953) extrapolation, and numerical analysis, showing the failure stress as a function of settlement.

Source: Authors (2024).

Figure 7 displays the bearing capacity results obtained through theoretical methods, extrapolation of the plate load test using Van der Veen's method (1953), and the numerical model. Initially, there is strong agreement between the bearing capacity results from the developed numerical model and the extrapolated plate load test. Conversely, the values from the theoretical methods were significantly higher than those from the experimental methodology (plate load test), yet comparable to the values from the numerical model for settlement levels of 40 mm. This indicates that the use of shear strength parameters derived from geomechanical classification to predict the bearing capacity of the soil-foundation system is appropriate.

The bearing capacity derived from the numerical model was initially based on a maximum settlement criterion of 40 mm, resulting in a value of 2500 kPa (Figure 6). However, adopting a stricter criterion of 25 mm maximum settlement reduces the bearing capacity to approximately 2150 kPa. Van der Veen's method (1953) yields values closer to those from numerical extrapolation with settlement limited to 25 mm, as recommended by classical authors such as Terzaghi et al. (1996). Nevertheless, these values remain lower than those predicted by theoretical methods, as illustrated in Figure 7. This comparison emphasizes the importance of considering settlement criteria in the interpretation of the presented results.

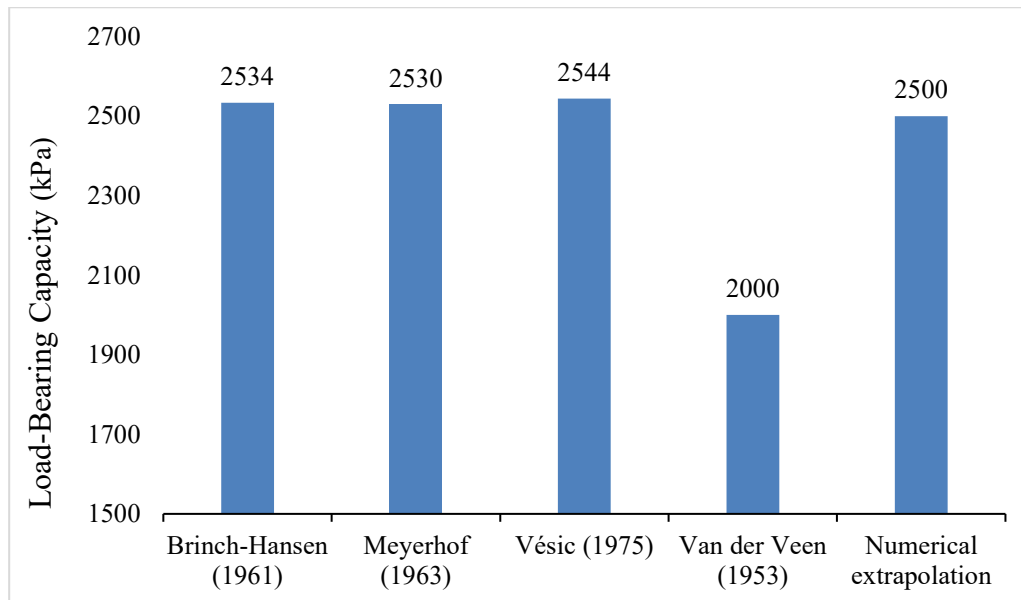


Figure 7 – Comparison of the values obtained for the load-bearing capacity of the soil-foundation system. Source: Authors (2024).

4. Conclusions

This study examined of rock blocks as a ground improvement technique for shallow foundations. Based on the results obtained, it was confirmed that this technique developed a material suitable for shallow foundation settlement with high load-bearing capacity compared to naturally occurring soils with lower strength, while also maintaining settlements within acceptable limits for residential constructions.

The two-dimensional numerical simulation facilitated the acquisition of a load-settlement curve that aligned closely with the experimental results, validating the methodology used for estimating the bearing capacity of the foundation material. This shows that numerical modeling was crucial for predicting the behavior of the soil-foundation system, replicating the loading conditions imposed during the field tests, and enabling the determination of geotechnical parameters, particularly those related to the rocky layer.

The application of the Van der Veen method (1953) achieved a satisfactory fit of the load-settlement curve from the plate load test, thereby allowing for the determination of the soil-foundation system's bearing capacity. The curve derived from the extrapolation of the field test results closely resembled that obtained from the numerical model, indicating that both approaches effectively represented the behavior of the studied material.

Finally, predicting the shear strength properties of the compacted rock block layer using the geomechanical classification system (GSI System) concepts to estimate the material's bearing capacity when utilized as a shallow foundation layer proved satisfactory. However, it is recommended that the cohesive parameter obtained from applying the concepts of the geomechanical classification system be divided by a safety factor of ten. Adopting this safety factor for the cohesive parameter was consistent, ensuring a reliable estimate of the material's load-bearing capacity.

Although a plate load test was performed to assess bearing capacity, direct shear tests were not conducted to acquire the shear strength parameters of the compacted rock block layer. Therefore, it is advised that this type of test be executed to directly ascertain the shear strength parameters, thereby enhancing the reliability of the bearing capacity calculations.

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References

- ABNT (2019). NBR 6489 – *Solo – Prova de carga estática em fundação direta*. Associação Brasileira de Normas Técnicas, Rio de Janeiro, Brasil.
- ABNT (2020). NBR 6122 – *Projeto e execução de fundações*. Associação Brasileira de Normas Técnicas, Rio de Janeiro, Brasil.
- ABNT (2020). NBR 6484 – *Execução de sondagens de simples reconhecimento dos solos*. Associação Brasileira de Normas Técnicas, Rio de Janeiro, Brasil.
- ABGE – Associação Brasileira de Geologia de Engenharia e Ambiental. Norma ABGE – 109/2024: *descrição e classificação de sondagens*. 1. ed. São Paulo: ABGE, 2024.
- ALBUQUERQUE, P. J. R. de; SILVA, G. S. da. Análise das alterações e avanços das normas de provas de carga em fundação profunda (ABNT NBR 16.903: 2020) e fundação direta (ABNT NBR 6489: 2019). In: 10º SEMINÁRIO DE ENGENHARIA DE FUNDAÇÕES ESPECIAIS E GEOTECNIA, 4 a 7 dez, 2023, São Paulo. *Anais...* São Paulo, 2023. p. 1-9.
- BRINCH HANSEN, J., (1961). A General Formula for Bearing Capacity, *Boletim Número 11*, Danish Geotechnical Institute, Copenhagen, pp. 38-46.
- CARNEIRO, A. D. A.; CHAGAS, G. D. S.; MOURA, A. S. Avaliação da compactação como melhoramento de um solo silto, argiloso, colapsível, um partidor de realização de ensaios oedométricos e provas de cargas diretas. *Revista de Engenharia Civil IMED*, Passo Fundo, v. 6, n.º 1, p. 3-19, jan – jun/2019. Disponível em: <https://seer.atitus.edu.br/index.php/revistaec/article/view/2287/2249>. Acesso em: 08 jun. 2024.
- CINTRA, J. C. A.; AOKI, N.; ALBIERO, J. H. *Tensão admissível em fundações diretas*. São Carlos: RiMa, 2011.
- DÉCOURT, L. (1992). SPT in non-classical material. ‘*Applicability of Classical Soil Mechanics Principles in Structured Soils*’, Proc. US/Brazil. Workshop, Belo Horizonte, Univ. Fed. Viçosa, MG, Brazil, pp. 67-100.
- FREITAS, M. C. de. *Avaliação de técnica de melhoria de solos colapsíveis por meio de colunas de solo laterítico compactado*. Dissertação (Mestrado em Geotecnia), Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, São Paulo, 2016. 201 f.
- HOEK, E. & BROWN, E. T. (1980). *Underground Excavations in Rock*. Institute of Mining and Metallurgy, London, UK, 527 p.
- HOEK, E.; MARINOS, P.; GSI – A geologically friendly tool for rock mass strength estimation. In: GEOENG2000 CONFERENCE, Melbourne, 2000. *Proceedings* [...]. Melbourne, 2000.
- HOEK, E.; CARRANZA-Torres. C. & CORKUM, B. (2002). Hoek-Brown failure criterion – 2002 Edition. *Proc. NARMS-TAC*. Conference, Toronto, Canada, Vol. 1, 267-273.
- MEYERHOF, G. G. Some recent research on the bearing capacity of foundations. *Canadian Geotechnical Journal*, v. 1, p. 16-26, 1963.
- MONTEIRO, T. M.; ARAÚJO, C. B. C. de; AGUIAR, M. F. P. de. Análise de métodos semi-empíricos nacionais e internacionais para determinação da capacidade de carga axial em estacas tipo raiz. *Revista Tecnologia*, Fortaleza, v. 38, n. 2, dez. 2017, p. 1-16. Disponível em: <https://www.researchgate.net/publication/324020741>. Acesso em: 07 jul. 2024.
- OLIVEIRA, K. E. B. B. de. *Solo cimento: avaliação econômica da utilização de camada cimentada para reforço de fundações superficiais*. Trabalho de Conclusão de Curso, Centro de Tecnologia e Recursos Naturais, Universidade Federal de Campina Grande, Campina Grande, Paraíba, 2018. 58 f.

- OLIVEIRA, R. F. V. de. *Análise de dois solos modificados com cimento para dimensionamento de pavimentos*. Dissertação (Mestrado em Engenharia Geotécnica), Núcleo de Geotécnica da Escola de Minas, Universidade Federal de Ouro Preto, Minas Gerais, 2011. 186 f.
- PEREIRA, V. B. S. *Análise comparativa entre o recalque de fundações rasas e profundas em edifício assentado sobre solo mole*. 2018, 82 f. Trabalho de Conclusão de Curso (Graduação em Engenharia Civil) – Universidade Federal de Alagoas, Delmiro Gouveia, 2018.
- RICARTE, A. V. D. *Avaliação do melhor método disponível para o cálculo da capacidade de carga de sapatas sobre solo melhorado com cimento*. Trabalho de Conclusão de Curso, Universidade Federal de Campina Grande – UFCG, Campina Grande, Paraíba, 2021. 70 f.
- ROCSCIENCE, RS2 – *Rocscience Software*. Disponível em: <https://www.rocscience.com/software/rs2>. Acesso em: 18 jun. 2024
- SILVA, J. S. da. *Estudo sobre tipos de fundações a empregar em solos da formação geotécnica Santa Maria no bairro Renascença da cidade de Santa Cruz do Sul/RS*. Trabalho de Conclusão de Curso, Universidade de Santa Cruz do Sul, Santa Cruz, Rio Grande do Sul, 2023. 83 f.
- TERZAGHI, K., PECK, R. B., & MESRI, G. (1996). *Soil Mechanics in Engineering Practice*. 3 ed. New York: John Wiley and Sons Co. 546 f.
- TEIXEIRA, A. H.; GODOY, N. S. D. Análise, projeto e execução de fundações rasas. In: *Fundações: teoria e prática*. 2 ed. São Paulo: PINI, 1998, p. 227-264.
- VAN DER VEEN, C. A capacidade de suporte de uma estaca. In: TERCEIRA CONFERÊNCIA INTERNACIONAL FUNDAÇÃO DE MECÂNICA DOS SOLOS E ENGENHARIA, 1953, Zurique. Anais... Zurique: [s.n], 1953. v. II
- VELLOSO, D. A.; LOPES, F, R. *Fundações: volume completo*. Rio de Janeiro: Oficina de Textos, 2011.
- VESIC, A. S., 1975. "Bearing capacity of shallow foundations". In: *Foundation Engineering Handbook*, New York, McGraw-Hill, pp. 121-147.