



Comparative Study of Piled Raft and Deep Foundation Systems for a 13-Storey Academic Building in Surabaya



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Abstract

Foundation selection for a multistorey building on soft ground is governed not only by pile capacity, but also by settlement, load sharing, construction constraints, and cost. This paper compares the original deep-foundation design for an academic building in Surabaya with two piled-raft alternatives. The building has 13 main floors, one roof level, and an overall height of 56 m. The original system comprises 251 driven piles, 0.60 m in diameter and 30 m long, connected by 1.20 m thick pile caps. Each piled-raft alternative uses a 1.00 m thick raft and 269 piles of the same diameter, but with a reduced length of 20 m and a spacing of 2.40 m. The alternatives differ only in pile type: bored or driven. Borehole BH-01 gives an average N-SPT value of 4.42, and the site is treated as Site Class SE. Structural Analysis using Finite Element Method was used to obtain the superstructure reactions, the Meyerhof method was applied to estimate axial pile capacity, and Geotechnical Analysis using Finite Element Method was used to study soil-foundation deformation. The total vertical reaction is 17,232.02 tons, while the maximum pile reaction under gravity and earthquake loading is 163.92 tons. Allowable capacities are 173.87 tons for the bored pile and 189.48 tons for the driven pile. geotechnical finite element settlements are 37.5 mm and 36.7 mm for the two piled rafts, compared with 243.2 mm for the raft without piles. Within the reported cost scope, the driven-pile raft has the lowest estimate at IDR 7.79 billion and provides the most favourable overall result, although vibration, construction quality, and field verification remain important in the final selection.

Keywords: deep foundation; foundation cost; piled raft; finite element method; settlement

1. Introduction

For multistorey academic buildings founded on soft ground, checking the nominal capacity of individual piles is not enough. Settlement, differential movement, load transfer, and the practicality of construction can be equally important. The case examined here is an academic building in Surabaya with 13 main floors and one roof level, giving 14 structural levels and an overall height of about 56 m. The site investigation shows weak near-surface soils, with N-SPT values increasing as the soil becomes denser at greater depth.

The original foundation consists of 251 driven piles, each 0.60 m in diameter and 30 m long, tied together by pile caps 1.20 m thick. Under this conventional arrangement, most of the building load is assumed to pass through the pile groups. A piled raft works differently. The raft remains in contact with the ground and contributes to carrying the load, while the piles mainly increase stiffness and limit settlement. As a result, pile length, number, and arrangement can be reconsidered, although adopting a piled raft does not automatically mean that fewer piles will be required [1], [2].

Field measurements support this shared-load interpretation. Watcharasawe et al. [24], for example, found that the raft beneath a high-rise building on soft clay carried roughly 10-20% of the total load, even though its resistance had been ignored in the original design. This observation is important because it shows why a comparison with a conventional deep foundation should consider raft-soil, pile-soil, and pile-pile interaction, rather than relying only on the capacity of a single pile.

Previous experimental and numerical work [20], [21], [23] also shows that piled-raft behaviour changes with pile number, layout, length, and spacing. Deb et al. [20] reported noticeable changes in load-settlement response, pile axial force, and raft bending moment when the pile configuration was altered. For soft clay, Elsaywaf et al. [21] found that longer piles and a larger number of piles reduced both total and differential settlement. Ferchat et al. [23] further noted that these interactions are fundamentally three-dimensional, so they are not always represented adequately by simple capacity checks.

There is therefore no single pile arrangement that can be regarded as optimum for every project. Nguyen et al. [25] related the load-sharing ratio to pile number and spacing, pile length, raft embedment, and the relative stiffness of the raft and piles. Yirsaw and Ashango [4] showed that changing pile spacing can increase the share carried by the raft in layered ground. Cao et al. [5], meanwhile, found that raft thickness had a stronger influence on moment distribution and differential settlement than on total settlement alone.

Experience from tall buildings suggests that piled rafts are best assessed through performance criteria rather than pile capacity alone. Abdel-Azim et al. [22] evaluated the Messeturm foundation in Frankfurt using total settlement, differential settlement, and shaft friction. In another urban high-rise project, Leppla et al. [27] used three-dimensional analysis with staged construction to keep foundation movements within acceptable limits. Both studies illustrate the need to connect the predicted geotechnical response with the demands and tolerances of the superstructure.

Piled-raft foundations have also been studied for several Indonesian high-rise projects, including the work reported by Lumintang [7]. Studies by Hariyanto et al. [8], [9], [32], [33], [34] underline a related point: numerical results are only meaningful when the input data are consistent, the model is checked, and the output is interpreted in line with the physical behaviour being represented. Even so, relatively few Indonesian studies have examined foundation configuration, Finite Element Modelling response, construction implications, and cost together for the same academic building.

Against this background, the present study examines how the building loads are transferred to the foundation and compares two piled-raft options - one using bored piles and the other driven piles - with the conventional deep foundation in the original design. The comparison covers axial capacity, pile reactions, settlement, bending moments, lateral movement, and estimated foundation cost. A particular feature of the case is that the modification changes the system from 251 piles of 30 m length connected by pile caps to 269 piles of 20 m length working together with a raft. The potential saving therefore comes from the shorter piles and raft contribution, not from a reduction in pile count.

2. Methodology

The work was carried out as a case study combining structural analysis, geotechnical calculations, finite-element modelling, construction review, and cost estimation. The building has 13 main floors, one roof level, and a total height of 56 m. Ground conditions were interpreted from boreholes BH-01 and BH-02, both extending to about 36 m. BH-01 was adopted as the controlling profile because its average N-SPT value, 4.42, is lower than the value of 7.00 obtained at BH-02. On the basis of this value, the site was treated as Site Class SE. The overall workflow is summarized in Figure 1. The procedure begins with the original building and ground data, proceeds through structural and geotechnical finite-element analyses, evaluates the existing pile-cap system and two piled-raft alternatives, and ends with a comparison of capacity, deformation, constructability, and direct foundation cost.

The geotechnical input is summarized in Figure 2, where the N-SPT profiles from BH-01 and BH-02 are presented together with the idealized stratigraphy and the representative foundation geometry used in the numerical model.

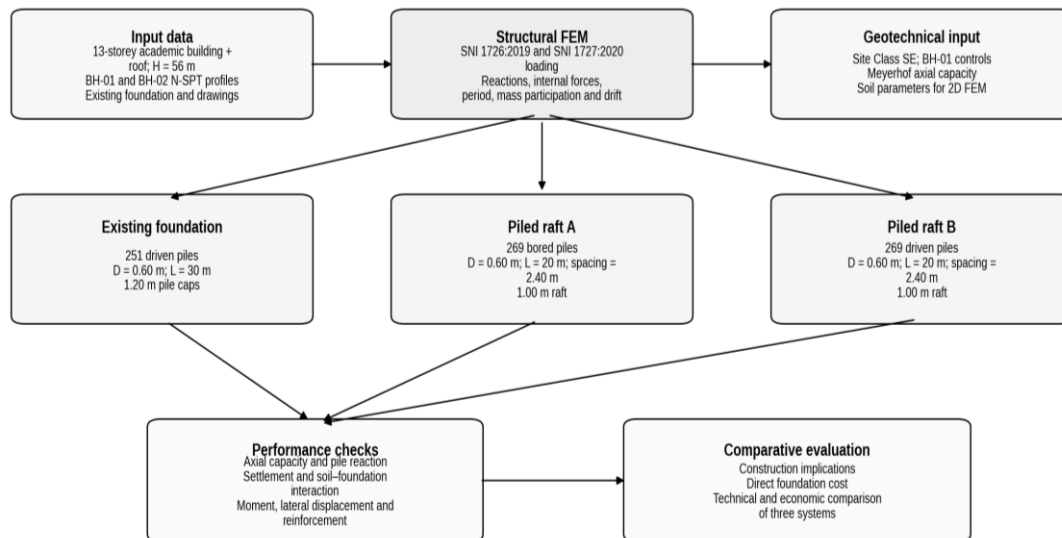


Figure 1. Research methodology and foundation alternatives considered in the study.

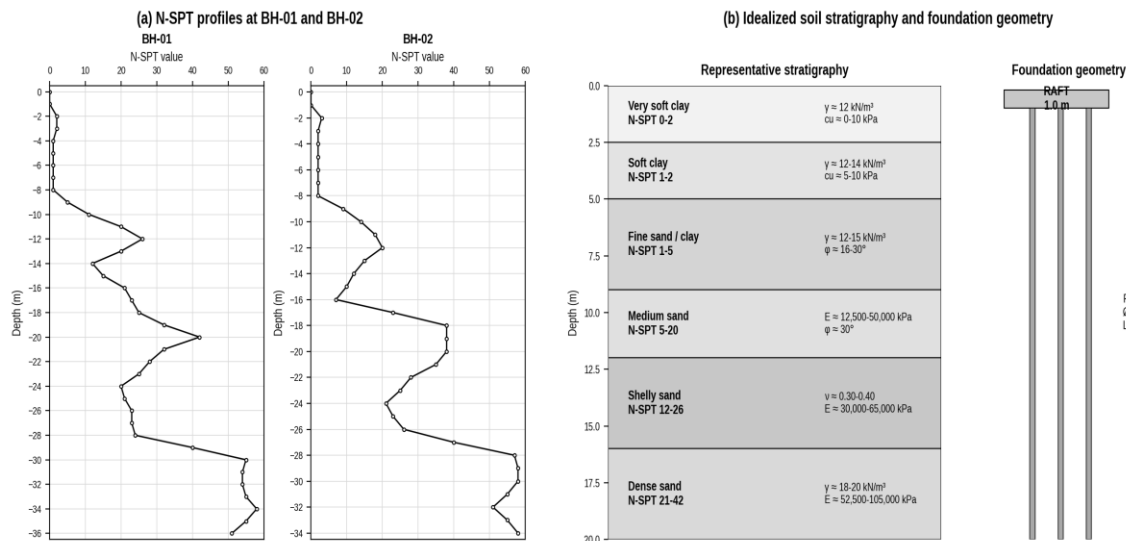


Figure 2. Combined geotechnical input: (a) N-SPT profiles at BH-01 and BH-02 and (b) idealized stratigraphy with representative foundation geometry.

Structural Finite Element was used to model the superstructure and obtain the support reactions, internal forces, natural periods, mass participation, and interstorey drift. The applied loads followed SNI 1726:2019 and SNI 1727:2020 [10], [11]. The resulting fundamental period was 2.332 s, the cumulative modal mass participation exceeded 90%, and the calculated interstorey drifts remained within the adopted limits. Reactions from the governing gravity and earthquake combinations were then transferred to the foundation assessment. This use of a global numerical model to identify critical forces and deformations before carrying out detailed checks is consistent with recent Indonesian finite-element studies of configuration-sensitive structures [28].

Allowable axial capacities for the bored and driven piles were estimated from the N-SPT profile using the Meyerhof method [15]. The ultimate capacity was taken as the sum of end bearing and shaft resistance, $Q_u = Q_p + Q_s$, and a factor of safety of 3 was applied. In the structural finite element foundation model, soil support was represented by vertical and horizontal springs derived using the Nakazawa approach. Geotechnical Analysis used a Mohr-Coulomb soil model under plane-strain conditions, with the required parameters obtained from the available N-SPT correlations and supporting references [12]-[17].

The model geometry and element-activation sequence in finite element are shown in Figure 3.

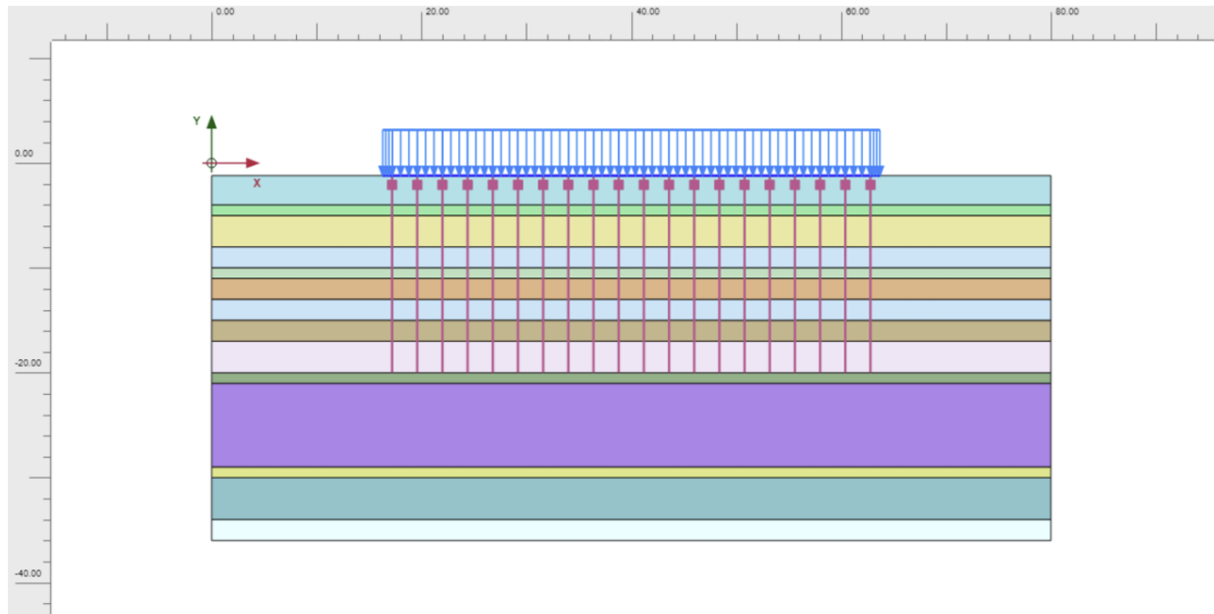


Figure 3. Piled-raft model and construction stages in Geotechnical Finite Element Method

Three foundation arrangements were considered. The first was the existing system of 251 driven piles connected by pile caps. The other two were piled rafts containing 269 bored piles and 269 driven piles, respectively. Both piled-raft models used a raft area of approximately 1,468.08 m², a raft thickness of 1.00 m, piles 0.60 m in diameter and 20 m long, a spacing of 2.40 m, and an edge distance of about 0.90 m. An unpiled raft was included in the geotechnical finite element analysis to show how much of the settlement reduction was provided by the piles. The comparison covered pile capacity, maximum pile reaction, settlement, moment demand, lateral displacement, reinforcement, and cost. The principal geometric and foundation-system differences among the three alternatives are summarized in Table 1.

Table 1. Foundation configurations considered in the comparison

Alternative	Connecting system	Pile type	Number	Diameter (m)	Length (m)	Raft/pile-cap thickness (m)
Existing foundation	Pile cap	Driven pile	251	0.60	30	1.20
Piled raft A	Raft	Bored pile	269	0.60	20	1.00
Piled raft B	Raft	Driven pile	269	0.60	20	1.00

3. Results and Discussion

3.1. Superstructure Vertical Reactions

The vertical reaction transferred from the superstructure is 17,232.02 ton-force. In the original design, this load is supported by 251 driven piles, 0.60 m in diameter and 30 m long. The piled-raft options instead use 269 piles of the same diameter but only 20 m long. Thus, the revised arrangement increases the pile count while reducing each pile by 10 m and allowing the raft to participate in load transfer. Structural finite element method gives a maximum single-pile reaction of 133.79 tons for D + L and 163.92 tons when earthquake effects are included.

The three-dimensional structural model and the pile layout within the raft are shown in Figures 4 and 5.

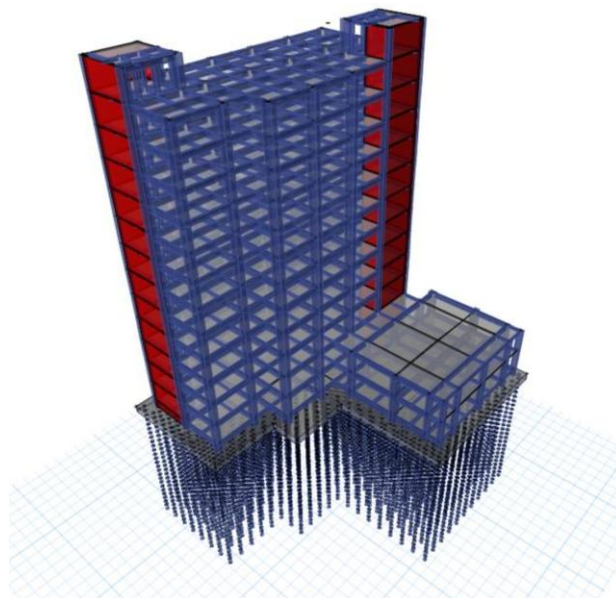


Figure 4. Three-dimensional structural and piled-raft model in Structural finite element method

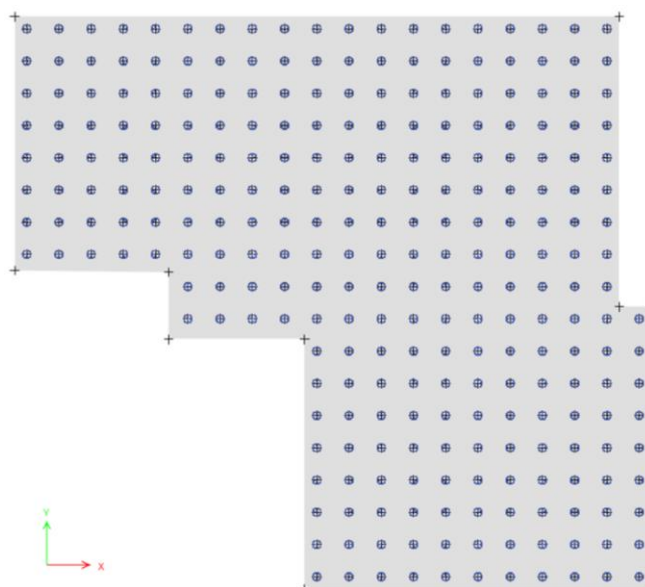


Figure 5. Pile layout in the piled-raft model.

3.2. Axial Bearing Capacity of Piles

At a diameter of 0.60 m and a length of 20 m, the calculated allowable capacity is 173.87 tons for a bored pile and 189.48 tons for a driven pile. The driven pile is therefore about 9.0% higher. This difference mainly reflects the shaft-resistance assumptions: driving tends to compact the surrounding soil, whereas drilling may reduce lateral stress near the bore. The governing reaction of 163.92 tons is below both allowable values. The structural section checks also give higher capacities than the applied reaction, namely about 223.76 tons for the bored pile and 243.20 tons for the driven pile.

Table 2. Comparison of pile axial bearing capacities

Pile type	Diameter (m)	Length (m)	Q_u (tons)	Allowable Q (tons)
Bored pile	0.60	20	521.61	173.87
Driven pile	0.60	20	568.44	189.48

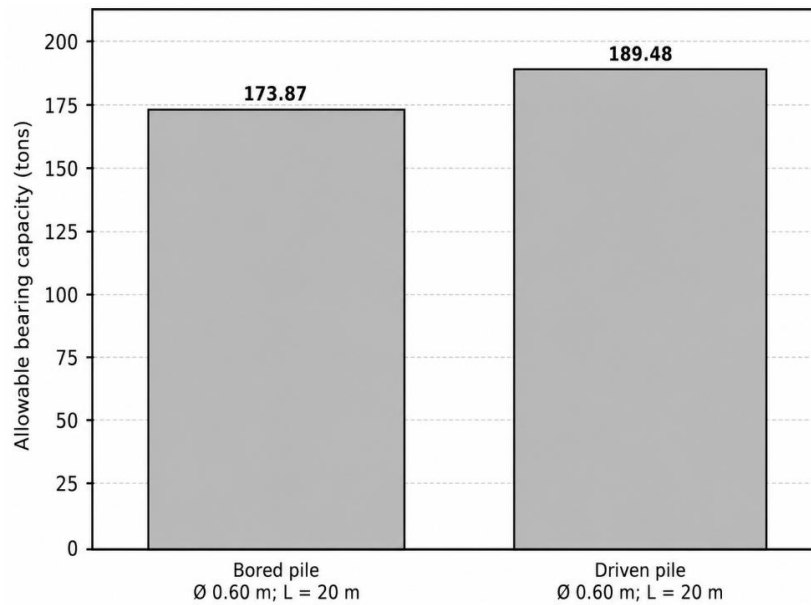


Figure 6. Comparison of allowable capacities of bored and driven piles.

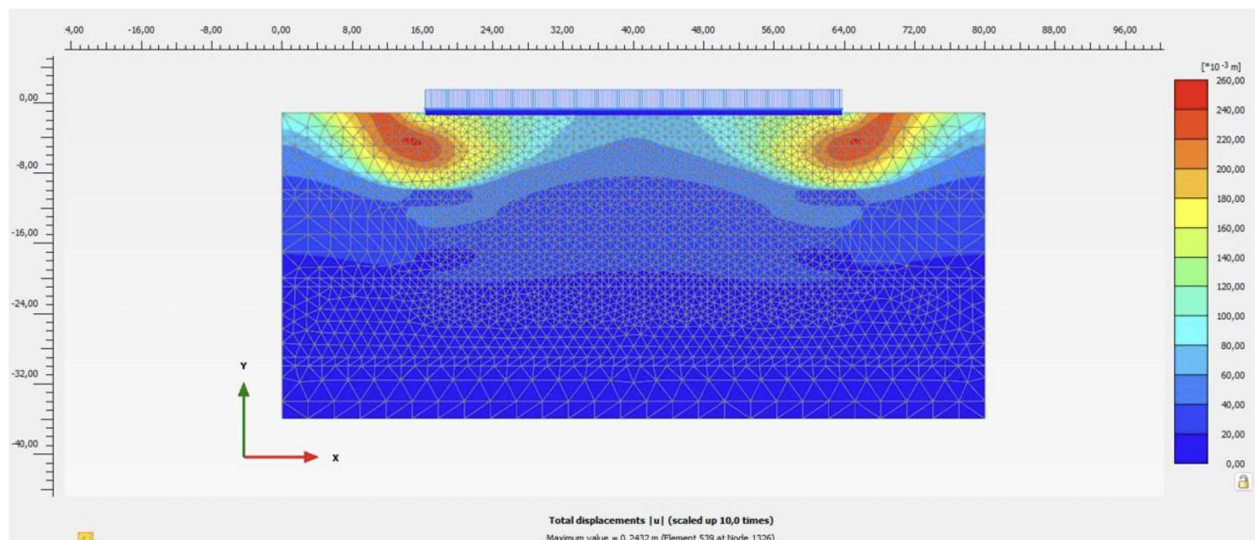
3.3. Settlement Response

The influence of the piles is most clearly seen in the settlement results. In Geotechnical Finite Element method, the raft without piles settles by 243.2 mm, which is greater than the adopted limit of 162 mm. With bored piles, the maximum settlement falls to 37.5 mm; with driven piles, it falls slightly further to 36.7 mm. These values represent reductions of about 84.6% and 84.9%, respectively, relative to the unpiled raft. Structural Finite Element gives a smaller maximum point settlement of 12.69 mm, but both modelling approaches place the piled-raft alternatives below the limit used in the original design. The maximum settlement values from the structural and geotechnical models are summarized in Table 3.

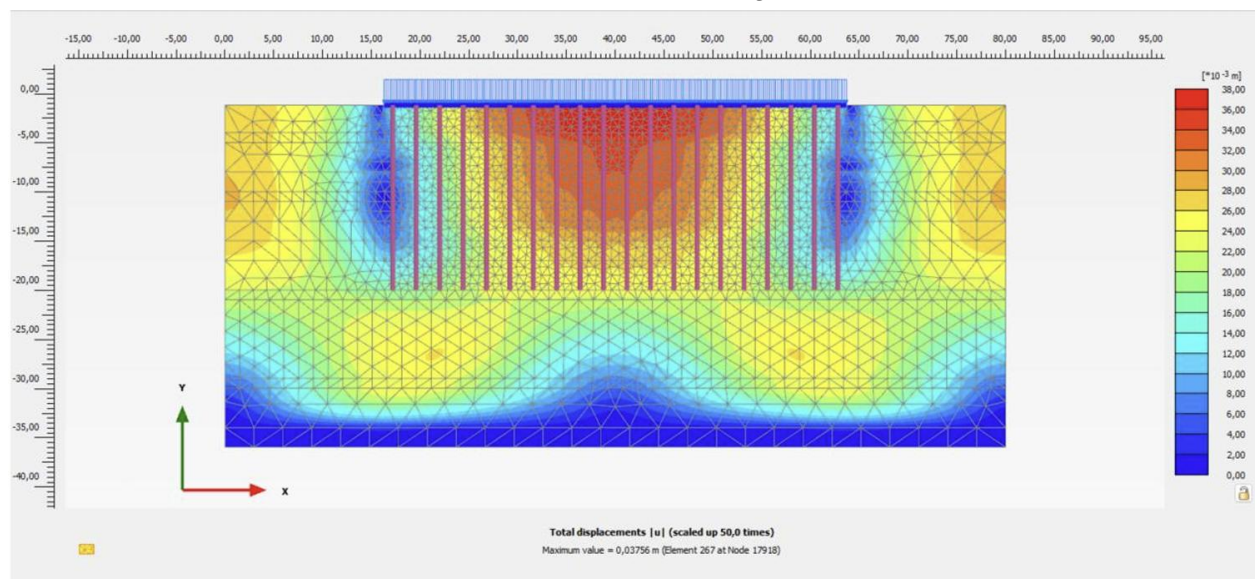
Table 3. Summary of maximum settlement

Foundation system	Structure Finite Element (mm)	Geotechnical Finite Element (mm)	Status
Piled raft + bored piles	12.69	37.5	Satisfies
Piled raft + driven piles	12.69	36.7	Satisfies
Unpiled raft	—	243.2	Does not satisfy

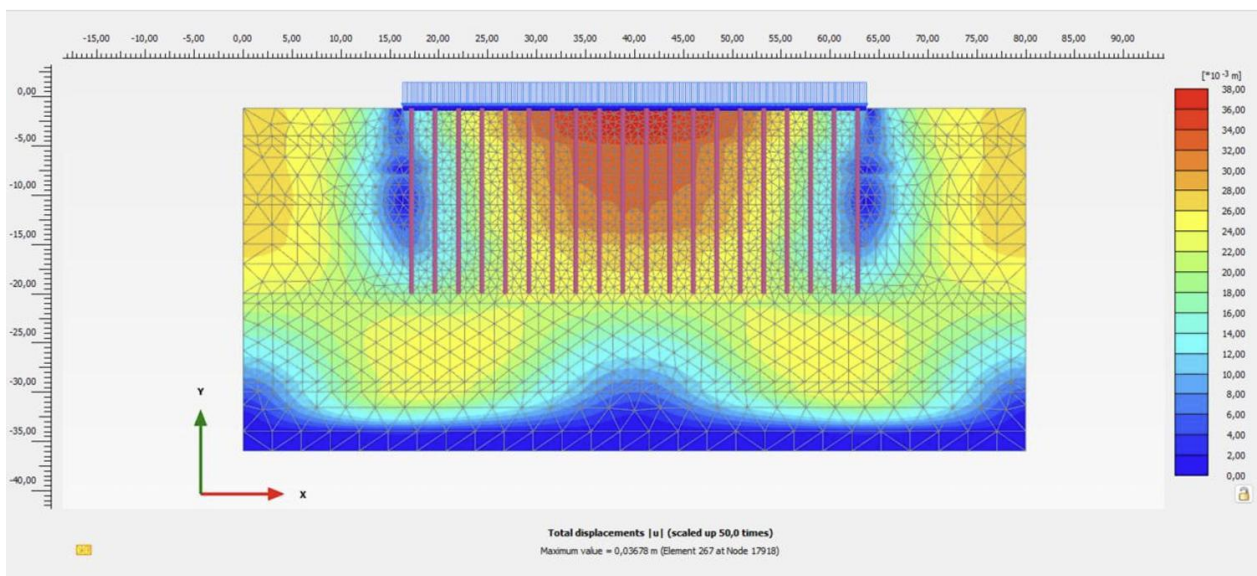
Figure 7 helps explain the numerical results. For the raft without piles, the settlement zone spreads across a broader part of the soil mass and reaches a value that is not acceptable under the adopted criterion. Once piles are introduced, the zone becomes more confined, and the peak settlement drops sharply. The contours for the bored-pile and driven-pile rafts are broadly similar because the foundation geometry is the same; the small difference in magnitude comes from the interaction and capacity parameters assigned to each pile type.



a. Maximum Value is 24.32 cm



b. Maximum Value is 3.756 cm



c. Maximum Value is 3.678 cm

Figure 7. Geotechnical Finite Element settlement contours: (a) unpiled raft, (b) piled raft with bored piles, and (c) piled raft with driven piles.

3.4. Bending-Moment Response of Foundation Elements

The maximum bored-pile moment from finite element is 91.01 kN.m, while the driven-pile value is 89.58 kN.m. Both are comfortably below the corresponding section capacities of 431.5 kN.m and 323.4 kN.m. For the raft, the maximum finite element moment is 514.99 kN.m, compared with a calculated flexural capacity of 5,930.38 kN.m. geotechnical finite element method reports characteristic moment values of 432.1 for the raft, 212.7 for the bored piles, and 249.8 for the driven piles. These outputs are useful for reading the response pattern of the plane-strain model, but they should not be compared directly with structural finite element values until they have been normalized to an equivalent width.

The numerical differences are expected because the two programs describe the soil-foundation system in different ways. structure finite element represents the ground through discrete springs attached to structural elements, whereas finite element method treats the soil as a continuous deformable medium. In this study, the programs are therefore used for different but complementary purposes, structure finite element provides section forces for structural checks, while geotechnical finite element is used to examine soil deformation and the interaction between the ground, raft, and piles.

Table 4. Maximum moments and capacities of foundation elements

Element	Structural Finite Element M (kN·m)	Capacity (kN·m)	Geotechnical	Status
			Finite Element 2D	
Raft	514.99	5,930.38	432.1	OK
Bored pile	91.01	431.5	212.7	OK
Driven pile	89.58	323.4	249.8	OK

Note: the design status is based on the structural finite element moment-to-capacity comparison. The Geotechnical Finite Element Method values indicate model response and require conversion to an equivalent width before direct structural comparison.

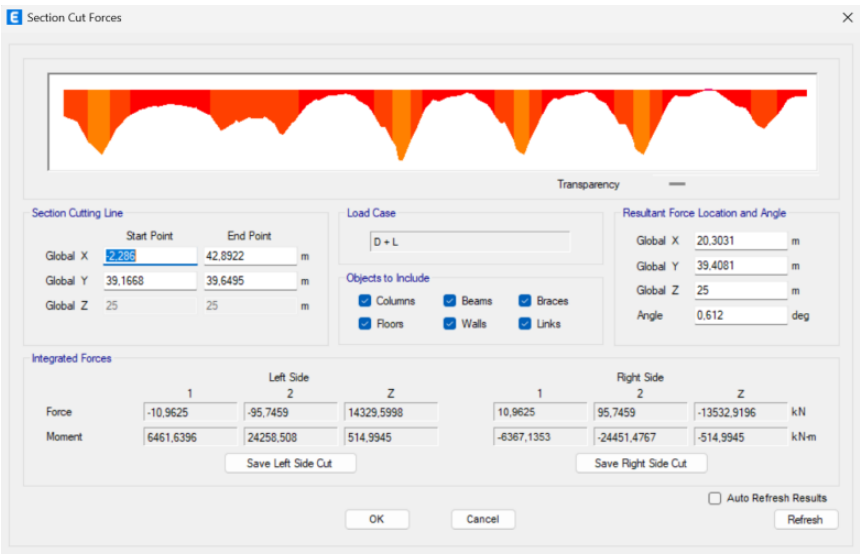


Figure 8. Raft-moment output from the structural finite element model.

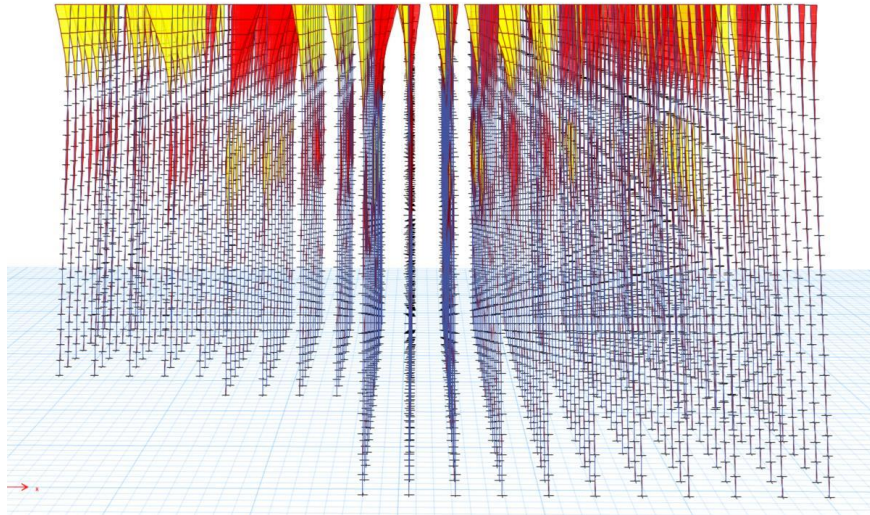


Figure 9. Bending-moment distribution in the bored piles from the structural finite element model.

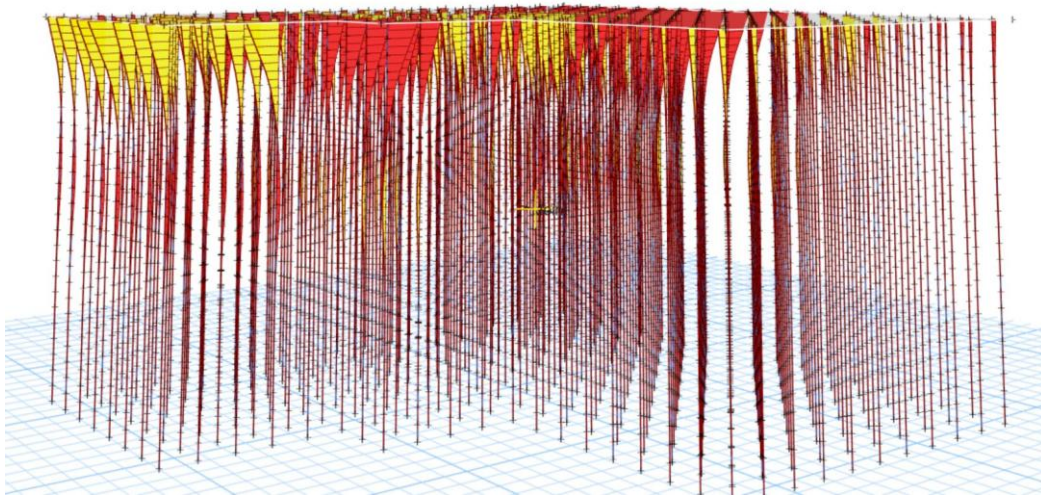


Figure 10. Bending-moment distribution in the driven piles from the structural finite element model.

3.5. Lateral Displacement under Service Conditions

The structural finite element model gives maximum lateral movements of 0.162 mm in the X direction and 0.037 mm in the Y direction. These are small relative to the 12 mm limit adopted from the project reference. For the service combination considered, the raft and pile group therefore provide substantial lateral stiffness. This result should still be viewed as a global model check; a detailed lateral pile assessment would normally use p-y curves or a fully three-dimensional soil model.

Table 5. Lateral displacement of the piled-raft system under service conditions

Condition	U _x max (mm)	U _y max (mm)
Piled raft - service condition	0.162	0.037

3.6. Reinforcement Design of Foundation Elements

The raft uses concrete with $f_c = 40$ MPa and reinforcing steel with $f_y = 420$ MPa. The design provides D25 bars at 125 mm spacing at both faces and in both principal directions, based on the calculated moments and minimum reinforcement requirements. D19 shear reinforcement at 500 mm spacing is also included. Punching shear was checked around the columns and pile heads so that the critical perimeters could be assessed against the capacity of the concrete and the reinforcement provided. The global-to-section verification adopted here is also consistent with evaluations of educational buildings in which software-derived actions are checked against section-capacity envelopes [31].

Each bored pile is reinforced with 15D22 longitudinal bars, giving a reinforcement ratio of approximately 2.05%, and D13 spiral reinforcement at 250 mm spacing. The general construction sequence begins with site clearing, setting out, and surveying, followed by drilling or driving, installation of reinforcement where required, pile concreting, excavation, lean concrete, raft formwork and reinforcement, and finally the mass-concrete pour. The main quality concerns differ between the two alternatives. Bored piles require careful control of slurry, bore-base cleanliness, and concrete continuity, while driven piles require close control of vibration, noise, alignment, and final pile position.

3.7. Material-Cost Comparison

Within the cost items included in the report, the bored-pile raft is estimated at IDR 9,843,782,522, the driven-pile raft at IDR 7,788,079,525, and the existing pile-cap foundation at IDR 8,419,460,191. On this basis, the driven-pile raft is about 7.50% cheaper than the existing system and 20.88% cheaper than the bored-pile raft. The bored-pile option, by contrast, is about 16.92% more expensive than the existing foundation. These figures are based on the quantities and unit rates used in the final-project report. They should not be read as whole-life project costs because indirect costs, programme effects, disruption, and construction risk were outside the calculation scope. Although this study is limited to direct foundation costs, recent Indonesian civil-engineering initiatives also show that material selection and resource recovery can influence the broader sustainability value of infrastructure solutions [29].

Table 6. Comparison of estimated foundation-work costs

Foundation alternative	Estimated cost (IDR)	Comparison with pile-cap system
Piled raft + bored piles	9,843,782,522	+16.92%
Piled raft + driven piles	7,788,079,525	-7.50%
Existing pile-cap foundation	8,419,460,191	Reference

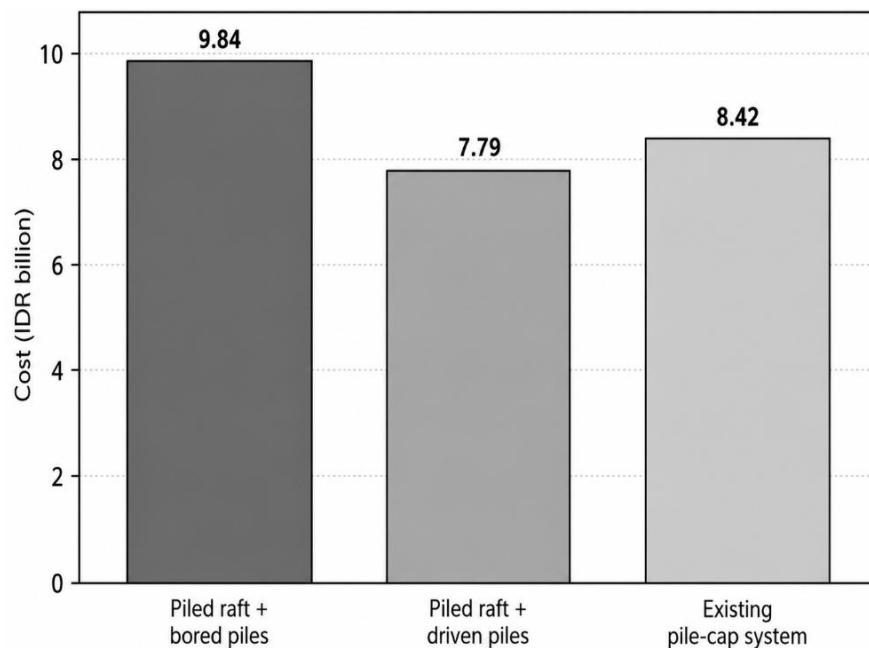


Figure 11. Comparison of estimated material costs for the three foundation alternatives.

3.8. Comparison of Piled Raft and Conventional Deep Foundation

The settlement comparison confirms that, in this case, the piles are acting mainly as settlement reducers and stiffness elements. Without piles, the raft settles by 243.2 mm; with either pile type, the calculated value is below 40 mm. This behaviour is consistent with the settlement-reducer concept described by Randolph [2]. It is worth noting, however, that the revised system is not more efficient because it uses fewer piles - the number rises from 251 to 269. Its advantage comes from reducing the pile length from 30 m to 20 m and allowing the raft to carry part of the load.

Both Structural and Geotechnical Finite Element do not give the same settlement, but this difference is understandable rather than contradictory. Structural Finite Element calculates movement through springs attached to

the pile nodes, while Geotechnical Finite Element develops deformation throughout the soil continuum. The structural value of 12.69 mm is useful for checking the consistency of the structural model. The geotechnical values of about 37 mm provide a fuller picture of the deformation pattern in the ground. Despite the difference in magnitude, both models lead to the same practical conclusion: the two piled-raft options remain within the adopted settlement criterion.

The driven-pile raft has the stronger numerical result in terms of allowable capacity and estimated cost. That does not make it the automatic choice for a university campus. Bored piles generate less vibration and may be preferable near occupied or sensitive buildings. Selection should therefore also account for site access, working space, the possibility of ground heave or damage during driving, the quality control needed for bored-pile concreting, and the programme for integrity and load testing. Independent field verification should therefore remain part of the final decision; recent infrastructure-assessment work has demonstrated the value of combining visual inspection with non-destructive testing to complement analytical results [30].

The 2.40 m spacing, equivalent to 4D, satisfies the criteria used in the present models. It should not, however, be described as an optimum spacing beyond this configuration. Previous parametric studies show that pile spacing, length, number, and raft thickness affect one another and jointly control load sharing and deformation [4], [5], [25]. A more complete optimization would compare several three-dimensional arrangements and include staged construction and consolidation.

For the alternatives examined, the driven-pile raft combines the highest calculated axial capacity, the smallest settlement, acceptable moments, and the lowest estimated cost. This conclusion is specific to the adopted arrangement of 269 piles, each 20 m long. It does not demonstrate that a driven-pile raft will always outperform a conventional deep foundation. In particular, the existing pile-cap system was not rebuilt in geotechnical finite element method with the same boundary conditions, so a fully equivalent settlement comparison is not available. For clarity, the principal technical and cost differences among the three alternatives are summarized in Table 7.

Table 7. Consolidated comparison of the existing deep foundation and piled-raft alternatives

Comparison parameter	Existing pile-cap foundation	Piled raft + bored piles	Piled raft + driven piles
Connecting system	Pile caps	1.00 m raft	1.00 m raft
Pile type	Driven	Bored	Driven
Pile number	251	269	269
Pile diameter (m)	0.60	0.60	0.60
Pile length (m)	30	20	20
Allowable pile capacity (tons)	Existing design basis	173.87	189.48
2D geotechnical FEM settlement (mm)	Not evaluated under identical FEM conditions	37.5	36.7
Estimated direct foundation cost (IDR billion)	8.42	9.84	7.79
Cost relative to existing system	Reference	+16.92%	-7.50%
Main construction consideration	Driving vibration and pile-cap works	Lower vibration; bore-quality control required	Driving vibration/noise; higher calculated axial capacity

Comparison parameter	Existing pile-cap foundation	Piled raft + bored piles	Piled raft + driven piles
Interpretation in this study	Baseline system	Technically acceptable but highest direct cost	Most favourable numerical capacity-settlement-cost balance

4. Conclusions

For the 13-storey academic building considered, the analysis indicates that a piled raft with 269 piles of 20 m length can satisfy the adopted capacity and deformation criteria, despite replacing an original system of 251 driven piles that are 30 m long. The allowable capacities are 173.87 tons for the bored pile and 189.48 tons for the driven pile, both above the maximum calculated pile reaction of 163.92 tons. Settlement is 12.69 mm in structural finite element model and 37.5 mm and 36.7 mm in the two geotechnical finite element piled-raft models, compared with 243.2 mm for the raft without piles. The calculated raft and pile moments also remain below their section capacities. Within the reported cost scope, the driven-pile raft is the least expensive option at about IDR 7.79 billion, or 7.50% below the existing pile-cap foundation, while the bored-pile raft costs about IDR 9.84 billion. The driven-pile raft is therefore the most favourable alternative in the numerical comparison.

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