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THE EFFECT OF BOREHOLE COLLAPSE ON THE STABILITY OF GROUP PILE FOUNDATIONS

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ABSTRACT

The stability and load-bearing performance of pile group foundations are critical in infrastructure development, particularly in deep foundations such as bored piles. This study investigates the impact of borehole wall collapse on the load-bearing capacity and overall performance of a pile group foundation in North Jakarta, Indonesia. The borehole collapse occurred between depths of 25.2 m and 31.8 m, resulting in shortened pile lengths and reduced axial capacity. Subsurface investigations identified poorly graded sand (SP) within the collapsed zone, which contributed to borehole instability. Finite Element Method (FEM) analysis was performed to compare three scenarios: the original 48-meter design, the existing 22-meter condition post-collapse, and a redesigned pile group with additional piles. The 22-meter design failed to meet the serviceability safety factor of 2.5, and several piles exceeded allowable limits. In contrast, the redesigned group fulfilled both bearing and displacement criteria, demonstrating improved structural performance. The findings emphasize the importance of design adaptation in response to construction anomalies to ensure the long-term safety and efficiency of deep foundations.

keywords : *Borehole Collapse, Pile Group Foundations, Bearing Capacity, FEM Analysis*

1. PRELIMINARY

The expansion of toll road infrastructure in Indonesia is a strategic initiative to improve national connectivity and foster economic growth. As part of this development, the implementation of reliable and structurally sound foundation systems is critical to ensuring the long-term performance and safety of various infrastructures. All structures, whether above or below ground, rely on foundations to transfer loads to the underlying soil strata. A foundation must be designed to distribute structural loads without exceeding the soil's bearing capacity to prevent excessive settlement or potential failure.

The foundation is the structure of the lower part of the building that is directly related to the ground or part of the building that is located below the ground surface which has the function of carrying the load of other parts of the building above it(Dwi et al., 2020). If the soil strength is exceeded, excessive settlement or collapse of the soil will occur.(Agustino & Suhendra, 2020)

In deep foundation systems such as bored piles, construction anomalies may lead to serious geotechnical problems. This study focuses on a case where borehole wall collapse occurred between depths of 25.2 m and 31.8 m, leading to a significant deviation from the intended pile depth. According to Chudyk et al., (2021) borehole instability is commonly observed in claystone, siltstone, shale, and weakly cemented sandstone layers, especially when disturbed by tectonic processes and drilling fluid infiltration. Such conditions weaken the osmotic cohesion of the rock matrix, resulting in increased fissuring and swelling pressure (Al Hanif & Al Islami, 2024).

At the affected site, subsurface investigation revealed the presence of poorly graded sand (SP) between 20 and 30 meters, which is known to exhibit weak intergranular friction and low confinement characteristics. The borehole collapse not only reduced the achievable depth but also caused partial soil cave-ins at unpoured pile locations. This directly impacted the axial and lateral load capacity of the piles and compromised the stability of the pile group system.

Pile bearing capacity is a crucial parameter in geotechnical engineering, as it ensures the structural performance under both vertical and horizontal loads (Oktarian & Rosyad, 2024). The reduction in depth significantly decreased the effective load transfer, necessitating a redesign involving additional piles and possible changes in pile configuration within the pile cap. As a structural component, the pile cap plays a vital role in load distribution and lateral restraint, especially in group pile arrangements. This study aims to evaluate the effect of borehole collapse on the stability and efficiency of the pile group using finite element method (FEM) analysis, and to propose a suitable redesign to restore structural integrity under the given soil conditions.

2. LITERATURE REVIEW

Soil Classification

The Unified Soil Classification System (USCS) divides soils into two main groups based on grain size distribution and plasticity, namely coarse-grained soils (gravel and sand) and fine-grained soils (silt and clay). Code symbols such as G (gravel), S (sand), M (silt), and C (clay) are used along with additional notations such as W (well graded), P (poorly graded), L (low plasticity), and H (high plasticity) to further describe soil characteristics. In the context of this research, SP (Poorly Graded Sand) classified soils are of primary concern due to their unstable, less cohesive and uniform grain structure that is prone to borehole wall collapse during drilling. This instability has a direct impact on not achieving the planned depth of the bored pile foundation, thus affecting the overall bearing capacity of the foundation (Braja M.Das, 2015) . Pooly granded soil is classified as poorly graded and fairly clean. It is said to be poorly graded because most of the sizes are uniformly graded with various sizes of split gradations (Gouw & Tjie-Liong, 2000).

Table 1. Unified soil classification

Criteria for assigning group symbols and group names using laboratory tests[a]				Soil classification: Group symbol	Soil classification: Group name[b]
Coarse-grained soils More than 50% retained on No. 200 sieve	Gravels More than 50% of coarse fraction retained on No. 4 sieve	Clean Gravels Less than 5% fines[c]	$C_u \geq 4$ and $1 \leq C_c \leq 3$[e]	GW	Well-graded gravel[f]
			$C_u < 4$ and/or $1 > C_c > 3$[e]	GP	Poorly graded gravel[f]
		Gravels with Fines More than 12% fines[c]	Fines classify as ML or MH	GM	Silty gravel[f,g,h]
			Fines classify as CL or CH	GC	Clayey gravel[f,g,h]
	Sands 50% or more of coarse fraction passes No. 4 sieve	Clean Sands Less than 5% fines[d]	$C_u \geq 6$ and $1 \leq C_c \leq 3$[e]	SW	Well-graded sand[i]
			$C_u < 6$ and/or $1 > C_c > 3$[e]	SP	Poorly graded sand[i]
		Sand with Fines More than 12% fines[d]	Fines classify as ML or MH	SM	Silty sand[g,h,i]
			Fines classify as CL or CH	SC	Clayey sand[g,h,i]
Fine-grained soils 50% or more passes the No. 200 sieve	Silts and Clays Liquid limit less than 50	Inorganic	PI > 7 and plots on or above "A" line[j]	CL	Lean clay[k,l,m]
			PI < 4 or plots below "A" line[j]	ML	Silt[k,l,m]
		Organic	$\frac{\text{Liquid limit—oven dried}}{\text{Liquid limit—not dried}} < 0.75$	OL	Organic clay[k,l,m,n] / Organic silt[k,l,m,o]
	Silts and Clays Liquid limit 50 or more	Inorganic	PI plots on or above "A" line	CH	Fat clay[k,l,m]
			PI plots below "A" line	MH	Elastic silt[k,l,m]
		Organic	$\frac{\text{Liquid limit—oven dried}}{\text{Liquid limit—not dried}} < 0.75$	OH	Organic clay[k,l,m,p] / Organic silt[k,l,m,q]
Highly organic soils	Primarily organic matter, dark in color, and organic odor			PT	Peat

Bearing Capacity

The ability of a foundation to withstand the maximum pressure or load permitted by the soil conditions in which the foundation is installed or placed is referred to as bearing capacity (Riadi & Dharmawansyah, 2023).

Geotechnical investigations, including sondir (CPT), core drilling (SPT) and laboratory testing, are used to determine the physical parameters and characteristics of the soil. A foundation must be designed to distribute structural loads without exceeding the soil's bearing capacity to prevent excessive settlement or potential failure (Pratama et al., 2024).

The calculation of bearing capacity is associated with a planning process that must consider the condition of the pile in the soil layer, whether the pile is retained at its tip (point bearing capacity) or retained by the attachment between the pile and the soil (friction bearing capacity). The bearing capacity of a single pile is obtained from the sum of the blanket bearing capacity and the tip bearing capacity calculated using an empirical correlation based on NSPT.

$$Q_{us} = Q_p + Q_s \text{ (kN)} \quad (1)$$
$$= A_p q_p + A_s q_s$$

where

Q_u = Ultimate bearing capacity of the pile (kN)

Q_p = End bearing capacity of the pile (kN)

Q_s = Skin friction capacity of the pile (kN)

In static analysis, design loads for shallow foundations and pile foundations are usually calculated by dividing the ultimate soil bearing capacity by a factor of safety (SNI, Persyaratan Perancangan Geoteknik, 2017).

$$Qall = Qu/SF \quad (2)$$

where

Q_{all} = allowable bearing capacity of piles (kN)

Q_u = ultimate bearing capacity (kN)

SF = safety factor

Group pile foundation

Group pile foundation is a type of foundation with a combined form of foundation poles that are joined at the top by a structure called a pile cap (Fernández, 2015). In Figure (a), it can be seen that the pressure bulbs on a single pile due to the load Q above the single pile, then it can be seen in Figure (b) when the pile is placed very close together, the stress on the pile is overlapping so that the soil between the poles is very stressed, group pile foundation is one type of foundation with a combined form of foundation poles combined at the top by a structure called a pile cap. Therefore, it is necessary to plan a good distance between poles so that failures in group pile foundations do not occur. It can be seen in figure (c) When the poles are placed far apart, it is also inefficient, this will make the costs required to treat the pile cap even greater, besides that the distance between the poles that will be too large will not provide more bearing capacity for the poles (Muni Budhu, 2010).

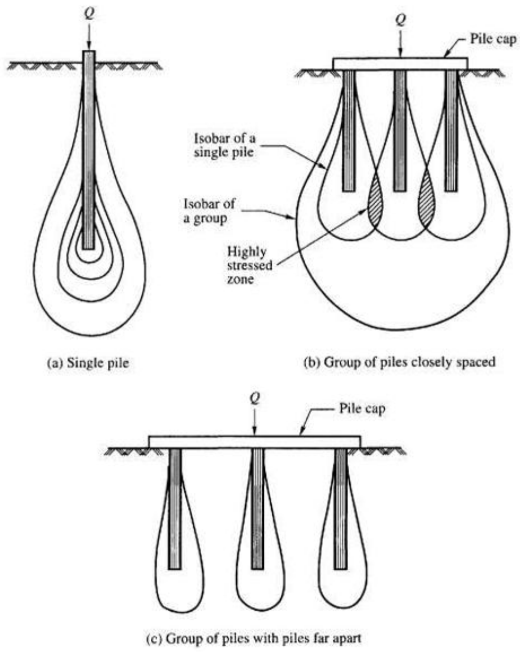

Figure 1. Pressure Bulbs in Pile Foundations

The ultimate capacity of the pile group by showing the pile efficiency factor is expressed by the following formula:

$$Q_{ug} = n \; x \; Q_{us} \; x \; \eta \qquad (3)$$

where

Q_{ug} = ultimate group capacity

Pile Group Efficiency

Group pile efficiency is the ratio between the bearing capacity of the group pole and the bearing capacity of a single pole. The value of group pole efficiency can be influenced by several factors, such as the distance between poles, the number, diameter, and length of a pole. Calculation of group pile efficiency with the Converse-Labarre method, as follows:

$$\eta = 1 - \left[\frac{(n-1)m + (m-1)n}{90mn}\right] tan^{-1}\frac{D}{d} \qquad (4)$$

where

n = number of columns

m = number of rows

D = diameter (m)

d = pile spacing (m)

3. METHODS

Location and Time

The study was carried out in North Jakarta, in the Special Capital Region of Jakarta (DKI Jakarta), Indonesia.

Data Collection

1. Borlog (soil types, physical properties, N-SPT)
2. Soil stratigraphy diagram
3. Construction chronology data
4. Construction drawings (pile type, dimensions, and materials)
5. Load data

Modeling Using a Program

The modeling in this study was carried out using finite element geotechnical software to simulate the actual condition of the existing foundation that does not match the planned depth, and redesign the foundation to meet the required stability and bearing capacity criteria. Modeling is done in three stages, namely:

1. Modeling of existing foundation conditions in accordance with the depth of the plan.
2. Modeling of existing foundation condition with new depth.
3. Remodeling (redesign) with the latest depth and number of piles to meet the safety factor.

4. RESULTS AND DISCUSSION

Soil Profile

Single Pile Bearing Capacity

Table 2. Calculation of single pile bearing capacity

Depth (m)	Soil	Type	N-SPT	Qs (kN)	Qb (kN)	Qu (kN)
0						
1.00	tanah		1			
2.00	tanah		0			
4.00	very soft	clay	0			
6.00	very soft	clay	1	12	92	104
10.15	very soft	clay	2	37	183	220
12.15	medium	clay	11	311	1007	1318
14.15	medium	sand	27	921	4807	5728
16.15	very dense	sand	50	2052	8902	10954
18.15	dense	sand	30	2730	5341	8071
20.15	very dense	sand	50	3245	8902	12147
22.15	dense	sand	34	4014	6053	10067
24.15	very dense	sand	53	5212	9436	14648
26.15	dense	sand	40	6116	7122	13238
28.15	dense	sand	41	7043	7300	14343
30.15	dense	sand	32	7767	5697	13464
32.15	stiff	clay	19	8239	1740	9979
34.00	very dense	sand	50	9370	8902	18271
36.15	very dense	sand	54	10590	9614	20204
38.15	very dense	sand	62	11992	11038	23030
40.15	stiff	clay	18	12440	1648	14088
42.15	very dense	sand	50	13570	8902	22472
44.15	hard	clay	32	14366	2930	17296
46.15	medium	sand	28	14999	4985	19984
48.15	hard	sand	29	15720	2655	18375
50.15	hard	clay	27	16392	2472	18864
52.15	hard	clay	47	17560	4303	21864
54.15	medium	sand	29	18216	5163	23379
56.15	medium	sand	32	18939	5697	24637
58.15	hard	clay	26	19586	2381	21967
60.15	stiff	clay	23	20158	2106	22264
62.15	stiff	clay	22	20705	2014	22720

A single pile bearing capacity analysis was carried out to determine the ultimate and permit capacity of each pile based on soil data from the field investigation. The calculations include end bearing capacity and shaft friction capacity, which are obtained from soil parameters and N-SPT test results.

From the results of the table above, the tip of the pole for the existing condition is at a depth of 52.15 m (pile length + pilecap thickness), the ultimate bearing capacity of the pole is 21864 kN. Then for the new pole plan the tip of the pole is at a depth of 22.15 m (pile length + pilecap thickness), the ultimate bearing capacity of the pole is 10067 kN. The pile allowable bearing capacity (Qallowable) is influenced by the safety factor according to the design criteria.

Analysis of Existing Group Pile Depth 48 meters

Pile Efficiency Calculation

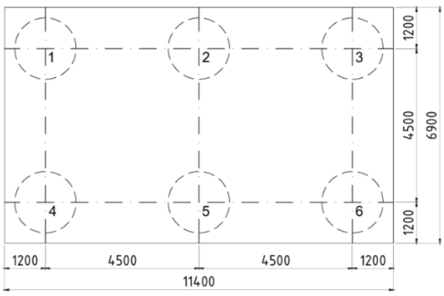

Figure 2. Pile group configuration

Table 3. Converse-Labarre Efficiency Calculation

Converse – Laberre			
m	3	d (m)	4.5
n	2	θ	21.80
D (m)	1.8	Efficiency	0.717

n pile : 6

Qu single : 21864 kN

Q group : Qu single*η*n
: 94109.2 kN

To evaluate the safety of the pile group under serviceability conditions, the calculated ultimate bearing capacity of the group (Qu group) must be compared to the applied working load. This comparison is conducted by dividing the group capacity by the service load to obtain the factor of safety. According to geotechnical design standards, the minimum required safety factor for serviceability limit state (SLS) is 2.5. The calculation is shown as follows:

$$\frac{Qu\ group}{P} \geq 2.5$$

$$\frac{94109.2}{21822} \geq 2.5$$

$$4.31 \geq 2.5$$

Displacement Results at Pile Head – 48 m Depth

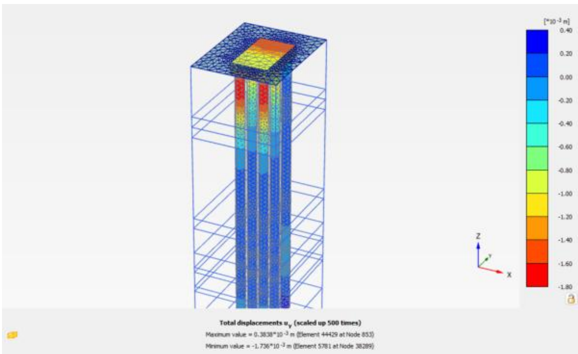

Figure 3. FEM-based displacement results at 48-meter pile head.

Table 4. Displacement results at pile head for 48-meter

Comb	Case	Displacement			control	
		ux	uy	Izin		
		mm	mm	mm		
SLS1	Min Fx	-0.5282	-1.736	25	OK	OK
SLS1	Min Fy	-0.9821	1.633	25	OK	OK
SLS4	Min Fz	0.9658	-2.377	25	OK	OK
SLS1	Min Mx	0.1486	1.584	25	OK	OK
SLS1	Min My	-0.5336	1.629	25	OK	OK
SLS1	Min Mz	-0.9821	-1.633	25	OK	OK

Analysis of Existing Group Pile Depth 22 meters

Pile Efficiency Calculation

Based on the efficiency calculation using the converse-labarre method, the ultimate bearing capacity value for the group is obtained as follows:

Q group : Qu single*η*n

: 43331.6 kN

$$\frac{Qu\ group}{P} \geq 2.5$$

$$\frac{43331.6}{21822} \geq 2.5$$

1.99 ≥ 2.5 NOT OK

Based on the calculation results, the comparison value between the ultimate bearing capacity of the pile group and the working load is 1.99. This value is less than the minimum limit of 2.5 required for the Serviceability Limit State (SLS) condition, so it is declared NOT OK. This means that the capacity of the pile group is insufficient to withstand the planned load at a depth of 22 meters, and design improvements such as increasing the number of piles, increasing the pile diameter, or changing the foundation configuration are required to meet the stability requirements.

Load distribution on each pile in a pile group

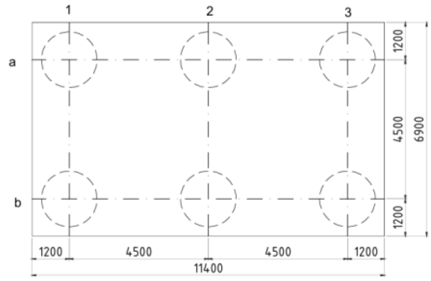

Figure 4. Pile group configurations

Table 5. Load Distribution Calculation for Each Pile in the Pile Group

Number pile	P	Mx	My	Pt	Q single	Control
	kN	kNm	kNm	kN	kN	
1a	21822	-13601	-5012	2908.0	4027	OK
1b	21822	-13601	-5012	4922.9	4027	NOT OK
2a	21822	-13601	-5012	2629.5	4027	OK
2b	21822	-13601	-5012	4644.5	4027	NOT OK
3a	21822	-13601	-5012	2351.1	4027	OK
3b	21822	-13601	-5012	4366.0	4027	NOT OK

In table 5 the load distribution on each pile within the group. Column Pt represents the total load received by each pile, and Q single is the ultimate capacity of a single pile (4027 kN). Some piles (1b, 2b, and 3b) exceed this capacity and are marked as "NOT OK", indicating they are unable to safely support the applied load. This suggests an uneven load distribution in the pile group.

Displacement Results at Pile Head – 22 m Depth

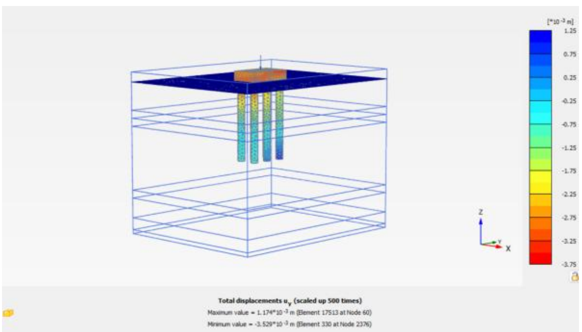

Figure 5. FEM-based displacement results at 22-meter pile head.

The displacement results at a pile depth of 22 meters show that all values remain below the allowable limit of 25 mm. Although several combinations produced relatively higher displacements compared to the 48 m design, the structure still meets the serviceability criteria.

Table 6. Displacement results at pile head for 22-meter

Comb	Load	Displacement			control	
		ux	uy	Izin		
		mm	mm	mm		
SLS1	Min Fx	-2.835	-3.529	25	OK	OK
SLS1	Min Fy	-4.131	-3.238	25	OK	OK
SLS4	Min Fz	-0.9817	-5.038	25	OK	OK
SLS1	Min Mx	1.673	2.802	25	OK	OK
SLS1	Min My	-2.524	2.912	25	OK	OK
SLS1	Min Mz	-4.131	-3.238	25	OK	OK

Analysis of New Pile Group Design

Pile Efficiency Calculation

Based on the efficiency calculation using the converse-labarre method, the ultimate bearing capacity value for the group is obtained as follows:

Q group : Qu single*η*n
: 79347.4 kN

$$\frac{Qu\ group}{P} \geq 2.5$$

$$\frac{79347.4}{21822} \geq 2.5$$

$$3.64 \geq 2.5 \quad \text{OK}$$

Load distribution on each pile in a pile group

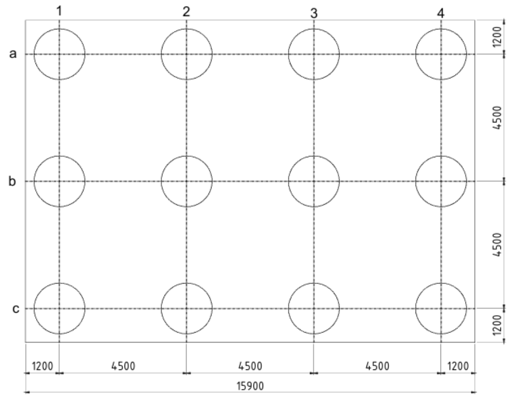

Figure 6. Pile group configurations

Table 7. Load Distribution Calculation for Each Pile in the Pile Group

Number pile	P	Mx	My	Pt	Q single	Control
	kN	kNm	kNm	kN	kN	
1a	21822	-13601	-5012	1174.3	4027	OK
1b	21822	-13601	-5012	1929.9	4027	OK
1c	21822	-13601	-5012	2685.5	4027	OK
2a	21822	-13601	-5012	1100.0	4027	OK
2b	21822	-13601	-5012	1855.6	4027	OK
2c	21822	-13601	-5012	2611.2	4027	OK
3a	21822	-13601	-5012	1025.8	4027	OK
3b	21822	-13601	-5012	1781.4	4027	OK
3c	21822	-13601	-5012	2537.0	4027	OK
4a	21822	-13601	-5012	951.5	4027	OK
4b	21822	-13601	-5012	1707.1	4027	OK
4c	21822	-13601	-5012	2462.7	4027	OK

Table 7 results show that all piles are within the allowable capacity, as indicated by the "OK" status in the control column. This indicates that the load is evenly distributed across the group and the pile group design is structurally safe under the given loading conditions.

Displacement Results of the New Pile Group Design

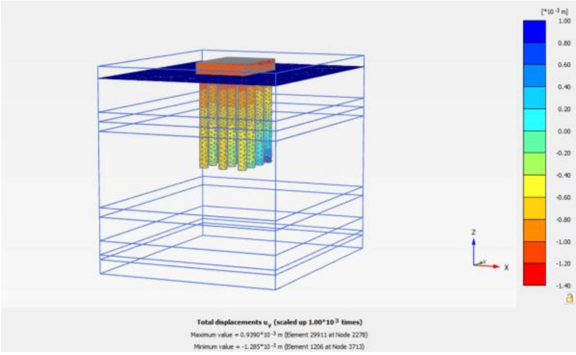

Figure 7. FEM-based displacement results at the pile head for the new 22-meter pile group design.

Table 8. Displacement results at pile head for 22-meter depth in the analysis of the new pile group design.

Comb	Load	Displacement			control	
		ux	uy	Izin		
		mm	mm	mm		
SLS1	Min Fx	-0.9747	-1.285	25	OK	OK
SLS1	Min Fy	-1.577	-1.249	25	OK	OK
SLS4	Min Fz	0.481	-2.068	25	OK	OK
SLS1	Min Mx	-0.6715	0.9593	25	OK	OK
SLS1	Min My	-0.9693	0.9669	25	OK	OK
SLS1	Min Mz	-1.577	-1.249	25	OK	OK

The displacement results for the new pile group design under various load combinations are shown in the table above. All calculated displacements in the x and y directions are well below the allowable limit of 25 mm, indicating that the proposed design satisfies serviceability requirements and provides adequate stability under the applied loads.

5. CONCLUSION

From the results of the above discussion, it can be concluded as follows:

a. This study investigates the impact of borehole wall collapse on the performance and safety of pile group foundations using FEM analysis. The collapse, occurring at depths between 25.2 m and 31.8 m, resulted in a significant reduction of pile length from the originally planned 48 meters to 22 meters. Analytical results showed that this reduction caused a substantial decrease in the axial load-bearing capacity of the piles, leading to an insufficient factor of safety (1.99 < 2.5) for the serviceability limit state. Several piles in the group also exceeded their individual capacity, indicating uneven and unsafe load distribution.

b. However, lateral displacements at the pile heads remained within the allowable limits across all load combinations, suggesting that the lateral stability of the foundation was not significantly affected. Thus, the impact of the borehole collapse primarily compromised axial bearing performance, while lateral behavior remained structurally safe.

c. To restore structural integrity, a redesigned pile group with an increased number of piles and optimized configuration was proposed. The new design successfully fulfilled all serviceability and safety requirements, demonstrating adequate axial and lateral stability under applied loads.

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