

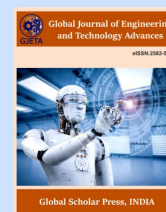


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(RESEARCH ARTICLE)



RISK MANAGEMENT ANALYSIS OF BORED PILE FOUNDATION WORK USING THE FAILURE MODE AND EFFECT ANALYSIS METHOD IN GOMBEL PRESERVATION PROJECT

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ABSTRACT

Gombel Lama Road in Semarang City is a strategic road connecting Upper Semarang and Lower Semarang which has a hilly topography and landslide-prone land, so that the bored pile foundation work in its preservation project has a high implementation risk. This study aims to identify the types of risks at each stage of bored pile work, calculate the Risk Priority Number (RPN) value for each failure mode, and formulate recommendations for priority risk control. This applied research uses a mixed-method approach that combines field observations, interviews, and document reviews with expert judgment questionnaires from 5 experts, analyzed using the Failure Mode and Effects Analysis (FMEA) method. The validity of the instrument is tested with the Content Validity Index (I-CVI and S-CVI), its reliability is tested with the Percentage of Agreement (PA) and the Intraclass Correlation Coefficient (ICC), while risk priority is determined through the RPN value ($S \times O \times D$) which is further analyzed with a Pareto diagram. The research results identified 40 valid failure modes in the preparation, drilling, reinforcement installation, casting, and concrete curing stages, with a total RPN of 826, an average of 21, a lowest value of 2, and a highest of 216. The highest risk failure mode is FM-23 related to concrete volume overbreak due to collapse of the borehole wall (RPN 216), followed by FM-04 related to static load of the drilling tool on the hole slope (RPN 84), and FM-30 related to water seepage affecting concrete hardening (RPN 60). Pareto analysis identified 16 of the 40 failure modes as priority groups (vital few) which contributed approximately 80% of the total risk. Risk control needs to be focused on reducing the occurrence and detection values through four main areas, namely the stability of the borehole wall and casing, the quality of bentonite and the casting process, the readiness of drilling equipment, and strengthening work and environmental safety, with actions following the control hierarchy of engineering, administrative, and personal protective equipment, accompanied by regular monitoring.

Keywords: Pareto diagram; Failure Mode and Effects Analysis (FMEA); risk management; bored pile foundation; Risk Priority Number (RPN)

1 INTRODUCTION

The national transportation system relies on road infrastructure to connect regions and drive economic growth. The Indonesian government prioritizes the construction and maintenance of more than 47,000 kilometers of road networks, although road infrastructure projects in areas with challenging geotechnical characteristics, such as mountainous areas and landslide-prone slopes, still face numerous complex challenges (Ministry of Public Works and Public Housing, 2026). In Semarang, the Old Gombel Road Preservation Project is a strategic initiative for a 1.27-kilometer road section connecting Upper and Lower Semarang on a steep, unstable terrain. A rehabilitation budget of IDR 17.5 billion has been allocated, with bored pile foundations up to 28 meters deep being used alongside other retaining structures to strengthen the landslide-prone slope. The complex geological conditions make the implementation of bored pile foundations in this project fraught with hazards, necessitating a comprehensive risk management evaluation to mitigate structural collapse, project delays, and workplace accidents.

Each technical stage of bored pile work, from drilling and reinforcement to concrete casting to pile integrity assessment, carries its own risk of failure. Previous research has shown that caving (collapse of the borehole wall), mud contamination in concrete, and drilling failure due to unexpected ground conditions are the most common problems encountered during the drilling and concrete pouring stages, while work accidents in bored pile work are generally caused by a combination of human error, improper work procedures, and faulty equipment. Failure Mode and Effects Analysis (FMEA) is a risk assessment technique that assesses the severity, frequency, and detectability of each failure mode, then integrates them into a Risk Priority Number (RPN) to determine mitigation priorities. The application of FMEA to various construction projects, from drainage channels and high-rise buildings to bridges, has proven to be able to systematically rank risks and assist in mitigation decision-making.

However, in-depth research on the application of FMEA to road preservation projects in hilly areas with complex geotechnical challenges such as Gombel Lama is still limited compared to research on high-rise building projects with relatively stable soil conditions. This gap is the basis of this research, which aims to (1) identify the types of risks at each stage of bored pile work, (2) analyze the RPN value for each failure mode using FMEA, and (3) formulate recommendations for priority risk control and mitigation strategies in the implementation of bored pile work on the Gombel Lama Preservation Project, so that it is expected to provide scientific contributions in the form of applicable mitigation recommendations for managing deep foundation risks in areas with landslide-prone topography.

2 LITERATURE REVIEW

Construction risk management is a systematic process for identifying, analyzing, and controlling risks that could potentially affect the quality, time, cost, and safety of a project. Bored pile foundations are a type of deep foundation made by drilling the ground to the planned depth, followed by installing a reinforcing frame and casting concrete using a tremie pipe, which is commonly used on slopes prone to landslides because it can also function as a retaining structure. The main stages include equipment mobilization, drilling, casing installation, reinforcement assembly, casting, and casing removal, with different potential failures at each stage, such as caving of the hole walls, drilling mud contamination, and concrete quality defects.

Failure Mode and Effects Analysis (FMEA) is a proactive risk analysis method that lists all potential failure modes, assesses their causes and effects, and then calculates the Risk Priority Number using the equation $RPN = S \times O \times D$, where S (severity), O (occurrence), and D (detection) are each rated on a scale of 1–10 (Stamatis, 2003). The higher the RPN value of a failure mode, the greater the priority of handling. The sorted RPN values are then analyzed using a Pareto diagram based on the 80/20 principle, which separates the priority risk group (vital few) that contributes approximately 80% of the total RPN from the minor risk group (trivial many), so that mitigation efforts can be focused efficiently.

Because the assessment of S, O, and D is subjective and relies on expert judgment, the validity of the instrument needs to be tested through the Content Validity Index (CVI), which consists of Item-level CVI (I-CVI) and Scale-level CVI (S-CVI/Ave), with a threshold of I-CVI = 1.00 and S-CVI/Ave $\geq$ 0.90 on a panel of five experts (Yusoff, 2019). Inter-rater consistency is further tested through the Percentage of Agreement (PA $\geq$ 80%) which measures pairwise agreement with a tolerance of one point (Belur et al., 2021), as well as the Intraclass Correlation Coefficient (ICC $\geq$ 0.75) two-way mixed effects model with absolute agreement type to capture the gradation of agreement in numerical data (Koo & Li, 2016). The application of the quantitative FMEA framework based on RPN and Pareto diagrams to bored pile, building, and bridge projects (Apriyan et al., 2017; Choiruddin & Dani, 2023; Mahu et al., 2025; Pratama & Nugraheni, 2025; Yusriliya & Nugraheni, 2024) is the main methodological reference of this study, while also confirming that the combination of quantitative assessment and qualitative interpretation provides a more comprehensive picture of construction risks.

3 RESEARCH METHODS

This research is an applied research with a mixed-method approach with a descriptive-analytical case study design on the Gombel Lama Road Preservation Project, Semarang City, which was carried out by PT Multi Cone with a contract value of ± Rp17,500,000,000.00 for 180 calendar days. The bored pile studied has a diameter of 800 mm and a depth of 28 meters at 21 points. The quantitative dimension is reflected in the calculation of RPN ($S \times O \times D$) which is processed using descriptive statistics and visualized with a Pareto diagram, while the qualitative dimension is present through the identification of failure modes based on field observations, interviews, and project document reviews.

The research respondents were 5 (five) experts selected purposively with the following criteria: minimum 3 years of experience in the field of road/deep foundation construction, possessing relevant expertise certification (SKA/SKT), having a minimum of a Bachelor's degree in Civil Engineering/Geotechnics/Construction K3, and having been directly involved or supervised bored pile work. The number of five experts was chosen because it produced 10 pairs of assessment combinations ($C_5^2 = 10$) that were adequate for the Percentage of Agreement test as well as representative for risk assessment consensus. Primary data collection was conducted through structured field observations and closed questionnaires scaled 1–10 for the parameters of Severity, Occurrence, and Detection for each failure mode, supplemented by in-depth interviews to explore contexts not covered by the questionnaire; secondary data were obtained from contract documents, project reports, soil investigation data, and related technical standards (SNI, PP SMK3, RSN13).

The initial failure mode list was compiled from literature studies and preliminary observations, then tested for content validity through I-CVI and S-CVI/Ave before being used as a risk assessment instrument; items with I-CVI < 1.00 were revised/reassessed or eliminated. The instrument's reliability was further tested through PA (threshold $\geq 80\%$, tolerance for one point difference in score) and ICC(A,k) two-way mixed effects model (threshold ≥ 0.75). After the instrument was declared valid and reliable, the FMEA questionnaire was distributed to the five experts to obtain consensus scores of S, O, and D (the average of the five assessors), which were then multiplied to form the RPN value for each failure mode. All RPN values were sorted from highest to lowest, their contribution percentage and cumulative percentage were calculated, and then visualized in a Pareto diagram with an 80% threshold to separate the priority risk group (vital few) from the minor risk group (trivial many). The final stage is the formulation of risk control recommendations focused on priority groups, following the engineering, administrative, and personal protective equipment control hierarchy.

4 RESULTS

4.1 Failure Mode Identification and Instrument Testing

Through literature review and preliminary observations, potential failure modes were identified across the preparation/mobilization, drilling, reinforcement installation, casting, and concrete maintenance stages of bored pile work. After being tested for content validity by a panel of five experts, 40 items obtained an I-CVI = 1.00 and were declared valid, while items with an I-CVI below the threshold were eliminated because they were deemed less relevant to the Gombel Lama field context. The overall S-CVI/Ave value was 1.00, far exceeding the 0.90 threshold, thus the instrument was declared to have good content validity. Reliability testing showed that the majority of items obtained PA above 80% for all three parameters (S, O, D), indicating uniformity of perception among experts, while the ICC(A,k) values for the Severity, Occurrence, and Detection parameters were 0.938; 0.888; and 0.896, respectively — all of which were in the good to very good category and exceeded the minimum threshold of 0.75 (Table 1). By fulfilling the validity and reliability criteria, the risk assessment data from the five experts can be used for further FMEA analysis.

Table 1: Summary of Instrument Validity and Reliability Test Results

Instrument Test	Results	Threshold	Status
I-CVI (40 items)	1.00	≥ 1.00	Valid
S-CVI/Ave	1.00	≥ 0.90	Valid (good)
Percentage of Agreement (PA)	> 80% on the majority of items	$\geq 80\%$	Reliable
ICC(A,k) – Severity	0.938	≥ 0.75	Reliable (very good)
ICC(A,k) – Occurrence	0.888	≥ 0.75	Reliable (good)
ICC(A,k) – Detection	0.896	≥ 0.75	Reliable (good)

Source: Author's analysis (2026)

4.2 FMEA Risk Assessment Results

The consensus values of Severity, Occurrence, and Detection were obtained from the average assessment of the five experts, then multiplied into the RPN value for 40 failure modes. The calculation results show that the RPN value ranges from 2 to 216 with a total of 826 and an average of 21 (Table 2). The average Severity (4) which is higher than Occurrence and Detection (each 2) indicates that the failure mode in bored pile work generally occurs rarely but has a relatively large impact when it occurs, while the small standard deviation of the three parameters strengthens the consistency of the assessment between experts, in line with the results of the reliability test in subsection 4.1.

Table 2: Descriptive Statistics of Severity, Occurrence, Detection, and RPN Assessments

Parameter	Average	Standard Deviation	Minimum	Maximum
Severity (S)	4	2	1	7
Occurrence (O)	2	1	1	7
Detection (D)	2	1	1	7
RPN (S×O×D)	21	36	2	216

Source: Author's analysis (2026)

4.3 Pareto Chart Ranking and Analysis

The RPN values of the 40 failure modes were sorted from largest to smallest to determine the priority of handling. Based on the Pareto 80/20 principle, 16 of the 40 failure modes (40%) were classified as priority group (vital few) with cumulative percentage of RPN $\leq 80\%$, while the remaining 24 failure modes (trivial many) contributed much smaller risk contributions (Table 3 and Figure 1). The failure mode with the highest RPN was FM-23 related to concrete volume overbreak due to borehole wall collapse (RPN 216; contribution 26.15%), far above the other modes, followed by FM-04 related to static load of drilling tool at the top of the hole slope (RPN 84) and FM-30 related to water seepage affecting concrete hardening (RPN 60). These three modes together contributed 43.6% of the total risk, confirming that the greatest risk of bored pile work on this project is concentrated in the drilling and casting stages.

Table 3: Ranking of 16 Priority Failure Modes (Vital Few) Based on RPN Value

Rk	FM Code	Failure Mode (Summary)	RPN	% Contribution	Cumulative %
1	FM-23	Overbreak of concrete volume due to collapse of borehole walls	216	26.15%	26.2%
2	FM-04	Static load of drill rig at the top of slope/borehole	84	10.17%	36.3%
3	FM-30	Water seepage affects the concrete hardening process	60	7.26%	43.6%
4	FM-34	The pile head elevation drops after the casing is removed	40	4.84%	48.4%
5	FM-05	Deep ground pressure (± 28 m) triggered a landslide in the hole wall.	40	4.84%	53.3%
6	FM-03	The drill tool has not been thoroughly inspected before being put into operation.	32	3.87%	57.1%
7	FM-14	Long rebars are difficult to lift on sloping sites.	24	2.91%	60.0%
8	FM-20	Tremmel pipe connection leak	20	2.42%	62.5%
9	FM-12	Bottom hole walls are prone to collapse (casing is not full)	20	2.42%	64.9%
10	FM-07	Casing is not completely upright/centered	20	2.42%	67.3%
11	FM-24	Tremmel pipe stuck due to casting too fast	18	2.18%	69.5%
12	FM-11	Drilling mud remains piled up on the narrow road	18	2.18%	71.7%
13	FM-22	Sudden rain reduces the quality of the concrete mix	16	1.94%	73.6%
14	FM-10	Rain makes the ground soft and easy to slide into holes	16	1.94%	75.5%
15	FM-40	Drilling residue mud pollutes drainage/lower slopes	15	1.82%	77.4%

16	FM-35	The safe radius of the drill/crane has not been stated in writing.	15	1.82%	79.2%
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Source: Author's analysis (2026)

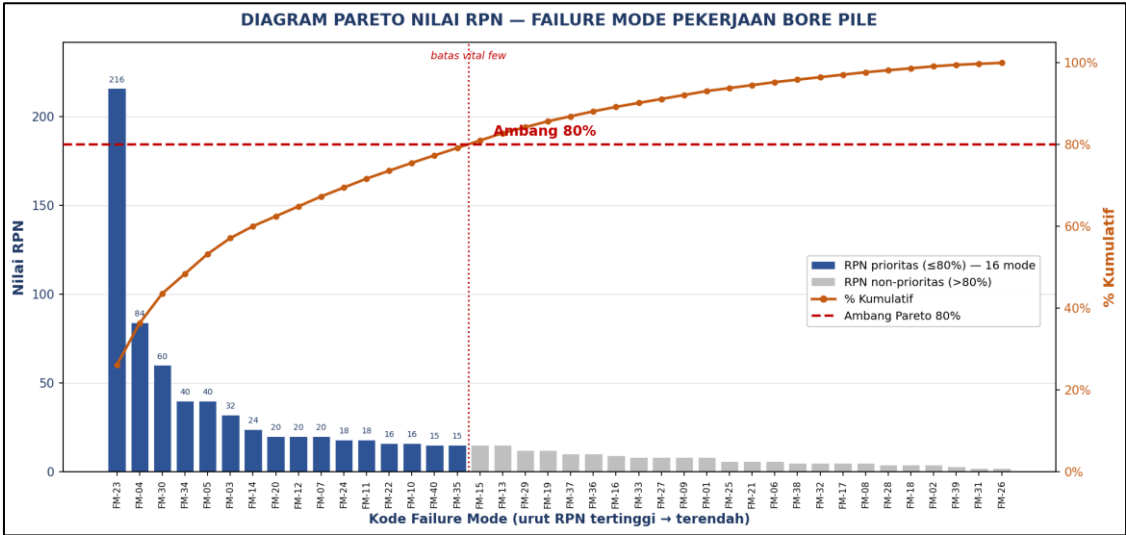


Figure 1: Pareto Diagram of RPN Values of Bored Pile Work Failure Modes

5 DISCUSSION

The highest RPN value in FM-23 (overbreak) is formed from a combination of Severity = 6, Occurrence = 6, and Detection = 6, with the Occurrence and Detection parameters far above the overall average (Occurrence 2.30 and Detection 1.93), which means that overbreak not only has the potential to occur frequently but is also difficult to detect early, so that the risk accumulates to be the most critical among all failure modes. This finding confirms that the highest risk of bored pile work at the research location stems from the interaction between geotechnical conditions, especially the instability of the borehole wall due to a depth of ± 28 meters, with the drilling and concrete casting process. This result is in line with the research of Yusriliya and Nugraheni (2024) who highlighted unstable soil conditions and weak supervision as the dominant sources of danger in bored pile foundations, but differs from Mahu et al. (2025) who placed the risk of workers being hit by heavy equipment during the preparation stage as the highest risk because it focused on work safety aspects. This difference shows that FMEA risk priorities are highly dependent on the technical and geotechnical characteristics of each project, so that the quantification of RPN in this study complements the qualitative findings of previous studies by determining the overbreak mode measurably as the most critical risk in the context of landslide-prone slopes.

Risk control recommendations are directed at 16 priority failure modes by suppressing the Occurrence and/or Detection values, because Severity is generally inherent to the failure character and is difficult to change. The highest priority is given to the three modes with the largest RPN: overbreak control (FM-23) is focused on maintaining the level and specific gravity of bentonite mud, installing additional casing in loose soil zones, and monitoring the actual concrete volume against the theoretical volume for early detection; the risk of static load on the drill rig (FM-04) is controlled through the provision of a reinforced work platform, analysis of soil bearing capacity and slope stability, and the implementation of a safe distance (setback distance) for the rig from the edge of the hole; while the risk of water seepage (FM-30) is controlled through dewatering, the use of concrete with anti-washout and retarder additives, and pile head protection during the curing period. The other 13 priority modes are grouped into four treatment areas: the stability of the hole wall and casing, the quality of bentonite and the casting process, the readiness of the drilling equipment through thorough inspections, and work-environmental safety through the confirmation of the safe radius, drilling mud management, and traffic management. All actions are structured according to the engineering, administrative, and personal protective equipment control hierarchy, accompanied by regular monitoring and re-evaluation of the RPN so that mitigation effectiveness can be measured, while the 24 non-priority modes remain controlled through supervision and routine work procedures with a more proportional allocation of resources.

6 CONCLUSION AND SUGGESTIONS

This study identified 40 valid failure modes in the implementation of bored pile foundation work for the Old Gombel Road Preservation Project, spread across the preparation, drilling, reinforcement installation, casting, and concrete curing stages, with the drilling and casting stages as the largest risk contributors. The total RPN value was 826 with an

average of 21, the lowest value of 2, and the highest 216, indicating a highly variable risk level between failure modes; the highest risk was found in FM-23 (overbreak, RPN 216), followed by FM-04 (drill rig static load, RPN 84) and FM-30 (water seepage, RPN 60). Pareto analysis identified 16 of the 40 failure modes (40%) as priority groups (vital few) contributing approximately 80% of the total risk, with control recommendations focused on the stability of the borehole wall and casing, the quality of bentonite and the casting process, the readiness of drilling equipment, and strengthening work-environmental safety, following the control hierarchy of engineering, administrative, and personal protective equipment.

Contractors and field supervisors are advised to prioritize the implementation of control measures on 16 priority failure modes, especially the three modes with the highest RPN (FM-23, FM-04, FM-30), accompanied by strengthening inspections, implementing SOPs, and consistent K3 supervision. Periodic monitoring and re-evaluation of RPN values after mitigation is implemented are necessary to measure the effectiveness of controls and adjust handling if the risk has not decreased as expected. Further research is recommended to develop analysis at different locations, objects, or implementation methods, combine FMEA with other methods such as Fault Tree Analysis, and expand the number of expert respondents to strengthen the generalizability of the risk analysis results.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Disclosure of conflict of interest

No Conflict of interest to be disclosed

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