Occupational Safety Risk Assessment of Drinking Water Supply System Construction in Complex Topography Using Fuzzy-FMEA and Fault Tree Analysis

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Salma Fidela Tiantara*
Department of Civil Engineering
Universitas Brawijaya
Malang, Indonesia
salmatiantarad@student.ub.ac.id

Agus Suharyanto
Department of Civil Engineering
Universitas Brawijaya
Malang, Indonesia
agus_ceub@yahoo.com

Yatnanta Padma Devia
Department of Civil Engineering
Universitas Brawijaya
Malang, Indonesia
yatnanta@ub.ac.id

Abstract*— The construction of Drinking Water Supply System in areas with complex topography faces heightened occupational health and safety (OHS) risks due to steep slopes, limited access, and unstable soil, yet existing OHS risk studies in Indonesian construction have concentrated on urban and high-rise projects, leaving the risk profile of rural water infrastructure in complex terrain largely unexamined. This study identifies, assesses, and prioritizes OHS risks in Drinking Water Suply System (Sistem Penyediaan Air Minum or SPAM) construction, using a hybrid Fuzzy Failure Mode and Effect Analysis (Fuzzy-FMEA) and Fault Tree Analysis (FTA) approach, and traces the root causes of priority risks to formulate mitigation strategies suited to the site topography. Conducted on projects in three villages in Tulungagung Regency, Indonesia, with 43 respondents selected through purposive sampling, the study identified 37 potential risks through field observation, interviews, and literature review, and assessed each on the Severity, Occurrence, and Detection parameters using a Mamdani fuzzy inference system. Four risks were classified as High Risk, led by heavy material handling failure and workers falling into the river during river-crossing work, with human and management factors dominating the root causes identified through FTA, and environmental factors (steep slopes and river proximity) contributing more prominently than in previous high-rise building studies. These findings indicate that complex topography reshapes OHS risk priorities away from the structural and height related risks typical of urban construction toward terrain driven hazards, and the study contributes a topography sensitive risk assessment framework together with targeted technical, human, management, and environmental control strategies for rural water infrastructure projects in similarly challenging terrain.

Keywords*—Complex Topography, Drinking Water Supply System, Fault Tree Analysis, Fuzzy FMEA, Occupational Health and Safety.

I. INTRODUCTION

The construction industry is consistently recognized as one of the sectors with the highest occupational accident rates in the world. In the United States, the construction sector recorded 1,069 worker fatalities in 2022, the highest among all industry sectors [1]. Globally, the International Labour Organization reported nearly 3 million deaths due to occupational accidents and work related diseases in 2019 [2]. The Employment Social Security Administration, known as BPJS Ketenagakerjaan in Indonesia, has recorded a continuing increase in occupational accident cases over recent years, and the construction sector remains one of the highest risk industries because of the complex, dynamic, and hazardous nature of its work [3], [4]. Access to clean water is part of Sustainable Development Goal (SDG) 6, which targets the availability and sustainable management of water and sanitation for all by 2030 [6]. Nevertheless, the global gap in water supply infrastructure remains large, and rural areas as well as regions with topographic challenges remain underserved [5]. In Tulungagung Regency, of 278,905 households, only 76,866 are served by piped clean water, leaving 202,039 households unserved a gap exacerbated by topography that varies from lowlands to mountains, with slope gradients reaching 40–60% and annual rainfall of 2,000–3,000 mm. These conditions expose the workers who build and develop Drinking Water Suply System (Sistem Penyediaan Air Minum or SPAM) to high Occupational Health snd Safety (OHS) risks, including accidents during excavation in unstable soil, falls from height during pipe installation on steep slopes, being struck by construction materials, and health risks from working in difficult terrain.

In Indonesia, construction OHS management is regulated primarily through a Ministerial Regulation [41], which mandates systematic hazard identification and risk assessment across all construction projects, complemented by sectoral regulations such as Peraturan Pemerintah No. 50 Tahun 2012 on the OHS Management System and Peraturan Menteri Kesehatan No. 5 Tahun 2018 on Occupational Health. Although these regulations mandate risk assessment in general terms, no specific quantitative methodology is prescribed, so practitioners must select techniques appropriate to each project's characteristics a gap this study seeks to address for the specific case of rural water infrastructure in complex topography.

Risk based OHS management in construction has developed rapidly over the past two decades, shifting from checklist based hazard identification toward multi criteria quantitative risk assessment frameworks [19]. Conventional FMEA, originally developed for manufacturing reliability engineering, computes the Risk Priority Number (RPN) as the product of Severity, Occurrence, and Detection scores rated on an ordinal scale [7]. Although computationally simple and widely adopted in construction safety studies [20], [21], this multiplicative approach has been criticized for assuming equal importance for the three criteria, for potentially producing identical RPN values from very different risk profiles, and for being highly sensitive to the discrete nature of ordinal rating scales [7]. To overcome these limitations, fuzzy set theory [8] has increasingly been integrated with FMEA to translate language based risk

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assessments such as “high,” “medium,” or “low” into continuous membership functions, thereby preserving the nuance of expert judgment while reducing the discretization artifacts of conventional rating scales [9], [10].

Fuzzy-FMEA has been applied in various construction contexts, including highway construction [22], building construction [36], and infrastructure projects more broadly [33], and has consistently shown better discrimination between risk scenarios than conventional RPN. As a complement to prioritization methods such as FMEA, FTA offers deductive top-down causal analysis capable of decomposing a failure event into its constituent basic events through Boolean logic gates [11], [12], a capability that pure prioritization methods such as FMEA or Analytic Hierarchy Process (AHP) weighted RPN do not possess [13]. Several studies therefore combine FMEA-based prioritization with FTA-based root cause analysis to obtain accountable risk rankings together with an applicable causal map for mitigation planning [22], [13].

In the Indonesian construction OHS literature specifically, previous FMEA and FTA based studies have been dominated by urban building construction contexts, including offices and high rise institutional buildings [13], [21], where dominant risk causes generally relate to work at height, structural formwork, and vertical material transport. In contrast, rural water infrastructure construction such as SPAM projects follows the natural contours of the terrain rather than a controlled building footprint, so workers are exposed to a qualitatively different risk profile shaped by slope stability, proximity to rivers, and dispersed linear work fronts. Related studies have also developed fuzzy-AHP approaches for water diversion projects in complex mountainous terrain [39], and have identified key risks in construction projects encompassing geographic and environmental factors [40]. Nonetheless, systematic OHS risk assessment of SPAM construction in complex topographic terrain has received relatively limited empirical attention, which constitutes the main motivation for this study.

This study aims to identify OHS risk factors at each stage of SPAM construction in areas with complex topography, to assess risk priorities using a hybrid Fuzzy-FMEA approach, and to trace the root causes of priority risks using FTA in order to formulate control strategies appropriate to the technical, human, management, and environmental characteristics of the project.

II. Research Method

A. Conceptual Framework

This study develops a risk analysis framework grounded in the specific characteristics of rural infrastructure construction on complex terrain, encompassing two main categories of risk sources: site operational conditions and construction methods [13]. Operational conditions include topography and slope gradient, soil and geotechnical characteristics, weather and rainfall intensity, proximity to rivers or other water bodies, and site accessibility. Construction methods include the selection of work methods appropriate to terrain constraints, the sequencing and coordination of work fronts, the suitability of equipment for sloping or confined areas, and productivity pressures arising from distant logistics. Together, these two categories determine occupational safety risk, project schedule performance, and ultimately the final project outcome forming the basis for risk identification, Fuzzy-FMEA prioritization, and mitigation strategy stages described in the following subsections.

B. Data Collection

The study was conducted on SPAM construction projects in three villages in Tulungagung Regency, East Java, Indonesia, specifically Kendal, Samar, and Sumberbendo villages selected for their complex topography, which includes steep slopes, karst formations, and proximity to rivers. Table 1 summarizes the topographic characteristics of each site. The scope of work covered intake construction, transmission and distribution pipe installation, water treatment plant installation, reservoir construction, road/river crossing work, and house connections.

TABLE I. Characteristics of the Three Study Areas

Study Location	Water Source	Topographic Character	Dominant Challenge
Kendal Village, Gondang District	Pump well	Gently rolling hills	Clay soil, slippery slopes
Samar Village, Pagerwojo District	Spring	Steep hills	High elevation, limited access
Sumberbendo Village, Pucanglaban District	River (pump)	Karst hills	Karst slopes, elevation changes

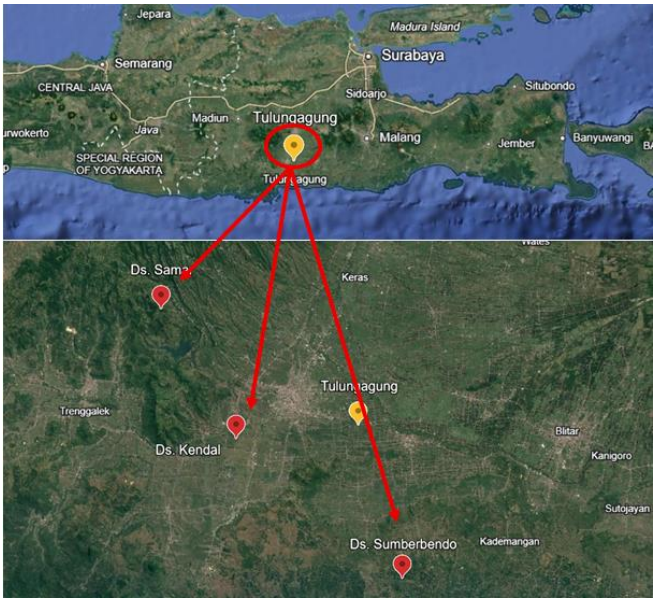


Fig. 1. Satellite imagery of the three SPAM construction villages.

The minimum sample size was first estimated using the Slovin formula as a threshold for adequacy given the finite population of N = 75 people directly engaged in the three SPAM projects and e = 10%, yielding a minimum of 43 respondents; Slovin's formula was used only to establish this minimum size, not to imply probability based random selection, since random sampling was not feasible across the three dispersed, topographically constrained project sites. Respondents meeting this minimum were subsequently selected through purposive sampling based on their direct, first hand involvement in the SPAM construction work at the time of data collection and their consequent ability to

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provide informed judgment on the Severity, Occurrence, and Detection of each risk scenario. Supervisory and expert respondents were additionally required to hold a formal oversight role (project owner representative, head of the infrastructure division, or a civil engineering academic with at least five years of relevant experience in construction or OHS) so that their judgments reflected managerial as well as field level perspectives. Table 2 summarizes the distribution of the 43 respondents across institutional categories and roles; the three respondents from the Community-Based Drinking Water Supply Management Group (KPSPAM/HIPPAM) were distributed evenly across the three villages (one per village), while the remaining categories were not tied to a single village because the consulting and government oversight roles spanned all three project sites. General work experience ranged from less than 5 years to more than 20 years across all respondent categories, as summarized in Table II; the three expert validators were additionally required to hold at least five years of experience specific to construction OHS. A separate, structured measure of years of OHS-specific field experience (as distinct from general construction work experience) was not collected for the field worker, consultant, and agency categories, which we note as a limitation of this study.

TABLE II. DISTRIBUTION OF RESPONDENTS

Respondent Category	N	Work Experience (years)	Description
Local Housing and Settlement Agency (Dinas Perkim)	3	5 – >20	Commitment-Making Officer (PPK), Head of Infrastructure/SPAM Section, and project supervision technical staff
Supervising/technical assistance consultant	3	5 – 20	Supervision consultants, each monitoring >1 village, familiar with field technical dynamics
Community-based drinking water supply management group (KPSPAM/HIPPAM)	3	<5 – 20	Evenly distributed across villages (1 person/village)
Field workers	34	<5 – >20	Foreman (3), head craftsman (3), pipe fitter (8), excavation worker (10), helper (7), site engineer (3)
TOTAL	43		

C. Risk Identification

OHS risk identification was carried out through field observation, respondent interviews, and literature review, then validated by the three expert respondents mentioned above. This process identified 37 potential risks distributed across six construction stages: site preparation, intake work, transmission work, water treatment plant (WTP) installation, reservoir work, and distribution/house connection work. Before data collection, the questionnaire instrument using a 1–5 ordinal rating scale for the Severity (S), Occurrence (O), and Detection (D) parameters was tested for validity using Pearson product moment correlation, with the criterion that the calculated r exceed the tabulated r ($n = 43$, $\alpha = 0.05$, r-table = 0.301), and tested for reliability using Cronbach's alpha with a minimum acceptable value of 0.70 [16]. All items were found valid and reliable, and all statistical procedures were performed using SPSS v.25.

D. Risk Assessment Analysis with Fuzzy-FMEA

Risk assessment was performed using a Mamdani fuzzy inference system implemented in the MATLAB Fuzzy Logic Toolbox. Each of the 37 risk scenarios was assessed by all 43 respondents on the S, O, and D parameters using the ordinal scales summarized in Tables 3–5, adapted from established FMEA rating conventions [7].

TABLE III. SEVERITY (S) RATING SCALE

Effect	Level / Impact	Value
Very High	Death, very large material loss	5
High	Severe injury; possible disability or loss of bodily function; large material loss	4
Medium	Moderate injury; lost workdays; requires medical treatment; substantial material loss	3
Low	Minor injury; moderate material loss	2
Very Low	Very minor injury; small material loss	1

TABLE IV. OCCURRENCE (O) RATING SCALE

Occurrence Level	Frequency	Value
Very high and almost unavoidable	1 in 3	5
High and frequent	1 in 20	4
Moderate and occasional	1 in 400	3
Low and rare	1 in 15,000	2
Very low and almost never	1 in 1,500,000	1

TABLE V. DETECTION (D) RATING SCALE

Detection	Detection Level	Value
Very Low	Controls almost cannot detect the failure	5
Low	Controls have very little ability to detect the failure	4
Medium	Controls can sometimes detect the failure, but not always	3
High	Controls have a high likelihood of detecting the failure	2
Almost Certain	Controls can detect the form and cause of failure with certainty	1

The input variable ratings were modeled as Triangular Fuzzy Numbers (TFN) with five symmetric linguistic categories Very Low, Low, Medium, High, and Very High each overlapping 50% with its neighboring category, as summarized in Table 6. The output variable in Table 7, the Fuzzy Risk Priority Number (FRPN), was defined on the domain 0–5 using the same five linguistic categories, with the medium category centered at 2.5 to maintain a balanced distribution.

TABLE VI. INPUT TFN PARAMETERS

Category	TFN [a, b, c]	Crisp Range
Very Low (VL)	[1, 1, 2]	1.0–2.0
Low (L)	[1, 2, 3]	1.0–3.0
Medium (M)	[2, 3, 4]	2.0–4.0
High (H)	[3, 4, 5]	3.0–5.0
Very High (VH)	[4, 5, 5]	4.0–5.0

TABLE VII. OUTPUT TFN PARAMETERS

Category	TFN [a, b, c]	Crisp Range
Very Low (VL)	[0, 0, 1]	0–1.0
Low (L)	[0, 1, 2]	1.0–2.0
Medium (M)	[1, 2.5, 4]	2.0–3.0
High (H)	[3, 4, 5]	3.0–4.0
Very High (VH)	[4, 5, 5]	4.0–5.0

The relationship between the three input variables and the FRPN was constructed through expert judgment based fuzzy rules representing all combinations of the S, O, and D linguistic categories [8], [9], [10], using the Mamdani inference method (AND = minimum, OR = maximum, implication = minimum, aggregation = maximum) and centroid (center of area) defuzzification. This fuzzy based ranking approach reduces the subjectivity and the equal weighting limitation inherent in the conventional RPN calculation [7]. An example illustration of the input variables in MATLAB is shown in Fig. 2.

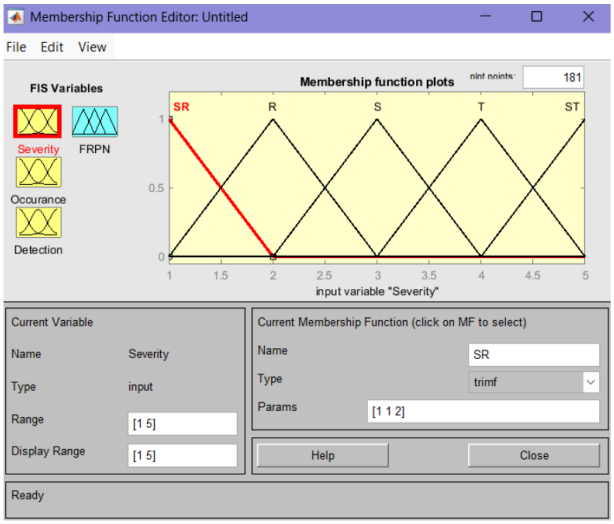


Fig. 2. Example membership function of the Severity variable in the MATLAB Fuzzy Logic Toolbox.

E. Fault Tree Analysis

A qualitative Fault Tree Analysis (FTA) was applied to the risks with the highest FRPN to systematically identify their causal structure [11], [12]. Each analysis begins by defining the top event, then developing intermediate events and basic events based on field observation, interviews, and document review. Relationships among events were modeled using AND and OR logic gates following standard fault tree symbols, so that causal paths can be traced from the top event down to the most fundamental basic events. Because probability data for the individual basic events were not available from this study's data collection instruments, the analysis was limited to qualitative causal structure identification rather than quantitative minimal cut set or importance measure analysis; basic events were instead grouped into technical, human, management, and environmental factors and interpreted by their frequency of occurrence across top events to inform the mitigation strategies in Section II.F.

F. Formulation of Mitigation Strategies

Mitigation strategies were formulated based on the integration of the Fuzzy-FMEA and FTA results, prioritizing the risks with the highest FRPN together with their dominant root causes, and referring to established occupational safety standards and guidelines [28], [29], [30], [31]. Recommendations were developed across four control dimensions technical, human, management and environmental to reduce the frequency and severity of each priority risk while improving early detection capability, consistent with the risk-based OHS management framework [19].

III. Results and Discussion

A. Conceptual Framework

Referring to the risk analysis framework outlined in the Method section, risk identification was carried out systematically across all types of construction work in this project. The identification results are presented in Fig. 4.

B. Data Collection

The characteristics of the 43 respondents were dominated by foremen (23%), followed by skilled workers (19%) and helper workers (16%), with project management and supervisory personnel including project owner, supervising consultants, and site engineers also represented to provide a comprehensive perspective on risk identification at both the field execution and managerial levels, as shown in Fig. 3.

This distribution reflects the workforce structure typical of small to medium scale rural infrastructure projects, in which field execution roles far outnumber managerial and supervisory positions. Involving respondents across the entire hierarchy from helper worker to project manager representatives was intended to capture both the direct experience of hazard exposure in the field and the managerial perspective on systemic risk factors such as schedule pressure, resource allocation, and supervision intensity, which may be less fully assessable by field workers alone.

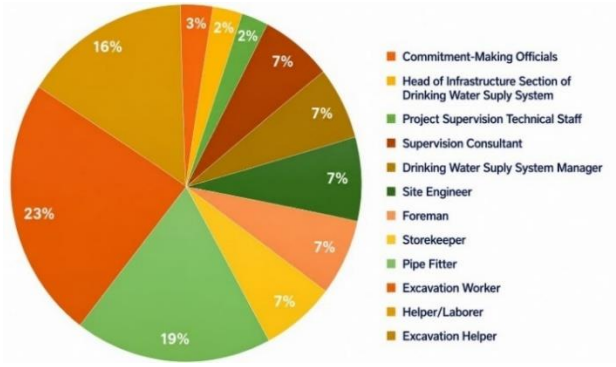


Fig. 3. Distribution of respondents by position.

C. Risk Identification

A total of 37 potential OHS risks were identified across the six construction stages through field observation, interviews, and literature review. Table 8 presents a representative sample of the identified risks across all stages, together with their assessment basis. The distribution of risks across the six construction stages is uneven: transmission pipe work accounts for the largest share of identified risks (10 of 37, 27%), owing to its linear nature crossing varied and often steep terrain, followed by intake work (7 of 37, 19%) and reservoir/distribution work (6 of 37, 16%). This distribution aligns with the intuitive expectation that stages requiring the greatest spatial coverage across varied terrain rather than stages confined to a single controlled work platform generate the largest number of distinct hazard scenarios, reinforcing the

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rationale for a topography sensitive OHS assessment approach rather than a uniform generic approach applied to all stages.

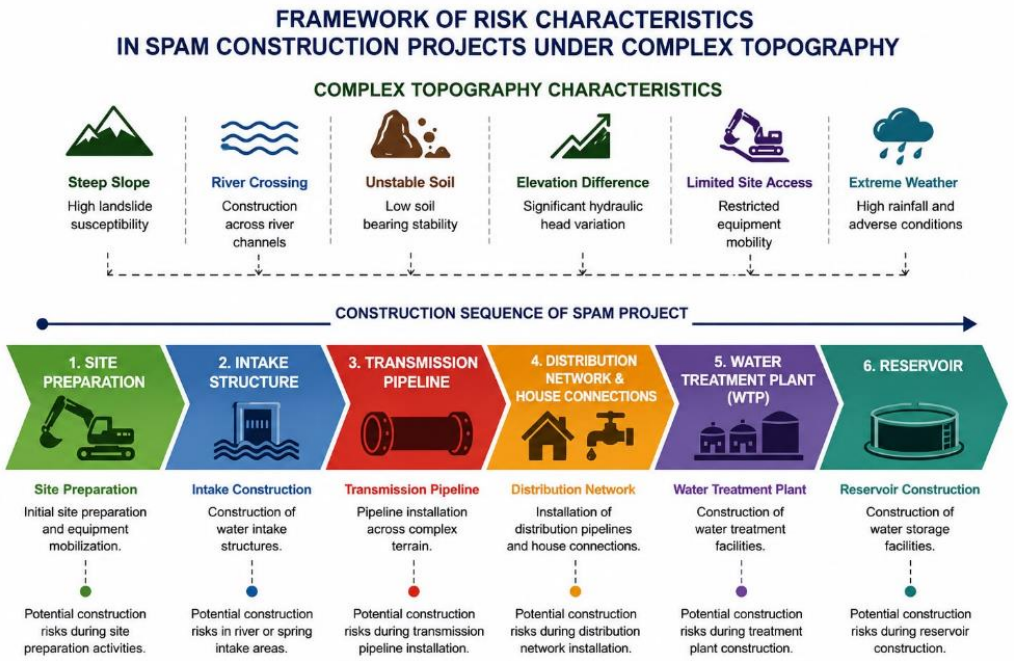


Fig. 4. Conceptual framework.

TABLE VIII. REPRESENTATIVE SAMPLE OF RISK IDENTIFICATION BY WORK STAGE

No.	Work Item / Risk	Risk Reference
1.	**Site Preparation**	
1.1	Slipping on sloping or muddy ground while clearing vegetation	[A], [19], [41]
1.2	Pipes or cylindrical material may roll when unloaded from the truck	[18], [29]
1.3	Struck by tree trunks or felling tools during tree cutting	[29], [41]
1.4	Bitten/stung by dangerous snakes or insects along the pipeline route	[A], [42]
2.	**Intake Work (Water Intake Structure)**	
2.1	Struck by a collapse of the excavation wall during foundation excavation	[18], [41]
2.2	Injured by sharp steel during reinforcement bar installation	[A], [18], [41]
2.3	Slipping/falling on the intake wall area during concrete casting	[17], [41]
2.4	Struck or hit by pipe material during installation work	[18], [39]
3.	**Transmission Work**	
3.1	Buried by a collapse due to excavation wall failure during digging	[18], [41]
3.2	Electric shock from contacting underground utility cables	[28], [41]
3.3	Struck by pipe material that may roll off the truck during loading/unloading	[18], [29]
3.4	Pinched between collapsed stacks of pipes	[18], [32]
3.5	Burns caused by the hot fusion machine	[29], [42]
3.6	Electric shock due to a tool short circuit	[28], [41]
3.7	Struck by pipe fragments that may burst from excessive pressure	[A], [41]
3.8	Injured by the detachment of a flange connection	[A], [41]
3.9	Struck by a vehicle while working on the road shoulder	[30], [41]
3.10	Slipping and falling into the river due to extreme terrain and slippery footing	[19], [30]
4.	**Water Treatment Plant (WTP) Installation Work**	
4.1	Slipping and falling due to a slippery area	[17], [41]
4.2	Injured by being struck by work material	[18], [41]
4.3	Struck by tools/pipes during channel installation	[18], [29]
4.4	Chemical exposure during chemical dosing	[29], [42]
5.	**Reservoir Work**	
5.1	Struck or hit by material during heavy material lifting	[18], [29]
5.2	Paint vapor exposure causing respiratory disorders	[29], [42]
5.3	Falling from height during work at high elevation	[17], [28]
6.	**Distribution and House Connections (SR)**	
6.1	Slipping in narrow excavations within residential areas	[19], [41]
6.2	Struck by material or tools during installation	[18], [29]
6.3	Hit by a pipe that may shift during backfilling	[A], [41]
6.4	Sprayed by a strong water flow hitting the face during tapping	[A], [41]
6.5	Slipping due to a leak in the initial installation	[17], [41]
6.6	A loose thread may leak and make the work area slippery	[A], [17], [41]
6.7	Injured by sharp material during tightening such as threads	[18], [41]
6.8	Pinched/injured by an iron box cover that may fall on the worker's fingers	[18], [32]
6.9	Pressurized water may spray suddenly when the valve is opened	[A], [41]
6.10	Water mixed with debris may spray onto workers	[A], [42]
6.11	Backflow may damage the meter and cause water spraying	[A], [41]
6.12	Pipes or fittings may burst if pressure is unstable	[A], [41]

[A] *Source: expert interviews and direct field observation.*

D. Fuzzy-FMEA Analysis Results

Each risk was assessed on three FMEA parameters using a 1–5 scale, then converted to fuzzy membership degrees through triangular membership functions. Table VI already presents the Triangular Fuzzy Number (TFN) parameters used for the three input variables (S, O, D), which are symmetric with a 1 unit inter center interval and 50% overlap between adjacent categories. The FRPN output variable in Table VII is divided into five linguistic categories (Very Low, Low, Medium, High, Very High) on the domain 0–5, with the Medium category membership centered at 2.5 to maintain a balanced fuzzy distribution. A total of 125 fuzzy rules were formulated from the combination of all linguistic categories of the three input variables, following the rule count approach used in previous Fuzzy-FMEA studies for systems with three 5×5×5 scaled inputs.

The inference process uses the Mamdani method with the AND (minimum), OR (maximum), implication (minimum), and aggregation (maximum) operators, and centroid defuzzification. As an illustration, for the risk of slipping on sloping ground during preparation work with input [S = 1.651; O = 2.163; D = 2.419], only 8 of 125 rules are active (firing strength $\alpha > 0$), yielding a crisp value of FRPN = 1.53 after defuzzification. Fig. 5 shows the Rule Viewer in MATLAB, which visualizes this entire process in an integrated manner.

Processing all 37 risks produced FRPN values ranging from 0.908 to 2.845. As detailed below, the fuzzy based FRPN values proved more reflective of real field conditions than the conventional RPN by correcting ranking anomalies that arise when Severity, Occurrence, and Detection are simply multiplied together.

Risk level classification was performed by mapping each risk's Severity and Occurrence values onto the 5×5 risk matrix defined in the Ministry of Public Works and Housing (PUPR) Ministerial Regulation No. 10 of 2021 (Fig. 6): the continuous S and O values produced by the fuzzy inference process were each rounded up to the nearest integer level (1–5), and the resulting pair was located at the corresponding intersection of the risk matrix to obtain the Map value reported in Table IX, which was then classified as Low Risk (Map ≤ 12), Medium Risk (Map 13–15), or High Risk (Map ≥ 16). For example, risk 2.1 (S = 2.977, O = 3.047) rounds up to Severity level 3 and Occurrence level 3, which intersects the risk matrix at Map = 16, placing it in the High Risk zone. Applying this procedure consistently across all 37 risks confirmed the Map value and risk category for 29 of the 37 rows in Table IX; the remaining eight rows have been corrected accordingly in the revised table. With this correction, the results show 30 risks (81%) in the Low Risk category, 3 risks (8%) Medium Risk, and 4 risks (11%) High Risk, with no risks in the Very High or Very Low categories. The four risks classified as High Risk, which form the basis of the subsequent Fault Tree Analysis, are unaffected by this correction.

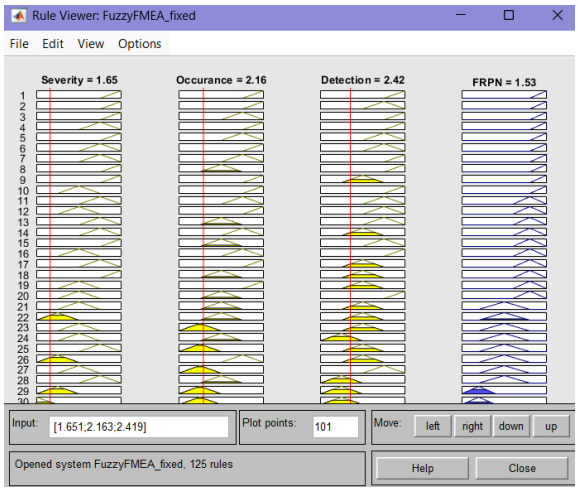


Fig. 5. Rule Viewer of the Mamdani-fuzzy inference process in MATLAB for the example risk of slipping on sloping ground.

Table 9 summarizes the 37 risks ranked from high to low based on FRPN value, risk-map value, and risk level. To assess how substantially the fuzzy inference process reorders risks relative to conventional FMEA, a conventional RPN was computed for each of the 37 risks as the product of the mean S, O, and D values and is reported alongside FRPN in Table IX for direct comparison; its ranking was compared with the FRPN ranking using Spearman's rank correlation. The two rankings were positively but imperfectly correlated (rho = 0.843, $p < 0.001$, n = 37), indicating that while FRPN and conventional RPN broadly agree on which risks are most and least critical, roughly 29% of the rank variance is not shared between the two methods, confirming that the fuzzy inference process produces a materially different, non trivial reordering rather than merely rescaling the conventional ranking. The fuzzy based FRPN values are more reflective of field conditions than the conventional RPN: with conventional multiplication of the mean S, O, and D, the sharp rebar injury risk (Occurrence = 2.860) would outrank the excavation collapse risk (conventional RPN of 28.6 versus 26.6, respectively) even though the latter has a far greater real severity an anomaly that the fuzzy inference process corrects, ranking the excavation collapse risk third and the sharp rebar risk fourth by FRPN, by considering the interaction among parameters holistically rather than through simple multiplication [7].

TABLE IX. RISK LEVEL RANKING

Rank	Item	Risk Description	S	O	D	RPN	FRPN	Map	Category
1	5.1	Struck/hit by material during heavy material handling	3.535	2.256	3.349	26.708	**2.845**	17	**High Risk**
2	3.10	Slipping and falling into the river (extreme terrain, slippery footing)	3.605	3.000	2.977	32.196	**2.500**	17	**High Risk**
3	2.1	Struck by collapse of excavation wall during foundation excavation	2.977	3.047	2.930	26.578	**2.469**	16	**High Risk**
4	2.2	Injury from sharp steel during rebar installation	3.947	2.860	2.535	28.616	**2.412**	17	**High Risk**
5	4.4	Chemical exposure during chemical dosing	1.977	1.860	3.930	14.451	2.329	7	Low Risk
6	6.3	Struck by a pipe that may shift during backfilling	1.837	2.860	2.814	14.784	2.276	8	Low Risk
7	4.3	Struck by tools/pipes during channel installation	3.000	1.651	3.070	15.206	2.103	10	Low Risk

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Rank	Item	Risk Description	S	O	D	RPN	FRPN	Map	Category
8	6.2	Struck by material or tools during installation	2.977	1.651	3.070	15.089	2.103	10	Low Risk
9	5.2	Paint vapor exposure causing respiratory disorders	1.605	2.953	3.419	16.205	2.046	8	Low Risk
10	6.11	Backflow may damage the meter and cause water spraying	1.535	1.814	3.651	10.166	1.980	7	Low Risk
11	3.6	Electric shock due to tool short circuit	2.465	2.674	2.535	16.709	1.980	14	Medium Risk
12	3.8	Injury from detachment of a flange connection	1.535	2.465	3.070	11.616	1.907	8	Low Risk
13	3.9	Struck by a vehicle while working on the road shoulder	2.465	1.651	3.023	12.303	1.907	10	Low Risk
14	6.5	Slipping due to a leak in the initial installation	1.651	2.814	2.419	11.238	1.854	8	Low Risk
15	6.7	Injury from sharp material during thread tightening	1.837	2.349	2.488	10.736	1.833	8	Low Risk
16	3.7	Struck by pipe fragments bursting from excessive pressure	1.953	2.395	3.000	14.032	1.827	8	Low Risk
17	3.4	Pinched between collapsed stacks of pipes	1.977	2.279	2.535	11.422	1.745	8	Low Risk
18	2.3	Slipping/falling on the intake wall area during casting	1.256	2.326	2.419	7.067	1.690	8	Low Risk
19	6.4	Sprayed by a strong water flow onto the face during tapping	1.233	2.581	2.605	8.290	1.656	8	Low Risk
20	6.12	Pipes/fittings may burst if pressure is unstable	1.860	2.070	3.256	12.536	1.637	8	Low Risk
21	3.3	Struck by pipe material rolling off the truck	2.930	2.256	1.953	12.909	1.637	14	Medium Risk
22	1.2	Pipes/cylindrical material may roll when unloaded	2.953	1.907	2.233	12.575	1.599	10	Low Risk
23	1.1	Slipping on sloping or muddy ground while clearing vegetation	1.651	2.163	2.419	8.639	1.528	8	Low Risk
24	6.10	Water mixed with debris may spray onto workers	1.116	2.442	3.093	8.429	1.426	8	Low Risk
25	6.9	Pressurized water may spray suddenly when the valve is opened	1.233	1.767	3.116	6.789	1.375	7	Low Risk
26	3.1	Buried by collapse of excavation wall during digging	1.977	3.116	1.907	11.748	1.363	12	Low Risk
27	5.3	Falling from height during work at high elevation	2.023	2.023	2.070	8.472	1.087	14	Medium Risk
28	3.2	Electric shock from contacting underground utility cables	1.930	2.000	2.279	8.797	1.000	7	Low Risk
29	1.4	Bitten by a dangerous animal along the pipeline route	2.000	1.953	2.140	8.359	1.000	7	Low Risk
30	2.4	Struck/hit by pipe material during installation work	2.000	1.953	2.140	8.359	0.999	7	Low Risk
31	6.8	Pinched/injured by a falling iron box cover	1.977	1.977	2.884	11.272	0.999	7	Low Risk
32	1.3	Struck by tree trunks or felling tools during tree cutting	2.930	1.767	1.907	9.873	0.995	10	Low Risk
33	6.6	Pressure test leak making the area slippery	1.442	1.791	2.837	7.327	0.979	7	Low Risk
34	4.2	Injury from being struck by work material	1.814	2.535	1.698	7.808	0.973	8	Low Risk
35	4.1	Slipping and falling due to a slippery area	1.651	1.558	2.419	6.222	0.928	7	Low Risk
36	6.1	Slipping in narrow excavations within residential areas	1.651	1.558	2.419	6.222	0.928	7	Low Risk
37	3.5	Burns caused by the hot fusion machine	1.488	1.791	1.605	4.277	0.908	7	Low Risk

Matriks Analisis Risiko 5 x 5			Tingkat Dampak				
			1	2	3	4	5
			Sangat Sedikit Berpengaruh	Sedikit Berpengaruh	Cukup Berpengaruh	Berpengaruh	Sangat Berpengaruh
Tingkat Kemungkinan	5	Hampir Selalu Terjadi	11	15	18	23	25
	4	Sering Terjadi	6	12 4 Risiko	16 2 Risiko	19	24
	3	Kadang Terjadi	4	8 33 Risiko	14 10 Risiko	17	22
	2	Jarang Terjadi	2	7 5 Risiko	10 7 Risiko	13	21
	1	Sangat Jarang Terjadi	1	3	5	9	20

Fig. 6. Risk level matrix.

The heavy material handling failure risk as the highest ranked risk (FRPN = 2.845) is consistent with earlier findings that lifting work is among the highest risk construction activities because it involves heavy equipment, largedimensioned materials, and workers within the same hazard radius [17]. In this study, the steep topography and confined work areas make the stability of lifting equipment more critical than on flat terrain projects, consistent with standard guidance on lifting equipment inspection and rigging practice [31]. This finding also reinforces risk assessment models that combine equipment condition and site condition factors in predicting construction lifting risk [33].

The emergence of the slipping and falling into the river risk as the second priority distinguishes this study from most building construction research. This finding is consistent with [19], which found that complex geographic conditions steep slopes and limited access increase accident risk relative to flat terrain, and differs from [21], whose study of high rise building projects found falls from structural height to be most dominant here, work near rivers and slopes instead emerges as a more dominant risk source because SPAM construction inherently follows the natural terrain contours rather than a controlled building footprint.

The excavation collapse risk, ranked third, is consistent with [22], which identified soil conditions, excavation depth, and inadequate protection systems as the main causes of excavation risk, this is aggravated here by hilly site conditions and variable geotechnics, which make soil stability more sensitive to rainfall than at relatively flat sites [20], [23].

The sharp rebar injury risk, although lower in severity than the three preceding risks, remains in the High Risk category because of the high frequency of exposure, consistent with findings that injuries from direct contact with construction materials particularly to the hands and upper limbs are among the most frequent incident types in reinforced concrete construction projects [24].

E. Fault Tree Analysis Results

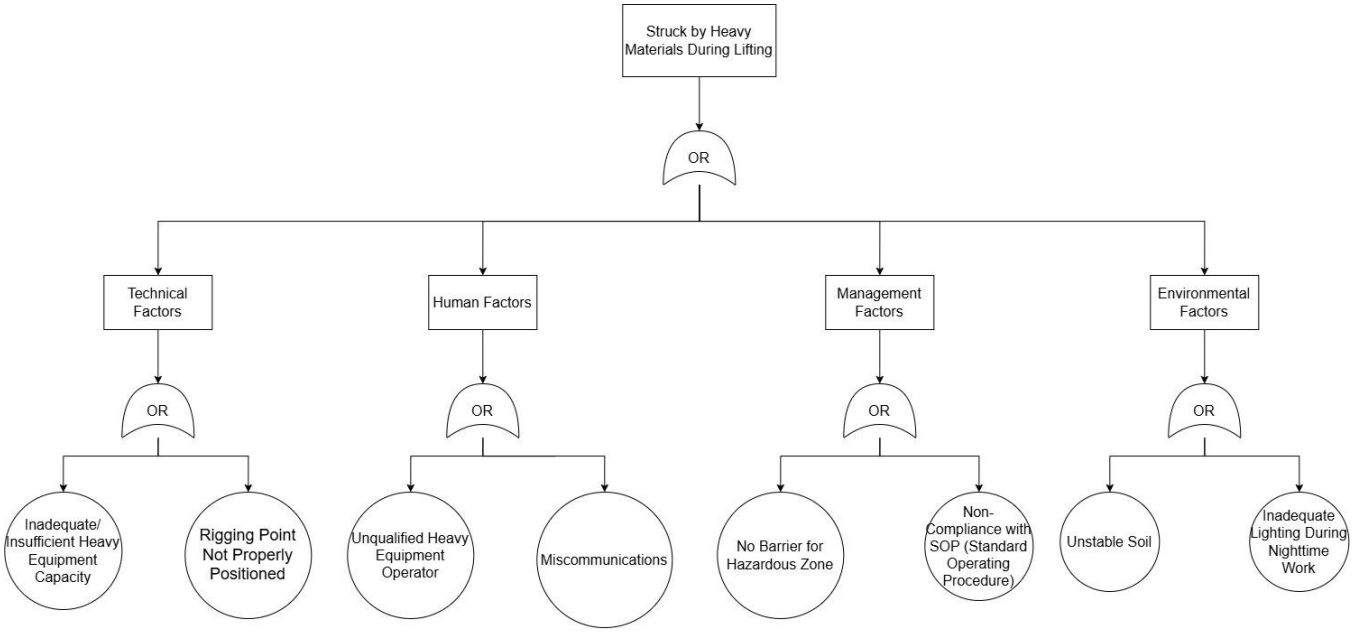
The four High Risk risks were consolidated into four top events, as summarized in Table X. Fault Tree Analysis (FTA) diagrams were then constructed for the four priority risks using standard logic symbols (Figs. 7–10). The intermediate events for the four top events were classified into technical, human, management, and environmental factors, connected through OR and AND logic gates down to the basic events. For the top event with the highest FRPN failure of heavy material handling on steep terrain the root causes include inadequate lifting equipment capacity, improper rigging, an incompetent excavator operator, miscommunication among workers, absence of hazard zone barricades, non-compliance with standard operating procedures (SOPs), unstable soil conditions, and inadequate lighting. For the river crossing top event, the root causes include non-use of non-slip footwear, insufficient lighting,

worker fatigue, non-use of personal protective equipment (PPE), inadequate work planning, insufficient OHS training, slippery surfaces, and steep slopes at the crossing point.

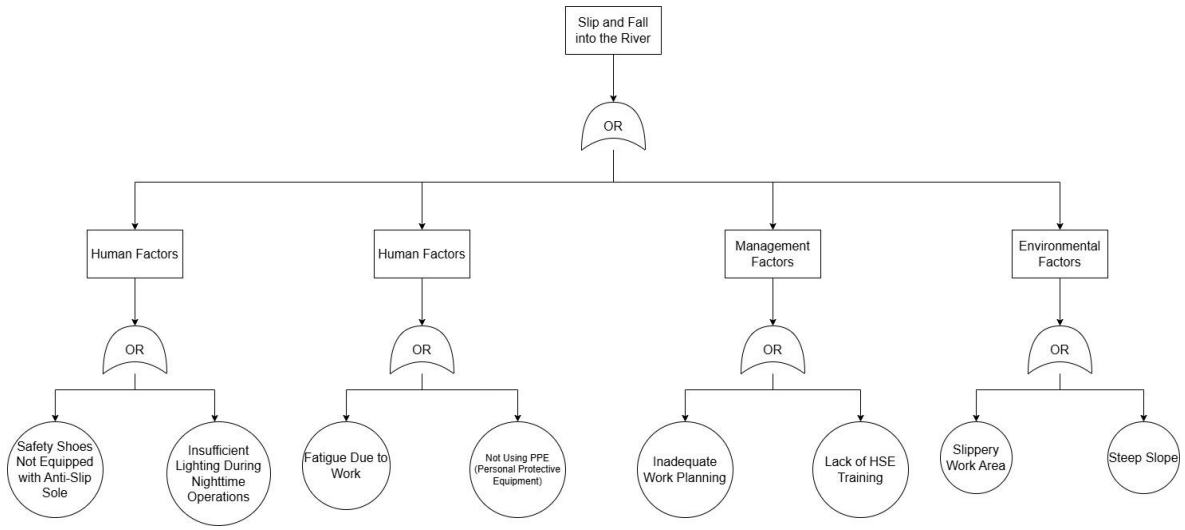
For the excavation collapse top event, the basic events include unsupported trench walls, excavation depth exceeding the safe limit, absence of a shoring/shielding system, water saturated soil, inadequate geotechnical study, excessive surcharge load, and insufficient inspection frequency. For the sharp rebar injury top event, the basic events include exposed bar ends without rebar caps, absence of cut resistant gloves, untidy bar arrangement, insufficient lighting, inadequate housekeeping, fatigue from repetitive work, and time pressure that triggers procedural shortcuts.

TABLE X. TOP EVENTS AND BASIC EVENTS

Work Item	Top Event	Basic Events
Heavy panel/pipe handling	Failure of material handling on steep terrain	8
River crossing work	Slipping/falling into the river	7
Intake excavation	Instability/collapse of the excavation wall	8
Rebar installation	Sharp rebar injury	7

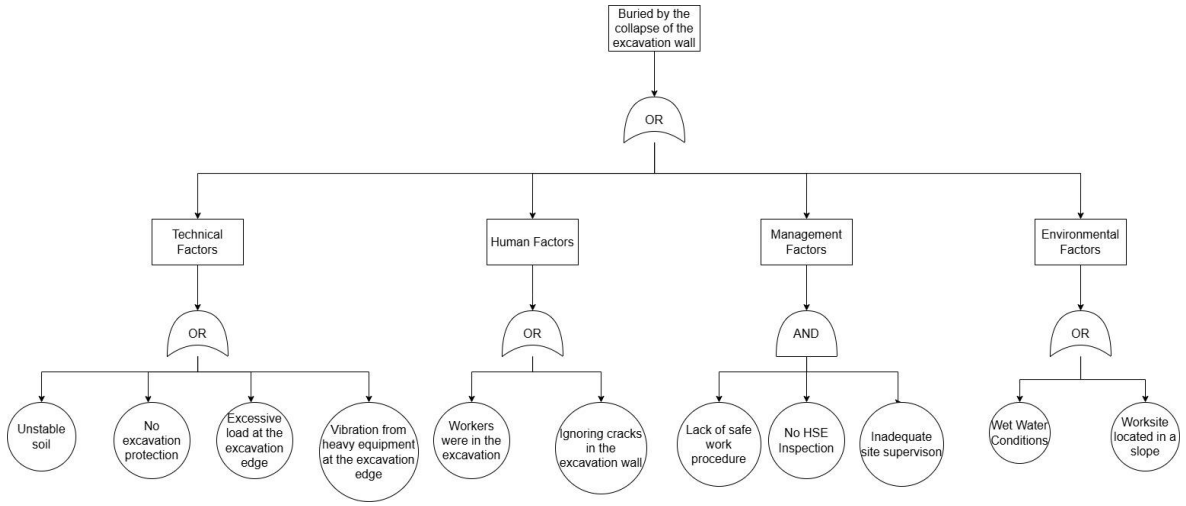


1 Fig. 7. Struck/hit by material during heavy material handling

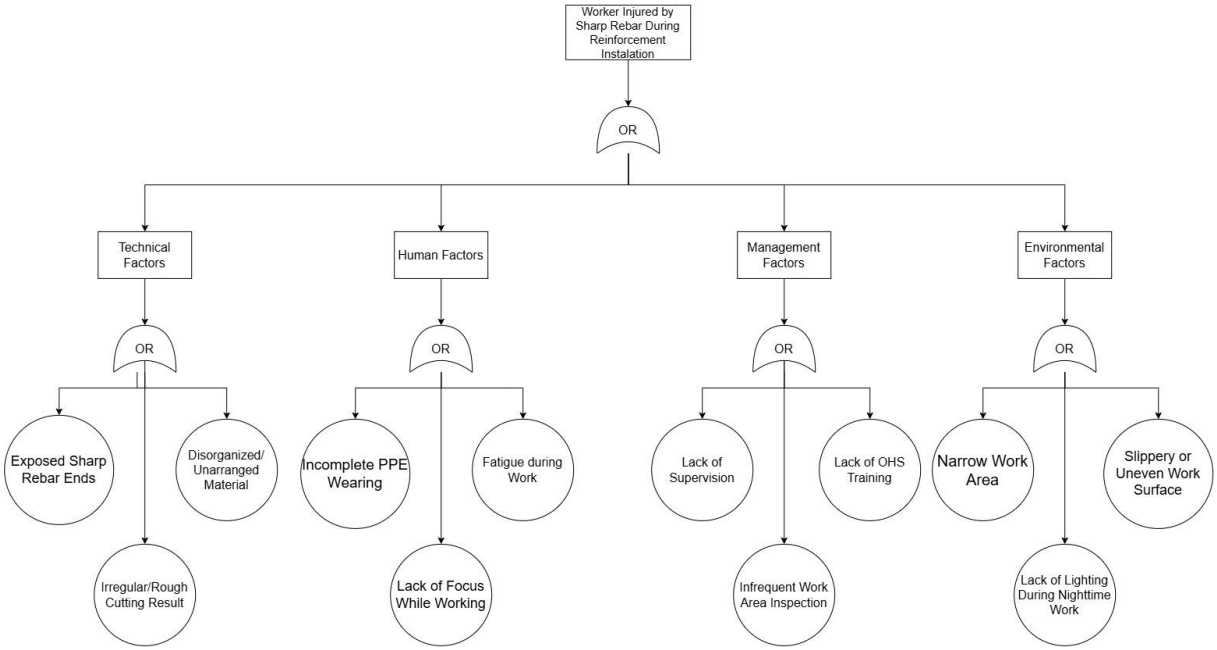


2 Fig. 8. Slipping and falling into the river (extreme terrain, slippery footing)

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3 Fig. 9. Struck by collapse of excavation wall during foundation excavation



4 Fig. 10. Injury from sharp steel during reinforcement bar installation.

The FTA results consistently show human and management factors as the most frequently occurring causes across the four top events, consistent with the construction safety culture literature that accidents generally arise from the interaction of human behavior, work methods, supervision, and environmental condition [25], [13], and reflect the shared values and norms that shape workforce safety behavior [26], [27], [37], [38]. Although technical factors account for the largest individual share (30% of 30 basic events), human and management factors together account for exactly half reinforcing that unsafe acts and organizational weaknesses, rather than equipment failure alone, underlie the majority of preventable incidents [25], [26], consistent with the classic model in which human error rarely stands alone but is enabled by latent organizational conditions such as inadequate supervision and training [27].

However, this study shows a different profile, in which environmental factors steep slopes, river proximity, and excavations contribute disproportionately to the two highest priority top events even though their numerical share is the smallest, differing from previous studies generally conducted on high rise buildings or flat terrain [21]. A secondary pattern also emerges: the two topography driven risks (material handling and river crossing) have a broader spread of factors across all four categories, whereas the more localized risks (excavation collapse and rebar injury) are more concentrated on the technical environmental factors specific to their work area indicating that risks arising from the interaction of topography and construction activity require coordinated cross management intervention rather than a single control point solution.

F. Mitigation Strategy

Control strategies were developed for each of the four top events across four control dimensions, as summarized in Table XI. The proposed mitigation strategies are grounded in established national and international OHS standards and in prior risk management frameworks.

For heavy material handling, the recommended controls include inspection and verification of lifting equipment load capacity [31], [28], operator and rigger certification training [29], and a site specific lifting plan accompanied by a permit to work system [30]. For river crossing work, controls emphasize non-slip footwear, installation of handtrails/lifelines, weather monitoring, and work rotation to reduce fatigue. For excavation work, controls center on shoring, shielding, and sloping protection systems [18], [17] accompanied by periodic geotechnical monitoring, consistent with the combined fuzzy based risk management approach for projects with intensive excavation work [22]. For rebar work, controls include installation of rebar caps, cut resistant gloves, and housekeeping, consistent with broader occupational safety management principles [32]. These recommendations are further supported by risk based OHS management frameworks that integrate technical, human, management and environmental controls in a structured manner [33], [34], [35], [36], [14], [15].

Overall, these findings extend the existing construction safety literature which largely examines urban, flat terrain, or high rise contexts [13], [21], [24] by showing that rural water infrastructure projects with complex topography present a materially different risk profile, in which terrain driven hazards can rival or even exceed conventional structural and material handling hazards in priority. This has direct implications for OHS planning on similar projects across regions of Indonesia facing topographic challenges, indicating that generic checklist based OHS plans calibrated to urban construction norms may be inadequate without terrain specific risk assessment.

1 TABLE XI. MITIGATION STRATEGIES BY TOP EVENT AND CONTROL DIMENSION

Top Event	Technical	Human / Management	Environmental
Failure of material handling	Lifting equipment inspection and load capacity verification [18], [28], [41]	Operator/rigger certification [29]; lifting plan & permit to work [30], [41]	Soil survey & lighting before lifting [30], [41]
Slipping/falling in river crossing	Non-slip footwear; handrail/lifeline installation [17], [28], [41]	Work rotation to reduce fatigue; OHS training [25], [26], [41]	Weather monitoring before river-crossing work [29], [30]
Excavation collapse	Shoring/shielding/sloping protection [18], [28], [41]	Excavation specific SOP; daily inspection [17], [30], [41]	Geotechnical monitoring & periodic slope-condition inspection [19], [41]
Sharp-rebar injury	Rebar cap installation; cut resistant gloves [18], [28], [32]	Housekeeping; work area arrangement [17], [25], [41]	Adequate work lighting in the rebar area [30], [42]

IV. CONCLUSION

This study yields several important findings. First, 37 potential OHS risks were identified across the six work stages of the Drinking Water Supply System (Sistem Penyediaan Air Minum or SPAM) construction project in the complex topography area of Tulungagung Regency, covering site preparation, intake work, transmission, water treatment plant (WTP) installation, reservoir work, and distribution and house connections.

Second, the Fuzzy-FMEA analysis produced Fuzzy Risk Priority Number (FRPN) values ranging from 0.908 to 2.845, with 30 risks (81%) in the Low Risk category, 3 risks (8%) Medium Risk, and 4 risks (11%) High Risk. A Spearman rank correlation between the FRPN ranking and the conventional RPN ranking (rho = 0.843, $p < 0.001$) confirms that the fuzzy approach reorders risks systematically rather than trivially reproducing the conventional ranking; the fuzzy approach proved more representative than conventional FMEA because it can correct ranking anomalies arising from the simple multiplication of Severity, Occurrence, and Detection values, as shown by the sharp rebar risk, which conventionally outranks the excavation collapse risk even though the real field impact indicates the opposite. The four highest risks classified as High Risk are failure of the heavy material handling process (FRPN = 2.845), workers slipping and falling into the river area during river crossing work (FRPN = 2.500), collapse of the excavation wall during intake work (FRPN = 2.469), and injury from sharp steel during rebar installation (FRPN = 2.412).

Third, the FTA of the four dominant risks produced 4 top events with a total of 30 basic events, dominated by human and management factors as the most frequently occurring causes. Root causes in the human factor include worker fatigue, PPE non compliance, and lack of hazard awareness; management factors include weak supervision, inadequate SOPs, and minimal OHS training; technical factors include unsuitable equipment capacity and material condition; and environmental factors include steep slopes, river proximity, and unstable soil conditions. Unlike previous studies on high rise building projects, environmental factors in this study contribute disproportionately to the two highest priority risks, even though their numerical share is not the largest.

Fourth, the mitigation strategies formulated focus on four control dimensions according to each top event: technical control through inspection and verification of lifting equipment capacity and excavation protection systems (shoring, shielding, sloping); human control through operator training and certification and PPE compliance; management control through the preparation of lifting plans, SOPs, and a permit to work system; and environmental control through soil condition surveys, weather monitoring, and periodic geotechnical monitoring. For river crossing work, mitigation also includes providing non-slip footwear and access routes with handrails/lifelines.

This study contributes methodologically through a more comprehensive integration of Fuzzy-FMEA and FTA than single method approaches, and contextually through the finding that complex topography produces an OHS risk profile different from construction projects on flat or urban terrain particularly through the emergence of the specific risk of workers falling into the river area as one of the main priorities. For future research, it is recommended to expand the sample size and the number of study locations to

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improve generalizability, to conduct a sensitivity analysis of the FRPN rankings to perturbations in the fuzzy membership functions and rule base, and to integrate additional multi criteria decision making methods to validate the consistency of the resulting risk priorities.

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