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Time–Cost–Quality Impact Assessment and FMEA-Based Prioritization of Geological, Environmental, and Operational Risks in Road Infrastructure Projects

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Abstract : *Road infrastructure projects are exposed to geological, environmental, and operational hazards that jointly determine delivery time, cost, and quality. Risk studies and guidance often address one hazard family at a time, and hazard lists are not always converted into ranked priorities that project managers can act on. This paper presents a structured, three-stage assessment of fifteen risk factors that commonly affect road projects. First, each factor is rated for its impact on project time, cost, and quality and aggregated into a composite impact index. Second, the factors are ranked using a probability–severity matrix. Third, seven critical failure modes are prioritized using Failure Mode and Effects Analysis (FMEA) with the Risk Priority Number (RPN). The results show that geological factors have the highest composite impact (mean 8.2 out of a maximum of 9), followed by operational (7.3) and environmental factors (6.5). Slope failure, earthquakes, and safety incidents are the only factors rated High on all three performance dimensions, and ten of the fifteen factors fall in the High priority tier. In the FMEA, project mismanagement (RPN 252), flooding (240), and material shortage (210) rank highest and together account for 55.5% of the total RPN. The qualitative ranking and the RPN agree on the severity of geological hazards but diverge for material supply, which illustrates the value of including detectability in prioritization. Illustrative mitigation scenarios indicate that the aggregate RPN could be reduced by roughly two-thirds if targeted controls are implemented. The ratings are judgement-based and require field validation, as discussed in the limitations.*

Keywords: road infrastructure; risk prioritization; failure mode and effects analysis; risk priority number; project time, cost and quality; geological hazards; environmental risk; operational risk

I. INTRODUCTION

1.1 Background

Roads are the backbone of economic activity and social connectivity. They carry goods and people, open access to markets and essential services, and support disaster response. Because they cross plains, hills, river valleys, forests, and settled areas, road projects meet a wide range of uncertainties during planning, design, construction, and maintenance [20]. These uncertainties translate into schedule delay, cost escalation, quality deficiencies, and safety incidents [19]. A study of 258 transport infrastructure projects found that nine out of ten had cost overruns [4], and the traditional performance triangle of time, cost, and quality remains the common language in which project outcomes are judged, even though it has been criticized as an incomplete measure of success [3].

Three families of risk dominate road projects. Geological risks, such as landslides, slope failure, flooding, erosion, and seismic activity, arise from terrain and subsurface conditions.

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Environmental risks arise from the interaction between construction activity and ecosystems, water, air, and communities, and from the regulatory regime that governs that interaction. Operational risks arise from the way the project is executed: labour, equipment, materials, supervision, coordination, and safety management. A questionnaire survey of construction projects in China, for example, identified 25 key risks that span the project life cycle and the responsibilities of different stakeholders [5].

1.2 Problem statement

Much published work addresses one family of risks in depth, for example landslide zoning, environmental impact assessment, or equipment reliability, using methods suited to that family. This is valuable, but it leaves project managers with separate lists that are not directly comparable. A manager deciding where to spend a limited mitigation budget needs to know how a slope failure compares with a labour shortage or a delay in environmental clearance, in terms that are meaningful for project performance. Two further gaps follow. First, the impact of each risk on time, cost, and quality is not always compared side by side across all three families, and a review of construction risk assessment reports that no comprehensive approach captures the impact of a risk on different project objectives [6]. Second, FMEA variants developed for highway projects rely on fuzzy and multi-criteria techniques [14], and there is value in a simpler, transparent procedure whose steps can be audited and compared against a basic probability–severity ranking.

1.3 Objectives and contributions

This paper addresses these gaps with the following objectives:

1. To compare the impact of fifteen geological, environmental, and operational risk factors on project time, cost, and quality using a common rating scale and a composite impact index.
2. To rank the factors by probability and severity and to assign each one to a High, Medium, or Low priority tier.
3. To prioritize seven representative failure modes across the three families using FMEA and the Risk Priority Number, and to compare the outcome with the qualitative ranking.
4. To illustrate, through transparent what-if scenarios, how targeted mitigation controls could change the RPN profile, and to link the results to monitoring indicators.

The contribution is an integrated and reproducible prioritization procedure that uses the same risk vocabulary and performance dimensions across all three hazard families, and an explicit comparison of two prioritization logics, probability–severity and FMEA. The focus of this paper is the comparative impact analysis, the ranking, and the quantitative prioritization of risks.

1.4 Organization of the paper

Section 2 reviews related work and states the research gap. Section 3 describes the methodology, including the risk factor set, rating scales, and calculation procedures. Section 4 reports the results. Section 5 discusses the findings, root causes, mitigation strategies, and monitoring indicators. Section 6 sets out limitations and future work, and Section 7 concludes.

II. BACKGROUND AND RELATED WORK

2.1 Risk assessment in construction projects

Risk management in projects is commonly organized around identification, analysis, evaluation, treatment, and monitoring, as set out in international guidance [1] and in project management practice [2]. A review of construction risk modelling and assessment found that probability–impact models remain the prevailing approach and that the literature lacks a comprehensive approach capable of capturing the impact of a risk on different project objectives [6]. Practical texts on construction risk present risk identification and assessment as the basis for decision-making under uncertainty [12]. A consistent way of comparing risks across geological, environmental, and operational categories is therefore still needed.

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2.2 Geological risks in road corridors

Roads in hilly, riverine, and seismic regions are exposed to landslides, rockfalls, slope instability, flooding, erosion, subsidence, and earthquake damage. Guidelines on landslide susceptibility, hazard, and risk zoning for land-use planning describe how zoning maps are prepared at different levels of detail, including linear zoning along roads and railways [7]. A review of landslide risk assessment and management proposes a framework for reducing landslide risk and discusses the applicability of the available assessment approaches [16]. Geological hazards can cause large and hard-to-reverse disruptions: they can block access, damage partially built works, and require redesign and stabilization, and they usually require early, site-specific investigation to be managed effectively.

2.3 Environmental risks and environmental impact assessment

Road construction involves clearing, excavation, haulage, and drainage alteration, which can affect habitats, water quality, air quality, and noise levels. Environmental impact assessment (EIA) is the established process for identifying, predicting, and mitigating such impacts before a project is approved [11]. Roads also have documented ecological effects once built, including local hydrologic and erosion effects and the fragmentation of habitats [17], and climate-related shifts in weather patterns can disrupt transport infrastructure [18]. From a project-performance perspective, environmental risk arises less from physical failure than from approval timelines, compliance obligations, mitigation costs, and the long-term sustainability of the completed road, including its resilience to climate-related events.

2.4 Operational risks

Operational risks originate inside the project organization. Labour availability and skill, equipment condition, material supply, workmanship, supervision, communication, and safety performance all influence productivity and outcomes. Delay is a common consequence of execution problems: a survey of construction projects in Saudi Arabia identified 73 causes of delay, and 70% of the projects surveyed experienced time overrun [15]. Unlike geological and environmental hazards, operational risks originate largely within the project organization and can be influenced through planning, training, maintenance, and governance, which makes their prioritization especially useful.

2.5 FMEA and the Risk Priority Number

FMEA is a structured technique that identifies how a system, process, or component can fail, the effects of each failure, and its causes, and then ranks failure modes so that corrective effort can be focused [8]. In the classical form, a failure mode receives scores for severity (S), occurrence (O), and detectability (D), usually on a 1–10 scale, and the Risk Priority Number is the product $RPN = S \times O \times D$. The method is attractive because it is simple, transparent, and applicable to mixed failure modes. Its deficiencies have also been widely discussed, and many alternative risk-priority models have been proposed [9]. In construction, FMEA has been extended with fuzzy logic and the analytic hierarchy process to address these drawbacks [13], and fuzzy FMEA has been applied to highway projects with cost, time, and quality as the prioritization criteria [14]. Commonly cited weaknesses are that the same RPN can result from very different combinations of S, O, and D, that the scales are ordinal rather than ratio, and that the three factors are implicitly weighted equally. The 2019 AIAG & VDA FMEA handbook for the automotive industry replaced the RPN with action-priority tables in which severity is considered first [10]. These limitations are considered in the interpretation of the results in this paper.

2.6 Research gap

The sources reviewed above show mature methods for individual hazard families, and fuzzy FMEA studies for highway construction already use cost, time, and quality as prioritization criteria [14]. What they do not offer is a simple, transparent procedure that (i) rates geological, environmental, and operational factors on the same time–cost–quality scale, (ii) ranks them by probability and severity, and (iii) contrasts that ranking with a conventional FMEA ranking that includes detectability, so that practitioners can see where the two logics agree and where they differ. A

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review of construction risk assessment makes a related observation, namely that the literature lacks a comprehensive approach for capturing the impact of a risk on different project objectives [6]. This paper addresses these three points for road infrastructure projects.

III. METHODOLOGY

3.1 Research design

The assessment follows the five-step procedure shown in Figure 1. The procedure moves from a defined risk factor set, through impact rating and probability–severity ranking, to FMEA-based prioritization of critical failure modes, and ends with mitigation scenarios and monitoring indicators. All steps use the same set of risk families and the same performance dimensions so that the outputs are directly comparable.

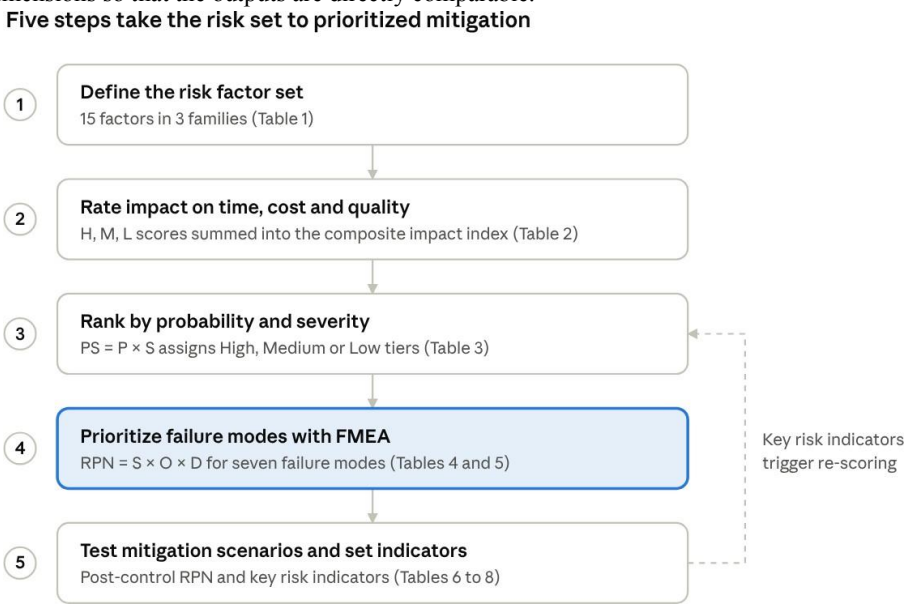


Figure 1. Five-step assessment procedure and the outputs produced at each step.

3.2 Risk factor set

Fifteen risk factors were selected to cover the three families: five geological, four environmental and regulatory, and six operational. The set reflects the hazards most frequently reported for road projects in hilly, flood-prone, and seismically active terrain, and the operational factors most often associated with delay, overrun, and defects. Table 1 lists the factors, their family, and typical consequences.

Table 1. Risk factors included in the assessment

ID	Risk factor	Family	Typical consequences for the project
G1	Landslide	Geological	Blocked access, damaged works, debris removal, stabilization
G2	Slope failure	Geological	Unstable cuts and embankments, retaining structures, redesign
G3	Flooding	Geological	Site inundation, equipment and material loss, suspended work
G4	Earthquake	Geological	Structural damage, inspection and redesign, safety hazards
G5	Soil erosion	Geological	Weakened embankments, drainage failure, maintenance demand
E1	Environmental clearance delays	Environmental	Late start, schedule disruption, redesign for approval
E2	Regulatory compliance issues	Environmental	Fines, stoppages, additional compliance cost
E3	Environmental degradation	Environmental	Habitat loss, pollution, reduced sustainability and quality
E4	Climate change effects	Environmental	Extreme rainfall, heat, accelerated pavement deterioration

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O1	Equipment failure	Operational	Downtime, repair cost, productivity loss
O2	Labour shortage	Operational	Reduced productivity, missed milestones
O3	Material supply delays	Operational	Idle labour and equipment, schedule slippage
O4	Material wastage	Operational	Higher procurement cost, reduced efficiency
O5	Poor workmanship	Operational	Defects, rework, premature deterioration
O6	Safety incidents	Operational	Injuries, stoppages, legal and reputational consequences

3.3 Impact rating and composite impact index

Each factor was rated High (H), Medium (M), or Low (L) for its potential effect on three performance dimensions: project time, project cost, and construction quality. The ratings reflect the typical consequences listed in Table 1 and the mechanisms by which each factor delays work, adds expenditure, or degrades the finished road. To allow aggregation, the ratings were mapped to the numerical scores H = 3, M = 2, and L = 1. The composite impact index (CII) of a factor is the sum of its three dimension scores:

$$CII = S_time + S_cost + S_quality$$

The index therefore ranges from 3 (Low on all dimensions) to 9 (High on all dimensions). The family-level index is the arithmetic mean of the CII values of the factors in that family. The numerical mapping is an analytical convenience and treats the categories as equally spaced, which is an assumption discussed in Section 6.

3.4 Probability–severity ranking

Each factor was also rated H, M, or L for probability of occurrence and for severity of consequences. With the same numerical mapping, a probability–severity score PS = P × S was computed, giving values from 1 to 9. The priority tier was assigned as follows: High for PS of 6 or more, Medium for PS of 3 to 5, and Low for PS of 2 or less. This rule reproduces the tiers used in the underlying assessment and makes the assignment transparent and repeatable.

3.5 FMEA and Risk Priority Number

Seven failure modes were selected to represent the three families and the project management dimension: soil instability, flooding, equipment failure, material shortage, regulatory non-compliance, worker injury, and project mismanagement. For each, severity, occurrence, and detectability were scored on a 1–10 scale, where 10 means the most severe consequence, the highest likelihood, and the lowest chance of detecting the failure before it causes harm. The Risk Priority Number was calculated as RPN = S × O × D, with a possible range of 1 to 1000. Failure modes were ranked in descending order of RPN, and each mode's share of the total RPN was computed to show how concentrated the risk is.

3.6 Mitigation scenarios

To show how prioritization supports decisions, an illustrative what-if analysis was carried out. For each failure mode, a targeted control was identified from the mitigation measures discussed in Section 5, and the occurrence and detectability scores were re-estimated under the assumption that the control is implemented effectively. Severity was held constant because the controls act on likelihood and detection, not on the consequence of an event once it occurs. These are target scenarios, not measured results.

3.7 Nature of the data and assumptions

The ratings used in this study are structured, judgement-based assessments compiled from a systematic analysis of the risk mechanisms affecting road projects. They are not derived from measurements on a specific instrumented project. The results should therefore be read as a transparent prioritization procedure with worked values, not as statistically estimated parameters for a particular road. Section 6 discusses the consequences of this choice and how it can be addressed through expert elicitation and project data.

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IV. RESULTS

4.1 Impact of risk factors on time, cost, and quality

Table 2 gives the impact ratings of the fifteen factors on the three performance dimensions together with the composite impact index (CII). Three factors, slope failure, earthquakes, and safety incidents, are rated High on all three dimensions and reach the maximum CII of 9. Landslides, flooding, and equipment failure follow with a CII of 8. Six factors have a CII of 7, and three factors, environmental clearance delays, environmental degradation, and material wastage, have the lowest CII of 6. No factor in the set falls below 6, which indicates that all of the selected factors have at least a moderate effect on project performance.

Table 2. Impact ratings and composite impact index (H = 3, M = 2, L = 1)

ID	Risk factor	Family	Time	Cost	Quality	CII
G2	Slope failure	Geological	H	H	H	9
G4	Earthquake	Geological	H	H	H	9
O6	Safety incidents	Operational	H	H	H	9
G1	Landslide	Geological	H	H	M	8
G3	Flooding	Geological	H	H	M	8
O1	Equipment failure	Operational	M	H	H	8
G5	Soil erosion	Geological	M	M	H	7
E2	Regulatory compliance issues	Environmental	M	H	M	7
E4	Climate change effects	Environmental	M	H	M	7
O2	Labour shortage	Operational	H	M	M	7
O3	Material supply delays	Operational	H	M	M	7
O5	Poor workmanship	Operational	M	M	H	7
E1	Environmental clearance delays	Environmental	H	M	L	6
E3	Environmental degradation	Environmental	L	M	H	6
O4	Material wastage	Operational	L	H	M	6

Across the three dimensions, cost is the most frequently affected: nine of the fifteen factors are rated High for cost, compared with eight for time and seven for quality. Time impact is concentrated in geological factors (four of five rated High) and in supply- and labour-related operational factors. Quality impact is concentrated in the factors that degrade the physical result, namely slope failure, earthquakes, erosion, environmental degradation, equipment failure, workmanship, and safety management.

4.2 Comparison of risk families

Averaging the CII within each family gives 8.2 for geological factors, 7.3 for operational factors, and 6.5 for environmental factors. Figure 2 shows the mean score of each family on each dimension. Geological factors score highest on all three dimensions, with mean scores of 2.8 for time, 2.8 for cost, and 2.6 for quality. Operational factors are more balanced, with mean scores of 2.3 for time and 2.5 each for cost and quality. Environmental factors have their strongest effect on cost (2.5) and a lower mean effect on time and quality (2.0 each), which is consistent with the compliance, monitoring, and mitigation expenditure that characterizes this family. The lower environmental mean should not be read as meaning these risks can be neglected: clearance delays and climate effects are High-priority items in Section 4.3, and environmental failures tend to surface late and be costly to reverse.

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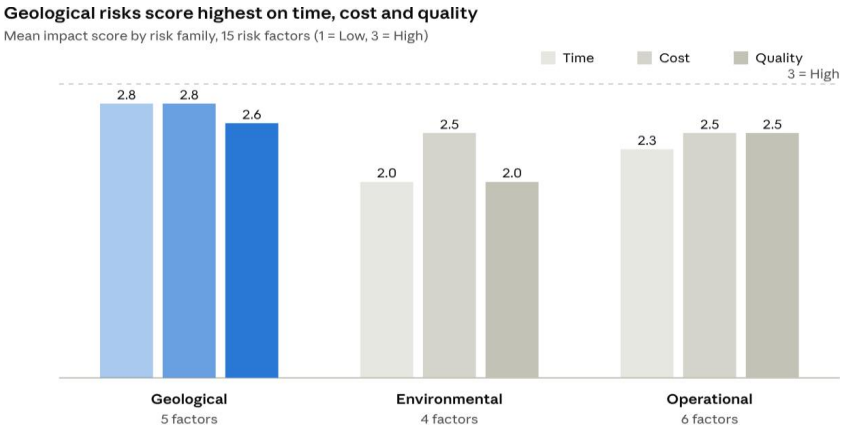


Figure 2. Mean impact score by risk family and performance dimension (1 = Low, 3 = High).

4.3 Probability–severity ranking

Table 3 ranks the factors by the probability–severity score and assigns the priority tier. Ten of the fifteen factors fall in the High tier, four in the Medium tier, and one, material wastage, in the Low tier. The High tier contains four of the five geological factors (landslide, slope failure, flooding, earthquake), two of the four environmental factors (clearance delays, climate change effects), and four of the six operational factors (equipment failure, labour shortage, poor workmanship, safety incidents). Landslide, slope failure, flooding, poor workmanship, and safety incidents share the maximum score of 9 because they combine a High probability with High severity in the conditions assumed for this study.

Table 3. Probability – severity ranking and priority tier (H = 3, M = 2, L = 1; High: PS ⩾ 6, Medium: PS 3 – 5, Low: PS ⩽ 2)

Risk factor	Probability	Severity	PS	Priority tier
Landslide	H	H	9	High
Slope failure	H	H	9	High
Flooding	H	H	9	High
Poor workmanship	H	H	9	High
Safety incidents	H	H	9	High
Earthquake	M	H	6	High
Environmental clearance delays	H	M	6	High
Climate change effects	M	H	6	High
Equipment failure	H	M	6	High
Labour shortage	H	M	6	High
Soil erosion	M	M	4	Medium
Regulatory compliance issues	M	M	4	Medium
Environmental degradation	M	M	4	Medium
Material supply delays	M	M	4	Medium
Material wastage	M	L	2	Low

The ranking and the composite impact index are consistent at the extremes. Factors with the highest CII, namely slope failure, earthquakes, and safety incidents, are all High tier, and the only Low-tier factor, material wastage, has one of the lowest CII values. The two measures answer different questions: the CII describes how much a factor would hurt if it occurred, while the PS score also reflects how likely it is. Earthquakes illustrate the difference. They have the maximum CII but only a Medium probability, which places them at the lower boundary of the High tier.

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4.4 FMEA-based prioritization

Table 4 presents the FMEA of the seven failure modes ranked by RPN. Project mismanagement has the highest RPN (252), followed by flooding (240) and material shortage (210). Soil instability (180), equipment failure (168), and worker injury (144) form a middle group, and regulatory non-compliance has the lowest RPN (72). The total RPN across the seven modes is 1266, and the top three modes account for 702 of it, or 55.5%. Risk is therefore concentrated in a small number of failure modes, which supports a focused treatment strategy. Figure 3 shows the RPN of each mode.

Table 4. FMEA results ranked by Risk Priority Number (RPN = S × O × D)

Rank	Failure mode	Family	Main cause	S	O	D	RPN	Share of total
1	Project mismanagement	Operation al	Poor planning, communication	7	6	6	252	19.9%
2	Flooding	Geologica l	Heavy rainfall, poor drainage	8	5	6	240	19.0%
3	Material shortage	Operation al	Supplier issues	6	7	5	210	16.6%
4	Soil instability	Geologica l	Poor soil assessment	9	4	5	180	14.2%
5	Equipment failure	Operation al	Lack of maintenance	7	6	4	168	13.3%
6	Worker injury	Operation al	Unsafe practices	9	4	4	144	11.4%
7	Regulatory non-compliance	Environm ental	Incomplete permits	8	3	3	72	5.7%
	Total						**1266**	100%

Shares are rounded to one decimal place and therefore sum to 100.1% in the column.

The mean RPN by family is 210 for the two geological modes, 193.5 for the four operational modes, and 72 for the single environmental mode. Because the number of modes per family differs, these values describe this set of failure modes and should not be treated as family-level risk estimates.

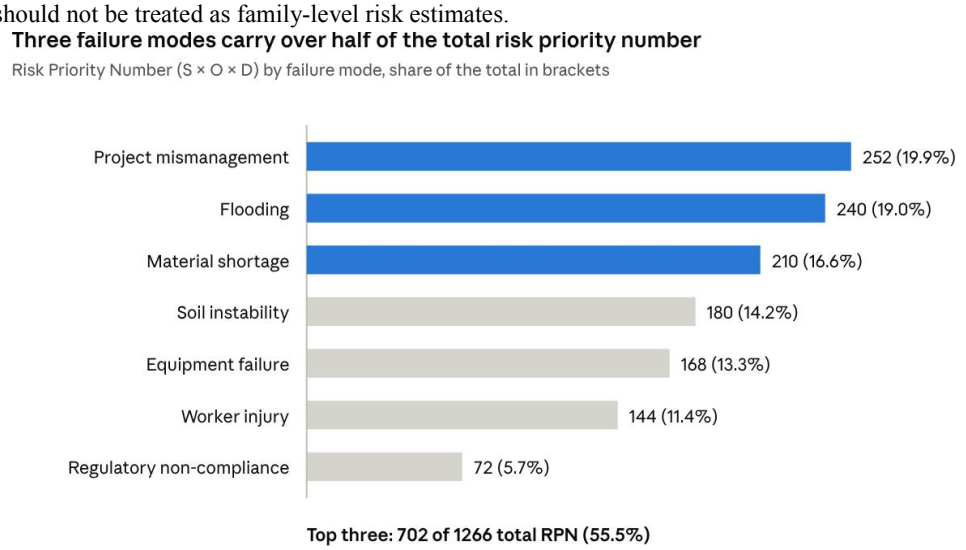


Figure 3. Risk Priority Number by failure mode, ranked from highest to lowest.

4.5 Context sensitivity: landslide and equipment failure

The same FMEA formula can be applied to context-specific cases. Table 5 shows two worked examples. For a landslide in hilly terrain, with severity 9, occurrence 7, and detectability 6, the RPN is 378, which is a Very High priority. For equipment failure with severity 6, occurrence 5, and detectability 4, the RPN is 120, a Moderate priority. The landslide RPN is therefore about 3.2 times the equipment RPN and calls for immediate, dedicated mitigation.

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Table 5. Worked context-specific RPN examples

Case	S	O	D	RPN	Priority level
Landslide risk (hilly terrain)	9	7	6	378	Very High
Equipment failure	6	5	4	120	Moderate

The landslide example also shows how strongly the result depends on site conditions. In the general FMEA in Table 4, soil instability, with occurrence 4 and detectability 5, has an RPN of 180. In steep, high-rainfall terrain, where occurrence is higher and warning is harder, the RPN is more than twice as large. Risk scores should therefore be recalibrated for each corridor, and a generic ranking should serve only as a starting point.

4.6 Comparison of the two prioritization logics

The probability–severity ranking (Table 3) and the FMEA (Table 4) agree on several points. Both place flooding, soil and slope instability, and equipment failure among the significant risks, and both place regulatory risk in a lower tier. They disagree in two informative ways. First, material supply is a Medium-tier factor in the probability–severity ranking (PS = 4) but ranks third in the FMEA (RPN 210). The FMEA gives it a high occurrence score of 7 and a moderate detectability score of 5, reflecting that shortages are frequent and are often noticed only when work has already stopped. Second, project mismanagement ranks first in the FMEA although it is not a separate factor in Table 3. Its severity is moderate (7), but both occurrence (6) and detectability (6) are high, because planning and coordination weaknesses are common and are often recognized late.

The highest-severity modes, soil instability and worker injury (S = 9), rank only fourth and sixth by RPN because their occurrence and detectability scores are lower. This is a known property of the RPN: a catastrophic but rarer and more detectable event can rank below a moderate but frequent and hidden one. The practical conclusion is that the two ranking logics are complementary. Probability–severity highlights where consequences are greatest, and the FMEA highlights where failures are likely to go unnoticed.

V. DISCUSSION

5.1 What drives the geological dominance

Geological factors have the highest composite impact because their consequences propagate across all three dimensions at once. A slope failure delays work while the slope is investigated and stabilized, adds cost through retaining structures, drainage, and repair, and leaves a quality risk if the underlying ground condition is not fully resolved. These events are also the least reversible and the most dependent on early information. Soil investigation, hazard mapping, and drainage design carried out before construction are therefore the most effective levers for reducing the impact of this family, and they should be funded in the planning stage and not treated as a contingency.

5.2 Root causes and interactions

Root cause analysis of the three families points to a small set of recurring causes. Geological problems most often trace back to insufficient site investigation and inadequate planning. Environmental problems trace back to incomplete assessment and weak stakeholder engagement. Operational problems trace back to inadequate planning and weak oversight, which show up as poor project management, safety incidents, equipment failures, and supply problems. These causes are organizational and informational as much as technical, which explains why project mismanagement ranks first in the FMEA.

The families also interact. Heavy rainfall that floods a site can damage equipment and stored material, which in turn creates supply delays and idle labour. Environmental restrictions on working areas or methods can constrain operations and raise the likelihood of delay. Equipment failure and labour shortage can amplify the effect of a geological event by slowing the response. Any prioritization that treats the families in isolation will therefore understate the combined effect, which supports assessing them with a common vocabulary and scale as done here.

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5.3 Mitigation strategies

Table 6 summarizes mitigation strategies by family, organized into preventive measures, monitoring and detection measures, and contingency responses. The structure follows the logic of the FMEA: preventive measures act on occurrence, monitoring measures act on detectability, and contingency measures limit the consequence once an event occurs.

Table 6. Mitigation strategies by risk family

Family	Preventive measures	Monitoring and detection	Contingency response
Geological	Geotechnical surveys, hazard zoning, slope stabilization, drainage and erosion control, resilient pavement design	Slope and groundwater monitoring, rainfall-based alerts, regular site inspection	Alternative routing, stocks of emergency repair material, pre-agreed recovery procedures
Environmental	EIA, environmental management plan, erosion and sediment control, habitat protection, early regulator and community engagement	Water, air, dust and noise monitoring, permit and compliance tracking	Design revision options, restoration and compensation measures, rapid regulator liaison
Operational	Preventive and predictive maintenance, workforce training, supplier vetting, quality assurance and control, project management software	Equipment downtime tracking, delivery tracking, safety audits and inspections, progress reviews	Backup suppliers, rented equipment, cross-trained crews, emergency response drills

5.4 Effect of targeted controls on the RPN profile

Table 7 shows the illustrative what-if scenario described in Section 3.6. Severity is unchanged and the occurrence and detectability scores are re-estimated assuming that the listed control is implemented effectively. Under these assumptions the total RPN falls from 1266 to 424, a reduction of 66.5%, and the reduction ranges from 55.6% for regulatory non-compliance to 70% for flooding and soil instability. Figure 4 compares the RPN before and after the controls.

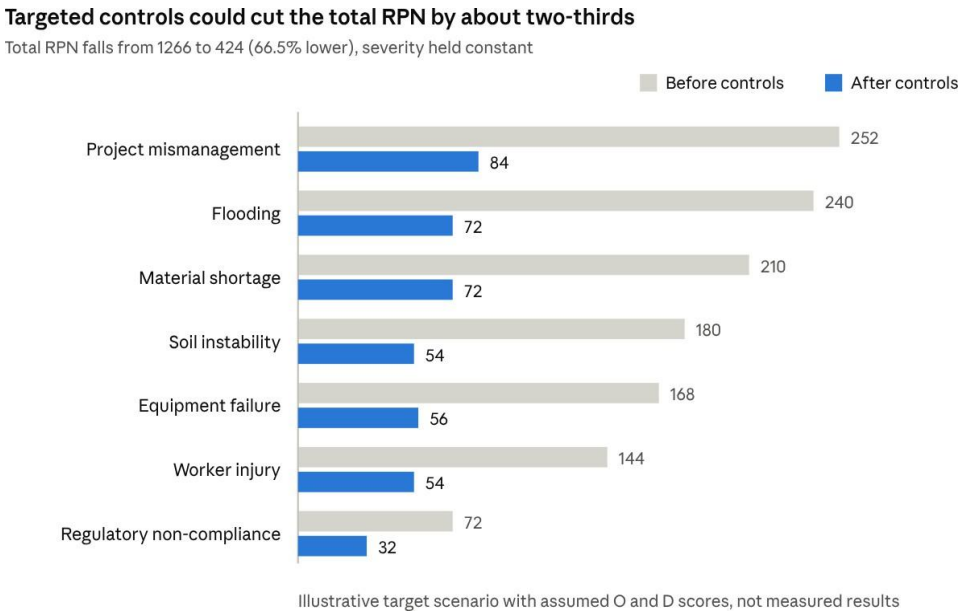


Figure 4. RPN of each failure mode before and after the targeted controls (illustrative scenario).

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Table 7. Illustrative pre- and post-mitigation RPN scenarios (target values, not measurements)

Failure mode	Targeted control	Before (S×O×D)	RPN before	After (S×O×D)	RPN after	Reduction
Project mismanagement	Project management software, governance and regular reviews	7×6×6	252	7×4×3	84	66.7%
Flooding	Drainage upgrades, early-warning and rainfall monitoring	8×5×6	240	8×3×3	72	70.0%
Material shortage	Supplier diversification and buffer stock	6×7×5	210	6×4×3	72	65.7%
Soil instability	Geotechnical survey and slope monitoring	9×4×5	180	9×3×2	54	70.0%
Equipment failure	Preventive and predictive maintenance	7×6×4	168	7×4×2	56	66.7%
Worker injury	Training, safety audits and inspections	9×4×4	144	9×2×3	54	62.5%
Regulatory non-compliance	Compliance checklist and early regulator engagement	8×3×3	72	8×2×2	32	55.6%
Total			**1266**		**424**	**66.5%**

Two observations follow. First, project mismanagement remains the highest-ranked mode after treatment (RPN 84), which suggests that governance and planning discipline deserve continuing attention and not a one-time fix. Second, soil instability and worker injury keep a severity of 9, so even a low RPN does not mean a low consequence. For these modes, controls that reduce the consequence itself, such as retaining structures and protective barriers on the geological side and engineered safeguards on the safety side, should accompany the controls that reduce likelihood and improve detection.

5.5 Monitoring indicators

Prioritization has lasting value only if it is updated as the project evolves. Table 8 lists key risk indicators that can be tracked for each family and that correspond to the highest-ranked failure modes. A sustained adverse trend in an indicator should trigger a review of the related RPN and of the effectiveness of the control.

Table 8. Key risk indicators linked to the prioritized risks

Family	Indicator	Linked risk	What a sustained adverse trend signals
Geological	Slope movement and groundwater level readings	Soil instability, landslide	Declining stability margin and rising occurrence
Geological	Rainfall relative to design drainage capacity	Flooding, erosion	Higher flooding probability and weaker detection
Environmental	Permit status and compliance audit findings	Regulatory non-compliance, clearance delay	Risk of stoppage or approval delay
Environmental	Dust, noise and water-quality measurements	Environmental degradation	Mitigation measures are not effective
Operational	Equipment downtime	Equipment failure	Maintenance regime is inadequate
Operational	Material delivery delay	Material shortage	Supply chain weakness, impending idle time
Operational	Accident and near-miss rate	Worker injury, safety	Safety culture and supervision gaps

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		incidents	
Operational	Schedule and cost variance	Project mismanagement	Planning or coordination failure

5.6 Practical implications

Several implications follow for project owners and contractors. First, funds and time for geotechnical and hydrological investigation should be committed before design is finalized, because this addresses the family with the highest impact. Second, management and coordination risk deserves explicit treatment in the risk register and not just assumption, because it ranked first in the FMEA and is often detected late. Third, supply planning, such as supplier diversification and buffer stocks for critical materials, is a low-cost measure that targets a failure mode that the FMEA ranks much higher than a probability–severity view alone. Fourth, safety management and training have a dual effect, reducing both the occurrence of injuries and their downstream effects on time, cost, and quality. Finally, early engagement with regulators and communities reduces the chance of clearance delay and non-compliance, which are less severe individually but add to schedule and cost pressure.

VI. LIMITATIONS AND FUTURE WORK

The findings have several limitations. First, the ratings are judgement-based and are not calibrated to measured data from an instrumented project, so the absolute values of the CII, PS, and RPN should not be treated as estimates for a specific corridor. Second, the mapping of H, M, and L to 3, 2, and 1 treats the categories as equally spaced [21], and the RPN uses ordinal scales as if they were ratio scales. Third, as discussed in Section 2.5, the RPN weights severity, occurrence, and detectability equally and can assign the same value to very different risk profiles. Fourth, the classification of regulatory compliance within the environmental family reflects its role in this study, and a different classification could alter the family means. Fifth, the mitigation scenarios are target values under the assumption of effective implementation and do not predict the outcome of a particular program.

Future work can address these limitations in four ways. Expert elicitation, for example through a structured survey or Delphi process [22] with engineers and project managers, would provide calibrated ratings and a measure of agreement. Multi-criteria methods such as the analytic hierarchy process [23] could weight severity, occurrence, and detectability explicitly, and action-priority rules could replace the plain RPN [10]. Probabilistic simulation could convert the ratings into distributions of schedule and cost outcomes, and geospatial hazard mapping could provide corridor-specific occurrence scores for geological risks. Finally, validation on one or more completed road projects, comparing predicted priorities with recorded delays, overruns, and defects, would test whether the procedure ranks risks in the same order as experience.

VII. CONCLUSION

This paper presented an integrated prioritization of fifteen geological, environmental, and operational risk factors for road infrastructure projects, using a common time–cost–quality impact scale, a probability–severity ranking, and an FMEA of seven failure modes. Geological factors have the highest composite impact, followed by operational and environmental factors, and slope failure, earthquakes, and safety incidents are the only factors rated High on all three dimensions. Ten of the fifteen factors fall in the High priority tier. In the FMEA, project mismanagement, flooding, and material shortage rank highest and account for over half of the total RPN, which shows that risk is concentrated and that focused treatment is efficient.

The comparison of the two prioritization logics shows that they are complementary. Probability–severity emphasizes consequence, while FMEA adds detectability and therefore elevates frequent, hidden failures such as supply shortages and weak project management. Illustrative scenarios indicate that targeted preventive and monitoring controls could reduce the aggregate RPN by about two-thirds, although severity-driven risks such as soil instability and worker injury still require controls on the consequence. Because the ratings are judgement-based, the procedure should be calibrated with expert elicitation and validated against project data before the numerical results are used for a specific project. As

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a transparent and repeatable method, however, it gives planners a practical way to decide where limited mitigation effort should go first.

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