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OPERATIONAL RISK ASSESSMENT IN NICKEL ORE LOADING, HAULAGE, AND STOCKPILE OPERATIONS: AN INTEGRATED HIRADC FRAMEWORK BASED ON FIELD OBSERVATION AND CRITICAL-CONTROL VERIFICATION

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Abstract

Nickel ore production involves continuous interaction between heavy equipment, haulage vehicles, field personnel, and changing site conditions. These activities can create serious occupational safety risks, particularly at loading points, along haul roads, and within stockpile areas. This study assessed operational risks associated with nickel ore loading, haulage, and stockpiling using an integrated Hazard Identification, Risk Assessment, and Determining Control (HIRADC) framework. The three month assessment covered 120 workers and 116 heavy equipment units, supported by 20 task exposure observations and six documented near miss cases. Eleven principal hazards were identified. Four hazards were classified as critical or potentially fatal, five as high risk, and two as low risk. The most urgent hazards were heavy equipment interaction, unsafe positioning near excavation or stockpile edges, inter unit communication failure, and fatigue among operators or grade control personnel. Communication failure produced the highest exposure adjusted event rate, while its critical control showed inconsistent implementation. The findings indicate that effective risk reduction in nickel ore operations requires more than the provision of personal protective equipment. Priority should be given to traffic control, exclusion zone enforcement, two way communication, fatigue management, haul road maintenance, and routine verification of critical controls under actual field conditions.

Keywords: critical control verification; HIRADC; haul road; loading point; nickel mining; occupational safety; risk assessment; stockpile

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Introduction

Nickel has become one of the strategic minerals behind stainless steel production, battery manufacturing, and low carbon energy systems. Indonesia occupies an important position in this supply chain, and the expansion of nickel extraction has increased the operational intensity of open pit mines. This growth is economically important, but it also places workers and equipment in a more demanding production environment (Awwal et al., 2025; Moldoveanu & Moraru, 2024; U.S. Geological Survey, 2026). In daily operation, excavators, dump trucks, bulldozers, light vehicles, supervisors, grade control personnel, and sampling teams may occupy the same active work area within a short time window (Hollá et al., 2024; Lombardi, Mauro, Fagnoli, et al., 2023). Open-pit nickel mining involves the simultaneous operation of excavators, dump trucks, light vehicles, support equipment, and field personnel in a continuously changing work environment. Ground conditions, traffic density, weather, visibility, material stability, and production demands can change considerably within a short period (Haka, 2023; Milošević et al., 2025; Moniri-Morad et al., 2024; Yu et al., 2017; Zhou, 2022). Consequently, occupational risks arise not from a single hazard source but from the interaction of technical, environmental, human, and organizational factors (Wardani et al., 2026). Effective safety management must therefore extend beyond regulatory compliance and become an integral component of operational planning, equipment management, production control, and workforce supervision (Leong, 2026).

The loading point, haul road, and stockpile form a continuous production sequence, but each area produces a different pattern of exposure. At the loading point, the main concern is the interaction between excavators, dump trucks, and workers who may enter blind spot zones or approach the edge of an excavation (Mu'afa & Ariastuti, 2024; Wardani et al., 2026). Along the haul road, risk is influenced by road width, gradient, drainage, surface condition, traffic density, dust, speed control, and the driver's physical condition (Everett & Jacobs, 1993; Fadhilah et al., 2023; Gragasini et al., 2018; Mohammad et al., 2026; Shafique, 2022). At the stockpile, reversing, dumping, material spreading, and inspection activities create risks related to vehicle contact, unstable dumping surfaces, and material movement (Flores, 2022; Korshunov et al., 2025; Kumalasari & Imaduddin, 2025; Sadewa & Hafid Syaifullah, 2025; Stewart, 2010).

Human and organizational factors are equally important. Communication breakdown, fatigue, weak supervision, poor compliance with exclusion zones, and delayed response during changing field conditions can reduce the effectiveness of procedures (Hollá et al., 2024; Jayakrishnan et al., 2013; Lombardi, Mauro, Fagnoli, et al., 2023; Putri et al., 2026; Sari et al., 2026). For this reason, a risk register that records only whether a control exists may provide an incomplete picture. A control should be judged by whether it is present, functioning, understood, and followed during the work itself (Awwal et al., 2025; Beš et al., 2025; Hwang et al., 2024; Lombardi, Mauro, Berardi, et al., 2023; Zhafir et al., 2026). HIRADC is widely used to identify hazards, assess risk, and determine control measures. The method is practical and familiar to mine safety teams because it links work activities with potential consequences and control priorities. However, conventional application often relies on static probability severity matrices. Such matrices are useful as a starting point, but they may not capture changes in road condition, visibility, traffic density, fatigue, exposure duration, near miss patterns, or compliance with critical controls (Beš et al., 2025; Burtan et al., 2025; Gutiérrez-Ruiz et al., 2021; Hollá et al., 2024; Korshunov et al., 2025; Lombardi, Mauro, Fagnoli, et al., 2023; Markovic et al., 2025; Murtadha et al., 2017; Ranjbari, 2023; Shi et al., 2023). Risk scores are often assigned at the job or process level and may remain unchanged despite variations in work shifts, weather conditions, road quality, traffic intensity, exposure duration, operator fatigue, communication reliability, and compliance with established controls (Aturupane, 2022; Benitez, 2022; Tolera et al., 2023; Zhafir et al., 2026; Zou et al., 2025). This simplification is a concern in open-pit mining, where operating conditions can change within hours. Consequently, risk ratings based on average or assumed conditions may not accurately represent the risks encountered during daily operations. Another limitation is the

limited use of exposure-related evidence and observable indicators of safety performance. Many risk assessments identify hazards and assign categorical risk levels without systematically considering near-miss records, observations of unsafe events, exposure frequency and duration, or the verified performance of existing controls (Burtan et al., 2025). Existing controls are frequently recorded as either present or absent without directly assessing their functionality or the level of compliance under field conditions. As a result, conventional assessments may identify priority hazards but provide limited evidence explaining why risks remain high, the operating conditions under which they increase, or the controls that require immediate improvement. Recent developments in occupational safety management have therefore placed greater emphasis on leading indicators, repeated field observations, exposure data, and the verification of critical controls (Baghaei Naeini & Badri, 2024; Burtan et al., 2025; Gutberlet et al., 2013; Lee & Inaba, 2004).

These approaches shift risk assessment from a predominantly static exercise toward a more evidence-based process capable of reflecting operational variability. Nevertheless, integrated applications remain limited in open-pit nickel mining, especially across loading-point, hauling-road, and stockpile activities where mobile-equipment interaction and changing field conditions generate persistent high-potential risks. To address this gap, the present study develops an Operational-Based Integrated HIRADC Framework for nickel mining operations. The framework combines task-level field observation, operational exposure, near-miss information, environmental conditions, human factors, and critical-control verification within the HIRADC process. The unit of observation is defined as a specific dump-truck activity performed within a designated work zone during a fixed observation period. Each observation records the work location, operational task, equipment involved, worker role, work shift, environmental conditions, identified hazards, existing controls, compliance status, unsafe events, near-miss occurrence, and exposure duration (Hollá et al., 2024; Jayakrishnan et al., 2013; Khrais et al., 2024; Lombardi, Mauro, Fagnoli, et al., 2023). This structure allows risk assessments to be repeated under different operating scenarios and facilitates comparisons across work areas, activities, environmental conditions, and levels of control performance. The study advances conventional HIRADC by shifting its application from a static, task-based checklist toward a framework that responds to actual operating conditions. Rather than relying solely on likelihood and severity scores, the proposed approach integrates hazard exposure, field conditions, control performance, and recorded safety events. This integration helps distinguish risks indicated by formal documentation from those encountered during operations and provides a more practical basis for prioritizing control measures according to their effectiveness in the field. (Al Zhafir et al., n.d.-a; Benitez, 2022; Zhafir et al., 2026).

This study develops and applies an Operational Based Integrated HIRADC Framework for nickel ore loading, haulage, and stockpile operations. The framework keeps the conventional probability severity structure, but adds field observation, near miss evidence, exposure adjusted event rates, independent assessor comparison, and critical control verification. The objective is to produce a risk assessment that is closer to the way work is actually performed in the field and more useful for prioritizing corrective action.

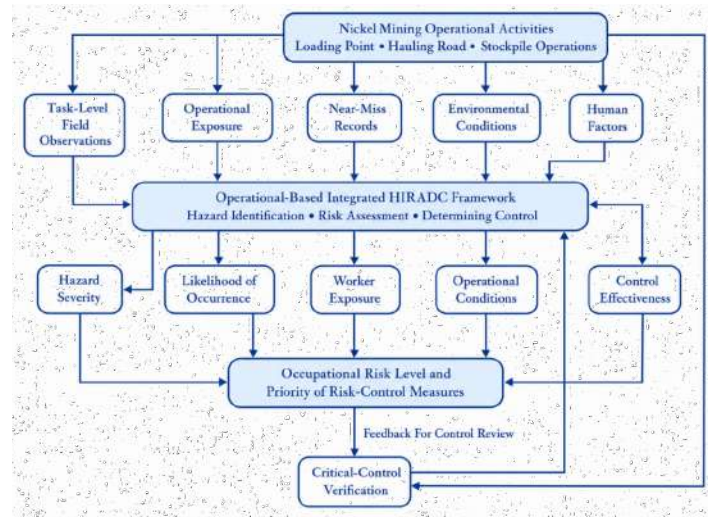


Figure 1. Integrated HIRADC inputs and assessment process

Research Methods

The study used an observational case study design at PT Makmur Lestari Primatama's nickel mining operation in North Konawe Regency, Indonesia. Field data were collected from April to June 2026. The assessment focused on three operational areas: loading point, haul road, and stockpile. These areas were selected because they represent the main sequence of ore movement and involve repeated interaction between mobile equipment and field personnel. The operation involved approximately 120 workers and 116 heavy equipment units, consisting of 50 dump trucks, 45 excavators, and 21 bulldozers. Observations were carried out during day and night shifts and covered dry and wet weather, normal and reduced visibility, different traffic densities, variable road surface conditions, and changes in production intensity. The primary unit of analysis was the task exposure observation. One observation was defined as a worker or equipment unit performing a specified task in a defined operational area during a 30 minute observation period. This approach (Mu'afa & Ariastuti, 2024; Zhafir et al., 2026) allowed the assessment to connect a risk score to an observed work situation, rather than to a broad occupation or generic production stage.

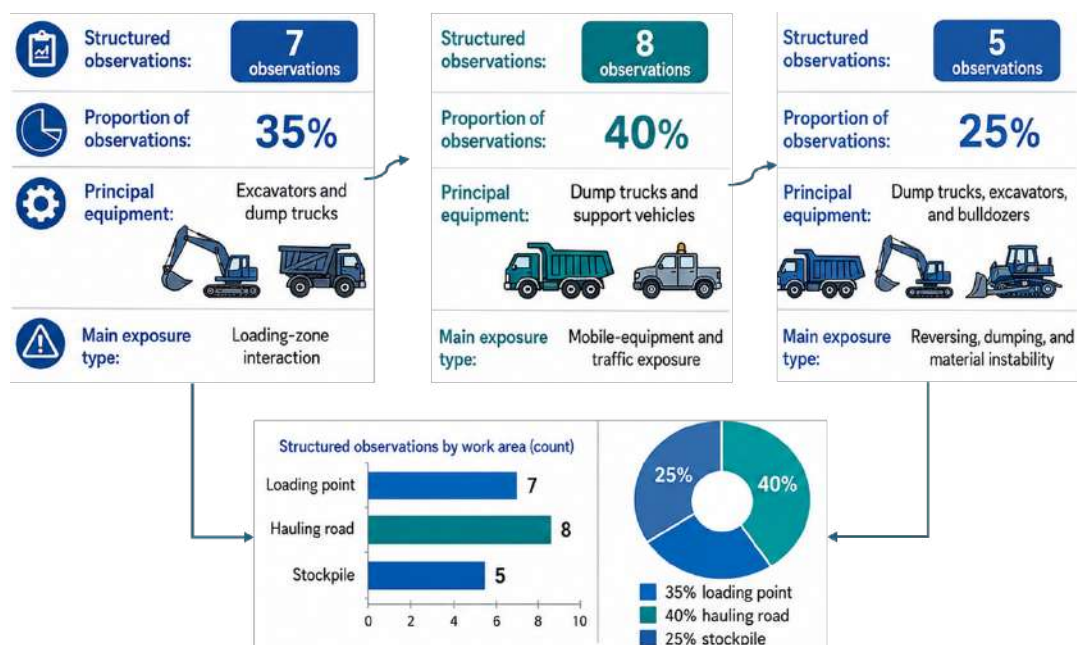


Figure 2. Operational observation profile by work area: loading – hauling – stockpiling

Field observations were organized according to the operational sequence of nickel ore movement. At the loading point, the assessment followed the movement of dump trucks from their approach to the excavator, positioning during loading, material transfer, grade-control inspection, ore sampling, and departure from the loading area. Along the haul road, the observations covered both loaded and empty truck movements, including queuing, passing, travelling through curves and gradients, and operating under limited visibility. At the stockpile, the observed tasks included reversing, dumping, material spreading, vehicle movement after unloading, inspection, and sampling activities.

Risk evaluation was carried out using the company-approved 5×5 probability–severity matrix. Probability was interpreted as the credible likelihood of an unwanted event occurring under the observed field conditions, while severity represented the most credible consequence if the event occurred. The field checklist was prepared based on the company's existing HIRADC register, operating procedures, mine-safety requirements, mobile-equipment interaction controls, and internal critical-control standards. For each observation, the recorded information included the work area, task, equipment involved, worker role, work shift, weather, visibility, road or ground condition, traffic intensity, identified hazards, existing controls, compliance status, unsafe acts or conditions, near-miss occurrence, and exposure duration.

Fatigue-related information was obtained from work schedules, shift duration, overtime, consecutive working days, elapsed time within the shift, rest-break availability, commuting duration, and observable signs of reduced alertness. The field indicators used to recognize fatigue included delayed responses, repeated procedural errors, reduced concentration, inconsistent communication, and loss of situational awareness. All fatigue-related information was analyzed at the group level and was not used for disciplinary purposes. The observation variables used in the study are summarized in Table 1.

Table 1. Study population, observational coverage, and analytical inputs

No.	Observation Variable	Description	Quantity
1	Observation period	Duration of field data collection	3 months
2	Workers observed	Workers involved in the observed activities	120 workers
3	Dump trucks	Dump trucks operating within the study areas	50 units
4	Excavators	Heavy equipment observed during operation	45 units
5	Bulldozers	Heavy equipment observed during operation	21 units
6	Total heavy equipment	Combined number of dump trucks, excavators, and bulldozers	116 units
7	Structured HIRADC observations	Formal observations conducted to identify hazards, assess risks, and evaluate existing controls	20 observations
8	Near-miss cases analyzed	Documented near-miss events analysed to identify recurring risk	6 cases
9	Independent assessors	Assessors responsible for evaluating risks and verifying the consistency of the assessments	3 assessors

Each activity was broken down into task steps to capture changes in hazard exposure within the same work area. For instance, truck positioning near an excavator, grade-control inspection inside the loading radius, and night hauling on a wet gradient present different risk conditions. This task-based approach helped identify hazard sources, exposure routes, and required controls more accurately.

The study covered workers and equipment directly involved in nickel ore production, including equipment operators, grade-control personnel, road-maintenance workers, supervisors, and safety personnel. The unit of analysis was a 30-minute task-exposure observation, defined as one worker or equipment unit performing a specific task in a designated operational area. In total, 20 structured HIRADC observations were conducted across loading, hauling, and stockpile activities, supported by six documented near-miss cases used to verify recurring hazard patterns.

HIRADC risk assessment

Risk was assessed using the company-approved 5×5 probability–severity matrix. Probability represented the likelihood of an unwanted event under existing operating conditions, whereas severity represented the most credible consequence. The initial risk score was calculated as Eq. (1) while the exposure adjusted event rate was calculated as Eq. (2).

$$R_i = P_i \times S_i \quad 1) \quad EAER = \frac{N}{E} \times K \quad 2)$$

Where R_i initial risk score, P_i probability rating and S_i severity rating. Then $EAER$ means exposure-adjusted event rate, N , number of observed hazards, unsafe acts, unsafe conditions, or near-miss events, E , operational exposure and K , standardization constant. In this case Probability ratings were informed by field observations and event history. The company risk matrix classified scores of 12–16 as high risk and a score of 25 as critical or fatal risk, with severity ratings considered the most credible outcome, including first-aid injury, medical-treatment injury, lost-time injury, permanent disability, single fatality, multiple fatalities, major equipment damage, and operational interruption. Structured field observations were conducted using a standardized checklist developed from the company's existing HIRADC register, relevant operating procedures, applicable mine-safety requirements, mobile-equipment interaction controls, and internal critical-control standards.

Table 2. Probability criteria for the HIRADC assessment

Score	Probability category	Operational definition	Indicative evidence
1	Rare	The event is unlikely to occur under normal operations and has not been recorded or observed within the available assessment period.	No relevant incident or near miss; infrequent task exposure; controls consistently implemented and verified.
2	Unlikely	The event could occur under abnormal conditions but is not expected during routine operations.	Isolated unsafe condition; low exposure frequency; minor control deviation; no recurring event pattern.
3	Possible	The event may occur occasionally during routine operations, particularly when operational or environmental conditions deteriorate.	Previous near miss; repeated unsafe condition; moderate exposure; variable control compliance.
4	Likely	The event is expected to occur repeatedly unless additional controls are introduced, or existing controls are strengthened.	Recurrent near misses or unsafe acts; frequent exposure; inadequate communication; inconsistent control implementation.
5	Almost certain	The event is highly likely or repeatedly observed during normal operations.	Frequent unsafe events; persistent control failure; continuous exposure; recurring incident pathway.

Table 3. Severity criteria for the HIRADC assessment

Score	Severity category	Personnel consequence	Equipment and operational consequence
1	Insignificant	No injury or minor discomfort requiring no medical treatment	Negligible equipment damage and no production interruption
2	Minor	First-aid injury or short-term reversible health effect	Minor repair and short-duration operational delay
3	Moderate	Medical-treatment injury, restricted work, or lost-time injury	Moderate equipment damage or temporary disruption of operations

4	Major	Permanent disability, serious occupational illness, or a single life-threatening injury	Major equipment damage, prolonged shutdown, or substantial production loss
5	Catastrophic	Single or multiple fatalities	Destruction of major equipment, extensive operational interruption, or major environmental consequence

Table 4. Proposed 5 × 5 HIRADC risk matrix

Severity	Probability 1: Rare	Probability 2: Unlikely	Probability 3: Possible	Probability 4: Likely	Probability 5: Almost certain
5—Catastrophic	5 M	10 M	15 H	20 C	25 C
4—Major	4 L	8 M	12 H	16 H	20 C
3—Moderate	3 L	6 M	9 M	12 H	15 H
2—Minor	2 L	4 L	6 M	8 M	10 M
1—Insignificant	1 L	2 L	3 L	4 L	5 M

Notes: L = low, M = moderate, H = high, and C = critical.

Table 5. Risk-classification and response criteria

Risk score	Risk category	Required response	Recommended completion period
1–4	Low	Maintain existing controls and monitor routine performance.	Routine monitoring
5–10	Moderate	Review existing controls and implement feasible improvements.	Planned corrective action
12–16	High	Introduce additional controls before continuing prolonged exposure; strengthen supervision and control verification.	Immediate or short-term action
20–25	Critical	Suspend or restrict the activity until effective controls reduce the risk to an acceptable level.	Immediate action before work resumes

The second domain assessed workplace and environmental conditions, including road quality, drainage, width, gradients, berm condition, weather, dust, lighting, and visibility. These factors were reviewed because they can affect vehicle stability, braking, maneuverability, and collision risk. The third domain focused on human factors, such as worker positioning, procedure compliance, PPE use, fatigue signs, response delay, situational awareness, and communication. The fourth domain examined safety management practices, including supervisor presence, pre-start briefings, inspections, permits, critical controls, and corrective actions, to determine whether field supervision and control systems were consistently applied.

Human-Factor and Fatigue Assessment

Fatigue-related information was obtained from work schedules, shift duration, overtime, consecutive working days, elapsed time within the shift, rest-break frequency, self-reported sleep duration, commuting duration, and observable signs of reduced alertness. Field indicators of fatigue included delayed reactions, repeated procedural errors, reduced concentration, inconsistent communication, loss of situational awareness, and inappropriate operational decision-making. These indicators were documented during structured field observations and, where necessary, cross-checked through discussions with supervisors or review of work-schedule records. All fatigue-related information was anonymized and analyzed at the group level. Individual data were not used for disciplinary purposes and were not reported in a form that could identify specific workers. To strengthen fatigue assessment, future observations should use a validated instrument when field conditions allow. The Karolinska Sleepiness Scale or the Samn-Perelli Fatigue Scale may be applied because both provide standardized measures of perceived sleepiness and work-shift fatigue.

Research Results and Discussion

Operational Coverage and Observation Characteristics

The 20 structured observations consisted of seven observations at the loading point, eight along the haul road, and five at the stockpile. The distribution was designed to provide risk informed operational coverage rather than proportional representation of the workforce. More observations were assigned to the haul road because this area involved longer exposure, continuous movement, and greater variation in road geometry, surface condition, visibility, traffic density, weather, and shift duration.

Table 6 presents the operational coverage used in the field assessment. The observations were distributed based on risk exposure, not workforce proportion. More observations were assigned to the hauling road because this area involved continuous vehicle movement, longer exposure, and greater changes in traffic, visibility, road condition, gradient, and weather. Loading-point observations focused on excavator, dump-truck, and worker interaction, while stockpile observations covered reversing, dumping, material spreading, and equipment movement near unstable edges. Together, these observations captured the main nickel ore production sequence from loading to hauling and stockpiling.

Table 6. Operational coverage of the field assessment

Parameter	Loading point	Hauling road	Stockpile	Total
Structured observations	7	8	5	20
Proportion of observations	35%	40%	25%	100%
Principal equipment	Excavators and dump trucks	Dump trucks and support vehicles	Dump trucks, excavators, and bulldozers	116 units
Main exposure type	Loading-zone interaction	Mobile-equipment and traffic exposure	Reversing, dumping, and material instability	—

Table 7. EAER calculation for priority hazards

No.	Hazard	N (observed events)	E (exposure hours)	K	EAER = (N/E)×K
1	Heavy-equipment interaction	3	10	1,000	300 per 1,000 h
2	Positioning near excavation/stockpile edge	2	10	1,000	200 per 1,000 h
3	Inter-unit communication failure	4	10	1,000	400 per 1,000 h
4	Operator/grade-control fatigue	2	10	1,000	200 per 1,000 h

N is the count of unsafe acts/conditions/near-misses recorded across the 20 observations for that hazard. E is the total relevant exposure time (e.g., 20 observations × 30 minutes = 10 hours). K is chosen for readability (per 1,000 hours, per 100 hours)

Table 8. Ratings from three assessors for five priority hazards

Hazard	Assessor 1 (P,S)	Assessor 2 (P,S)	Assessor 3 (P,S)	Agreement
Heavy-equipment interaction	4,5	4,5	3,5	Partial (P differs)
Positioning near edge	4,5	4,5	4,5	Full
Communication failure	4,4	4,5	4,5	Partial (S differs)

Hazard	Assessor 1 (P,S)	Assessor 2 (P,S)	Assessor 3 (P,S)	Agreement
Fatigue	4,5	3,5	4,5	Partial (P differs)
Elevation difference	4,4	4,4	4,4	Full

Table 9. Critical-control verification results

Critical hazard	Critical control	Present?	Functioning?	Complied with?	Verification status
Heavy-equipment interaction	Exclusion zone + spotter	Yes	Partial	65%	Verified - partial
Positioning near edge	Edge barrier/bund wall	Yes	Yes	80%	Verified
Communication failure	Mandatory two-way radio	Yes	Inconsistent	55%	Not verified
Fatigue	Work-hour limits + rest breaks	Partial	Not measured	-	Not verified

Across the loading point, hauling road, and stockpile, eleven principal hazards were identified: heavy-equipment interaction, unsafe positioning near excavation or stockpile edges, dust exposure, elevation differences, slippery or soft road surfaces, narrow road sections, exhaust emissions, inter-unit communication failure, fatigue, work-related stress, and heat exposure. The risk level of each hazard varied according to the work area and operating condition. At the loading point, the main concern was close interaction between excavators, dump trucks, and field personnel. Along the hauling road, risks were strongly influenced by traffic movement, road geometry, visibility, surface condition, communication, and operator fatigue. At the stockpile, the main risks were related to reversing, dumping, material instability, and equipment movement near unstable edges.

Table 7 presents the Exposure-Adjusted Event Rate (EAER) for four critical hazards. The EAER was calculated from the number of observed unsafe acts, unsafe conditions, or near-miss events divided by the relevant exposure time and standardized per 1,000 exposure-hours. Inter-unit communication failure recorded the highest EAER at 400 events per 1,000 exposure-hours, followed by heavy-equipment interaction at 300 events per 1,000 exposure-hours. Unsafe positioning near excavation or stockpile edges and fatigue each recorded 200 events per 1,000 exposure-hours. These values should be interpreted as comparative indicators within the observation dataset, not as long-term accident rates.

Table 8 shows that assessor judgments were generally consistent. Full agreement was obtained for unsafe positioning near edges and elevation differences, while minor differences appeared for heavy-equipment interaction, communication failure, and fatigue. These differences did not change the overall risk priority because the hazards remained within the high or critical categories.

Table 9 verifies whether the critical controls were available, functional, and followed in the field. Edge protection showed the strongest performance, with 80% compliance and verified control status. In contrast, two-way radio communication had only 55% compliance and was not verified, making communication failure the most urgent control weakness. Heavy-equipment interaction was only partially controlled because exclusion zones and spotters were not consistently effective. Fatigue controls also remained weak because work-hour limits and rest breaks were not fully measured or verified. Overall, risk priority was determined by combining field exposure, observed unsafe events, assessor judgment, and control performance. This approach provides a stronger basis for corrective action than relying only on a conventional probability-severity matrix.

Table 10. Dominant hazards and credible accident pathways across operational areas

Operational area	Dominant hazards	Credible unwanted event	Potential consequence
Loading point	Blind spots, incorrect positioning, falling material, worker entry into active loading zone	Worker or vehicle struck by excavator or dump truck	Serious injury, fatality, or equipment damage
Hauling road	Slippery road, different elevation, narrow road, poor visibility, fatigue, miscommunication	Collision, rollover, road departure, or loss of control	Multiple injuries, fatality, major equipment damage
Stockpile	Reversing, unstable dumping surface, edge exposure, material collapse	Collision, vehicle overturning, or burial	Serious injury, fatality, or production disruption

The findings indicate that occupational risk cannot be generalised across the entire nickel ore production chain. Each operational area presents different initiating events, exposure patterns, and accident pathways and therefore requires controls tailored to its specific operating conditions.

HIRADC Risk Classification

As shown in Table 11, four hazards were classified as critical or fatal risks, each with a probability score of 4, a severity score of 5, and a total risk score of 20. These hazards were heavy-equipment interaction, unsafe positioning near excavation or stockpile edges, inter-unit communication failure, and operator or grade-control fatigue. Although they occurred in different work areas, each could lead to fatal collision, fall, burial, or rollover events. Equipment movement across different elevations was classified as high risk with a score of 16 because it could trigger loss of control or rollover. These findings show that the main risk drivers were mobile-equipment interaction, worker position, communication reliability, road condition, and human factors. Therefore, the four critical hazards require immediate control improvement, while the elevation-related hazard requires close monitoring and preventive action.

Table 11. Critical and High-Priority Hazards

No	Hazard	Risk	P	S	Risk Score	Risk Level
1	Heavy-equipment interaction	Collision/contact	4	5	20	Critical/Fatal
2	Standing at cliff edge	Fall/burial	4	5	20	Critical/Fatal
3	Inter-unit miscommunication	Struck/grazed	4	5	20	Critical/Fatal
4	Fatigue among grade control personnel	Collision/rollover/fall	4	5	20	Critical/Fatal
5	Unit enters different-elevation area/road	Fall into depression/rollover	4	4	16	High

The highest risks were mainly driven by the interaction between mobile equipment, worker position, communication failure, and human factors, rather than by single physical hazards. Of the 11 identified hazards, two (18.18%) were classified as low risk, five (45.45%) as high risk, and four (36.36%) as critical/fatal. This means that nine hazards (81.82%) required immediate intervention or close monitoring. The results confirm that safe nickel ore production depends on strong engineering controls, clear procedures, traffic management, supervision, reliable communication, and worker compliance.

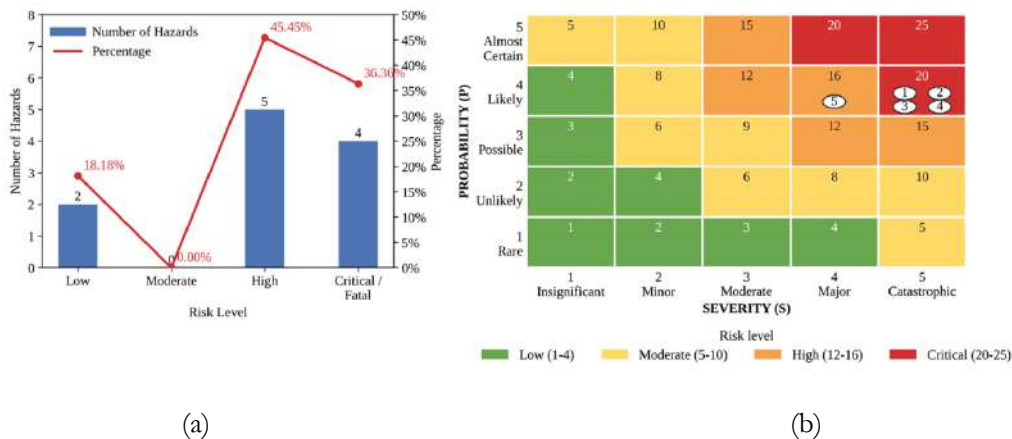


Figure 3. HIRADC risk assessment results: (a) distribution of the 11 identified hazards by risk category; and (b) probability–severity positions of the five priority hazards

Control priorities should follow the accident pathway in each operational area. At the loading point, the most important measures are strict exclusion zone enforcement, physical separation between workers and active equipment, positive communication before workers enter the loading radius, and equipment status confirmation before inspection or sampling begins. Along the haul road, attention should be given to road width, berm and drainage condition, speed control, traffic segregation, passing rules, and mandatory radio communication at intersections and blind sections. At the stockpile, risk reduction should emphasize controlled dumping, reversing management, material stability inspection, edge protection, and separation between sampling activity and active equipment routes. The findings also show that fatigue should be treated as an operational control issue, not merely as an individual worker problem. Long shifts, limited rest opportunities, night work, high production pressure, dense traffic, and reduced visibility can weaken attention and decision making even when formal procedures are available. For this reason, fatigue management should be measured, supervised, and included in routine control verification.

Conclusion

This study assessed occupational safety risks in nickel ore loading, haulage, and stockpile operations using an Operational Based Integrated HIRADC Framework. The framework combined probability severity scoring with direct field observation, near miss review, exposure adjusted event rate calculation, independent assessor comparison, and critical control verification. This approach provided a more realistic picture of risk because it examined how the work was actually performed under changing field conditions.

Eleven principal hazards were identified. Four hazards were classified as critical or potentially fatal: heavy equipment interaction, unsafe positioning near excavation or stockpile edges, inter unit communication failure, and fatigue among operators or grade control personnel. Five hazards were classified as high risk and two as low risk. Overall, 81.82 percent of the identified hazards required immediate intervention or enhanced monitoring under the company risk criteria.

The results demonstrate that personal protective equipment and administrative procedures are not sufficient for controlling the most severe hazards in nickel ore operations. The most important improvements are physical separation between personnel and equipment, stronger exclusion zone enforcement, reliable two way communication, safer haul road and stockpile conditions, fatigue management, and routine confirmation that critical controls remain functional in the field.

The main contribution of this study is the connection between HIRADC risk scoring and operational evidence. By linking risk scores with exposure, near miss occurrence, field condition, assessor judgement, and control performance, the framework helps distinguish hazards that are only documented in a register from hazards that remain active during daily production. Future

work should apply the framework across different mines, seasons, and production conditions and evaluate whether repeated use reduces near misses, unsafe events, and serious incidents.

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