

Risk-Based HSE Assurance Framework for Construction Plant & Equipment: A Case Study of Nh-31d Road Project

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Abstract- Highway construction projects involve high-risk work environments due to simultaneous operations, interactions between moving equipment and personnel, fluctuating ground conditions, and time-sensitive pressures. Construction machinery poses significant HSE risks including high energy movements, rotating components, lifting operations, and maintenance activities, with hazards such as being struck by or caught in between, entanglement, electrical hazards, and fire and explosion risks, along with dust, noise, vibration, and ergonomic exposures. This dissertation presents a Risk-Based HSE Assurance Framework for the NH-31D road project, focusing on hazard identification, risk prioritization, controls, verification, and continuous improvement across equipment lifecycle stages. The framework integrates HIRA, hierarchy of controls, work authorization, and energy isolation supported by Equipment Fitness Assurance (Green Card), PTW, and LOTO. Safeguards, inspections, audits, and corrective measures act as verifiable controls. The framework improves equipment availability, utilization, and effectiveness of HSE controls while enhancing prevention and compliance.

Index Terms- Construction plant and equipment, HIRA, HSE assurance, LOTO, PTW

I. INTRODUCTION

Highway construction projects involve large-scale mechanized operations executed under dynamic site conditions, where multiple activities are carried out simultaneously across various work fronts. The interaction between moving construction equipment, personnel, and continuously changing ground conditions makes these projects inherently high-risk in nature. Construction plant and equipment such as graders, loaders, compactors, cranes, crushers, batching plants, WMM plants, hot mix plants, and diesel generator sets play a critical role in productivity and project execution, but also represent

significant sources of Health, Safety, and Environment (HSE) risks.

These risks arise due to high energy operations, moving and rotating components, lifting activities, electrical systems, and frequent maintenance and repair tasks. Common hazards include struck-by and run-over incidents, caught in/between accidents, entanglement with rotating machinery, lifting failures, electrical hazards, and fire risks. In addition to safety concerns, plant operations also expose workers to occupational health risks such as dust, noise, vibration, and ergonomic strain during maintenance activities.

The NH-31D (Ghoshpukur–Salsalabari) road project, being a large infrastructure project involving continuous deployment of heavy machinery, required a systematic and structured approach to manage these risks effectively. Traditional safety practices based on general precautions are not sufficient to manage complex equipment-related hazards. Therefore, a risk-based approach integrating hazard identification, risk assessment, control implementation, and verification becomes essential.

This study focuses on developing a Risk-Based HSE Assurance Framework for construction plant and equipment, incorporating Hazard Identification and Risk Assessment (HIRA), hierarchy of controls, Safe Work Methods (SWM), Permit to Work (PTW), Lockout/Tagout (LOTO), equipment fitness assurance (Green Card system), engineering safeguards, and audit-based continual improvement. The framework aims to ensure systematic identification of hazards, prioritization of risks, implementation of effective controls, and continuous

verification to enhance overall safety performance and operational efficiency.

II. LITERATURE REVIEW

Construction plant and equipment safety has been widely studied in infrastructure and highway projects, where mechanized operations significantly increase exposure to high-energy hazards and complex work environments. Literature consistently identifies major accident categories in construction as struck-by incidents, caught-in/between hazards, electrocution, and falls, commonly referred to as the “Focus Four” hazards. In the context of plant and equipment, struck-by and caught-in/between hazards are particularly critical due to continuous interaction between moving machinery, workers, and rotating components such as conveyors and crushers.

Hazard Identification and Risk Assessment (HIRA) is recognized as a fundamental tool for systematic identification and prioritization of risks. Most studies adopt qualitative or semi-quantitative methods using probability–severity matrices to classify risks and guide control measures. The hierarchy of controls—comprising elimination, substitution, engineering controls, administrative controls, and personal protective equipment—provides a structured approach for risk reduction, with emphasis on higher-order controls to minimize reliance on human behavior.

Safe Work Methods (SWM) and Permit to Work (PTW) systems are widely used to translate risk assessment into operational control. SWM outlines task-wise hazards and precautions, while PTW ensures formal authorization for high-risk activities such as maintenance, hot work, and work near energized systems. Studies indicate that these systems are effective when supported by supervision and verification; however, their effectiveness reduces when treated as routine documentation without field validation.

Lockout/Tagout (LOTO) is identified as a critical control for hazardous energy management during maintenance and servicing of equipment. It prevents unintended energization and release of stored energy, which are common causes of severe injuries in

construction plant operations. Literature emphasizes that LOTO effectiveness depends on proper identification of all energy sources, training, and strict implementation discipline.

Equipment inspection and fitness assurance systems act as preventive controls by ensuring that only safe and compliant equipment is allowed for operation. Pre-use checks, periodic inspections, and documented fitness systems such as “Green Card” serve as gatekeeping mechanisms to prevent unsafe equipment from entering the work environment. Engineering safeguards including machine guarding, interlocks, emergency stop systems, and dust control measures are recognized as effective controls, but require continuous monitoring and maintenance to ensure their effectiveness over time.

Safety assurance in construction projects is increasingly linked with verification systems such as inspections, internal audits, and corrective and preventive action (CAPA) processes. Standards such as ISO 45001 emphasize monitoring, performance evaluation, and continual improvement through audit-based systems. Literature highlights that the success of these frameworks depends on closure of non-conformities, accountability, and integration of safety performance indicators with operational management.

Overall, existing studies establish that while hazard identification and control measures are well defined, gaps often remain in ensuring consistent implementation and verification. This highlights the need for an integrated assurance framework that links HIRA, control systems, work authorization, equipment fitness, and audit-based continual improvement to ensure sustained safety performance in construction plant and equipment operations.

III. PROBLEM IDENTIFICATION

Despite the implementation of safety systems and operational controls in construction projects, plant and equipment-related risks continue to persist due to practical challenges in execution. In large highway projects such as NH-31D, continuous deployment of heavy machinery across multiple work fronts leads to increased interaction between personnel and

equipment, creating conditions for struck-by, caught-in/between, and maintenance-related hazards.

Analysis of project data highlights specific operational concerns. Although equipment availability was observed to be high (around 98%), utilization remained relatively low (approximately 32%), indicating inefficiencies in deployment and presence of surplus equipment. Excess equipment contributes to site congestion, increasing the probability of unsafe interactions and movement-related incidents. Additionally, breakdowns result in emergency repair activities, which are often carried out under time pressure, leading to higher risk exposure due to bypassing of safeguards and inadequate control measures.

Further analysis shows that Internal Hire Charge (IHC) losses are largely attributed to surplus equipment and breakdowns. These factors not only impact cost and productivity but also create unsafe conditions such as overcrowded work zones, unplanned maintenance, and increased dependency on temporary or unsafe practices.

Existing safety systems such as HIRA, PTW, LOTO, and inspection mechanisms are often implemented as standalone processes. However, a key gap lies in the lack of integration between hazard identification, control implementation, verification, and performance monitoring. In many cases, controls are defined but not consistently verified for effectiveness in field conditions, resulting in recurrence of similar safety issues.

Therefore, there is a need for an integrated and systematic Risk-Based HSE Assurance Framework that connects hazard identification, risk prioritization, control implementation, equipment fitness assurance, and audit-based verification. Such an approach is essential to ensure not only the presence of safety systems but also their effectiveness in reducing risk and improving overall equipment safety performance.

IV. METHODOLOGY

The methodology adopted in this study is based on a structured case study approach using project systems, operational records, and safety practices implemented

at the NH-31D (Ghoshpukur–Salsalabari) road project. The objective of the methodology is to establish a Risk-Based HSE Assurance Framework for construction plant and equipment by systematically integrating hazard identification, risk assessment, selection of control measures, work execution controls, and verification mechanisms into a unified and practical approach. The methodology is designed to reflect actual site conditions, where multiple equipment types operate simultaneously, and where both routine and non-routine activities contribute to varying levels of risk exposure.

The study considers a comprehensive range of construction plant and equipment deployed in the project environment, including earthmoving equipment, compaction machinery, lifting devices, crushers, batching plants, wet mix macadam plants, hot mix plants, diesel generator sets, and supporting vehicles. The methodology covers all critical stages of the equipment lifecycle, namely mobilization, erection and commissioning, routine operation, refuelling, preventive maintenance, and breakdown repair. This lifecycle-based coverage ensures that hazards associated with both operational and maintenance phases are captured, as maintenance and repair activities are often associated with higher risk exposure due to involvement of hazardous energy, removal of safety guards, and proximity to moving and rotating components.

The methodology is supported by project-based data and evidence collected from established systems and records. These include equipment deployment and utilization records, maintenance schedules and breakdown history, inspection and equipment fitness documentation under the Green Card system, Permit to Work (PTW) and Lockout/Tagout (LOTO) records for high-risk activities, hazard identification and risk assessment (HIRA) formats, internal audit reports, non-conformity reports (NCR), corrective and preventive action (CAPA) records, and operational performance indicators such as equipment availability, utilization, Internal Hire Charge (IHC) recovery, operation and maintenance cost, and spares inventory management practices. The use of such data ensures that the methodology is grounded in actual operational conditions rather than theoretical assumptions.

Hazard identification forms the first technical step of the methodology and is carried out using a combined approach to ensure completeness. The equipment-wise approach identifies hazards inherent to specific machinery and systems, including interaction between moving equipment and personnel, exposure to rotating and moving parts, lifting and rigging operations, electrical risks from power distribution systems, and fire hazards associated with fuel handling and plant operations. In parallel, an activity-wise approach is used to identify hazards across different stages of work, including mobilization, commissioning, operation, refuelling, maintenance, and breakdown repair. This dual approach ensures that hazards are identified not only based on equipment characteristics but also based on the changing nature of work conditions, particularly during non-routine activities where risk levels are typically higher.

Following hazard identification, risk assessment is performed using the Hazard Identification and Risk Assessment (HIRA) methodology. Each identified hazard is evaluated based on probability and severity criteria, where probability represents the likelihood of occurrence and severity represents the potential consequence in terms of safety, health, and environmental impact. A risk matrix is used to combine these parameters and classify risks into high, medium, and low categories. This classification enables prioritization of critical hazards and ensures that high-risk activities receive focused attention in terms of control implementation and supervision. The structured application of HIRA ensures consistency in risk evaluation across different equipment categories and operational activities.

Based on the risk assessment outcomes, appropriate control measures are selected in accordance with the hierarchy of controls. Preference is given to engineering controls, as they provide inherent risk reduction by eliminating or minimizing exposure at source. These include physical guarding of rotating components, installation of interlocking systems in plant operations, emergency stop mechanisms, safe starter systems, and dust control arrangements. Engineering controls are supported by administrative measures such as defined procedures, supervision, training and competency requirements, and

communication mechanisms to ensure correct implementation during execution. Personal protective equipment is considered as a supplementary control where risks cannot be eliminated through higher-order measures.

A critical element of the methodology is the integration of HIRA outcomes with Safe Work Methods, ensuring that risk assessment is effectively translated into practical work execution. This integration involves breaking down each activity into sequential steps and mapping identified hazards and control measures to each step. This ensures that control measures are applied at the point of execution rather than remaining as part of documentation. The linkage between HIRA and Safe Work Methods enhances consistency in execution, improves supervision, and reduces variability across work crews and shifts.

High-risk activities identified through the HIRA process are further managed using Permit to Work and Lockout/Tagout systems. The Permit to Work system ensures formal authorization of critical tasks by verifying hazards, precautions, and responsibilities before commencement of work, while Lockout/Tagout ensures isolation of hazardous energy sources during maintenance and repair activities. The implementation of LOTO procedures prevents unintended energization, startup, or release of stored energy, which are common causes of severe incidents during equipment servicing. These systems function as critical control barriers for maintaining safety during high-risk operations.

Equipment safety and readiness are ensured through the Equipment Fitness Assurance system, commonly referred to as the Green Card system. This system is used as a gatekeeping mechanism to ensure that only inspected and compliant equipment is permitted for operation. Equipment is subjected to systematic inspection to verify the condition of safety-critical components such as braking systems, guarding, warning systems, and emergency controls. Equipment found to be non-compliant is restricted from operation until corrective actions are completed, thereby preventing unsafe equipment from being deployed at the worksite.

Verification of control effectiveness is an integral part of the methodology and is achieved through routine inspections, planned internal audits, and monitoring systems. Structured checklists are used to verify the condition and effectiveness of engineering controls, administrative measures, and operational practices. Non-conformities identified during inspections and audits are recorded through NCR and tracked using CAPA systems to ensure timely closure. This verification mechanism ensures that control measures remain effective over time and that deviations are systematically addressed.

In addition to control verification, performance monitoring is carried out using key operational indicators such as equipment availability, utilization, maintenance adherence, IHC recovery, O&M cost trends, and inventory control performance. These indicators establish a direct linkage between operational efficiency and HSE performance, highlighting how maintenance discipline, equipment reliability, and control implementation influence safety outcomes. High equipment availability combined with controlled utilization reduces breakdown-driven exposure, while effective spares management prevents unsafe temporary repairs and recurrent failures.

The methodology ultimately generates structured outputs including hazard identification registers, HIRA-based risk prioritization, control measures aligned with the hierarchy of controls, Safe Work Methods for execution, and verification systems including inspections, audits, and CAPA processes. These outputs collectively form a comprehensive Risk-Based HSE Assurance Framework that ensures systematic risk management, effective control implementation, and continuous improvement in construction plant and equipment operations.

V. DATA ANALYSIS & RESULTS

The analysis of construction plant and equipment performance was carried out using operational data from the NH-31D project to evaluate the effectiveness of the Risk-Based HSE Assurance Framework. The evaluation is based on quantitative indicators including equipment availability and utilization, Internal Hire Charge (IHC) recovery and

loss distribution, operation and maintenance (O&M) cost behavior, spares and inventory management, diesel generator (DG) productivity, and plant efficiency. These parameters provide a direct linkage between equipment performance and associated HSE risk exposure.

Equipment performance analysis indicates that overall availability was maintained at approximately 98%, reflecting strong maintenance discipline and effective preventive maintenance practices. However, utilization was observed at only ~32%, indicating that a significant proportion of equipment remained idle or underutilized. This mismatch between availability and utilization led to excess equipment presence at site, which directly contributed to congestion and increased interaction between vehicles and workmen. From an HSE perspective, this condition increases the probability of struck-by and run-over incidents, as multiple equipment operate or remain stationed within limited working zones.

The analysis of Internal Hire Charge (IHC) shows a recovery of approximately 89.89%, with loss breakup indicating that 86.4% of losses are due to surplus equipment and 12.7% due to breakdowns. The high percentage of surplus equipment confirms inefficient deployment, resulting in overcrowding and unsafe movement conditions. Breakdown-related losses indicate frequent equipment failure requiring intervention. From a safety perspective, breakdowns lead to emergency repair activities, which involve direct exposure to hazardous energy, removal of guarding systems, and work inside danger zones, significantly increasing risk compared to planned maintenance conditions.

Operation and maintenance cost analysis indicates that O&M cost is approximately 16% of equipment acquisition value, with periodic variation depending on breakdown intensity. Higher O&M cost reflects increased repair frequency and spares consumption. This directly correlates with increased worker exposure to maintenance activities such as electrical troubleshooting, hot work, mechanical repair, and confined equipment areas, all of which carry higher risk levels. Conversely, improved preventive maintenance reduces breakdown frequency and

minimizes high-risk intervention activities, thereby improving overall safety control.

Inventory and spares management analysis shows a measurable improvement in control, with non-moving spares reduced from 35.6% to 24.3%. ABC analysis identifies that a small number of items contribute to a major portion of inventory value, while XYZ analysis categorizes spares based on usage variability. This improvement indicates better planning and control of critical spare parts. From an HSE perspective, availability of critical spares ensures timely replacement of defective components, thereby reducing incidents related to oil leakage, equipment failure, and fire hazards. It also eliminates the need for temporary or unsafe repair methods, which are commonly associated with repeated failures and increased exposure to hazards.

Diesel generator productivity analysis shows variation from 0.8 to 3.3 kWh/litre, indicating significant differences in operating efficiency across DG sets. Lower productivity values are associated with higher fuel consumption, poor maintenance condition, and inefficient load management. This results in increased emissions, higher noise levels, and thermal exposure, contributing to occupational health risks. Additionally, increased fuel handling and leakage probability raise fire hazard risks. Higher productivity levels indicate stable operation and support reliable power supply for plant safety systems such as interlocks, emergency stops, and lighting, which are critical for safe plant operation.

Plant efficiency analysis indicates that batching plants operated at 71%–90% efficiency, WMM plants at 48%–61%, and hot mix plants at 77%–83%. Lower efficiency, particularly in WMM plants, indicates frequent stoppages and operational instability. This leads to increased manual intervention for troubleshooting and maintenance, exposing workers to rotating machinery, conveyor systems, and electrical panels. Higher efficiency reflects stable operation, reduced stoppages, and minimal manual intervention, thereby reducing exposure to hazardous zones and improving overall safety performance.

The implementation of engineering controls and improvement initiatives further strengthened both

operational performance and safety outcomes. Systems such as interlocking arrangements, guarding of rotating parts, emergency stop mechanisms, limit switches, and dust control systems were implemented as primary barriers. These controls reduced direct exposure to hazards by controlling risk at source. Additional improvements such as energy monitoring systems and optimized electrical supply reduced dependency on diesel generators, leading to improved efficiency and lower environmental and fire risks.

The combined analysis of performance indicators demonstrates a clear relationship between equipment management practices and HSE performance. High availability with controlled maintenance, improved spares discipline, and reduced breakdown frequency leads to lower need for emergency interventions, which are typically high-risk. Reduction in surplus equipment minimizes congestion-related hazards, while improved plant efficiency reduces operator exposure to unsafe conditions.

Overall, the results validate that the Risk-Based HSE Assurance Framework effectively integrates operational performance with safety control by linking HIRA-based risk prioritization, control implementation, equipment fitness assurance, and audit-based verification. This integration results in measurable improvement in both equipment performance indicators and reduction of high-risk exposure conditions in construction plant and equipment operations.

The methodology integrates structured tools including HIRA, equipment classification, equipment fitness assurance (Green Card), PTW and LOTO systems, and performance monitoring indicators such as availability, utilization, IHC, and inventory classification (ABC–XYZ), forming a comprehensive framework for risk-based HSE management.

VI. CONCLUSION

The present study develops and validates a Risk-Based HSE Assurance Framework for construction plant and equipment through detailed analysis of operational performance data from the NH-31D highway project. The findings establish a strong and measurable interrelationship between

equipment management practices, operational efficiency, and HSE risk exposure, demonstrating that safety performance in construction environments is significantly influenced by the manner in which plant and equipment are deployed, maintained, and controlled.

The analysis highlights a critical imbalance between equipment availability and utilization, where availability is maintained at approximately 98%, while utilization remains limited to around 32%. This disparity indicates that a substantial proportion of equipment remains idle, resulting in surplus deployment across work fronts. Such conditions lead to physical congestion, restricted movement corridors, and increased interaction between equipment and workforce. From a risk perspective, this directly translates into elevated exposure to struck-by and run-over hazards, thereby establishing that over-deployment of equipment is not merely an operational inefficiency but a significant safety risk factor.

Further, the IHC loss distribution provides quantitative validation of this relationship, with 86.4% of losses attributed to surplus equipment and 12.7% to breakdowns. While surplus equipment contributes to unsafe site geometry and movement risks, breakdowns introduce a different risk dimension by triggering emergency maintenance conditions. These breakdown-driven interventions require direct engagement with hazardous energy sources, removal of protective systems, and manual access to critical components, thereby significantly increasing the probability and severity of incidents. This establishes that breakdown frequency is a direct indicator of elevated high-risk exposure in plant operations.

The influence of maintenance dynamics on HSE performance is further supported by O&M cost behavior, which is observed at approximately 16% of equipment acquisition value. Increased maintenance demand reflects higher repair frequency and spares consumption, which in turn leads to repeated exposure of personnel to high-risk environments such as electrical systems, constrained mechanical zones, and hot work activities. Conversely, effective preventive maintenance reduces the occurrence of

such interventions, demonstrating that maintenance discipline functions as a primary control mechanism for reducing high-risk exposure rather than merely a reliability function.

Inventory management analysis adds another critical dimension to the framework by linking spares control with safety outcomes. The reduction of non-moving inventory from 35.6% to 24.3% indicates improved material planning and availability of critical components. This directly eliminates the need for temporary repairs and repeated equipment operation under defective conditions, which are common precursors to incidents such as oil leakage, fire hazards, and mechanical failures. Thus, spares discipline contributes to risk reduction by enabling timely restoration of equipment integrity and preventing degradation of safety conditions.

The variation observed in DG productivity (0.8–3.3 kWh/litre) and plant efficiency (WMM: 48–61%, batching: 71–90%, HMP: 77–83%) further reinforces the linkage between operational stability and risk exposure. Lower efficiency and productivity levels indicate unstable operating conditions, increased stoppages, and frequent requirement for manual intervention. These interventions expose personnel to hazardous zones including rotating machinery, conveyors, and electrical systems, thereby increasing the probability of incidents. In contrast, stable and efficient operation reduces human intervention and limits exposure, validating that operational stability acts as a preventive safety control by minimizing interaction with hazard sources.

The effectiveness of the framework is further strengthened through the implementation of engineering controls such as guarding systems, interlocks, emergency stop mechanisms, and process improvements. These controls act at the source level by eliminating or reducing hazard exposure. When integrated with administrative systems such as HIRA, Safe Work Methods, Permit to Work, and Lockout/Tagout, along with equipment fitness assurance through the Green Card system, a layered and interdependent control structure is established. This multi-barrier approach ensures that hazards are systematically identified, controlled, and verified

across all stages of operation and maintenance, thereby enhancing reliability of safety controls.

Verification mechanisms through inspections, audits, and NCR–CAPA closure systems play a critical role in sustaining the effectiveness of controls. Continuous monitoring of performance indicators such as availability, utilization, and maintenance adherence ensures that deviations are identified and corrected, thereby maintaining alignment between planned controls and actual field conditions. This demonstrates that assurance is not achieved through implementation alone, but through continuous verification and feedback-based improvement.

Overall, the findings confirm that the Risk-Based HSE Assurance Framework effectively integrates hazard identification, risk prioritization, control implementation, and performance monitoring into a unified system. The framework not only improves equipment reliability and operational efficiency but also significantly reduces exposure to high-risk conditions arising from congestion, breakdowns, and uncontrolled maintenance activities.

The study contributes by establishing a clear, data-driven relationship between equipment performance indicators and HSE outcomes, demonstrating that safety can be systematically enhanced through structured equipment management practices. The proposed framework is practical, scalable, and directly applicable to large infrastructure projects, providing a structured pathway for achieving sustained improvement in both operational performance and safety assurance in construction plant and equipment management.

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