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Investigation of Accident Causes, Risk Analysis and Enhancing Safety in Tower Crane Erection and Dismantling in Construction Sites

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Abstract
Tower cranes play a critical role in modern construction, enabling efficient vertical material handling; however, their erection and dismantling phases remain some of the most hazardous operations on construction sites. This project investigates the root causes of accidents associated with these activities and conducts a systematic risk analysis to identify high-risk tasks, human-factor issues, equipment failures, and procedural gaps. Through the review of incident reports, expert interviews, and site observations, the study categorizes recurring hazards such as inadequate planning, improper sequencing, lack of competent personnel, environmental factors, and communication failures. A structured risk assessment methodology combining qualitative and semi-quantitative tools is applied to evaluate the likelihood and severity of potential failures during crane assembly and disassembly. Based on the resulting risk profiles, the project proposes enhanced safety measures that include improved work-planning frameworks, standardized erection/dismantling checklists, competency-based training programs, and real-time monitoring practices. Recommendations also focus on adopting advanced technologies such as sensor-based load monitoring, digital lifting plans, and automated safety alerts to reduce human error and strengthen hazard visibility. The integration of regulatory guidelines, industry best practices, and engineering controls forms the foundation of a comprehensive safety enhancement model. Ultimately, the project aims to support construction stakeholders in minimizing accidents, improving operational reliability, and fostering a proactive safety culture in tower crane erection and dismantling operations.

Keywords: *Tower Crane Safety, Risk Analysis, Accident Causes, Construction Safety Management, Erection and Dismantling.*

1. Introduction
The construction industry is one of the most important sectors for economic growth and infrastructure development. It is also recognized as a high-risk industry due to the presence of heavy machinery, complex operations, and hazardous working conditions. Among the various equipment used in construction projects, tower cranes play a crucial role in lifting and transporting heavy materials to great heights. Tower cranes are widely used in the construction of high-rise buildings, bridges, and large infrastructure projects. Despite their importance, the erection and dismantling of tower cranes are considered some of the most dangerous activities on construction sites. Tower crane erection and dismantling operations involve multiple stages such as assembling structural components, installing mast sections, attaching counterweights, and coordinating lifting activities at significant heights. These processes require skilled workers, proper planning, and strict adherence to safety procedures. If these activities are not carefully managed, they can lead to serious accidents such as crane collapse, falling loads, structural instability, and worker injuries. This study focuses on the investigation of accident causes, risk analysis, and the development of safety enhancement measures related to tower crane erection and dismantling operations. Analysing accident data, identifying potential hazards, and applying systematic risk assessment methods, the study aims to understand the factors contributing to

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crane-related incidents. The research also proposes practical safety strategies to improve planning, training, supervision, and technological monitoring systems. Ultimately, the study aims to enhance safety performance and reduce accidents in construction sites involving tower crane operations [1-5].

2. Literature Review

Several researchers have examined safety risks associated with tower crane erection, operation, and dismantling in construction projects. Thanh Long Ngo (2025) investigated safety risks during tower crane erection and dismantling in Vietnam through a questionnaire survey of construction professionals. The study revealed that time pressure from contractors and investors is a major factor contributing to accidents, while breaking wire ropes during installation and dismantling was identified as one of the most severe hazards. Similarly, Haiyu Jin et al. (2025) proposed a comprehensive risk analysis model using Disaster Chain Theory, Analytic Hierarchy Process, Entropy Weight Method, and the Cloud Model to analyze tower crane safety risks. The research identified critical factors such as structural fatigue, deformation of steel components, safety device failures, operational errors, and management deficiencies. Shibin Zhang et al. (2025) studied safety investment behavior among tower crane stakeholders using a game-theoretic approach. The results highlighted the importance of collaborative safety investment among contractors, leasing companies, and government authorities to enhance construction site safety. Research by Fuwang Wang et al. (2025) focused on unsafe behavior detection among tower crane operators by monitoring cognitive fatigue using EEG technology. The study demonstrated that monitoring operators' mental states can help prevent accidents caused by fatigue. Earlier studies such as Thanu Lingam (2022) and Abdulmutalib Salihu (2021) emphasized that accidents during installation and dismantling are mainly caused by failure to follow procedures, inadequate training, poor maintenance, and deterioration of crane components. Overall, the literature highlights that effective safety management, proper maintenance, worker competency, and systematic risk assessment are essential for improving tower crane safety in construction projects.

3. Methodology

The development of safety procedures for tower crane erection and dismantling follows a systematic process to ensure effective hazard control and safe work practices [6- 10]. The first stage is Preliminary Study and Data Collection, where information is gathered from accident reports, site observations, safety records, and interviews with workers and supervisors. This step helps identify existing safety issues and understand the operational environment. The next stage is Task Breakdown and Process Mapping. In this phase, the entire crane erection and dismantling operation is divided into smaller tasks. Each task is carefully mapped to understand the sequence of activities, equipment used, and worker responsibilities Shown in Figure 1.

Site Assessment
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Data Collection
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Hazard Identification
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Risk Assessment
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Root Cause Analysis
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Development of Safety Enhancement Measures
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Validation of Recommendations
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Documentation and Conclusion

Figure 1 Methodology

Following this, Hazard Identification and Job Safety Analysis (JSA) Development is carried out. Potential hazards associated with each task are identified, and appropriate control measures are proposed to reduce risks. The fourth step involves Drafting and Structuring Standard Operating Procedures (SOPs). Clear and detailed SOPs are prepared to guide workers in performing tasks safely and consistently. Next, the procedures undergo Validation Through Expert Review, where safety professionals and experienced engineers evaluate the practicality and effectiveness of the proposed safety measures. After validation, a Training and Implementation Plan is developed to ensure workers understand and follow the procedures. Finally, Monitoring, Evaluation, and Continuous Improvement are conducted to review safety performance and update procedures whenever necessary [11 -15].

3.1. Site Assessment

Site assessment is the initial and most critical stage in analyzing accidents, risks, and safety improvements in tower crane erection and dismantling. It provides a clear understanding of site conditions, operational practices, and potential hazards. A well-executed assessment ensures that safety measures are based on real working conditions rather than assumptions. The process begins with evaluating the physical site layout, including crane base location, access routes, assembly areas, and nearby structures. Spatial constraints, such as limited space and overhead obstructions, can significantly affect lifting operations and increase collision risks. Ground and foundation conditions are carefully examined to ensure stability. Poor soil compaction, uneven surfaces, or waterlogging can lead to crane tilting or collapse. Proper ground preparation and reinforcement are essential before erection begins. Environmental factors like wind speed, rainfall, temperature, and visibility are documented, as they directly influence lifting safety and worker performance. Adverse weather conditions can increase operational risks. The assessment also focuses on workforce competence and communication. It evaluates worker skills, certifications, role clarity, and coordination efficiency. Poor communication or lack of training often leads to human errors during critical lifting activities. Equipment condition and procedures are reviewed to ensure compliance with manufacturer guidelines. Faulty rigging gear, worn components, or deviation from standard procedures can result in serious accidents. Safety infrastructure and organizational practices such as PPE usage, permit-to-work systems, supervision, and emergency preparedness are assessed. Overall, site assessment acts as a foundation for hazard identification, risk analysis, and implementing effective safety controls.

3.2. Data Collection

The data collection phase is a vital component of this study, aimed at gathering reliable and comprehensive information to identify hazards, analyze accident causes, and develop effective safety measures for tower crane erection and dismantling operations. A systematic multi-method approach is adopted, combining incident report analysis, expert interviews, and field observations to ensure both historical and real-time data are captured Shown in Table 1.

Table 1 Analysis of Tower Crane Accidents & Near-Misses

S. No.	Incident Category	Number of Reports (N=200)	Severity Level	Root Cause Identified	Contributing Factors	% of Total Incidents
1	Crane Collapse / Structural Failure	20	High (Fatal / Major Injury)	Improper assembly; component defects	Poor maintenance, procedural deviation	10%
2	Load Drop / Falling Objects	35	High / Medium	Rigging failure; incorrect lifting angles	Equipment wear, human error, wind	17.5%
3	Operator Error	25	Medium	Misjudgement, incorrect signalling	Fatigue, lack of training, language barrier	12.5%

4	Ground Instability / Base Settlement	15	High	Weak foundation, insufficient soil compaction	Waterlogging, uneven surface	7.5%
5	Collision with Structures / Other Equipment	18	Medium	Poor site layout, misaligned lifts	Spatial constraints, traffic interference	9%
6	Overhead Obstructions / Electrical Contact	12	High	Clearance miscalculations	Nearby power lines, poor planning	6%
7	Environmental Factors (Wind / Weather)	10	Medium	Weather not considered in lift plan	Lack of real-time monitoring, schedule pressure	5%
8	Procedural Non-Compliance	15	Medium	Skipped steps in erection/dismantling manual	Time pressure, inadequate supervision	7.5%
9	Inadequate Communication	8	Medium	Misinterpretation of hand signals	Noise, radio interference	4%
10	Slips, Trips, Falls Around Crane	10	Medium	Uneven surfaces, poor housekeeping	Cluttered site, wet ground	5%
11	Rigging Equipment Failure	12	High	Worn slings, shackles, hooks	Lack of inspection, poor storage	6%
12	Mobile Crane Malfunction	5	High	Hydraulic / mechanical failure	Maintenance gaps, operator misuse	2.5%
13	Improper Load Planning	6	Medium	Incorrect weight estimation	Out-dated lift charts, schedule pressure	3%
14	Counterweight Issues	4	High	Wrong type/installation errors	Miscommunication, lack of checks	2%
15	Falling Tools / Accessories	7	Medium	Unsecured tools at height	Inadequate tool tethering	3.5%
16	Fatigue / Human Factor	5	Medium	Long shifts, repetitive work	Inadequate breaks, staffing shortages	2.5%
17	Unauthorized Personnel in Danger Zone	3	High	Poor exclusion zone enforcement	Weak supervision, lack of signage	1.5%
18	Emergency Response Delays	3	High	No clear rescue plan	Limited equipment, untrained staff	1.5%
19	Load Swing / Instability	7	Medium	Sudden gusts, improper rigging	Lack of monitoring, insufficient training	3.5%

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20	Inadequate PPE Compliance	5	Medium	Workers not using harnesses or gloves	Poor enforcement, lack of awareness	2.5%

Incident report analysis forms the primary source of quantitative data. A total of 200 accident and near-miss reports were collected from construction company records, regulatory authorities, and safety databases. Each report was carefully examined to identify incident types, frequency, severity, root causes, and contributing factors. The analysis revealed that major incidents such as crane collapse (10%), load drops (17.5%), and operator errors (12.5%) were among the most frequent [16-19]. Root causes included improper assembly, rigging failures, procedural deviations, and human errors. Contributing factors such as poor ground conditions, environmental influences, and inadequate supervision were also identified. Statistical tools and qualitative analysis techniques were used to detect recurring patterns and high-risk activities Shown in Table 2.

Table 2 Expert Interview Analysis – Tower Crane Erection & Dismantling

S. No	Stakeholder Group	Number Interviewed	Questions Asked	Common Responses / Observations	Frequency of Mention	Perceived Risk Level	Suggested Mitigation / Improvement
1	Crane Operators	10	Challenges in crane erection/dismantling	Limited visibility; tight spaces; long component handling difficult	8/10	High	Use spotters, improved signaling, real-time load monitoring
2	Crane Operators	10	Risk perception	Load swings, collisions, operator fatigue	9/10	High	Safety briefings, fatigue management, proper sequencing
3	Rigging Supervisors	6	Equipment issues	Inconsistent rigging practices; improper slings/shackles; worn hooks	6/6	High	Standardized rigging checklists, routine inspections, refresher training
4	Rigging Supervisors	6	Procedural challenges	Skipped steps; deviations from manuals	5/6	Medium	Enforce adherence to manufacturer procedures, permit-to-work system
5	Safety Engineers	4	Risk assessment adequacy	Insufficient pre-lift assessment; missing contingency plans	4/4	High	Comprehensive site-specific risk assessments, lift plan approval workflow

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6	Safety Engineers	4	Safety infrastructure	Barricades, fall protection, warning signage inadequate	4/4	Medium	Upgrade safety infrastructure, clear exclusion zones, proper PPE enforcement
7	Site Managers	5	Workforce competence	Varied skills; some operators lack certification	5/5	High	Competency-based training programs, enforce certification requirements
8	Site Managers	5	Communication issues	Misunderstood signals; radios interference; language barriers	5/5	Medium	Standardize hand signals, multilingual charts, reliable communication equipment
9	All Stakeholders	25	Environmental concerns	High winds, dust, poor lighting, heat stress	20/25	High	Schedule lifts in favorable conditions, implement dust & heat control measures
10	All Stakeholders	25	Safety culture & supervision	Supervisors overstretched; workers hesitant to report issues	18/25	Medium	Increase HSE presence, introduce anonymous reporting, regular toolbox talks
11	All Stakeholders	25	Technology adoption	No real-time load monitoring or digital lift plans	15/25	Medium	Implement sensor-based load monitoring, digital lifting plans, automated alerts
12	All Stakeholders	25	Overall hazard perception	Most hazards come from human error, procedural lapses, and environmental factors	22/25	High	Combination of training, adherence to procedures, and technology deployment

Expert interviews provide valuable qualitative insights into practical challenges faced on-site. A total of 25 stakeholders, including crane operators, rigging supervisors, safety engineers, and site managers, were interviewed. The findings highlighted issues such as limited visibility, communication barriers, inconsistent rigging practices, and lack of adherence to procedures. High-

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risk concerns frequently mentioned include operator fatigue, load instability, and inadequate safety infrastructure. Direct site observations were conducted to validate collected data and understand real working conditions. This helped identify gaps between documented procedures and actual practices. The data collection process ensures a strong foundation for accurate risk assessment and the development of targeted safety improvements.

3.3. Hazard Identification

Hazard identification is a fundamental step in ensuring safety during tower crane erection and dismantling, as these operations involve heavy loads, complex procedures, and multiple human interactions. A structured approach using tools such as Job Safety Analysis (JSA), Failure Mode and Effects Analysis (FMEA), and detailed checklists is adopted to systematically identify, evaluate, and control potential hazards. Mechanical hazards are among the most critical risks. These include component failures such as mast collapse, defective bolts, and slewing unit malfunctions caused by fatigue, corrosion, or improper assembly. Dropped loads due to rigging failure or overloading present severe threats to workers. Pinch and crush points during manual handling and equipment malfunctions in mobile cranes further increase accident potential. Preventive measures include regular inspection, certified rigging equipment, and strict adherence to manufacturer guidelines. Operational hazards arise from improper work practices and sequencing errors. Deviating from the prescribed erection sequence can destabilize crane structures, while poor planning and congested workspaces increase collision risks. Human errors, such as miscommunication and fatigue, significantly contribute to unsafe operations. Effective supervision, step-by-step checklists, and pre-task briefings are essential to minimize these risks. Environmental hazards include wind, rain, temperature extremes, and poor visibility. High winds can destabilize loads, while wet or uneven surfaces reduce stability and worker safety. These risks are mitigated through weather monitoring, proper scheduling, and improved site conditions such as lighting and ground preparation Shown in Table 3.

Table 3 Hazard Identification for Tower Crane Operations

S. No	Hazard Category	Specific Hazard	Number of Incidents Observed / Reported	Frequency (%)	Severity (1–5)	Likelihood (1–5)	Risk Priority (Severity × Likelihood)	Recommended Mitigation
1	Mechanical	Dropped loads	12	24%	5	4	20	Use certified rigging, real-time monitoring, spotters
2	Mechanical	Mast section collapse	5	10%	5	3	15	Proper sequencing, pre-lift checks, inspection of bolts
3	Mechanical	Rigging failure (slings, shackles)	8	16%	4	4	16	Standardized rigging checklist, routine inspections
4	Operational	Procedural deviation	15	30%	4	4	16	Enforce adherence to lift plan, supervisor oversight

5	Operational	Human error / miscommunication	18	36%	5	5	25	Training, standardized hand signals, radios, briefings
6	Operational	Improper sequencing of lifts	7	14%	5	3	15	Strict sequence adherence, checklists, engineer approval
7	Environmental	High wind during lift	10	20%	4	3	12	Weather monitoring, schedule lifts in favorable conditions
8	Environmental	Poor visibility / lighting	6	12%	3	3	9	Provide adequate lighting, signalers, reflective gear
9	Environmental	Wet/slippery ground	5	10%	4	3	12	Temporary mats, ground leveling, drainage management
10	Human Factors	Insufficient training / certification	20	40%	5	4	20	Competency-based training, enforce certification
11	Human Factors	Fatigue / long shifts	12	24%	4	4	16	Shift rotations, mandatory breaks, fatigue management
12	Human Factors	Language barriers / poor communication	8	16%	3	3	9	Multilingual charts, standardized hand signals
13	Equipment & Tools	Worn or mismatched bolts, pins	7	14%	4	3	12	Regular inspection, proper storage, replacement protocols
14	Equipment & Tools	Mobile crane failure	4	8%	5	3	15	Routine inspection, preventive maintenance, certified operators
15	Safety Infrastructure	Inadequate fall protection / barricades	9	18%	5	3	15	Install anchor points, safety nets, exclusion zones
16	Safety Infrastructure	Missing or unclear signage	6	12%	3	3	9	Install visible warning signs, barricade critical zones

Human-related hazards focus on workforce competency and behavior. Insufficient training, communication breakdowns, and fatigue are major contributors to incidents. Standardized

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communication systems, competency-based training, and proper shift management help reduce these risks. Hazard identification categorizes risks into mechanical, operational, environmental, human, and equipment-related factors. This systematic process enables prioritization of high-risk activities and supports the development of targeted safety measures, forming a strong foundation for effective risk management and accident prevention.

3.4. Risk Assessment

Risk assessment is a critical process for evaluating and controlling hazards associated with tower crane erection and dismantling. These operations involve complex interactions between equipment, environment, and human factors, making a structured approach essential. This study adopts a combined qualitative and semi-quantitative methodology, integrating hazard identification, probability–severity scoring, and risk matrix evaluation to classify risks into low, medium, high, and intolerable levels. The assessment begins with hazard identification, where potential risks are systematically recorded from site inspections, incident reports, and expert inputs. Common hazards include unstable ground conditions, improper assembly sequencing, rigging failures, mobile crane overloading, adverse weather conditions, and inadequate exclusion zones. Human-related risks such as miscommunication, fatigue, lack of competency, and procedural violations are also key contributors Shown in Table 4.

Table 4 Hazard Register (Based on Global Accident Trends & Semi-Quantitative Scoring)

No	Hazard Category	Specific Hazard	Global Accident Contribution (%)	P (1–5)	S (1–5)	R	Risk Level	Notes / Statistical Basis
1	Ground Conditions	Unstable or soft ground during mobile-crane setup	12% of erection-related incidents	4	5	20	High	Frequent cause of crane tipping and instability
2	Assembly Sequencing	Incorrect assembly of mast/slew unit	15% of erection/dismantling failures	3	5	15	High	Misalignment/ incorrect bolting commonly found in incident reports
3	Rigging Failure	Worn wire ropes, slings, shackles	10% of lifting accidents	3	4	12	Medium	Failure often due to poor inspection regimes
4	Component Fatigue	Hidden cracks or deformation in mast/jib	8% of structural failures	2	5	10	Medium	Most severe but relatively lower probability
5	Mobile Crane Overload	Exceeding lifting charts or side loading	11% of mobile-crane related fatalities	3	5	15	High	Often caused by improper load assessment
6	Wind Conditions	Lifting during high wind speeds (>9–12 m/s)	18% weather-related incidents	4	5	20	High	Wind is a major factor in erection phase collapses

7	Visibility Issues	Fog, dust, night operations	6% of weather-related accidents	3	3	9	Medium	Leads to communication and alignment errors
8	Exclusion Zone Failure	Workers struck by falling objects	22% of crane-related fatalities	4	5	20	High	Leading global cause of deaths in crane operations
9	Human Error	Miscommunication between riggers/signal men	25% of erection errors	4	4	16	High	Particularly common in multilingual crews
10	Fatigue	Long shifts during critical lifts	5% of recorded incidents	3	3	9	Medium	Under-reported but persistent risk factor
11	Procedural Non-Compliance	Deviating from method statements	30% of erection/dismantling accidents	4	5	20	High	Leading root cause across multiple studies
12	Tool Failure	Incorrect torqueing of bolts	7% of assembly errors	3	4	12	Medium	Torque misapplications linked to slewing unit failures
13	Climbing Frame Misuse	Incorrect climbing-sequence execution	36.8% of fatal crane-climbing accidents (Korea study)	4	5	20	High	One of the deadliest crane activities
14	Counterweight Removal Error	Premature removal during dismantling	14% of dismantling accidents	3	5	15	High	Causes sudden imbalance or overturn
15	Weather Shifts	Sudden rain / storms during lifts	10% weather-related	3	4	12	Medium	Reduces soil strength & load visibility
16	Electrical Hazards	Overhead power-line contact	8% of crane accidents worldwide	2	5	10	Medium	Catastrophic but avoidable with planning
17	Traffic Interface	Site traffic conflicting with crane lifts	5% of lifting near-misses	3	3	9	Medium	Common in congested urban areas
18	Operator Competence	Inexperienced mobile/tower crane operator	28% of major incidents	4	5	20	High	Strong link between certification gaps & accidents

19	Communication Failure	Radio malfunction, unclear signals	12% of critical lifts	4	4	16	High	Repeated factor in mast-alignment issues
20	Falling from Height	Workers climbing mast frames	9% of fatalities during erection	3	5	15	High	PPE usage and anchor points often inadequate
21	Equipment Non-Inspection	Skipped pre-lift checks	18% of operational errors	4	4	16	High	Strong correlation with component failures
22	Structural Collapse	Catastrophic mast or jib failure	2% overall but highest severity	1	5	5	Low (but critical)	Rare but catastrophic; must remain monitored
23	Weather-Temperature Extremes	Hydraulic malfunction or brittleness	4% temperature-related failures	2	3	6	Low	Impacts mechanical components gradually
24	Inadequate Supervision	Poor oversight of subcontractors	20% of procedural deviations	4	4	16	High	Found in globally reviewed accident reports
25	Emergency Preparedness Gap	No rescue plan for climbers	Contributes to >50% delayed rescues	3	5	15	High	Major contributor in increasing fatality rate
26	Load Swing	Uncontrolled load motion from wind or poor control	17% of lifting near-misses	4	4	16	High	Affects mast/jib installation accuracy
27	Improper Storage	Damaged components from poor storage	6% material-related issues	2	3	6	Low	Impacts long-term reliability
28	Faulty Instruments	Sensor malfunction (LMI, A2B, wind sensors)	3% of major incidents	2	4	8	Medium	Rare but significant during erection
29	Crane-Mat Failure	Incorrect or inadequate mats	7% of ground-related failures	3	5	15	High	Strong correlation with overturning
30	Time Pressure	Rushing operations due to deadlines	18% contributor to procedural failures	4	4	16	High	A major organizational contributor

The statistical analysis of hazards associated with tower-crane erection and dismantling highlights a clear dominance of human, procedural, and environmental factors in contributing to accidents. The highest-risk items procedural non-compliance (30%), climbing-frame misuse (36.8%), exclusion-zone failures (22%), and wind-related hazards (18%) consistently show Risk Ratings of 20, reflecting both high probability and catastrophic severity. Human-factor issues, including miscommunication (25%), operator incompetence (28%), and inadequate supervision (20%), also fall within high-risk thresholds, emphasizing the need for competency-based training and stronger supervision frameworks. Ground-related hazards such as unstable soil (12%) and crane-mat failure (7%) remain critical contributors to crane instability, while mechanical and equipment-related hazards including rigging failure (10%), component fatigue (8%), and torqueing errors (7%) reflect the consequences of inadequate inspection and maintenance regimes. Environmental influences, particularly high winds, visibility issues, and sudden weather shifts, significantly affect lift stability and decision-making. Low-probability but high-severity hazards such as structural collapse (2%) remain essential considerations due to their catastrophic consequences. Overall, the dataset demonstrates that most high-risk events are preventable through improved planning, disciplined procedural adherence, enhanced inspection routines, and strengthened real-time communication systems.

3.5. Root Cause Analysis

Root Cause Analysis (RCA) is a systematic method used to identify the underlying causes of accidents during tower crane erection and dismantling. These operations involve complex interactions between equipment, workers, and environmental conditions, making it essential to go beyond immediate causes and uncover deeper systemic issues. RCA helps in understanding not only what happened, but why it happened, enabling effective corrective and preventive actions. The primary objective of RCA in this study is to analyze accident scenarios and determine the chain of events leading to failures. It focuses on identifying both immediate causes—such as improper bolt tightening, rigging failure, or miscommunication—and root causes, including inadequate training, poor supervision, weak safety planning, and organizational pressure. This approach shifts the focus from blaming individuals to addressing system-level deficiencies. Structured tools such as the 5 Whys technique, Fault Tree Analysis (FTA), and Fishbone (Ishikawa) diagrams are used to conduct the analysis. The 5 Whys method helps trace problems back to their origin by repeatedly questioning “why” an incident occurred. FTA visually maps how multiple failures combine to cause major events like crane collapse, while Fishbone diagrams categorize causes into human, equipment, procedural, environmental, and management factors. The analysis reveals that accidents rarely result from a single factor; instead, they arise from the interaction of multiple risks such as human error, equipment defects, adverse weather, and procedural deviations. Based on RCA findings, key preventive measures include competency-based training, strict adherence to procedures, regular equipment inspections, improved communication systems, and enhanced supervision. Overall, RCA plays a crucial role in reducing accidents, improving safety performance, and strengthening safety culture in construction projects.

3.6. Development of Safety Enhancement Measures

Tower crane erection and dismantling are high-risk construction activities requiring precise coordination, technical expertise, and strict adherence to safety procedures. Based on findings from risk assessment and Root Cause Analysis (RCA), effective safety enhancement measures are developed to address both immediate hazards and underlying systemic issues. A key focus area is strengthening work planning procedures. Detailed lifting and erection plans must be prepared prior to operations, clearly defining sequencing, load capacities, equipment requirements, and safety precautions. Site-specific risk assessments should evaluate ground conditions, environmental factors, and nearby structures. Proper planning also includes contingency and emergency response procedures to manage unexpected situations. The implementation of standardized checklists ensures consistency and minimizes human error. Pre-erection, during-operation, and dismantling checklists help verify equipment condition, correct assembly steps, and compliance with safety requirements. These checklists act as control tools and provide documentation for audits and regulatory compliance. Supervisory oversight plays a crucial role in maintaining safety. Continuous monitoring of operations, enforcement of safety procedures, and regular toolbox talks ensure that workers follow approved methods. Strong supervision promotes accountability and prevents unsafe practices. Another essential measure is competency-based training programs. Workers must be trained in crane assembly procedures, safe lifting techniques, hazard identification, and emergency response. Certification and periodic skill assessments ensure that only qualified personnel perform critical tasks, reducing human error. Enhanced communication systems improve coordination between crane operators, riggers, and signalers. Reliable radio communication, standardized hand signals, and multilingual visual aids reduce misunderstandings during lifting operations. Permit-to-work systems further ensure that all safety conditions are verified before work begins. The integration of advanced technologies such as load monitoring sensors, digital lifting simulations, automated safety alerts, and environmental monitoring systems provides real-time risk detection and control. Finally, continuous safety monitoring and improvement through audits, near-miss reporting, and worker feedback ensures that safety practices evolve. These combined measures significantly reduce accident risks and promote a proactive safety culture.

3.7. Validation of Recommendations

Validation of recommendations is a crucial step to ensure that the proposed safety measures for tower crane erection and dismantling are practical, effective, and applicable in real construction environments. It confirms that the developed safety framework can successfully address the identified hazards and root causes. Without validation, safety measures may remain theoretical and fail to deliver meaningful improvements in site safety. The validation process begins with expert consultation and professional review. Industry experts such as crane operators, safety engineers, and project managers evaluate the proposed measures based on their practical experience. Their feedback helps assess feasibility, identify implementation challenges, and ensure alignment with real-world construction practices and regulatory requirements. Pilot testing is another important validation method. Selected safety measures, including checklists, communication systems, and monitoring tools, are implemented on a limited scale during actual crane operations. This allows observation of their performance under real conditions. Pilot testing helps identify practical issues, such as difficulties in using equipment or gaps in worker understanding, enabling necessary improvements before full-scale implementation. Simulation and mock-up exercises further support validation by testing safety procedures in controlled environments. Digital simulations of lifting operations help verify crane stability and risk control measures, while mock drills allow workers to practice communication and emergency response procedures. These methods provide both visual and analytical evidence of effectiveness. Additionally, comparison with international best practices ensures that the recommendations align with globally accepted safety standards. This enhances the credibility and reliability of the proposed framework. Finally, feedback and continuous improvement play a vital role. Input from workers and supervisors helps refine procedures, while implementation readiness assessments ensure that organizations have adequate resources and training. Overall, validation ensures that safety measures are reliable, practical, and ready for effective implementation.

Documentation and Conclusion

Proper documentation plays a vital role in ensuring the success and reliability of safety improvement initiatives in tower crane erection and dismantling operations. It provides a systematic record of all research activities, including hazard identification, risk assessment, root cause analysis, and the development of safety enhancement measures. By organizing these elements into a structured format, documentation enables construction professionals and safety managers to clearly understand the basis of the proposed strategies and apply them effectively in real-world scenarios. The compiled documentation integrates data from site observations, accident reports, and expert inputs, presenting a comprehensive overview of risks and their contributing factors. It also highlights the outcomes of risk assessments and Root Cause Analysis, emphasizing that most crane-related accidents result from a combination of human, technical, environmental, and organizational factors rather than a single cause. The study concludes that improving safety in tower crane operations requires a holistic approach. Key measures include detailed planning, competency-based training, strong supervision, effective communication systems, and the use of advanced technologies such as real-time monitoring and safety alerts. The structured safety model developed in this project serves as a practical framework for minimizing risks and enhancing operational reliability. Overall, this research reinforces the importance of proactive safety management. Implementing the recommended measures and continuously improving safety practices, construction organizations can significantly reduce accidents and promote a strong and sustainable safety culture.

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