

Assessment of Safety Protocols in Tower Crane Operations on High-Rise Construction Sites

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Abstract

The use of tower cranes is essential in modern high-rise construction due to their ability to lift heavy materials to significant heights. Tower crane operations pose serious safety risks, including equipment failure, structural collapse, and human error, which can result in accidents, injuries, or fatalities. This project aims to assess the effectiveness and adequacy of current safety protocols associated with tower crane operations on high-rise construction sites. The study investigates existing safety standards, compliance practices, and risk mitigation strategies through a combination of literature review, field observations, and stakeholder interviews involving crane operators, site managers, and safety inspectors. The research focuses on identifying common safety lapses, analyzing accident reports, and evaluating the implementation of industry regulations such as OSHA (Occupational Safety and Health Administration) and ISO standards. Particular attention is given to factors like crane erection and dismantling procedures, load handling, weather considerations, operator training, and communication systems on site. The findings highlight gaps between prescribed safety protocols and actual on-site practices, with key challenges including inadequate supervision, insufficient training, and non-compliance due to project deadlines. The project further recommends actionable improvements such as enhanced safety audits, mandatory certifications, adoption of real-time monitoring technologies, and the integration of automated safety alerts. The ultimate goal is to contribute to safer working environments by promoting a culture of proactive risk management and regulatory adherence. The addressing both human and technical dimensions of tower crane operations, this assessment provides valuable insights for construction firms, safety regulators, and policy-makers aiming to reduce crane-related incidents and improve overall construction site safety.

Keywords: Tower Crane Safety, High-Rise Construction, Risk Assessment, Safety Compliance (OSHA & ISO), Proactive Risk Management.

1. Introduction

High-rise construction projects rely heavily on tower cranes for lifting and transporting heavy materials to significant heights. These cranes play a critical role in improving construction efficiency, reducing manual labor, and enabling the rapid development of modern infrastructure. Tower crane operations involve complex mechanical systems, heavy loads, and dynamic environmental conditions, making them one of the most hazardous activities on construction sites. Accidents related to tower cranes can result in severe injuries, fatalities, structural damage, and major project delays. Therefore, ensuring strict safety protocols and effective operational management is

essential to protect workers and maintain project stability. Safety protocols in tower crane operations typically include proper lift planning, certified operator training, routine inspection and maintenance, risk assessment procedures, and adherence to regulatory standards. Despite the existence of these guidelines, many construction sites continue to experience incidents due to inadequate supervision, human error, insufficient training, and non-compliance with safety procedures. Environmental factors such as high wind speeds and poor visibility can also increase the risk of crane-related accidents. This study focuses on the

assessment of safety protocols in tower crane operations on high-rise construction sites. The objective is to evaluate existing safety practices, identify potential gaps in implementation, and analyze the effectiveness of current safety measures. Examining accident data, operational procedures, and regulatory compliance, the study aims to provide practical insights and recommendations to enhance crane safety management and reduce accident risks in high-rise construction environments.

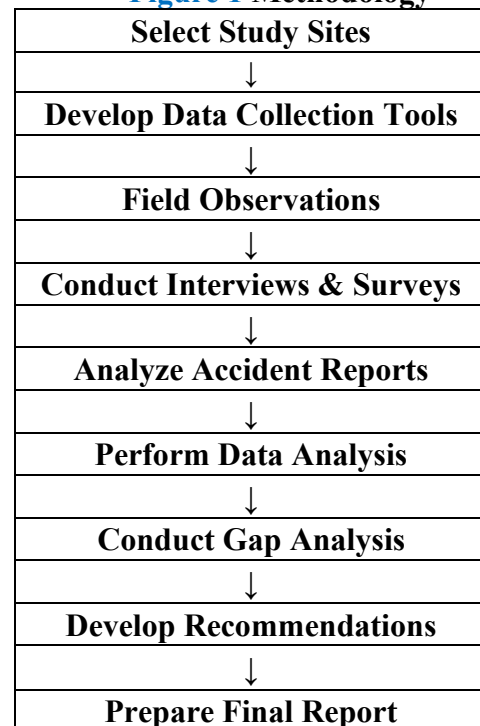
2. Literature Review

Several researchers have examined different aspects of tower crane safety, automation, and operational efficiency in construction environments. Recent studies highlight the integration of advanced technologies, engineering improvements, and risk assessment models to enhance crane safety and performance. Enliu Yuan and Jian Yang (2025) proposed a digital twin framework for tower cranes that establishes a physical-to-virtual connection using computer vision techniques. Their study improved crane object detection accuracy from 93.85% to 95.45% using an enhanced YOLOv5 algorithm and DIOU-NMS method. The research also used 3DResNet for operation mode recognition, achieving an accuracy of 87%. However, the model was limited to physical-to-virtual interaction and requires further development to create a complete digital twin system. Ahmad Bala Alhassan and Syed Muhammad Umair Arif (2025) developed an experimental dataset to analyze tower crane dynamics, focusing on payload oscillations and trolley trajectories. Their work provides valuable data for machine learning-based control systems to reduce oscillations and improve operational efficiency. Jianten Goh and Yihai Fang (2025) examined crane operation user interfaces (UI) and proposed a framework to evaluate visualization systems that support operators during real-time lifting operations. Their findings highlight the importance of clear visual communication for improving operational safety. Engineering-focused studies have also contributed to safety improvements. Md Nazmul Hasan Dipu et al. (2024) used finite element analysis to identify an optimal trapezoidal crane hook design that enhances the factor of safety and reduces structural stress. Similarly, Matthias Thomas et al. (2024) proposed a model-based velocity tracking

control system for tower cranes to reduce payload sway and improve operational stability. From a safety management perspective, Haleh Sadeghi and Xueqing Zhang (2024) developed a knowledge-based decision support system for automated safety risk assessment in crane operations. Their model identified 42 critical safety risks and prioritized hazards such as falling loads, electrocution, and fall from heights. Additionally, Yin Junjia et al. (2024) analyzed hoisting accident cases and emphasized that machinery collapse, falling loads, and worker falls are the most common causes of crane-related accidents. Earlier research by Vahid Kargar and Mehdi Jahangiri (2022) applied fuzzy fault tree analysis to evaluate crane overturning risks, while Chung-Suk Cho et al. (2017) highlighted the importance of regulatory compliance and worker training under OSHA crane safety standards. Overall, existing literature demonstrates that improving tower crane safety requires a combination of technological innovation, engineering design improvements, effective risk assessment frameworks, and strong regulatory enforcement.

3. Methodology

Figure 1 Methodology



3.1. Select Study Sites

Selecting appropriate study sites is a crucial step in ensuring the reliability, relevance, and applicability of the research findings. For this study on the assessment of safety protocols in tower crane operations on high-rise construction sites, a systematic and structured approach was adopted to identify representative construction projects where tower cranes are actively used. The main objective of selecting these sites was to observe real-time crane operations, evaluate existing safety practices, and analyze how safety protocols are implemented under different working conditions. Several important criteria were considered during the site selection process. First, project scale and building height were taken into account, focusing primarily on high-rise construction projects typically exceeding 25 stories, where tower cranes play a critical role in vertical material handling. Such projects involve complex lifting operations and higher safety risks, making them suitable for detailed safety assessments. Another key factor was the type of tower crane used, including hammerhead, luffing jib, climbing frame, and self-erecting cranes. Studying different crane types helps identify variations in operational procedures, safety requirements, and potential hazards. Construction phase was considered to observe safety practices during different stages such as crane erection, active lifting operations, and dismantling, each of which presents unique risks. The selection process also included geographical diversity, covering sites located in different regions with varying climatic conditions and regulatory environments. Furthermore, projects managed by different company profiles, such as multinational contractors, mid-sized firms, and local contractors, were included to compare organizational safety culture and training practices. Overall, six construction sites across three regions were selected for detailed study. This diverse selection provided comprehensive insights into crane safety management, helping identify safety gaps, best practices, and opportunities for improving tower crane operation safety in high-rise construction projects.

3.2. Develop Data Collection Tools

The effectiveness of this research largely depends on

the quality and reliability of the data collected. To assess safety protocols in tower crane operations on high-rise construction sites, well-structured and appropriate data collection tools were developed. Due to the complex nature of crane operations and the variety of safety issues involved, the study adopted a mixed-methods approach that combines both qualitative and quantitative techniques. The primary data collection tools include structured observation checklists, survey questionnaires, and semi-structured interview guides. These tools were designed to gather information from multiple stakeholders such as crane operators, safety officers, site engineers, supervisors, and project managers. The structured observation checklist was developed to record real-time safety practices and compliance with established safety standards during crane operations. This tool helps researchers systematically observe activities such as crane erection procedures, operational safety practices, maintenance and inspection routines, use of personal protective equipment (PPE), weather monitoring, and emergency preparedness. Each observation item is recorded using options such as “Yes,” “No,” or “Not Applicable,” allowing the results to be easily analyzed and compared across different construction sites. The survey questionnaire was designed to collect information on workers’ perceptions, awareness, and experiences related to crane safety. The survey includes sections on worker demographics, safety training, protocol compliance, supervision effectiveness, risk factors, and the use of modern safety technologies. Most responses are measured using a Likert scale, which enables statistical analysis and identification of patterns in safety attitudes and behaviors. Semi-structured interviews were conducted with experienced professionals such as safety managers and crane operators to obtain deeper insights into operational challenges, organizational safety culture, and incident experiences. Together, these data collection tools provide comprehensive and reliable information, supporting a detailed evaluation of tower crane safety protocols. As shown in Table 1 Safety Protocol Compliance and Stakeholder Survey Results Across Study Sites different construction sites.

**Table 1 Safety Protocol Compliance and Stakeholder Survey Results Across Study Sites
different construction sites**

Safety Parameter / Survey Item	Site 1 (n=15)	Site 2 (n=12)	Site 3 (n=18)	Site 4 (n=10)	Site 5 (n=14)	Site 6 (n=11)	Overall (%)
Observation Checklist Compliance (%)							
Crane Setup & Erection Procedures	87%	75%	92%	80%	78%	85%	83.6%
Operational Safety (Load Handling & Signaling)	80%	70%	85%	75%	73%	82%	77.5%
PPE Usage Compliance by Operators and Ground Crew	90%	88%	94%	85%	80%	89%	87.7%
Equipment Maintenance and Inspection	85%	68%	88%	78%	75%	83%	79.5%
Weather Monitoring and Safety Measures	78%	65%	82%	70%	68%	75%	73.0%
Emergency Preparedness & Rescue Plan Availability	85%	72%	90%	77%	70%	80%	79.0%
Survey Questionnaire Results (Likert Scale % Agree)							
Adequacy of Safety Training Programs	67%	60%	72%	65%	62%	68%	65.7%
Effectiveness of Supervision and Enforcement	55%	50%	60%	52%	48%	58%	53.8%
Perceived Risk due to Weather Conditions	75%	80%	70%	78%	82%	77%	77.0%
Pressure to Meet Project Deadlines Leading to Risks	62%	70%	65%	68%	72%	66%	67.2%
Usefulness of Technology (Load Sensors, Alerts)	80%	72%	85%	75%	78%	82%	78.7%
Confidence in Emergency Procedures	70%	65%	75%	68%	60%	72%	68.3%

3.3. Field Observations

Field observations are a vital component of this study, providing direct insight into how safety protocols are implemented during tower crane operations on high-rise construction sites. Unlike document reviews or interviews, field observations allow researchers to examine real-time activities and identify gaps between established safety procedures and actual site practices. The observations focused on key operational stages such as crane erection, load handling, and crane dismantling. Additional aspects such as operator behavior, communication methods, supervision levels, use of safety equipment, and environmental conditions were also carefully monitored. The main objective of field observations

was to evaluate the level of compliance with established safety standards such as OSHA regulations, ISO guidelines, and national construction safety codes. Observations aimed to verify whether crane operations followed approved procedures, identify unsafe work practices, and assess the effectiveness of supervision and safety enforcement. Particular attention was given to the use of Personal Protective Equipment (PPE), the condition of crane components, communication between crane operators and ground personnel, and the influence of environmental factors such as wind and rainfall on crane operations. As shown in TABLE 2. Field Observation Findings Across Six Construction Sites.

Table 2 Field Observation Findings Across Six Construction Sites

Observation Criteria	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Compliance Average (%)	Issues Identified
Crane Erection Supervised by Certified Personnel	Yes	No	Yes	Partial	No	Yes	66.7%	Lack of supervision at Sites 2 & 5
Use of Erection Checklists	Yes	No	Yes	Yes	No	Partial	66.7%	No checklist system at Sites 2 & 5
PPE Usage by Operators	Yes	Yes	Yes	Yes	Yes	Yes	100%	None
PPE Usage by Ground Workers	Partial	No	Yes	Yes	Partial	No	58.3%	Inconsistent PPE enforcement at Sites 2, 5, & 6
Proper Load Rigging Observed	Yes	Partial	Yes	Yes	No	Yes	75.0%	Unsafe rigging at Site 5
Effective Communication During Lifting	Radio	Hand	Radio	Hand	None	Radio	—	Site 5 lacked any system; Site 2 and 4 relied only on hand signals
Weather Monitoring Systems in Use	Yes	No	Yes	No	Yes	Yes	66.7%	No monitoring at Sites 2 & 4
Emergency Stop/Rescue Plan Available	Yes	Partial	Yes	No	Partial	Yes	66.7%	Incomplete or missing at Sites 2, 4 & 5
Safety Supervisor Present During Operations	Yes	No	Yes	Yes	No	Yes	66.7%	Lack of supervisory oversight at Sites 2 & 5
Load Charts and Limits Displayed on Cranes	Yes	Yes	Yes	No	No	Yes	66.7%	Absent at Sites 4 & 5

Field observations were conducted across six high-rise construction sites selected for their diversity in project scale, crane types, and management practices. Trained observers used structured observation checklists to record safety practices systematically. Each observation session lasted between two and four hours and was scheduled during different stages of construction activities to capture a comprehensive understanding of crane operations. The observations revealed that while most sites followed basic safety procedures, several gaps existed in areas such as PPE compliance among ground workers, communication systems during load handling, and weather monitoring practices. In some cases, inadequate supervision and pressure to meet project deadlines led to unsafe practices. Overall, field observations provided valuable practical insights that supported the identification of safety weaknesses and opportunities for improving crane operation safety management[1 – 10].

3.4. Conduct Interviews & Surveys

To effectively evaluate the implementation of safety protocols in tower crane operations on high-rise construction sites, this study adopted a mixed-method approach that combined quantitative surveys and qualitative interviews. This dual method allowed the research to capture both measurable data and detailed experiential insights from various stakeholders involved in crane operations. Participants included crane operators, signalers, ground workers, site supervisors, and safety officers working across the selected construction sites. The survey questionnaire was designed to collect structured information regarding safety awareness, training levels, protocol compliance, risk perception, and the use of safety technologies. The survey consisted primarily of Likert-scale questions ranging from “Strongly

Agree” to “Strongly Disagree,” enabling the statistical analysis of attitudes and behaviors related to safety practices. In addition, a few open-ended questions were included to allow respondents to share personal experiences, identify safety challenges, and propose improvements. Approximately 120–150 responses were collected across the six construction sites, ensuring a broad representation of roles and experience levels. Complementing the surveys, semi-structured interviews were conducted with selected key stakeholders, including crane operators, safety managers, and site supervisors. Each site contributed two to three participants for interviews, resulting in a total of 15–18 in-depth interviews. These interviews lasted around 45–60 minutes and focused on understanding the real-world challenges of implementing safety protocols, communication barriers, training effectiveness, and the influence of organizational decisions on operational safety. The interviews provided detailed narratives of near-miss incidents, operational difficulties, and safety culture within construction organizations. Participants also discussed issues such as time pressure, inadequate supervision, and limited access to modern safety technologies. By comparing the findings from surveys with interview insights and field observations, the study was able to identify discrepancies between reported safety practices and actual site behavior. This integrated approach provided a comprehensive understanding of safety management challenges and supported the development of practical recommendations for improving tower crane safety on high-rise construction projects[11 – 17]. As shown in Table 3 Survey Results

Table 3 Survey Results

Survey Variable	Strongly Agree (%)	Agree (%)	Neutral (%)	Disagree (%)	Strongly Disagree (%)	Mean Score (1–5)	Observations
Received adequate crane-specific training	38%	32%	16%	10%	4%	3.90	Training quality varies; newer workers report gaps.

Safety protocols are clearly communicated	34%	41%	12%	9%	4%	3.93	Better communication observed in larger firms.
Always use PPE during crane operations	47%	30%	10%	9%	4%	4.06	Ground crew showed slightly lower compliance than operators.
Supervisors regularly enforce safety rules	28%	37%	14%	15%	6%	3.66	Supervision is inconsistent; depends on workload and staffing.
I feel pressured to ignore safety protocols to meet deadlines	12%	28%	22%	30%	8%	3.06	Around 40% admitted feeling at least occasional pressure.
I am aware of emergency rescue procedures	36%	33%	17%	10%	4%	3.87	Many lacked clarity about crane-specific emergency steps.
Site has reliable weather monitoring systems	21%	31%	20%	21%	7%	3.38	Mid-sized and smaller sites had limited access to equipment.
Communication tools (radios, signals) are effective	29%	40%	18%	9%	4%	3.81	Hand signals still widely used; radios more common at urban sites.
Load limits are strictly followed	24%	44%	17%	10%	5%	3.72	Risk of overload more prevalent during peak construction phases.
Technology improves crane safety	35%	39%	15%	8%	3%	3.95	Positive outlook overall, though adoption remains low in smaller companies.

3.5. Analyze Accident Reports

The analysis of accident reports represents a fundamental stage in evaluating the effectiveness of safety protocols in tower crane operations on high-rise construction sites. This phase involved a systematic review of 120 documented accident and incident reports obtained from safety databases, construction company records, regulatory publications, and industry case studies. The primary objective was to identify recurring accident patterns,

determine root causes, and understand the operational circumstances under which these incidents occurred. Key aspects considered during the analysis included human error, equipment malfunction, procedural violations, environmental conditions, and organizational shortcomings. The classification of accident types revealed that Load Drop or Falling Object incidents were the most frequent, accounting for 26.7% of the total cases. These incidents are typically associated with improper rigging

techniques, inadequate load securing, or communication failures between crane operators and signal personnel. Despite being common, they also caused several fatal and major injuries due to the height and weight of materials involved. The second most critical category was Crane Collapse or Structural Failure, representing 15% of cases, but

responsible for the highest number of fatalities. Such incidents often occur due to foundation instability, improper crane erection procedures, or structural overloading. As shown in Table 4 Classification of Accidents by Type, Table 5 Root Cause Analysis, Table 6 Contributing Organizational Factors.

Table 4 Classification of Accidents by Type

Sl. No	Accident Type	No. of Cases	Percentage (%)	Severity Level (Major/Minor/Fatal)
1	Load Drop / Falling Object	32	26.7%	8 Fatal / 14 Major / 10 Minor
2	Crane Collapse / Structural Failure	18	15.0%	10 Fatal / 6 Major / 2 Minor
3	Electrical Contact (Power Lines)	14	11.7%	4 Fatal / 6 Major / 4 Minor
4	Overturning due to Wind	10	8.3%	5 Fatal / 3 Major / 2 Minor
5	Mechanical Failure (Hoist/Brake)	16	13.3%	2 Fatal / 9 Major / 5 Minor
6	Rigging Failure	12	10.0%	3 Fatal / 5 Major / 4 Minor
7	Collision with Structures	8	6.7%	1 Fatal / 4 Major / 3 Minor
8	Unauthorized Operation	10	8.3%	2 Fatal / 5 Major / 3 Minor
Total		120	100%	

Table 5 Root Cause Analysis

Sl. No	Root Cause Category	Frequency	Percentage (%)
1	Human Error (Operator Misjudgment, Fatigue)	38	31.7%
2	Inadequate Training / Certification	22	18.3%
3	Equipment Failure / Poor Maintenance	24	20.0%
4	Procedural Lapses / SOP Violation	18	15.0%
5	Environmental Factors (High Wind, Rain)	12	10.0%
6	Lack of Supervision	6	5.0%
Total		120	100%

Table 6 Contributing Organizational Factors

Sl. No	Organizational Issue	No. of Cases	Percentage (%)
1	Project Deadline Pressure	28	23.3%
2	Inadequate Safety Audits	20	16.7%
3	Poor Communication (Signal Failure)	18	15.0%
4	Lack of Preventive Maintenance Schedule	22	18.3%

5	Insufficient Risk Assessment Before Lifts	32	26.7%
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Mechanical failures, particularly related to hoists and braking systems, accounted for 13.3% of incidents, highlighting the importance of preventive maintenance and equipment inspections. Additionally, electrical contact with overhead power lines (11.7%) and rigging failures (10%) further emphasize the need for strict hazard identification and operational planning before lifting activities. Environmental factors such as high wind conditions contributed to crane overturning incidents, demonstrating the significance of weather monitoring and adherence to operational limits. Root cause analysis revealed that human error was the dominant factor, contributing to 31.7% of accidents, followed by equipment failure (20%) and inadequate training (18.3%). Organizational issues such as insufficient risk assessment, deadline pressure, and poor communication also played a significant role in many incidents. Overall, the accident report analysis confirms that tower crane accidents are rarely caused by a single factor; instead, they result from a combination of technical, human, and organizational deficiencies. These findings provide critical insights for strengthening safety protocols, improving operator training programs, and enforcing preventive maintenance strategies in high-rise construction projects.

3.6.Perform Data Analysis

After compiling and categorizing accident data from 120 documented tower crane incidents in high-rise construction projects, a structured data analysis process was conducted to convert raw information into meaningful safety insights. The primary objective of this phase was to identify accident trends, evaluate risk patterns, and determine the key factors influencing tower crane safety performance. Analytical tools such as Microsoft Excel, Python-based statistical packages, SPSS, and Tableau were used to ensure systematic, accurate, and reproducible results. Both quantitative and qualitative analytical methods were applied to gain a comprehensive understanding of crane-related safety issues.

3.6.1. Quantitative Statistical Analysis

The quantitative analysis focused on calculating incident rates, frequency distribution, and equipment reliability indicators. Incident rates were standardized per 100,000 working hours to allow comparison across construction sites of varying project sizes and durations. The results showed that projects with higher construction intensity and multiple crane operations recorded higher incident rates. Frequency distribution analysis indicated that load drop incidents accounted for the highest proportion of accidents, followed by crane collapse, mechanical failures, and electrical contact cases. Another key metric used was Mean Time Between Failures (MTBF), which measured the reliability of crane components such as hoists, braking systems, and wire ropes. Sites that followed preventive maintenance schedules showed higher MTBF values, indicating improved equipment reliability and reduced mechanical failures.

3.6.2. Qualitative and Trend Analysis

Qualitative evaluation of accident reports, supervisor feedback, and worker interviews revealed several behavioral and organizational factors contributing to incidents. Common issues included inadequate training, communication failures, and pressure to meet project deadlines. Temporal analysis further showed that accidents were more frequent during extended working hours and peak construction stages, while environmental analysis highlighted the role of high wind speeds and poor visibility in increasing operational risks. Overall, the data analysis confirmed that tower crane accidents are influenced by a combination of technical, human, and organizational factors, emphasizing the need for integrated safety management strategies.

3.7.Conduct Gap Analysis

Following the completion of the data analysis phase, a gap analysis was conducted to evaluate the differences between existing tower crane safety practices and recognized industry standards. The purpose of this analysis was to identify weaknesses in current operational procedures and determine areas where safety performance could be improved. By comparing actual site practices with established

regulatory frameworks and industry best practices, the study aimed to highlight deficiencies that may contribute to accidents and unsafe working conditions. Regulatory guidelines from organizations such as the Occupational Safety and Health Administration and safety management principles recommended by international standards were used as benchmark references for the evaluation. The gap analysis focused on several critical safety domains, including employee training and competency, lift planning procedures, equipment maintenance practices, supervision and communication systems, emergency preparedness, and documentation management. A structured evaluation framework was developed to assess each domain based on three levels of compliance: fully compliant, partially compliant, and non-compliant. Evidence for this assessment was gathered through site observations, safety audits, accident records, maintenance logs, and interviews with crane operators and safety personnel. The findings revealed several important gaps between ideal safety requirements and actual practices. Training programs were found to be inconsistent, with limited refresher training and incomplete documentation of worker competency. Lift planning and risk assessment procedures were sometimes generic and lacked site-specific hazard evaluation. Preventive maintenance schedules were not always strictly followed, increasing the likelihood of mechanical failures. In addition, supervision levels varied across sites, and communication systems between crane operators and ground personnel were not always reliable. The analysis also identified weaknesses in emergency preparedness and safety documentation. Emergency response plans existed but were rarely practiced through drills, and safety audits lacked comprehensive follow-up actions. Furthermore, project deadline pressure occasionally influenced operational decisions, leading to shortcuts in safety procedures. The gap analysis confirmed that while basic safety policies are present, inconsistencies in implementation, monitoring, and management commitment remain significant challenges. Identifying these gaps provides a clear foundation for developing targeted corrective actions to strengthen tower crane safety management on high-rise construction sites.

3.8. Develop Recommendations

Based on the findings obtained from the data analysis and gap analysis phases, a set of targeted recommendations has been developed to address the key safety deficiencies identified in tower crane operations on high-rise construction sites. These recommendations are designed to improve safety performance, reduce accident risks, and strengthen overall crane safety management systems. The proposed measures are practical, evidence-based, and aligned with recognized regulatory requirements and industry best practices. Each recommendation focuses on improving operational efficiency while ensuring the protection of workers and equipment. One of the primary recommendations is to strengthen training and competency management. Since human error was identified as a major contributing factor to accidents, organizations should implement structured training programs for crane operators, riggers, and signalers. This includes mandatory refresher training, competency assessments, and proper certification before personnel are assigned to crane operations. Another key recommendation is the implementation of detailed lift planning and risk assessment procedures. Construction sites should adopt a formal permit-to-lift system, ensuring that every lifting activity is properly planned and approved by qualified supervisors. Site-specific risk assessments, load calculations, and weather evaluations must be conducted before crane operations begin. Improving preventive maintenance and equipment monitoring is also essential. Regular inspections, scheduled maintenance, and proper documentation of crane components can significantly reduce mechanical failures and unexpected equipment breakdowns. Technological improvements such as wind speed monitoring systems, load moment indicators, and communication devices between crane operators and ground personnel should also be introduced to enhance operational safety. Strengthening supervision, emergency preparedness, and organizational safety culture is crucial. Management should prioritize safety over production pressure, conduct regular safety audits, and encourage workers to report hazards without fear. Implementing these recommendations will significantly improve safety

standards and reduce tower crane-related accidents in high-rise construction projects.

3.9.Prepare Final Report

The final phase of the study involves compiling all research findings, analyses, and recommendations into a comprehensive and well-structured report. This report serves as the primary document that summarizes the entire assessment of safety protocols in tower crane operations on high-rise construction sites. Its main purpose is to present the study results in a clear, organized, and professional format that can support informed decision-making by organizational leadership and safety management teams. The report begins with a cover page, executive summary, and introduction that outline the project objectives, background of tower crane safety challenges, and the overall scope of the study. Subsequent sections describe the research methodology, including the data collection procedures, accident report analysis, and analytical tools used during the study. These sections provide transparency and ensure the reliability of the research process. Further sections of the report present the key findings from statistical analysis, temporal and environmental evaluations, and qualitative insights obtained from accident reports and site observations. Visual representations such as tables, charts, and graphs are included to make the results easier to interpret. The report also highlights the outcomes of the gap analysis, identifying discrepancies between existing practices and industry safety standards. Based on these findings, the report provides prioritized recommendations and a structured implementation plan to improve tower crane safety management. Additionally, a monitoring and evaluation framework is included, outlining key performance indicators such as incident rate reduction, training compliance, and maintenance reliability. The final report functions as a strategic document that guides policy improvements, resource allocation, and continuous safety enhancement in high-rise construction projects.

3.10. Result And Discussion

The analysis of 120 documented tower crane-related accident cases in high-rise construction projects provided important insights into the patterns, causes, and systemic weaknesses affecting crane safety

performance. The results indicate that tower crane accidents are rarely caused by purely technical failures; instead, they are strongly influenced by human and organizational factors.

The findings show that fatal incidents accounted for approximately 29% of the total cases, confirming the high-risk nature of tower crane operations. Among the various accident categories, load drop or falling object incidents were the most common, representing about 26.7% of cases, followed by crane collapses and structural instability events. Most accidents occurred during active lifting operations rather than during erection or dismantling phases, highlighting the importance of effective operational control and supervision. Root cause analysis revealed that human error contributed to nearly one-third of the incidents. Factors such as incorrect load estimation, improper signaling, failure to follow lift plans, and fatigue during extended working hours were frequently observed. Organizational factors were also significant, contributing to approximately 45% of the cases. Deadline pressure, inadequate lift planning, and insufficient supervision often encouraged unsafe work practices. Temporal and environmental analysis further showed that accidents were more frequent during peak construction stages, overtime shifts, and adverse weather conditions such as high wind speeds. In many cases, lifting operations continued even when environmental conditions exceeded safe operational limits. The results highlight a clear gap between documented safety policies and actual on-site practices. Strengthening training programs, preventive maintenance, supervision, and safety culture is essential to reduce tower crane-related accidents in high-rise construction projects.

Conclusion

This study comprehensively assessed the effectiveness of safety protocols in tower crane operations on high-rise construction sites through systematic data analysis, gap evaluation, and evidence-based recommendations. The findings clearly indicate that tower crane accidents are primarily influenced by human and organizational factors rather than purely mechanical failures. Fatal incidents accounted for a significant proportion of total cases, underscoring the high-risk nature of

lifting operations in vertical construction environments. Load drop incidents, procedural violations, and inadequate lift planning were identified as the most critical contributors to accidents. Human error, often linked to insufficient training, fatigue, and communication breakdowns, emerged as the dominant root cause. Additionally, organizational shortcomings such as deadline pressure, weak supervision, and incomplete risk assessments further amplified safety vulnerabilities. These results highlight the need for stronger compliance with established regulatory frameworks, including guidelines from the Occupational Safety and Health Administration and international standards issued by the International Organization for Standardization. The study concludes that effective tower crane safety requires an integrated and proactive risk management approach. Strengthening training programs, enforcing structured lift planning, adopting preventive maintenance systems, integrating real-time monitoring technologies, and fostering leadership-driven safety culture are essential measures for reducing incident rates. Aligning operational practices with regulatory standards and promoting accountability at all organizational levels, construction firms can significantly enhance worker safety, improve compliance, and ensure sustainable high-rise project performance.

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