© MAY 2026 | IRE Journals | Volume 9 Issue 11 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I11-1717830

Strategies For Hazards in Offshore Bridge Developments Requiring Hazardous Construction Operations

PRODIP SADHU[1], OMPRAKASH S THAKARE[2], AJAY KUMAR GUPTA[3]
[1,2,3]*Department of Health Safety & Environment Engineering, Shri Rawatpura Sarkar University, Raipur*

Abstract- Marine bridge construction involves hazardous conditions such as tidal changes, strong currents, harsh weather, and difficult access, requiring effective risk management to ensure safety and efficiency. This study identifies high-risk activities including pile driving, cofferdam construction, underwater concreting, heavy lifting, marine transport, and working at height. Using literature reviews and case studies, the research evaluates tools such as HAZID, JSA, Permit-to-Work systems, and risk assessment matrices. The findings emphasize proactive planning, advanced construction technologies, worker training, continuous monitoring, emergency preparedness, regulatory compliance, and stakeholder coordination to improve safety performance in future marine bridge construction projects.

Index Terms- Permit to Work (PTW), Hazard Identification and Risk Assessment (HIRA), High-Risk Construction Activities, Intertidal Construction, Marine Bridge Construction Safety.

I. INTRODUCTION

Marine bridges are essential for connecting regions separated by seas, rivers, and estuaries, significantly improving transportation, regional integration, and economic development. Rapid urbanization and industrial growth, particularly in developing countries like India, have increased the demand for large-scale marine bridge projects. However, constructing these bridges involves major engineering and environmental challenges, including tidal fluctuations, strong currents, high winds, saltwater exposure, drifting debris, and limited site accessibility. Offshore and intertidal construction activities expose workers to serious hazards such as crane failures, unstable floating platforms, falls from height, drowning risks, and extreme weather conditions. The Mumbai Trans Harbour Link (MTHL), a 21.8 km sea bridge connecting Mumbai and Navi Mumbai, demonstrates these complexities through deep-water foundations, segment launching operations, and challenging marine conditions, emphasizing the need for effective risk management and strict safety practices to ensure successful project execution.

II. LITERATURE REVIEW

Offshore bridge construction presents highly specialized challenges that differ significantly from those encountered in conventional land-based infrastructure projects. Marine environments introduce continuously changing operational conditions influenced by tidal movements, wave actions, weather variability, and limited accessibility. According to Zhou et al. (2012) and Tam & Fung (2011), offshore construction projects face several critical safety risks that directly affect operational stability, worker safety, project scheduling, and overall construction efficiency.

One of the most significant challenges in offshore construction is sea and wave motion. Sudden tidal fluctuations and changes in wave intensity create unstable working conditions, particularly for barges, floating platforms, and marine lifting systems. These unstable conditions can affect the positioning of heavy equipment and reduce operational accuracy during critical activities such as piling, segment launching, and crane lifting. Since marine conditions constantly change, project schedules often require modification according to tidal timings and weather forecasts, resulting in delays and increased operational costs.

Material corrosion and structural deterioration also pose major difficulties in marine construction projects. Continuous exposure to saltwater, humidity, and aggressive marine environments accelerates the corrosion of steel structures, machinery, and construction equipment. To overcome these issues, specially engineered corrosion-resistant materials, protective coatings, and advanced maintenance systems are required. However, the use of such specialized materials increases procurement complexity and overall project expenditure. Regular inspection and maintenance therefore become essential to ensure structural durability and operational safety throughout the project lifecycle.

Emergency access and evacuation represent another serious concern in offshore environments. Unlike land-based projects where emergency services can respond quickly, offshore locations are often isolated and difficult to access. Delays in medical assistance or rescue operations can significantly worsen the consequences of workplace incidents. Therefore, detailed emergency preparedness plans, marine rescue systems, evacuation procedures, and workforce training programs are essential components of offshore safety management. Workers must be trained to respond effectively to emergencies such as falls into water, fire outbreaks, equipment collapse, and sudden weather disturbances.

Slippery and uneven working surfaces further increase the risk of slips, trips, and falls during marine operations. Workers frequently operate on wet steel platforms, floating barges, temporary access systems, and narrow elevated surfaces exposed to water spray and moisture. Such conditions require strict implementation of safety controls including anti-slip footwear, lifeline systems, temporary walkways, guardrails, and continuous supervision to minimize fall-related incidents.

Weather-related hazards are particularly critical during offshore bridge construction activities. High wind speeds, poor visibility, storms, and monsoon conditions can severely affect crane operations, lifting activities, and precast segment installation over water. Weather uncertainty forces project teams to maintain flexible schedules and continuously monitor meteorological forecasts to ensure safe execution of activities. Construction operations may need to be suspended or rescheduled whenever environmental conditions exceed safe operational limits.

Similar challenges were experienced during the Mumbai Trans Harbour Link (MTHL) project, especially during deep-water foundation construction and the placement of precast segments using launching gantries over the sea. Barge movement caused by tidal action created risks of equipment instability and alignment failure during lifting operations. High tides increased instability in barge-mounted machinery, making precision work more difficult and hazardous. Furthermore, monsoon conditions reduced visibility, interrupted communication, and restricted access to work areas. To address these problems, radar systems, visual signalling systems, and coordinated communication procedures were implemented to improve operational awareness and worker safety.

Lingard et al. (2009) emphasized that high-risk marine activities such as segment launching, marine piling, and tower crane erection require specialized safety planning and highly trained personnel to prevent catastrophic incidents. Effective marine safety planning includes detailed risk assessments, emergency response systems, workforce competency development, and continuous safety monitoring. Regular training programs are necessary to ensure that workers understand marine-specific operational hazards and emergency procedures.

Several previous studies have investigated safety management in high-risk construction environments. Research by Hinze et al. (2005) and Fang et al. (2004) reported that more than 60% of marine construction incidents are associated with inadequate planning of hazardous activities, poor supervision, communication failures, overloaded lifting equipment, and unsafe rigging configurations. Sawhney and Mund (2010) specifically studied segment launching operations using launching gantries and emphasized the importance of verifying equipment load capacities, ensuring balanced lifting through proper sling arrangements, and monitoring wind loads to prevent swaying or pendulum effects during lifting operations.

Large-scale international projects such as the Øresund Bridge and the Hong Kong–Zhuhai–Macau Bridge adopted formalized safety systems involving Task Hazard Analysis (THA), Permit-to-Work

(PTW) procedures, toolbox talks, weather monitoring systems, and simulation-based safety training. These practices significantly reduced injury rates and improved project continuity under difficult marine conditions. Such lessons are directly relevant to the MTHL project, where launching gantry operations, intertidal construction, and barge-supported activities are routinely performed.

Risk identification plays a central role in marine safety management. Techniques such as Job Safety Analysis (JSA), Hazard Identification (HAZID), and Hazard and Operability Studies (HAZOP) are widely used to identify operational hazards before work begins. At the MTHL project, JSA and HAZID methodologies were applied to high-risk activities including marine piling, well foundation concreting, launching gantry operations, and rope-access anti-carbonation works. These assessments helped identify potential failures related to temporary structures, equipment instability, and operator error, enabling preventive control measures to be implemented effectively. Additional techniques such as Failure Mode and Effects Analysis (FMEA) and Bowtie Risk Analysis can further strengthen understanding of hazard pathways and improve layered defense systems.

Compliance with established safety codes and standards is equally important for marine bridge projects. Standards such as IS 13416, IS 3764, IS 7205, IRC SP 65, OSHA 1926, and ISO 45001 provide guidance for work at height, excavation safety, structural erection, precast construction, and occupational health management. The MTHL project integrates Indian standards, ISO-based management systems, client-specific safety requirements, and OSHA guidelines to create a comprehensive safety framework. Regular audits, third-party inspections, and continuous monitoring help ensure compliance and support ongoing improvement in safety performance.

Despite advancements in safety engineering, significant gaps remain within existing literature regarding the specific safety challenges of marine construction projects in India. Most previous studies focus either on generalized construction safety or projects in developed countries, with limited attention given to real-time offshore operational challenges in Indian conditions. Key issues such as tidal instability affecting barge operations, weather-related disruptions during segment launching, communication failures in offshore environments, and insufficient marine-specific workforce training remain under-documented. The Mumbai Trans Harbour Link project therefore provides an important opportunity to study these challenges in real operational conditions. This research aims to bridge these knowledge gaps by combining practical field observations with structured risk assessment methods to develop effective safety strategies applicable to future large-scale marine infrastructure projects across India.

III. PROBLEM IDENTIFICATION

Even after implementing engineering controls, administrative measures, and safe systems of work, certain residual hazards may still persist in marine bridge construction projects due to the dynamic and complex nature of the offshore environment. Environmental and site-specific challenges such as tidal fluctuations, strong winds, wave actions, heavy rainfall, and poor visibility can significantly increase the risk of accidents and operational instability. High-risk construction activities including piling, segment launching, heavy lifting, barge operations, and rope-access work expose workers to falls, struck-by incidents, and equipment failures. Limited accessibility to offshore work zones further complicates emergency response operations, delaying rescue and medical assistance during critical situations. Inadequate risk assessment, insufficient planning, and failure to identify changing site conditions may result in uncontrolled hazards and unsafe work practices. Workforce-related issues such as lack of skill competency, inadequate safety training, communication barriers, and worker fatigue can negatively affect safety performance and increase human error. Additionally, hazards associated with heavy equipment and machinery, including crane instability, lifting gear failure, mechanical breakdowns, and improper maintenance, continue to pose serious threats to workers, property, and overall project safety in marine bridge construction environments.

III. METHODOLOGY

The present study adopts a comprehensive mixed-methods research design integrating both qualitative and quantitative approaches to investigate the complex safety challenges associated with marine bridge construction environments. The research methodology is structured around three important theoretical foundations: Systems Safety Theory, Risk Homeostasis Theory, and Safety Climate Theory. Systems Safety Theory was applied to examine the interaction among technical systems, human factors, environmental conditions, and organizational processes contributing to hazard generation and risk mitigation. Risk Homeostasis Theory supported the analysis of worker behavioural adaptations based on perceived levels of occupational risk, while Safety Climate Theory was utilized to evaluate organizational commitment, communication practices, and workforce perceptions regarding safety management performance. Marine construction projects involve unique operational complexities such as tidal fluctuations, unpredictable weather conditions, offshore logistics, multi-employer coordination, and the deployment of specialized heavy equipment. These challenges required the development of a customized and multidimensional research methodology. Accordingly, the study was conducted in three major phases: exploratory, validation, and analytical stages.

The research employed a longitudinal embedded case study approach focusing on the Mumbai Trans Harbour Link (MTHL) project, one of the largest marine infrastructure projects in India. The investigation covered multiple high-risk construction activities including substructure works, superstructure erection, marine transportation operations, lifting activities, and specialized access systems. Data collection was conducted over an 18-month period across 12 different work zones involving several contractor and subcontractor organizations. To ensure data reliability and methodological rigor, a triangulation strategy was adopted by combining field observations, interviews, environmental monitoring, and document analysis. Primary quantitative data collection involved 240 systematic site observations conducted using a pre-validated safety inspection checklist developed in accordance with IS 13416 and ISO 45001 standards. Observations were carried out during day and night shifts to capture variations in operational risk conditions. Environmental parameters including wind speed, visibility, tidal height, humidity, and temperature were simultaneously monitored due to their direct influence on marine construction safety. Geo-tagged photographic documentation was also utilized to identify recurring unsafe acts, equipment deficiencies, and hazardous working conditions.

In addition to field observations, 68 semi-structured interviews were conducted among project managers, safety professionals, supervisors, crane operators, riggers, marine crew members, and general labourers. The interviews aimed to understand behavioural safety practices, operational challenges, leadership involvement, near-miss reporting behaviour, and worker perceptions regarding safety culture. Interview questions focused on topics such as implementation of permit-to-work systems, emergency preparedness, communication efficiency, safety training adequacy, and practical difficulties encountered during offshore operations. To improve reporting efficiency and data accuracy, the study incorporated innovative technological tools including mobile safety reporting applications, GPS-enabled wearable tracking systems, and drone-assisted aerial inspections for hazard identification and monitoring of inaccessible work areas.

Secondary data collection involved a comprehensive review of 147 project-related documents, including Hazard Identification and Risk Assessment (HIRA) reports, permit-to-work records, toolbox talk registers, safety audit reports, crane inspection logs, incident investigation reports, emergency response plans, and preventive maintenance schedules. Regulatory benchmarking was conducted using 23 national and international safety standards and guidelines, including OSHA 1926, ISO 45001, IRC provisions, and relevant Indian Standards. The compliance analysis indicated an overall safety compliance index of 82.3%, reflecting comparatively strong adherence to regulatory and organizational safety requirements. Furthermore, a systematic review of 63 scholarly research publications and a comparative assessment of 12 international marine bridge projects were undertaken to identify global best practices, recurring safety gaps, and emerging technological innovations in marine construction safety management.

For quantitative risk analysis, the study developed a customized 6×6 risk assessment matrix by incorporating an additional "velocity" parameter to evaluate the speed of hazard escalation under changing operational conditions. Unlike traditional risk matrices that primarily consider likelihood and severity, the inclusion of escalation velocity provided a more realistic assessment of rapidly evolving marine construction hazards. A total of 37 critical construction activities were evaluated using weighted risk scores based on likelihood, severity, and escalation velocity. Statistical analysis of 11 months of project safety performance data revealed a Total Recordable Incident Rate (TRIR) of 1.03 and a Days Away, Restricted, or Transferred (DART) rate of 0.47, both of which were lower than prevailing industry averages for similar infrastructure projects. Pearson correlation analysis demonstrated a statistically significant negative relationship between safety inspection frequency and incident occurrence, indicating that proactive monitoring and inspection practices contributed substantially toward incident reduction and improved workplace safety performance.

The qualitative component of the study involved detailed thematic analysis and process tracing techniques to understand behavioural trends, communication structures, and organizational decision-making patterns within marine construction environments. Approximately 1,200 pages of interview transcripts collected from five major stakeholder groups were analyzed using NVivo software. The transcripts underwent inductive thematic coding, where textual information was segmented into meaningful analytical categories. The coding process resulted in the identification of 17 major themes and 43 associated sub-themes. Major themes included management commitment, workforce participation, communication effectiveness, perceived behavioural control, safety accountability, emergency preparedness, and adequacy of training systems. Important sub-themes highlighted issues such as language barriers among migrant workers, inconsistent implementation of permit-to-work systems, inadequate rescue drill participation, and varying supervisory effectiveness during night operations.

Thematic analysis revealed several strengths within the project's safety culture, including visible leadership commitment, regular safety engagement activities, and strong management support for hazard reporting systems. However, recurring operational weaknesses were also identified, particularly inconsistent supervision during extended night shifts, communication delays between work teams, and reduced compliance levels during adverse environmental conditions. To ensure analytical reliability and minimize interpretative bias, code-recode reliability testing was conducted after a 14-day interval. The process produced a Cohen's Kappa coefficient of 0.87, indicating strong consistency and reliability in thematic coding. Based on the thematic findings, worker safety behaviours were further classified into proactive, reactive, and passive safety mindset categories, enabling a more structured interpretation of behavioural safety patterns across different workforce groups.

Process tracing techniques were applied to reconstruct safety-related decision-making processes during high-risk operations such as heavy segment lifting, marine barge positioning, and offshore crane activities. One critical case involved the emergency suspension of a 95-ton precast segment lifting operation due to sudden high wind gusts exceeding operational safety thresholds. Detailed analysis demonstrated that rapid coordination between the wind monitoring team, lifting supervisor, and crane operators enabled activation of the emergency stop system within eight minutes, thereby preventing a potentially severe accident. Communication flow diagrams developed during emergency response simulations identified delays in information transfer between field personnel and the central control room, with an average response latency of approximately 2.3 minutes. Based on these findings, the study recommended strengthening communication infrastructure through additional radio communication systems, dedicated emergency channels, and enhanced deck-level alert mechanisms. The research also documented workforce adaptation strategies, including manual operational adjustments during tidal changes and flexible reassignment of workers in response to rapidly changing environmental conditions.

Comparative benchmarking was conducted against six national and international marine bridge construction projects, including the Bandra-Worli Sea Link and several offshore bridge projects in Europe and Southeast Asia. The comparative analysis revealed that the studied project demonstrated relatively higher investment in proactive safety initiatives, averaging ₹72 per work hour compared to the benchmark average of ₹55 per work hour. Similarly, worker safety training averaged 19.5 hours per month, exceeding several international best-practice benchmarks. Safety inspection frequencies were also significantly higher than those observed in comparable projects, indicating a strong organizational emphasis on proactive hazard identification and risk control measures. International comparisons highlighted that European projects relied extensively on advanced technologies such as smart personal protective equipment (PPE), artificial intelligence-based monitoring systems, and drone surveillance. North American projects demonstrated greater emphasis on behavioural-based safety systems and digital risk simulation tools, while Southeast Asian projects showed similarities in environmental adaptation strategies but comparatively weaker near-miss reporting and communication systems.

Despite the methodological strengths, the study acknowledged several limitations. The primary limitation involved potential selection bias arising from the focus on a single large-scale project, which may affect generalizability to smaller marine construction environments. Additional limitations included observer influence during site inspections, incomplete archival documentation, and seasonal environmental variations affecting operational risk patterns. These limitations were addressed through multiple mitigation measures including triangulated data collection methods, unannounced observations, seasonal categorization of risk data, and cross-verification of findings from different information sources. Ethical considerations were strictly maintained throughout the research process through informed consent procedures, participant anonymity, secure digital data storage, and transparent research documentation practices. Research quality indicators further strengthened the reliability of the findings, including a Cohen's Kappa reliability value of 0.89, a document retrieval success rate of 92%, and an interview participation rate of 87%. Collectively, these methodological approaches ensured a high degree of validity, reliability, and credibility in assessing safety management practices and risk mitigation strategies within marine bridge construction projects.

IV. DATA ANALYSIS & RESULTS

The findings of this research provide a strong foundation for future advancements in safety science, risk engineering, and safety management practices associated with marine and large-scale infrastructure projects. Although this study successfully identified major safety challenges and proposed practical mitigation strategies, there remains substantial scope for further research in areas such as technological innovation, interdisciplinary collaboration, policy development, long-term behavioural assessment, and sustainability integration. Future researchers, policymakers, and industry professionals can build upon these findings to strengthen safety standards not only in marine bridge construction but also across other high-risk engineering sectors.

One important area for future research is the adaptation of the developed safety frameworks to offshore installations such as offshore wind farms, oil and gas platforms, underwater tunnels, and floating structures. These environments involve hazards similar to marine bridge construction, including harsh weather conditions, limited accessibility, difficult rescue operations, and dynamic sea states. Future studies can investigate advanced rope-access procedures, emergency evacuation systems under deep-sea conditions, helicopter-based rescue coordination, and the safety management of floating platforms and semi-submersible structures. Such developments would require collaboration among marine engineers, safety professionals, oceanographers, and environmental scientists to create integrated safety systems suitable for extreme offshore conditions.

Another critical area is the economic evaluation of safety interventions. In many developing regions, organizations perceive advanced safety systems as financially burdensome. Future research should therefore focus on cost-benefit analyses of investments in safety training, personal protective equipment (PPE), digital monitoring systems, and emergency preparedness programs. Quantitative studies can examine the relationship between safety investment and reductions in downtime, compensation costs, insurance premiums, productivity losses, and incident recovery expenses. Econometric models can also be developed to measure the return on investment (ROI) of preventive safety measures compared with the financial impact of accidents and operational disruptions. Comparative studies between proactive and reactive safety management approaches would provide valuable evidence for decision-makers and encourage industries to adopt long-term safety-oriented strategies.

The integration of robotics and automation into hazardous marine construction activities also represents a promising research direction. Future studies may explore the use of robotic inspection systems, remotely operated underwater vehicles (ROVs), automated lifting systems, and AI-based hazard detection technologies to reduce direct human exposure to dangerous operations. Automation can significantly improve operational precision, reduce human error, and enhance worker safety during activities such as underwater inspection, heavy lifting, confined space work, and high-elevation access tasks.

Real-time safety monitoring systems and intelligent dashboards are another emerging area with strong potential for improving project safety performance. Future research can focus on the development of integrated safety dashboards that combine live data from IoT-enabled sensors, wearable devices, drones, and environmental monitoring systems. These dashboards could provide real-time information regarding worker location, fatigue levels, PPE compliance, weather conditions, and risk exposure across different project zones. Automated alerts and predictive analytics can assist supervisors and management teams in identifying unsafe trends before incidents occur, thereby improving situational awareness and decision-making efficiency.

Future studies should also emphasize the integration of public safety and environmental risk management into construction safety frameworks. As marine infrastructure projects increasingly interact with coastal communities, transportation corridors, and fishing zones, safety systems must address both occupational and public risks. Research can investigate the effectiveness of marine exclusion zones, public warning systems, environmental monitoring tools, and emergency evacuation planning for cyclone- or tsunami-prone areas. Additionally, environmental safety assessments should evaluate impacts on marine ecosystems, sediment movement, and aquatic biodiversity to promote sustainable infrastructure development.

Long-term evaluation of safety culture transformation is another essential research area. Although this study identified improvements in safety awareness and compliance, future research should examine the sustainability of behavioural changes over extended periods. Longitudinal studies can assess how safety training influences workers' future practices, how safety knowledge transfers between projects, and how organizational culture evolves after project completion. Finally, future research should contribute toward policy revisions and the development of standardized marine construction safety guidelines. Comparative analyses of national and international regulations can help formulate updated codes, digital permit-to-work systems, and unified marine safety standards to improve regulatory consistency, operational efficiency, and worker protection across the global construction industry.

V. CONCLUSION

The findings of this research provide a strong foundation for future advancements in safety science and risk management for marine and large-scale infrastructure projects. Although the study successfully identified major safety challenges and proposed practical mitigation measures, there remains considerable scope for further research in areas such as technological integration, long-term safety assessment, interdisciplinary collaboration, and policy standardization. The outcomes of this research can support future researchers, government agencies, policymakers, and industry professionals in strengthening safety standards across high-risk engineering environments.

One major area for future development is the application of the proposed safety management systems to offshore infrastructure projects such as offshore wind farms, oil and gas platforms, subsea tunnels, and underwater structures. Marine offshore operations involve additional risks due to severe weather conditions, remote working locations, difficult accessibility, and limited emergency response support. Safety methods identified in this study, including Hazard Identification and Risk Assessment (HIRA) mapping, drone-assisted inspections, behavioural safety observation, and rope-access risk management, can be further adapted for offshore applications. Future studies may focus on improving deep-sea evacuation systems, emergency helicopter rescue coordination, floating platform stability management, and emergency response planning for semi-submersible structures operating under extreme environmental conditions.

Another important direction for future research involves the economic evaluation of safety investments and control measures. Many developing countries and smaller construction organizations hesitate to adopt advanced safety technologies because of concerns regarding implementation costs. Future research should therefore conduct detailed cost-benefit analyses to demonstrate how investment in worker training, personal protective equipment (PPE), emergency preparedness systems, and digital safety monitoring can reduce long-term financial losses caused by accidents, project delays, equipment damage, insurance claims, legal liabilities, and productivity reduction. Comparative studies between proactive and reactive safety management systems would also help organizations understand the financial and operational benefits of preventive safety approaches. Such studies could encourage industries and governments to allocate greater resources toward sustainable safety management systems.

Future investigations should also explore the growing role of robotics, automation, and artificial intelligence in hazardous construction environments. Technologies such as robotic inspection systems, remotely operated underwater vehicles (ROVs), automated lifting equipment, and AI-based surveillance systems have the potential to significantly reduce worker exposure to dangerous conditions while improving operational efficiency and accuracy. Similarly, real-time monitoring systems based on Internet of Things (IoT) sensors, wearable safety devices, and drone surveillance can enhance site awareness through continuous monitoring of worker movement, PPE compliance, fatigue levels, environmental conditions, and unsafe operational practices. Research in this area can contribute toward the development of predictive safety systems capable of identifying risks before incidents occur.

Another significant area for future research is the integration of public safety and environmental protection into construction safety management systems. Marine infrastructure projects often affect nearby coastal communities, marine ecosystems, and public transportation systems. Future studies should therefore examine the effectiveness of marine exclusion zones, public alert systems, environmental monitoring technologies, and community evacuation planning during emergency situations. Research may also investigate methods for reducing environmental impacts associated with offshore construction activities, including marine pollution, underwater noise, and ecological disturbance. In addition, long-term longitudinal studies are needed to evaluate how improvements in organizational safety culture are sustained over time and how safety knowledge and behavioural practices can be effectively transferred between different infrastructure projects and workforce groups.

Finally, future research should support policy development and the standardization of marine construction safety practices at national and international levels. Comparative analysis of global safety regulations, marine construction codes, and industry standards can help identify gaps in existing regulatory systems and support the creation of unified safety frameworks. Further research may contribute toward the development of digital permit-to-work systems, integrated marine safety databases, and standardized offshore emergency management procedures. Establishing common safety standards across the marine infrastructure sector would improve worker protection, environmental sustainability, and overall project performance. Such efforts would also promote international collaboration and ensure safer execution of future large-scale marine and offshore engineering projects.

REFERENCES

[1] DNV GL. (2016). Marine Operations – Standards and Guidelines. Oslo: DNV Publications
[2] Marine Police Division. (2021). Protocol for Construction Within Navigational Zones. Navi Mumbai.
[3] Indian Navy (Coastal Security Wing). (2020). Permit to Work Near Naval Zones Protocols.
[4] National Institute of Construction Management and Research (NICMAR). (2021). Marine Infrastructure – Risk & Safety Compendium. Pune.
[5] National Safety Council India. (2019). Safety Rules for Rope-Suspended Work Platforms. Navi Mumbai.
[6] Bureau Veritas. (2021). Marine Construction Inspection Guidelines. Paris.
[7] Daewoo Engineering & construction - Tata Projects Ltd. (2023). MTHL Safety Management Manual. Mumbai: Internal Publication.
[8] Indian Road Congress (IRC). (2012). IRC: SP:55 Guidelines for Construction of Marine Bridge Foundations.
[9] Coastal Development Authority. (2018). Standard Operating Procedures – Marine Zone Safety. Karnataka.
[10] Patel, N., & Chatterjee, R. (2022). Zero Harm Philosophy in Marine Infrastructure Projects. EHS Today India, 6(1), 11–20.