Mapping Slip Trip& Fall and Crowd Crush Hazards at Fisherman's Wharf: A Triangulation of Physical, Observational, and Survey Data

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Abstract

Fisherman's Wharf in Tamsui, Taiwan, is a popular coastal tourist destination that attracts large numbers of visitors, increasing the likelihood of Slip, Trip and Fall (STF) and Crowd Crush hazards. This study evaluates risk levels, examines hazard-generating activities, and identifies the root causes of risk to develop more effective and sustainable control measures. It integrates Hazard Identification and Risk Assessment (HIRA), Job Safety Analysis (JSA), and Root Cause Analysis (RCA) within a comprehensive risk assessment framework. Data derive from 300 hours of field observation, visual documentation, and a survey of 96 respondents, including visitors, employees, and site managers. HIRA assesses risk levels and identifies priority areas, JSA examines high-risk activities, and RCA investigates the underlying causes of risk. The results show that Zone C (Floating Pier and Stairs) presents the highest STF risk, with a HIRA score of 12 (High Risk), while Zone B (Lover's Bridge) records the highest Crowd Crush risk, with a HIRA score of 16 (High Risk). Walking on damp and slippery surfaces emerges as the principal contributor to STF incidents. In contrast, visitor congestion, two-way pedestrian flows, and the tendency of visitors to stop for photographs drive Crowd Crush risks. RCA findings highlight several key root causes, including inadequate anti-slip surface treatments, insufficient preventive facility inspections, and ineffective crowd management practices. These findings underline the need to upgrade physical infrastructure, improve visitor flow management, and strengthen safety systems through systematic near-miss monitoring and reporting.

Keywords: *Crowd Crush, Hazard Identification And Risk Assessment, Job Safety Analysis, Root Cause Analysis, Slip Trip and Fall*

1. Introduction

Fisherman's Wharf in Tamsui, New Taipei City, Taiwan, is a prominent coastal tourism destination that seamlessly integrates the multifaceted functions of an active fishing port, a vibrant recreational hub, and a publicly accessible waterfront space [1]. This location attracts substantial numbers of both domestic and international visitors, offering a diverse array of amenities, including operational piers, extensively used pedestrian walkways, a variety of restaurants and commercial establishments, and the iconic Lover's Bridge, which serves as a landmark feature and primary attraction within the area [2]. The destination experiences notably high visitor volumes, particularly on weekends, national holidays, and during special seasonal events or festivals, all of which contribute to significantly elevated levels of human activity and congregation throughout the site. Such intensified foot traffic, while economically beneficial, inevitably gives rise to a range of potential safety hazards that warrant careful consideration. This prevailing condition underscores the critical importance of visitor safety as a fundamental priority that must be systematically and proactively addressed within the broader framework of tourism area management and operational governance [3],[4].

One of the most common hazards found in coastal tourist areas is Slips, Trips, and Falls (STF) [5]. These risks are influenced by multiple factors, including slippery surfaces caused by seawater or rain, changes in pedestrian walkway elevation, deterioration of flooring materials, and visitor behavior while walking [6]. In addition to causing minor injuries, STF incidents can also result in serious harm that requires medical attention [7]. In high-traffic areas, STF incidents not only directly affect the victims but may also disrupt visitor flow and diminish the overall quality of the tourist experience.

Beyond STF, high-density tourist areas are also susceptible to crowd crush a condition in which pressure between individuals in a crowd increases due to high visitor density in confined spaces [8]. The risk of crowd crush typically begins to rise when crowd density exceeds four people per square meter [9]. At Fisherman's Wharf, such conditions can potentially occur around Lover's Bridge and along the pathways leading to the pier, particularly when visitors pause to enjoy the view or take photographs, thereby creating bottlenecks that obstruct pedestrian movement [10].

Numerous studies on STF and crowd crush have been conducted using methods such as Hazard Identification and Risk Assessment (HIRA), Job Safety Analysis (JSA), and Root Cause Analysis (RCA). However, most of these studies apply these methods separately. As a result, their findings tend only to describe risk levels or hazardous activities, without identifying the relationships among underlying root causes. Consequently, the control recommendations that emerge often focus on addressing symptoms rather than the fundamental causes of risks.

In light of this, the present study integrates HIRA, JSA, and RCA to produce a more comprehensive risk analysis. HIRA[11] is used to identify and map risk levels across each observation zone; JSA[12] is employed to analyze activities that have the potential to cause accidents; and RCA[13] is utilized to identify the root causes of risks, enabling the formulation of more effective control measures. It is anticipated that the integration of these three methods will contribute to the development of safety management systems for coastal tourism areas and serve as a reference for managers seeking to continuously enhance visitor safety and comfort.

Figure 1. Study Area: Tamsui Fisherman's Wharf

Figure 1 illustrates the study location at Tamsui Fisherman's Wharf, Taiwan. The site is divided into three primary zones: the Boardwalk, Lover's Bridge, and the Floating Pier & Stairs area. These zones were selected based on their activity intensity, pedestrian density, and hazard potential identified through field observations. The zoning map serves as the basis for risk identification and hazard distribution analysis throughout the study area.

2. Method

The present investigation employed a quantitative descriptive approach utilizing a case study design conducted at Fisherman's Wharf, Tamsui, New Taipei City, Taiwan. The research site was deliberately selected due to its prominence as a popular coastal tourist destination that attracts a substantial volume of domestic and international visitors, thereby rendering it particularly susceptible to Slip, Trip, and Fall (STF) incidents and Crowd Crush hazards. To ensure the comprehensiveness and reliability of the observational data, field observations were systematically carried out over a cumulative total of 300 hours, strategically distributed across weekdays, weekends, and public holidays. This extended and temporally diverse observation schedule was designed to capture a wide spectrum of visitor activity patterns, fluctuations in crowd density, and variations in environmental conditions including tidal influences, rainfall events, and humidity levels that collectively influence the occurrence and severity of safety risks within the study area.

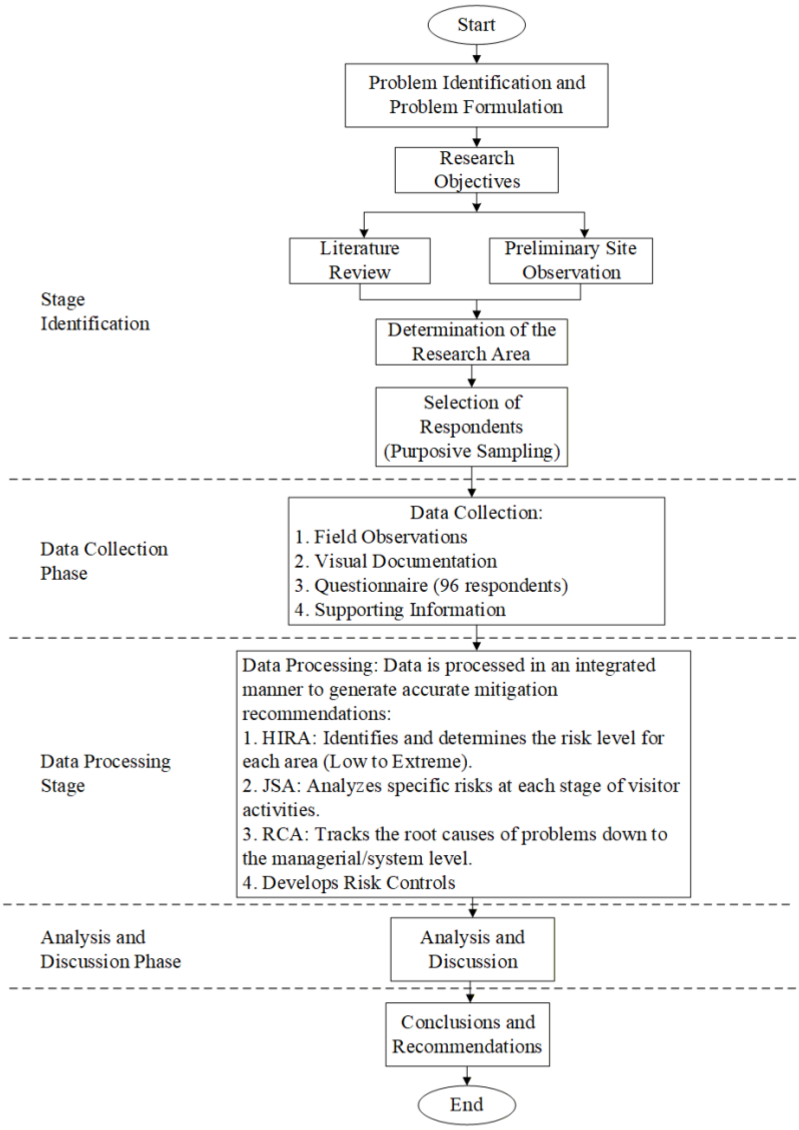

Figure 2. Research Methodology Flowchart

The research methodology employed in this study followed a systematic and sequential workflow, beginning with the initial identification of safety problems and formulation of research objectives, followed by a comprehensive literature review to establish the theoretical foundation. A preliminary site observation was then conducted to gain contextual familiarity with the study location, which facilitated the determination of observation zones and the selection of respondents through purposive sampling techniques.

Data collection encompassed multiple sources, including direct field observations, visual documentation, interviews with site management personnel, and questionnaire Specifically, a survey of 96 respondents (comprising visitors, employees, and site managers) was conducted to identify hazards for the Risk Register and calculate risk scores based on Likert-scale perceptions. To operationalize these findings, the survey responses were integrated into the JSA. This integration analyzed reported near-misses alongside environmental, human, facility, and management risk triggers to prioritize actionable control measures and safety SOPs. The sample size was determined using a sampling formula for an unknown population, applied at a 95% confidence level with a 10% margin of error, which yielded a minimum requirement of 96 respondents. A purposive sampling technique was adopted, whereby respondents were selected based on their direct involvement in activities within the study area to ensure the relevance and representativeness of the collected information.

The collected data were subsequently processed in an integrated manner through the sequential application of three complementary analytical methods HIRA for risk identification and spatial prioritization, JSA for activity-based hazard analysis, and RCA for root cause tracing down to the managerial and systemic levels culminating in the development of targeted risk control recommendations. The final stages of the research comprised in-depth analysis and discussion of the findings, leading to the formulation of conclusions and practical recommendations for safety enhancement at the study site.

The data were analyzed by integrating three complementary methods: Hazard Identification and Risk Assessment (HIRA), Job Safety Analysis (JSA), and Root Cause Analysis (RCA). The HIRA method was employed to identify hazards and assess the level of risk in each observation zone based on Likelihood (L) and Consequence (C) scores using a 5 × 5 risk matrix in accordance with ISO 31000:2018. The risk score was calculated using Equation (1):

$$Risk\ Score = Likelihood \times Consequences \quad (1)$$

The resulting risk scores were then classified into four categories Low, Moderate, High, and Extreme Risk to establish priorities for risk control in each observation area [14].

Subsequently, Job Safety Analysis (JSA) was conducted to identify activities with the potential to cause accidents during both operational tasks and visitor activities. Each activity was systematically broken down into individual work steps, potential hazards associated with each step were identified, the corresponding level of risk was evaluated, and appropriate control measures were proposed based on the hierarchy of risk controls.

The final stage involved Root Cause Analysis (RCA) to determine the underlying causes of risks classified as High Risk [15]. The analysis utilized the 5 Whys technique and the Fishbone Diagram (6M+E), encompassing the factors of Man, Machine, Method, Material, Measurement, Management, and Environment [16], [17]. The findings from the RCA were used to formulate technical, administrative, and managerial control recommendations aimed at reducing the likelihood of future incidents through sustainable risk mitigation strategies.

The integration of these three methods provided a comprehensive analytical framework. HIRA was used to prioritize risks according to their location and severity, JSA was applied to identify activity-based hazards contributing to those risks, and RCA was employed to determine their root causes. Consequently, the proposed control measures focused not only on mitigating the consequences of identified hazards but also on preventing their underlying causes, thereby enhancing overall safety management at Fisherman's Wharf.

3. Results and Discussion

Hazard Identification and Risk Assessment (HIRA)

The Hazard Identification and Risk Assessment (HIRA) was employed as the primary analytical tool to identify potential hazards and systematically evaluate risk levels within each observation zone at Fisherman's Wharf. The assessment combined Likelihood and Consequence scores using a 5 × 5 risk matrix in strict accordance with the ISO 31000:2018 framework. To ensure data representativeness, field observations were conducted for over 300 cumulative hours across 30 consecutive days (March–April 2026), strategically covering weekdays, weekends, and holidays to capture peak and off-peak visitor patterns. The schedule utilized daily 8-hour sessions covering morning, afternoon, and evening to systematically analyze safety risks under varying lighting, tidal cycles, and weather fluctuations.

The hazard identification process revealed two predominant categories of risk within the study area: Slip, Trip, and Fall (STF) and Crowd Crush. STF hazards were observed most frequently on wooden walkways, stairways, and pedestrian paths that are regularly exposed to seawater inundation and rainwater accumulation, which significantly reduce surface friction and increase the likelihood of pedestrian loss of balance. In contrast, Crowd Crush hazards were found to be concentrated in high-density visitor congregation points, most notably along Lover's Bridge, where tourists frequently paused for photography or to enjoy scenic vistas during peak visitation hours, thereby creating localized bottlenecks that impede smooth pedestrian flow and elevate pressure within the crowd.

The risk assessment results for each observation zone are systematically presented in Table 1, which provides a clear comparative overview of the risk profiles across the three designated areas.

Table 1. Risk Assessment Results Using HIRA

Area	Risk Type	Likelihood	Consequence	Risk Score	Risk Level
Zone A (Boardwalk)	STF	3	3	9	Moderate
Zone B (Lover’s Bridge)	Crowd Crush	4	4	16	High
Zone C (Floating Pier & Stairs)	STF	4	3	12	High

As clearly shown in Table 1, Zone C (Floating Pier & Stairs) exhibited the highest STF risk among all zones, with a risk score of 12, which falls within the High Risk category. Concurrently, Zone B (Lover's Bridge) registered the highest Crowd Crush risk, achieving a score of 16, also classified as High Risk. These findings collectively indicate that both locations demand prioritized attention for risk control interventions when compared to other zones within the study area. To facilitate more intuitive spatial interpretation and support evidence-based decision-making, the HIRA results were subsequently visualized as a risk map, offering clearer geographical representation of hazard distribution, as illustrated in Figure 3.

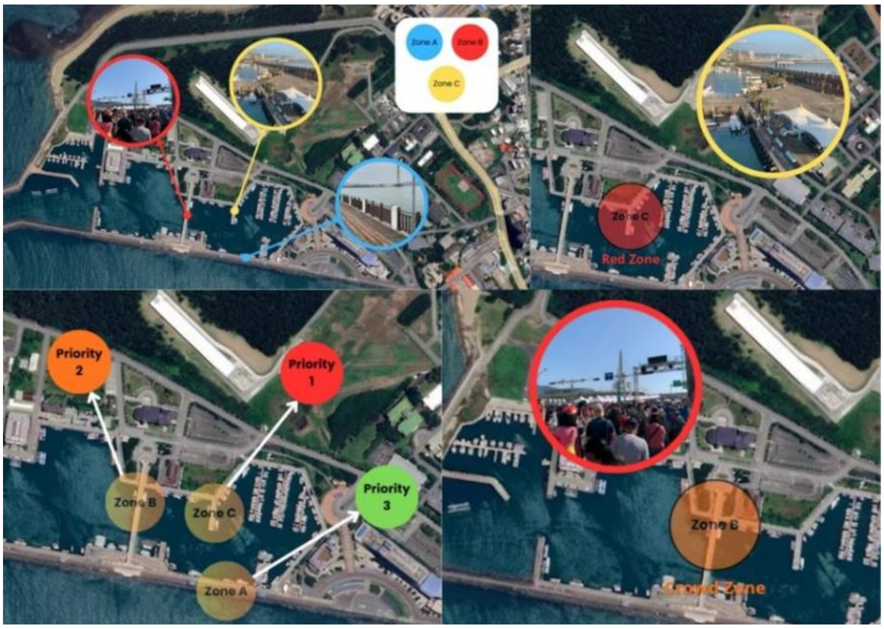

Figure 3. Risk Map of Fisherman's Wharf Based on the HIRA Results

Figure 3 clearly demonstrates that STF hazards are predominantly concentrated around the Floating Pier & Stairs area, whereas Crowd Crush hazards are primarily localized at Lover's Bridge. This spatial visualization not only pinpoints the priority zones requiring immediate risk mitigation measures but also serves as a critical foundation for the subsequent Job Safety Analysis (JSA), enabling a more targeted and activity-specific examination of the contributing factors and underlying mechanisms behind these identified risks.

Job Safety Analysis (JSA)

Following the identification of priority locations through the HIRA processJob Safety Analysis (JSA) is adapted for visitor activities using the activity deconstruction principle to identify "hidden hazards" within high-risk zones. This approach is highly suitable for the tourism context as it examines the interaction between dynamic visitor behaviors such as walking, queuing, or stopping for photography and complex physical infrastructure. By breaking these activities into sequential operational steps, the study develops specific safety Standard Operating Procedures (SOPs) that address procedural gaps and optimize risk management in maritime environments. The JSA approach involved a detailed decomposition of key visitor activities into sequential operational steps, followed by the identification of associated hazards at each stage, the evaluation of corresponding risk levels, and the determination of appropriate control measures tailored to the nature of each activity. A comprehensive summary of the JSA results is presented in Table 2, which delineates the linkages between zones, activities, hazards, and recommended interventions.

Table 2. Summary of Job Safety Analysis Results

Zone	Main Activity	Potential Hazard	Primary Risk	Control Measures
Zone A	Walking	Slippery surface	Slip, Trip, and Fall (STF)	Routine cleaning and anti-slip flooring
Zone B	Gathering and photography	High visitor density	Crowd Crush	One-way pedestrian flow and visitor capacity control
Zone C	Using stairs and pier	Wet stairs and deck	Slip, Trip, and Fall (STF)	Anti-slip strips, handrails, and regular inspections

The JSA findings indicate that walking on wet wooden pedestrian surfaces constitutes the most significant contributing factor to STF incidents across the study area. This hazard is exacerbated by frequent seawater spray and periodic rainfall, both of which substantially reduce the coefficient of surface friction, thereby increasing the likelihood of pedestrian loss of balance particularly when visitors move at elevated speeds or exhibit reduced situational awareness due to environmental distractions. Concurrently, photography and extended gathering on Lover's Bridge were identified as the primary behavioral contributors to Crowd Crush risk. This phenomenon arises because tourists tend to pause simultaneously at popular vantage points, thereby creating localized congestion and bottlenecks that severely obstruct the natural flow of pedestrian movement, especially during peak operational hours when visitor volumes are at their highest.

Such congestion conditions significantly amplify physical pressure within the crowd, particularly in sections where walkway width is inherently constrained and egress options are limited. Empirical support for these observational findings was derived from questionnaire survey data collected from 96 respondents, which revealed that approximately 49% of visitors had experienced near-miss events during their visit including instances of nearly slipping on wet surfaces or being inadvertently pushed by surrounding crowds. This substantial proportion of reported near-misses provides compelling evidence that hazardous conditions are not merely theoretical but are actively and regularly encountered by users in the study area. These empirical insights further corroborate and reinforce the earlier HIRA results, conclusively confirming that Zone C (Floating Pier & Stairs) and Zone B (Lover's Bridge) represent the highest-priority areas for targeted safety interventions. The elevated risk status of these zones is attributable to the synergistic interplay between adverse environmental conditions such as persistent moisture and surface deterioration and sustained high visitor density, which collectively heighten the probability and potential severity of adverse incidents.

Root Cause Analysis (RCA)

Risks that were classified as High Risk through the preceding HIRA and JSA processes were subsequently subjected to an in-depth Root Cause Analysis (RCA) to uncover the fundamental drivers underlying the persistent occurrence of STF and Crowd Crush incidents. The RCA employed two complementary investigative tools: the Fishbone Diagram (Ishikawa or cause-and-effect diagram) and the 5 Whys technique. The Fishbone Diagram was validated through data triangulation and cross-verification with site management and operational staff, based on an integrated analysis of 300 hours of field observations and survey responses from 96 stakeholders. The identified causal relationships were further verified using the 5 Whys technique and informal staff feedback to ensure they accurately reflected site conditions. This analysis aimed to identify the underlying systemic causes of STF and

Crowd Crush risks and support the development of effective countermeasures. The Fishbone analysis for STF risk is presented in Figure 5.

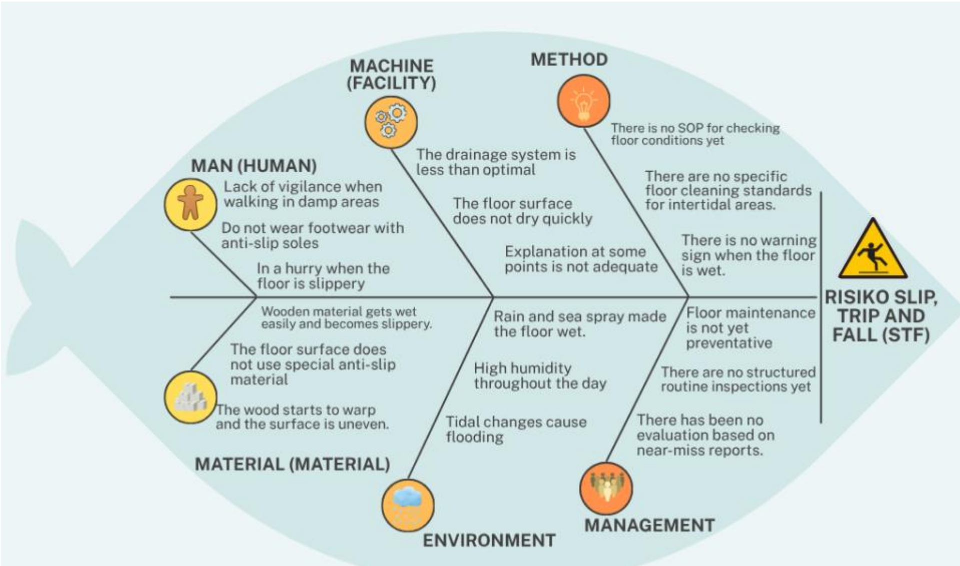

Figure 4. Fishbone Diagram for Slip, Trip, and Fall Risk

As illustrated in Figure 5, the dominant causal categories contributing to STF risk were associated with Material, Environment, and Management factors. More specifically, continuous and prolonged exposure of the pedestrian surface to seawater intrusion and tidal flooding resulted in persistently slippery conditions, while the inherent characteristics of the coastal environment including high ambient humidity, salt spray, and frequent wet-dry cycles accelerated the deterioration of flooring materials and compromised their structural integrity over time. Furthermore, the absence of structured preventive facility inspections permitted several hazardous conditions, such as warped wooden planks and uneven surface elevations, to remain unaddressed for extended periods, thereby increasing the cumulative exposure of visitors to preventable risks. A corresponding Fishbone analysis was conducted for Crowd Crush risk, the results of which are systematically presented in Figure 6.

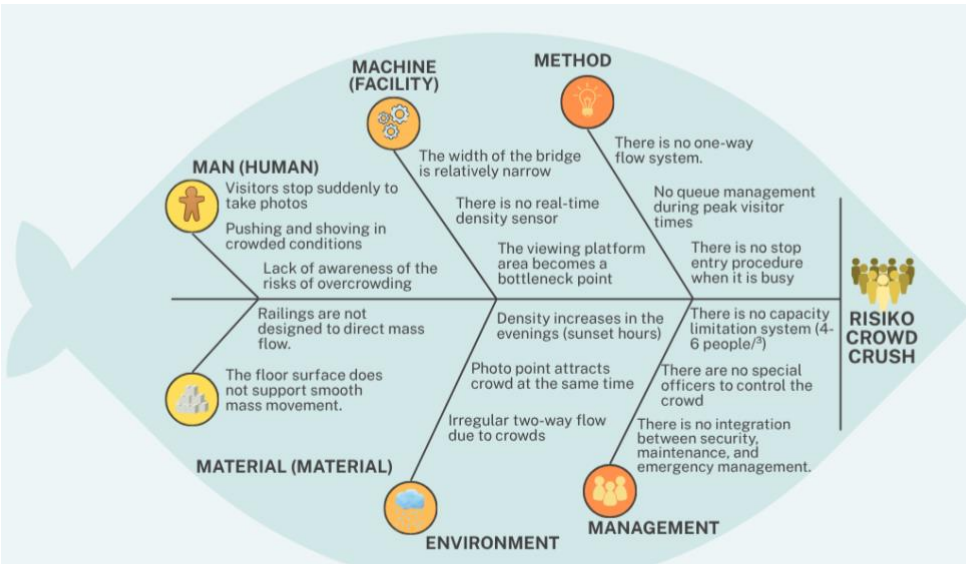

Figure 5. Fishbone Diagram for Crowd Crush Risk

The findings presented in Figure 6 indicate that the primary contributing factors to Crowd Crush incidents were predominantly concentrated within the Management, Method, and Environment categories. Specifically, the lack of a real-time crowd monitoring system capable of detecting density thresholds in real time, the continued reliance on conventional and passive visitor flow management strategies, and the inherently limited physical capacity of pedestrian pathways collectively amplified the likelihood of severe crowd congestion during peak visitation periods. These factors interact synergistically, as the absence of accurate density data prevents timely operational adjustments, while narrow walkways constrain natural dispersion, thereby creating conditions conducive to hazardous crowd pressures.

The Fishbone Diagram served as a comprehensive mapping tool to categorize potential causal factors across 6M+E dimensions. From this macro-identification, the most dominant direct causes specifically 'slippery surfaces' for STF and 'visitor congestion' for Crowd Crush were selected for deeper investigation using the 5 Whys technique. This iterative questioning progressively traced the causal chain layer by layer until underlying systemic root causes were revealed. This approach establishes clear traceability by drilling down from visible physical symptoms (Environment and Material categories in the Fishbone) to underlying systemic failures (Management and Method categories). A synthesized summary of the 5 Whys results for both risks is presented in Table 3, which consolidates the direct causes, root causes, and corresponding control strategies.

Table 3. Summary of the 5 Whys Analysis

Risk	Direct Cause	Root Cause	Controls
STF	Slippery surfaces from seawater/rain exposure	Inadequate slip-resistant materials and weak maintenance	Anti-slip materials (R12/R13), regular inspections, preventive maintenance
Crowd Crush	Visitor congestion at Lover's Bridge	No real-time crowd monitoring and poor peak-hour flow control	Real-time monitoring, one-way flow, capacity limits, entry control

The 5 Whys analysis summarized in Table 3 progressively traced high-priority risks from physical symptoms to their systemic origins. For STF in Zone C, slippery conditions from seawater and rain persisted due to suboptimal drainage and unsuitable flooring, revealing a lack of standardized anti-slip material selection and structured preventive inspection protocols. For Crowd Crush in Zone B, extreme sunset congestion from photography stops escalated due to spatial constraints and the absence of one-way flow procedures, identifying the root cause as the lack of an adaptive, real-time crowd management system.

These results demonstrate that both risks are driven primarily by systemic deficiencies in management practices and operational protocols rather than physical site conditions alone. Consequently, effective risk control necessitates a multifaceted approach that simultaneously upgrades physical infrastructure, refines operational procedures, and integrates monitoring technologies to ensure comprehensive and sustainable visitor safety.

Discussion

The integration of HIRA, JSA, and RCA within a unified analytical framework establishes a structured and hierarchical risk management pathway that logically links hazardous locations, risk-generating activities, and underlying causal factors. Within this tripartite framework, HIRA serves to prioritize high-risk zones based on spatial risk profiling, JSA identifies critical hazardous activities through task-level decomposition, and RCA uncovers the systemic root causes that perpetuate these risks, thereby enabling a more comprehensive and actionable risk mitigation strategy than would be achievable through the independent application of any single method.

The empirical findings of this study indicate that STF risk at the Floating Pier & Stairs area is primarily driven by the combined effects of coastal environmental exposure characterized by persistent moisture, salt spray, and tidal influences and the resultant slippery walking surfaces, which substantially reduce pedestrian traction. This observation is consistent with established literature confirming that surface condition is a key determinant of Slip, Trip, and Fall incidents in public environments, particularly in outdoor coastal settings where environmental factors are beyond immediate managerial control.

Similarly, the Crowd Crush risk identified at Lover's Bridge confirms that high pedestrian density in spatially confined areas significantly disrupts natural flow dynamics, increases interpersonal physical pressure, and elevates the potential for dangerous crowd surges, particularly at bottleneck locations where walkway width is constricted and egress is limited. Effective mitigation of these combined risks should therefore extend beyond isolated physical improvements such as surface replacement or structural repairs to encompass a broader portfolio of operational and managerial controls.

On the basis of these integrated analytical findings, the following priority measures are recommended: the application of high slip-resistance flooring materials with appropriate R12/R13 ratings, the implementation of routine preventive maintenance schedules incorporating regular surface inspections and timely repairs, the deployment of one-way pedestrian flow systems during peak visitation periods to regulate movement direction and reduce counterflow conflicts, and the installation of real-time crowd density monitoring technologies capable of providing early warnings and supporting adaptive visitor management at Fisherman's Wharf. Collectively, these measures are anticipated to substantially enhance the overall safety management system and improve the quality of the visitor experience.

4. Conclusion

This study successfully identified, analyzed, and evaluated Slip, Trip, and Fall (STF) and Crowd Crush risks at Fisherman’s Wharf, Tamsui, through the integrated application of Hazard Identification and Risk Assessment (HIRA), Job Safety Analysis (JSA), and Root Cause Analysis (RCA). The findings revealed that the highest STF risk was concentrated in Zone C (Floating Pier & Stairs), which recorded a high risk score of 12, primarily attributable to persistently slippery walking surfaces and adverse coastal environmental conditions. Conversely, the highest Crowd Crush risk was identified in Zone B (Lover's Bridge), with a risk score of 16, driven by high visitor density in spatially constrained areas and the formation of bottlenecks at popular photographic vantage points.

The JSA results further indicated that walking on wet wooden surfaces and gathering in confined spaces constituted the most hazardous visitor activities, while the RCA conclusively demonstrated that STF incidents are predominantly rooted in the use of materials unsuitable for coastal environments and the absence of systematic preventive inspections, whereas Crowd Crush incidents stem from the lack of real-time crowd monitoring systems and the continued reliance on non-adaptive flow control measures during peak periods. Collectively, the integrated methodological framework proved effective in establishing clear linkages between high-risk locations, critical hazardous activities, and their underlying systemic causes.

On the basis of these findings, the following priority control measures are recommended: the installation of high slip-resistance flooring materials (R12/R13), the implementation of routine preventive maintenance and inspection schedules, the enforcement of one-way pedestrian flow systems during peak visitation hours, the establishment of visitor capacity limits at bottleneck zones, and the deployment of real-time crowd density monitoring technologies to enable adaptive and responsive safety management. These interventions are expected to substantially mitigate the identified risks and.

Despite its contributions, this study has several limitations. The reliance on self-reported near-miss data may introduce recall bias, while the respondent sample was dominated by young, first-time visitors, limiting the representativeness of the findings. In addition, the study was conducted at a single site within a specific timeframe, preventing the assessment of long-term seasonal variations such as typhoon seasons. The absence of official incident records also required greater reliance on observational and perceptual data. Future research should expand the geographic scope to other coastal destinations to evaluate the generalizability of the HIRA–JSA–RCA model, incorporate machine learning for visitor density prediction, empirically test anti-slip materials in maritime settings, and conduct longitudinal observations across different seasons to better capture environmental risks.

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