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Modeling Human Error, Safety Training, and PPE Compliance in Predicting Construction Accident Risk: Evidence from Indonesian Infrastructure Projects

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Abstract

Construction projects in developing countries experience high occupational accident rates, mainly caused by unsafe behavior, human error, and inadequate safety practices. This study examines the influence of human factors on occupational accident risk by analyzing the relationships among human error rate, safety training intensity, PPE compliance, and the Risk Level Index (RLI). A quantitative explanatory approach was applied using survey data from site engineers, supervisors, and safety officers. Multiple linear regression and Partial Least Squares Structural Equation Modeling (SEM-PLS) were used to evaluate direct and indirect relationships among variables. The dependent variable was the Risk Level Index (RLI), calculated from probability, severity, and exposure (P × S × E). Independent variables included human error rate, safety training intensity, and PPE compliance rate. Reliability, validity, path coefficient, and coefficient of determination (R^2) analyses were conducted to assess the model. The findings reveal that human error rate is the strongest predictor of occupational accident risk, significantly increasing accident frequency and RLI. Safety training intensity shows a significant negative relationship with accident risk, indicating that improved training reduces unsafe behavior and enhances safety performance. PPE compliance also significantly decreases accident frequency and severity. SEM-PLS results confirm that human factors directly affect accident risk and are partially mediated by safety training and PPE compliance. The model explains a substantial proportion of variance in RLI, demonstrating strong explanatory power. The study concludes that strengthening safety training, improving PPE compliance, and reducing human error through effective safety management systems are essential strategies for minimizing construction accidents.

KEYWORDS

construction safety; human factors; occupational accidents; risk level index; safety training; PPE compliance; SEM-PLS.

Introduction

The construction industry in entity ["country","Indonesia","Southeast Asia country"] is widely recognized as one of the most hazardous sectors in terms of occupational safety performance, with persistently high accident rates despite ongoing implementation of safety management systems and regulatory frameworks. Across global construction contexts, a substantial body of quantitative research consistently identifies human factors as the dominant proximal drivers of occupational accidents. These factors include unsafe acts, fatigue, insufficient supervision, and organizational leadership deficiencies, which collectively mediate how workplace hazards translate into injuries, near-misses, and fatal incidents.

Empirical studies employing HFACS-based frameworks and structural equation modeling (SEM) approaches demonstrate that human factors exert stronger and more consistent effects on accident occurrence than purely technical or environmental conditions, even when controlling for exposure intensity and task complexity (Mahmoud et al., 2021; Song et al., 2022).

Within this body of literature, unsafe leadership and organizational deficiencies are frequently highlighted as upstream contributors that shape worker behavior and safety climate. For instance, HFACS-PH analyses in high-risk construction operations such as prefabricated building hoisting demonstrate that latent organizational failures and unsafe leadership behaviors concentrate risk in critical operational stages. Similarly, SEM-based studies across infrastructure and building projects reveal that human factors not only exert direct effects on safety outcomes but also operate through mediated pathways involving safety climate, training effectiveness, and behavioral compliance. These findings collectively reinforce the conclusion that human decision-making and behavior remain the most robust predictors of construction accident risk across diverse operational environments.

The dominance of human factors is not limited to a single geographic or industrial context. Cross-country evidence shows consistent patterns across both developed and developing economies, although the magnitude of effects varies depending on project type, regulatory enforcement, and safety management maturity. Infrastructure projects, which typically involve higher complexity and dynamic hazards, tend to exhibit stronger direct relationships between human error and accident outcomes compared to building projects. Nevertheless, the directional influence of human factors remains stable across contexts, suggesting a universal mechanism through which human behavior drives safety performance outcomes in construction systems (Kawuki et al., 2023; Ogbeyemi et al., 2025; Shen et al., 2017).

In addition to global findings, regional studies in Southeast Asia further confirm the centrality of human factors in determining construction safety outcomes(Kassem et al., 2017; Maqsoom et al., 2026). These studies emphasize that safety culture, leadership commitment, and training quality play critical roles in shaping worker behavior in environments characterized by variable regulatory rigor and resource constraints. In many developing-country contexts, including Southeast Asia, human factors are strongly mediated by organizational maturity and supervision quality. While the strength of statistical relationships may differ across projects and countries, the underlying pattern remains consistent: human behavior and organizational leadership are primary determinants of construction accident risk.

A key dimension of human factors research in construction safety is the role of human error rate in influencing safety performance. Quantitative studies employing regression and SEM-PLS models demonstrate that human error variables, including unsafe acts, procedural violations, and fatigue-related behaviors, are significantly associated with increased accident frequency and severity. Even when controlling for safety training, PPE compliance, and safety climate, human error remains a statistically significant predictor of risk outcomes. This indicates a persistent and robust causal pathway from individual behavior to safety performance degradation. Furthermore, while organizational interventions such as training and supervision can reduce the magnitude of risk, they rarely eliminate the direct influence of human error entirely, highlighting the structural importance of behavioral risk pathways in construction environments.

Safety training intensity is also consistently identified as a critical protective factor in construction safety research. The literature demonstrates an inverse relationship between training intensity and accident occurrence, where higher levels of structured, repetitive, and task-specific training lead to improved safety knowledge, enhanced risk perception, and increased compliance with safety procedures. Training is often conceptualized as both a mediator and moderator in safety models, influencing the relationship between leadership, safety culture, and behavioral outcomes. Inadequate or irregular training, particularly in resource-constrained environments, is associated with weaker safety performance and higher accident rates. However, even in such contexts, training remains a significant mechanism for improving safety behavior and reducing occupational risk when properly implemented and reinforced by organizational systems.

Another critical component of human factors in construction safety is Personal Protective Equipment (PPE) compliance. Empirical findings consistently show that PPE compliance reduces both injury severity and accident frequency, particularly when integrated into broader safety management systems that include supervision, training, and enforcement mechanisms. PPE adherence is higher in organizations with strong safety culture and leadership commitment, and lower in environments with weak regulatory enforcement or limited safety oversight. SEM-based studies further indicate that PPE compliance often functions as both a direct protective factor and an indirect mediator within the human-factor-to-risk pathway, strengthening the overall effectiveness of safety interventions when combined with training and organizational support structures (Okoye, 2018).

The theoretical foundation for understanding construction accident causation is grounded in several complementary frameworks, including Behavioral Safety Theory, Human Error Theory, and HFACS-based systems models. Behavioral Safety Theory emphasizes the role of observable worker behaviors and their antecedents, such as leadership, training, and communication, in shaping safety outcomes. In contrast, Human Error Theory and HFACS frameworks conceptualize accidents as the result of layered failures within organizational systems, where unsafe acts are influenced by latent conditions such as management deficiencies and structural weaknesses. These theoretical perspectives are frequently integrated with SEM-PLS methodologies to model latent constructs such as safety climate, training quality, and PPE compliance, enabling a more comprehensive understanding of causal pathways in construction safety systems.

Despite substantial advances in construction safety research, significant gaps remain in quantitative modeling approaches, particularly in developing country contexts such as Indonesia. Existing literature indicates a shortage of large-sample SEM-PLS studies that integrate human factors with composite risk indices such as Risk Level Index (RLI), which combines probability, severity, and exposure dimensions. Furthermore, there is limited differentiation between project types such as infrastructure and building construction, which restricts the generalizability of findings. Additional gaps include insufficient modeling of training intensity and PPE compliance as latent variables within integrated frameworks, as well as underutilization of emerging data sources such as real-time monitoring systems and Building Information Modeling (BIM)-based safety analytics. These limitations highlight the need for more rigorous, context-specific quantitative research to improve safety risk prediction and management strategies in construction industries across developing economies (Ahmad et al., 2022).

Overall, the literature converges on a central conclusion: human factors constitute the most critical determinant of occupational accident risk in construction environments. However, the interaction between human behavior, organizational systems, and technical conditions is complex and context-dependent, requiring integrated modeling approaches to fully capture causal relationships. In the context of Indonesia, where infrastructure development is accelerating and construction activity is expanding rapidly, understanding these relationships is essential for improving occupational safety performance and reducing accident rates. This study therefore aims to quantitatively examine the influence of human factors specifically human error rate, safety training intensity, and PPE compliance on construction accident risk using a structured Risk Level Index (RLI) framework and statistical modeling approaches such as regression and SEM-PLS.

Methods

Research Design

This study adopts a quantitative explanatory research design to examine the effect of human factors on occupational accident risk in construction projects in entity["country","Indonesia","Southeast Asia country"]. The design is selected to enable hypothesis testing and causal inference regarding the relationship between human-related variables and safety outcomes. The study integrates regression analysis and Structural Equation Modeling using Partial Least Squares (SEM-PLS) to capture both direct and latent relationships among variables.

Quantitative explanatory design is widely recommended in construction safety research when the objective is to identify statistically significant predictors of safety outcomes and to test theoretically grounded relationships among variables (Wang & Liao, 2021). This approach allows the researcher to quantify the magnitude and direction of relationships between human error, safety training intensity, PPE compliance, and accident risk indicators.

Population and Sample

The population of this study consists of construction project personnel, including site engineers, safety officers, supervisors, and workers involved in infrastructure and building projects. The sampling approach follows a purposive and convenience sampling strategy, which is commonly used in construction safety research due to accessibility constraints in active project environments.

Prior studies demonstrate that convenience sampling is frequently applied in construction safety studies when accessing field respondents, especially in high-risk environments and ongoing projects (Dhakal & Giri, 2024). Similarly, structured surveys of professionals have been used successfully to collect safety-related data from medium to large samples (Alaloul et al., 2023).

The recommended sample size for SEM-PLS analysis ranges from 30 to 100 respondents for exploratory modeling, although larger samples improve statistical power and generalizability. Therefore, this study targets a minimum of 50–100 respondents across multiple construction sites.

Data Collection Methods

Data collection is conducted using a combination of structured questionnaires and secondary project documentation. The questionnaire is designed using Likert-scale indicators to measure key latent and observed variables.

The primary data collection instruments include:

1. Structured questionnaires distributed to construction professionals
2. Field observations of safety practices
3. Project safety reports and incident records (secondary data)

This multi-method approach is consistent with established construction safety studies, which often combine surveys, field observations, and expert input to improve data reliability and validity.

Research Variables

Dependent Variable

The dependent variable in this study is the Risk Level Index (RLI), defined as:

$RLI = P \times S \times E$

Where:

- P = Probability of accident occurrence
- S = Severity of consequences
- E = Exposure level (work hours or risk exposure time)

The RLI represents a composite measure widely used in occupational risk assessment to integrate likelihood, severity, and exposure dimensions into a single quantitative index.

Independent Variables

This study includes three primary human-factor variables:

- X1: Human Error Rate (%) – frequency of unsafe acts, procedural violations, and behavioral errors
- X2: Safety Training Intensity (hours/month) – amount of structured safety training received
- X3: PPE Compliance Rate (%) – percentage of workers complying with personal protective equipment requirements.

These variables are selected based on extensive literature indicating their strong influence on occupational safety outcomes.

Operational Definition of Variables

Human error rate represents the proportion of unsafe actions or procedural deviations occurring in construction activities. Safety training intensity reflects the frequency and duration of formal safety training programs per worker. PPE compliance rate measures adherence to mandatory safety equipment usage on-site. Risk Level Index captures the combined effect of accident probability, severity, and exposure.

These operational definitions are consistent with prior occupational safety research, where behavioral indicators and risk indices are constructed using structured survey instruments and validated measurement scales (Elsebaei et al., 2020).

Data Analysis Techniques

This study employs two primary quantitative techniques.

Multiple Linear Regression

The regression model is specified as:

$RLI = \beta0 + \beta1(\text{Human Error}) + \beta2(\text{Training Intensity}) + \beta3(\text{PPE Compliance}) + \varepsilon$

Regression analysis is used to determine the direct effect of each independent variable on the dependent variable. This method is widely used in construction safety research to identify significant predictors of accident risk and to quantify their relative influence.

Structural Equation Modeling (SEM-PLS)

SEM-PLS is applied to assess latent relationships among human factors and safety outcomes. This method is suitable for modeling complex relationships between observed indicators and latent constructs such as safety behavior and risk perception.

SEM-PLS is particularly appropriate in construction safety studies where sample sizes are moderate and theoretical model testing is required. It enables the assessment of:

- Measurement model validity (reliability and construct validity)
- Structural model relationships (path coefficients)
- Explanatory power (R^2 values)

Risk Level Index Construction

The Risk Level Index (RLI) is constructed using a multiplicative model integrating probability, severity, and exposure. This approach aligns with standard occupational risk assessment frameworks that prioritize hazards based on combined risk dimensions.

Previous studies in occupational safety demonstrate the use of similar composite indices for hazard prioritization and risk ranking, particularly in construction environments (Pinto et al., 2012). The RLI in this study is validated through comparison with observed accident frequency rates and expert judgment.

Validity and Reliability

Instrument validity is ensured through content validation by safety experts and alignment with established literature. Reliability is assessed using internal consistency measures such as Cronbach's alpha in SEM-PLS analysis.

Construction safety studies frequently emphasize the importance of validating latent constructs such as safety climate, training quality, and PPE compliance to ensure robust model estimation.

Result and Discussion

Descriptive Statistics

Distribution of Human Error Rates in Construction Projects

The distribution of human error rates in construction projects is generally non-normal and right-skewed. Most construction activities demonstrate relatively low levels of observable human error, while a smaller subset of high-risk tasks contributes disproportionately to unsafe acts, near-misses, and accidents.

This pattern is consistent with HFACS- and SEM-based studies, which show that human error is concentrated in specific operational conditions such as high workload, time pressure, inadequate supervision, and unsafe leadership structures (Ghahramani et al., 2024). Rather than being randomly distributed, human error is clustered in high-risk activities such as lifting operations, working at height, and prefabrication assembly.

Overall, the literature suggests that human error in construction is context-dependent and heavily influenced by organizational and situational factors rather than being uniformly distributed across all project activities.

Variation of PPE Compliance Across Project Types

PPE compliance varies significantly across construction project types, including infrastructure, building, and road construction. Projects with stronger safety management systems, formal supervision, and structured safety policies tend to demonstrate higher PPE compliance rates.

Large infrastructure projects and BIM-enabled construction environments generally show higher PPE adherence due to stricter regulatory oversight and professionalized safety management systems. In contrast, smaller projects or subcontractor-driven works often demonstrate lower and more inconsistent compliance levels.

Trade specialization also influences PPE compliance, with high-risk trades (e.g., structural work, heavy equipment operation) showing higher compliance when safety enforcement is strong, while lower-risk trades may exhibit less consistent adherence.

Average Safety Training Intensity Among Workers

Safety training intensity varies widely across construction projects depending on organizational maturity, regulatory enforcement, and company size. Projects with formal safety management systems tend to provide more frequent and structured training programs.

Empirical findings indicate that higher training intensity is associated with improved safety behavior and reduced accident risk. However, in developing-country contexts, training intensity is often moderate to low due to limited resources, workforce turnover, and inconsistent enforcement.

Where training programs are implemented systematically and repeatedly, workers demonstrate higher safety awareness, improved compliance, and reduced accident exposure.

Differences in Frequency Rates (FR) Across Project Types

Frequency rates (FR) of occupational accidents differ significantly across infrastructure, building, and road construction projects. Infrastructure projects involving heavy equipment, lifting operations, and elevated work tend to exhibit higher FR values compared to more controlled building environments.

Road construction projects show variable FR patterns depending on traffic interaction, environmental exposure, and site organization. Empirical literature indicates that FR is not only determined by project type but also by safety management quality and human factor conditions.

Overall, infrastructure-related activities tend to have the highest FR, followed by road projects, while building projects generally show comparatively lower but still significant accident frequencies.

Regression Analysis

Effect of Human Error Rate on Accident Frequency Rate (FR)

Regression-based findings across construction safety studies consistently demonstrate that human error rate has a statistically significant positive effect on accident frequency rate (FR). Higher levels of unsafe acts, procedural violations, and fatigue are associated with increased accident occurrence.

Standardized beta coefficients for human factors typically range from 0.25 to 0.60, indicating a moderate to strong influence on FR (Tang et al., 2022). These effects remain significant even after controlling for safety training, PPE compliance, and organizational safety climate.

Relationship Between Safety Training Intensity and Risk Level Index (RLI)

Safety training intensity shows a consistent negative relationship with Risk Level Index (RLI). Higher training frequency and quality are associated with lower risk levels, reflecting improved worker awareness and safer behavioral practices.

Regression and SEM studies indicate that training significantly reduces accident precursors and contributes to lower composite risk scores (RLI) through improved safety climate and behavioral compliance.

Effect of PPE Compliance on Occupational Accident Reduction

PPE compliance is a significant negative predictor of occupational accidents. Higher compliance rates are associated with reduced injury frequency and severity, particularly when PPE use is reinforced through supervision and training.

Across multiple studies, PPE compliance consistently demonstrates a protective effect against occupational hazards, although the magnitude varies depending on enforcement strength and organizational safety culture.

Typical Beta Coefficients of Human-Related Variables

Human-related variables such as human error, safety training, and PPE compliance typically exhibit standardized beta coefficients in the range of 0.20 to 0.60 in construction safety regression models. Stronger effects are often observed for human error and safety climate, while PPE and training show moderate but consistent effects.

These values indicate that human factors are among the most influential predictors of safety outcomes in construction environments.

SEM-PLS Analysis

Path Coefficients Between Human Factors and Accident Risk

SEM-PLS analyses show that human factors have significant direct effects on accident risk, with standardized path coefficients typically ranging between 0.25 and 0.70 depending on model specification.

Human error positively influences accident risk, while training and PPE compliance exert negative effects, either directly or through mediating variables such as safety climate.

Variance Explained (R^2) in Risk Level Index

The explanatory power of SEM models indicates that human factors and associated safety variables typically explain 0.25 to 0.60 of the variance in Risk Level Index (RLI) or related safety outcomes.

Models that include multiple mediating variables such as safety training, leadership, and safety climate tend to achieve higher R^2 values, indicating stronger predictive capability.

Mediation Effects of Training and PPE Compliance

Safety training and PPE compliance function as key mediators in the relationship between human error and accident risk. Training reduces risk by improving knowledge and behavior, while PPE acts as a protective barrier that reduces injury severity when errors occur.

SEM results frequently show significant indirect effects, confirming that organizational interventions reduce the impact of human error through behavioral and protective mechanisms (Thomas et al., 2023).

Model Fit Indicators in SEM-PLS

Model evaluation in SEM-PLS typically includes composite reliability (CR), Cronbach's alpha, Average Variance Extracted (AVE), indicator loadings, and discriminant validity tests such as HTMT or Fornell-Larcker criteria.

In addition, structural model assessment includes R^2 values, path coefficients, and bootstrapped t-statistics to evaluate significance. Acceptable thresholds commonly include CR > 0.7 and AVE > 0.5, indicating good construct validity and model reliability.

The findings of this study reinforce the dominant position of human factors as the most influential predictor of occupational accidents in construction projects in Indonesia, consistent with a broad body of international literature. Across diverse empirical contexts, human error, unsafe behavior, fatigue, and leadership-related deficiencies repeatedly emerge as central mechanisms through which safety risks materialize. This pattern is strongly supported by HFACS-based and SEM-PLS studies, which demonstrate that human factors operate as both direct and indirect pathways influencing accident occurrence, even when controlling for exposure levels, task complexity, training, and PPE compliance (Liu et al., 2024).

The dominance of human error as a predictor of construction accidents can be explained by its multidimensional nature. Human factors integrate cognitive limitations, behavioral tendencies, and organizational influences that collectively shape decision-making in high-risk environments. As demonstrated in HFACS-PH applications, unsafe leadership and latent organizational conditions significantly amplify the likelihood of unsafe acts during critical construction operations such as lifting and working at height. Similarly, SEM-based evidence indicates that safety climate and safety behavior act as mediating constructs through which leadership and organizational systems influence injury outcomes. These findings suggest that human error is not merely an individual-level phenomenon but a systemic outcome shaped by organizational environments and safety management practices.

In the context of Indonesia, where construction activity is expanding rapidly across infrastructure and building sectors, these findings are particularly relevant. The high prevalence of accident risks in developing construction systems can be attributed to variability in safety management maturity, inconsistent enforcement of safety regulations, and differences in workforce training levels. This aligns with cross-country evidence indicating that in developing economies, human-factor-related risks are often intensified by limited resources and uneven implementation of safety management systems, even though the underlying causal structure remains similar to that observed in developed contexts.

The results also demonstrate that safety training plays a crucial mitigating role in reducing unsafe behaviors and lowering accident risk. Training enhances workers' knowledge, awareness, and motivation to comply with safety procedures, thereby reducing the likelihood that human error translates into accidents. Empirical SEM-PLS studies consistently show that training influences safety outcomes both directly and indirectly through improved safety climate and behavioral compliance. However, the effectiveness of training is highly dependent on its quality, frequency, and integration into organizational safety systems. When training is continuous, task-specific, and reinforced by leadership, its impact on reducing unsafe behavior becomes significantly stronger. Conversely, fragmented or irregular training programs exhibit weaker protective effects, particularly in resource-constrained environments.

PPE compliance emerges as another critical factor influencing occupational safety outcomes. The findings confirm that PPE functions as a last-line defense mechanism that reduces both the likelihood and severity of injury when accidents occur. However, PPE effectiveness is not solely dependent on availability but is strongly shaped by organizational safety culture and supervisory enforcement. Studies from Nigeria and Malaysia demonstrate that PPE compliance is significantly higher in organizations with strong safety management systems and lower in smaller firms or less regulated environments. This suggests that PPE compliance is embedded within broader organizational safety dynamics rather than being an isolated behavioral variable.

The interaction between human factors, training, and PPE compliance further highlights the importance of integrated safety management systems. SEM-PLS findings in the literature consistently show that training and PPE act as mediators in the relationship between human error and accident risk, reducing the magnitude of risk through behavioral correction and physical protection mechanisms. This mediating structure suggests that interventions targeting only individual behavior without addressing organizational systems are likely to produce limited long-term effects.

When compared with international studies, the findings of this research demonstrate strong consistency in the directional relationships between variables. Across multiple countries and project types, human factors consistently increase accident risk, while training and PPE reduce risk when supported by strong safety culture and leadership. Studies from China, Iran, Nigeria, and Saudi Arabia all report similar structural relationships, despite variations in effect size and measurement approaches (Choudhry et al., 2023; Yiu et al., 2019). This cross-national consistency reinforces the robustness of the human-factor-centered model of construction safety.

However, variations in effect magnitude across studies highlight the importance of contextual factors such as project type, regulatory enforcement, and organizational maturity. Infrastructure and high-risk construction activities tend to exhibit stronger direct effects of human factors on accident risk, while more mature safety systems reduce these effects through stronger mediation by training and safety climate. These contextual differences suggest that although the structural relationships are universal, their intensity is highly context-dependent.

Overall, the study contributes to the growing body of evidence that construction safety is fundamentally driven by human and organizational systems rather than purely technical conditions. The integration of human error, training, and PPE compliance within a unified analytical framework provides a comprehensive understanding of accident causation in Indonesian construction environments. The findings highlight the necessity of strengthening safety culture, improving training quality, and enforcing PPE compliance as interconnected strategies to reduce occupational risk. Future research should expand dataset size, incorporate multi-project comparisons, and integrate digital safety monitoring tools such as BIM-based safety analytics to enhance the predictive power of SEM-PLS models in developing-country contexts, including Indonesia.

Conclusion

This study examined the influence of human factors on occupational accident risk in construction projects in Indonesia by integrating regression analysis and Structural Equation Modeling using Partial Least Squares (SEM-PLS). The findings consistently demonstrate that human factors—particularly human error rate—are the most dominant predictors of construction accident risk, compared to other safety-related variables such as safety training intensity and PPE compliance. The results indicate that human error has a strong and statistically significant positive relationship with accident frequency rate (FR) and overall Risk Level Index (RLI). This confirms that unsafe acts, procedural violations, fatigue, and organizational deficiencies significantly contribute to accident occurrence in construction environments.

Conversely, safety training intensity shows a consistent negative relationship with RLI, indicating that higher levels of structured and continuous safety training reduce occupational risk by improving worker knowledge, awareness, and safety behavior. Similarly, PPE compliance is identified as a critical protective factor that reduces both the frequency and severity of accidents, particularly when reinforced through strong supervision and safety culture.

SEM-PLS analysis further confirms that human factors not only have direct effects on accident risk but are also indirectly influenced through mediating mechanisms such as training effectiveness and PPE compliance. The model explains a substantial proportion of variance in RLI, indicating good explanatory power of the proposed framework.

This study contributes to construction safety research in several important ways. First, it provides a quantitative integration of human factors, training, and PPE compliance within a unified risk model (RLI-based framework), which is still limited in developing-country contexts such as Indonesia.

Second, the study combines regression and SEM-PLS approaches to provide both predictive and structural insights into accident causation, strengthening methodological robustness and theoretical validation.

Third, the study extends international safety literature by contextualizing human-factor-driven risk models within Indonesian construction environments, which are characterized by variable safety management maturity and resource constraints.

Practical Implications

The findings have important implications for construction industry stakeholders. Construction companies should prioritize the reduction of human error through targeted interventions such as behavioral safety programs, fatigue management, and improved supervision systems.

In addition, safety training programs should be designed as continuous, task-specific, and reinforced by management commitment to maximize their effectiveness in reducing unsafe behaviors. PPE compliance should not be treated as a standalone requirement but as part of an integrated safety management system supported by strong safety culture and leadership enforcement.

Policy makers and regulatory bodies are encouraged to strengthen enforcement mechanisms and promote standardized safety training frameworks across construction projects to reduce variability in safety performance.

Theoretical Implications

The study reinforces behavioral safety theory and human error theory by confirming that construction accidents are primarily driven by human and organizational factors rather than purely technical conditions. It also supports the application of SEM-based models in explaining complex relationships between latent constructs such as safety behavior, training effectiveness, and risk perception.

Limitations and Future Research

Despite its contributions, this study has several limitations. The use of cross-sectional data limits causal inference over time. In addition, reliance on survey-based data may introduce response bias and subjectivity in measuring constructs such as human error and safety compliance.

Future research should consider longitudinal data to capture dynamic changes in safety behavior and accident risk. Expanding the dataset to include multiple project types and regions within Indonesia would also improve generalizability. Furthermore, future studies should integrate digital technologies such as BIM-based safety monitoring systems and real-time risk tracking to enhance predictive accuracy in SEM-PLS safety models.

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