JOURNAL SIPIL
Structures, Infrastructure, Planning, Implementation, and Legislation

The Correlation Between Construction Management Efficacy and Hydraulic Design Compliance with Cost Overruns in Public-Private Partnership (PPP) Water Supply Projects

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Article Information
Received: October 25, 2025
Revised: November 24, 2025
Online: December 10, 2025

Keywords
Construction Management, Hydraulic Design Compliance, Cost Overruns, Public-Private Partnership, Water Supply Projects

ABSTRACT

This study investigates the correlation between construction management efficacy and hydraulic design compliance with cost overruns in Indonesian Public-Private Partnership (PPP) water supply projects. Employing a mixed-methods approach, the research integrates quantitative analysis of official project data (contract values, DEDs, QC reports) with qualitative stakeholder insights. Key findings demonstrate a significant negative correlation between effective managerial oversight and cost overruns (r = -0.632), and similarly, between strict hydraulic adherence and cost overruns (r=-0.527). Unforeseen site conditions and design modifications were confirmed as significant exacerbating factors. The results highlight the imperative for integrated risk management, combining rigorous managerial scrutiny and unwavering technical discipline to mitigate budgetary risk. Policy recommendations emphasize enhancing inter-stakeholder coordination, enforcing technical standards, and leveraging digital monitoring tools to improve PPP project efficiency and sustainability.

***Keywords**: Construction Management, Hydraulic Design Compliance, Cost Overruns, Public-Private Partnership, Water Supply Projects*

DOI: https://doi.org/10.69855/sipil.v1i2.322
Available online at website: https://gpijournal.com/index.php/sipil
PUBLISHED BY : GPress Indonesia

Structures, Infrastructure, Planning, Implementation, and Legislation (SIPIL)
Vol. 01. No. 2, October 2025

INTRODUCTION

Cost overruns in Public-Private Partnership (PPP) water supply schemes present a formidable challenge, encompassing both practical and theoretical dimensions within the infrastructure domain. On a practical level, these budgetary escalations compromise the efficient allocation of public and private capital, threaten the sustainability of the projects, and potentially undermine the reliability of water services provided to the public (Yescombe, 2021). Public-Private Partnership (PPP) models in water supply projects integrate private sector expertise to address public infrastructure gaps, but persistent cost overruns threaten their sustainability (Ameyaw and Chan, 2015). Effective construction management efficacy and hydraulic design compliance emerge as critical factors influencing these overruns, as lapses in either domain escalate financial risks through delays and rework. This introduction examines their correlations to inform better project strategies. Particularly in emerging economies such as Indonesia, cost increases are frequently attributable to suboptimal construction management practices and insufficient adherence to technically prescribed hydraulic designs (Nguyen & Zhang, 2023). The inherent technical complexity associated with pipeline installation, water treatment facilities, and the necessary integration of responsibilities between public and private sectors introduces layers of risk and potential budget overruns a primary concern for PPP project governance (Ameyaw et al., 2022).

Consequently, a profound understanding of construction management effectiveness and the fidelity to hydraulic design standards emerges as a critical element for mitigating cost escalation risks in these vital projects (Flyvbjerg, 2014). Therefore, a robust emphasis on the implementation of sophisticated project control systems, including the integral use of the Earned Value Management (EVM) methodology, is unavoidable for the continuous monitoring of cost and schedule performance (Kerzner, 2022). A clear project governance framework that equitably allocates cost risk between public and private partners is a fundamental prerequisite (World Bank, 2017). A failure to identify and mitigate risks from the earliest planning phases, such as material price volatility or unforeseen regulatory changes, exponentially increases the probability of significant cost deviations. Furthermore, delays in obtaining permits or land acquisition often act as external factors that substantially exacerbate the impact of suboptimal construction management, transforming minor issues into major budgetary crises. The lack of managerial foresight in anticipating these interconnected technical and external challenges directly translates into higher financial exposure for both the project consortium and the public sector, cementing the argument for proactive, integrated risk governance across all project life cycles.

A body of recent literature has underscored the critical role of high-quality construction management in minimizing project cost overruns, particularly within PPP frameworks for infrastructure. Suhendra and Satrio (2020) compellingly argue that robust risk management protocols and effective cross-functional coordination are essential determinants for achieving targeted project budgets and schedules. Furthermore, research conducted by He, Zhang, and Wang (2020) indicates that non-adherence to hydraulic specifications, such as utilizing substandard materials or employing non-compliant installation procedures, carries a significant potential for inducing substantial rework and subsequent cost augmentation. Another finding, presented by Osei-Kyei and Chan (2023), emphasizes the necessity of integrating construction management controls with technical design supervision to ensure successful PPP project execution. Nevertheless, the majority of these existing investigations typically adopt a macro-level perspective and rarely integrate valid, primary empirical data from water provision projects, which possess unique risk characteristics.

Additionally, many studies rely on incomplete secondary data, thus hindering the development of a comprehensive and precise understanding of cost overrun dynamics in this specialized sector. This

limitation establishes a critical methodological void, where verified and granular empirical data from actual project sites including specific details regarding pipe installation failures, unexpected leakage rates, or deviations in water quality testing procedures are insufficiently analyzed to pinpoint the precise cost drivers. It is crucial to shift the focus from general qualitative studies on macro-causes of PPP failure to micro-level quantitative analysis of how daily technical decisions on the construction site and the effectiveness of engineer supervision directly impact cost variance. This absence of detailed primary data impedes the development of accurate predictive models capable of anticipating the rework risk induced by both hydraulic design non-conformance and weak site management. Addressing this data gap is paramount for generating actionable insights that move beyond generic recommendations, enabling targeted interventions focused on technical fidelity and managerial accountability in complex water infrastructure development.

A substantial gap persists in the academic literature concerning the empirical correlation between the effectiveness of construction management and strict hydraulic design compliance with cost overruns in PPP water supply initiatives. Numerous studies treat construction management facets and hydraulic design principles in isolation, failing to examine their simultaneous relationship using valid and comprehensive real-world project data (Nguyen & Zhang, 2023; Suhendra & Satrio, 2020). Moreover, prior research has largely favored qualitative methodologies, which, while broad in scope, often lack the depth required for rigorous statistical analysis of the interplay between technical and managerial variables. This limitation creates an opportunity for further investigation, utilizing verified primary-secondary data sourced directly from governmental bodies, such as the Ministry of Public Works and Housing (PUPR), the Ministry of Finance, and Bappenas, which contain detailed information regarding project contracts, cost realizations, technical designs, and construction progress.

This segregated approach fundamentally fails to capture the synergistic dynamic where a managerial failure to effectively supervise and implement a complex hydraulic design becomes the core critical flashpoint for cost drivers. Future research must explicitly test for interaction variables, for instance, how construction quality management moderates the relationship between the technical complexity of the hydraulic design and the resulting rate of rework. The use of official government data, encompassing detailed contract change orders (*addenda*) and technical field inspection reports, allows for significantly higher external validity and reliability compared to subjective surveys or interviews. This is a crucial methodological step towards building robust causality models that demonstrate not just *that* cost overruns occur, but statistically prove *why* the interaction between technical and managerial factors drives these cost increases. Such precision is essential for developing evidence-based policy that effectively targets the root causes of budgetary failures in highly technical PPP environments.

This research aims to address the identified literature gap by examining the correlation between construction management effectiveness and adherence to hydraulic design standards on cost overruns within Indonesia's PPP-based water supply projects. The study employs a quantitative approach, utilizing statistical correlation analysis on primary-secondary data obtained from credible government institutions. The novelty of this research lies in the simultaneous integration of both managerial and technical variables and the utilization of accurate and comprehensive official data. Consequently, the findings are anticipated to offer significant scholarly contributions and practical implications for policymakers, project managers, and academics focused on developing robust methods for cost overrun risk mitigation and enhancing the efficiency of PPP project implementation. The study's results are expected to validate a structural model that links superior construction management practices and high hydraulic design compliance to measurable reductions in final project costs.

The practical contributions will include the development of an integrated performance assessment framework that can be utilized by both government and private partners to proactively quantify and assess cost risk. This enables targeted policy interventions, such as mandating the use of integrated Building Information Modeling (BIM) technology to minimize hydraulic design conflicts before physical construction even begins. Furthermore, these findings will provide an empirical basis for revising PPP contract clauses, particularly concerning the allocation of risks related to changes in technical specifications and delays caused by deficient site management, which can critically enhance investor confidence and project bankability. The overall goal is to shift PPP project governance from reactive crisis management to proactive, data-driven optimization of both cost and quality.

METHODS

1. Research Approach

This investigation adopts a Mixed-Methods Approach, strategically combining Quantitative and Qualitative methodologies to achieve a holistic understanding of the intricate correlation between construction management effectiveness, adherence to hydraulic design specifications, and subsequent cost overruns in Indonesian Public-Private Partnership (PPP) water supply projects (Creswell & Creswell, 2018).

a. The Quantitative Core primarily involves statistically testing the relationships among key variables using rigorous secondary data extracted directly from authenticated project documentation.
b. The Qualitative Component is dedicated to generating rich, in-depth insights that serve as interpretive validation and contextual explanation for the statistical findings. This is achieved through structured interviews with key personnel and detailed field documentation.

Data Triangulation: This mixed-methods design is paramount for achieving robust data triangulation. The statistical results (e.g., a strong negative correlation between effective management and costs) are significantly enriched by a contextual understanding derived from the qualitative phase. This qualitative inquiry specifically aims to uncover operational causal mechanisms such as the rationale for material substitutions that deviate from specifications or the time pressures leading to shortcuts in technical pipe installation. By moving beyond mere descriptive statistics to understand why these relationships exist, the research can formulate practical, immediately actionable recommendations for both managerial and technical personnel.

2. Study Subjects and Data Sources

The research subjects are PPP water supply projects successfully executed across Indonesia within the preceding five years. Project selection prioritizes the availability of complete and authenticated data essential for robust empirical analysis. Crucial selection criteria focused heavily on the explicit recording of deviations from the Detailed Engineering Design (DED) specifications such as changes in pipe diameters or documented failures during hydraulic system pressure testing which are necessary for accurately measuring the technical independent variables.

Key Secondary Data Sources Analyzed: Data were obtained directly from official financial and technical records of relevant government agencies and Project Implementing Units, including:

a. Cost Data: Initial contract values versus final project realization costs (used to compute the Cost Overrun variable).
b. Technical Design Data: Detailed Engineering Design (DED) documentation and corresponding hydraulic technical specifications.

c. Execution Data: Construction progress reports and official records of scope changes (Change Orders), which serve as a key quantitative proxy for suboptimal project management and reactive risk handling.
d. Quality Assurance Data: Results from quality control (QC) assessments of materials and installation work.
e. Site Risk Data: Initial site survey reports detailing prevailing field conditions and existing technical risks.

The utilization of this secondary data, sourced directly from official records, significantly addresses a major weakness in prior literature: the reliance on unverifiable or incomplete data, thereby bolstering the internal validity of the correlation and regression findings regarding managerial oversight and technical execution outcomes.

3. Research Procedures

The study was structured across three interconnected phases:

A. Phase I: Secondary Data Collection and Verification (Quantitative Basis)

This phase established the foundation for the quantitative analysis.

1) Initial Data Acquisition: Secondary data were collected concurrently from key government institutions: the Ministry of Public Works and Housing (PUPR), the Ministry of Finance, the National Development Planning Agency (Bappenas), and relevant Project Implementing Units.
2) Rigorous Verification:
   a) Financial Data: Validated through cross-audits of financial statements against administrative records.
   b) Technical Data: DED documentation and construction reports were analyzed against on-site technical compliance records.
3) Quantitative Data Management (Tabulation): Verified data were organized into a central database using a data matrix table. This critical procedure involved cross-checking financial records (e.g., payments made) against physical and technical progress reports (e.g., volume of work completed) to ensure that reported cost overruns were genuine indicators of executed physical work or necessary rework, and not merely accounting discrepancies. An example of the data structure is presented below:

Project ID	Initial Contract Value (IDR)	Final Cost (IDR)	Cost Overrun (%)	Hydraulic Compliance Score (Ordinal Scale)	Number of Change Orders	Management Effectiveness Score
PPP-001	500.000.000.000	585.000.000.000	17.0	4 (High)	5	8.2 (Excellent)
PPP-002	750.000.000.000	877.500.000.000	17.0	4 (High)	8	6.5 (Good)

Note: The data is an illustrative example based on the empirical average of 38 Indonesian drinking water PPP projects (average cost overrun of 17.4%). Actual values were obtained from official documents of the Ministry of Public Works and Housing (PUPR), the Ministry of Finance, and Bappenas through cross-verification of financial reports vs. physical/technical progress (DED & QC reports).

B. Phase II: Quantitative Statistical Analysis

The verified data were processed using SPSS and AMOS software packages. Primary Analysis: Structural Equation Modeling (SEM) was deployed. The deployment of SEM is essential because it allows for the testing of complex, simultaneous causal relationships, such as how construction management effectiveness might mediate or moderate the influence of hydraulic design compliance on final costs, thereby providing a far more nuanced view than simple linear regression. Correlation analysis (Pearson) and multiple regression were used for preliminary exploration.

C. Phase III: Contextual Qualitative Data Collection

Following initial quantitative findings, structured interviews were conducted with designated project managers, design engineers, and site supervisors. Objective: To comprehensively identify construction management constraints and obtain in-depth operational explanations for the statistical results (e.g., interpreting why projects with high cost overruns had low hydraulic compliance scores). This qualitative input serves as the interpretive validation, significantly strengthening the causal pathways identified by the SEM model.

4. Instruments and Data Analysis

1. The instruments employed include:
    a. Quantitative Instruments: Secondary Data Collection Templates tailored for auditing financial records, DED documents, and QC reports. These templates were specifically designed to measure variables with high precision, such as using a ratio scale for Cost Overrun (percentage of original contract value) and converting technical audit compliance scores to an ordinal scale for Hydraulic Design Compliance.
    b. Qualitative Instruments: Structured Interview Guides and Field Observation Protocols.
2. Data Analysis Techniques:
    a. Quantitative: Pearson correlation tests, multiple linear regression, and the core method, SEM, were used to identify the strength and nature of causal relationships among variables (Nguyen & Zhang, 2023).
    b. Qualitative: Thematic Analysis was applied to interview transcripts to identify recurring patterns, themes, and underlying contextual causes.
3. Validity and Reliability:
    a. Validity: Content Validity for the interview instruments was ensured through expert review by specialists in PPP and hydraulic engineering. Construct Validity for quantitative instruments was maximized by ensuring accurate conversion of real-world data (costs, deviations) into measurable variables.
    b. Reliability: Tested using Cronbach's Alpha analysis for any scaled qualitative instruments and cross-consistency checks for secondary data, guaranteeing that the obtained results are consistent and replicable.

RESULTS

1. Statistical Analysis of Construction Management Effectiveness on Cost Overruns

The quantitative assessment examined the relationship between the effectiveness of construction management and cost overruns within Indonesian PPP water supply projects.

$$CO\ (\%) = \frac{C_{final} - C_{Initial}}{C_{Initial}} \times 100\%$$

Where: C_{final} is the Final Realized Cost, and $C_{Initial}$ is the Initial Contract Value.

Pearson correlation analysis demonstrated a statistically significant inverse correlation, with a coefficient of r = -0.632, p < 0.01, between construction management effectiveness and the magnitude of cost escalation. This finding implies that projects characterized by higher managerial efficacy consistently experienced lower cost overruns. Primary obstacles hindering effectiveness and contributing to cost increases included frequent project scope expansion (change orders) and substantial delays in material procurement (Suhendra & Satrio, 2020; Nguyen & Zhang, 2023). This strong negative correlation (r = -0.632) suggests that every increase in construction management maturity such as reinforced scope control and more realistic scheduling substantially contributes to a reduction in cost overrun risk. Specifically, recurring issues with change orders and delayed material procurement statistically serve as direct proxies for failures in managerial planning and coordination. Within the PPP context, where risk allocation is vital, poor construction management effectiveness directly transfers financial burdens to the project, often through justified contractor claims resulting from disruptions caused by disorganized management. The financial impact of material delays, for example, is compounded by contractual penalties and the substantial cost of idle equipment on site. This underscores the need for managerial certification standards for PPP project personnel.

a) Correlation between Initial Contract Value and Final Realization

analysis was performed with the form:

$$\text{Cost Overrun} = \beta_0 + \beta_1 \times \text{Initial Contract Value} + \epsilon$$

The analysis indicated an average cost overrun of 17.4% relative to the original contract price. The linear regression coefficient, β_1 = 0.74, was statistically significant (p = 0.003), confirming that initial budget projections are frequently inaccurate. Furthermore, the data showed that the variance of cost overruns amplified in projects with larger contract values, suggesting increased complexity in their management.

The statistically significant regression coefficient β = 0.74 confirms that initial budget estimates are highly susceptible to optimism bias and a failure to integrate realistic quantitative risk assessments during the planning phase. This inaccuracy often stems from superficial geotechnical and site surveys conducted prior to contract signing, which forces substantial design revisions (*re-scoping*) once construction commences, automatically triggering cost spikes. Therefore, stricter pre-contract due diligence, incorporating probabilistically calculated cost contingencies, is a necessary prerequisite to curb initial budget deviation, recognizing that larger scale inevitably introduces more systemic interaction risks.

2. Hydraulic Design Compliance and its Impact on Project Costs

A sub-analysis focusing on hydraulic design compliance revealed that discrepancies between field execution and the Detailed Engineering Design (DED) resulted in an average cost increment of 12.1% due to necessary rework and modifications of the hydraulic infrastructure. The correlation test between the design compliance score and cost overruns yielded r = -0.527, p < 0.05, suggesting a moderate but statistically significant inverse relationship (He et al., 2020). The 12.1%average cost increase attributed to technical rework highlights that hydraulic design non-compliance is a quantifiable and significant cost driver, second only to general management failure.

This moderate negative correlation (r = -0.527) empirically validates that any technical deviation, such as installing pipes at the wrong gradient, using non-standardized fittings, or neglecting specified DED pump parameters, creates a cascading effect requiring system dismantling and reconstruction. This not only wastes material but also causes schedule delays, triggering significant overhead costs. Hence, investment in highly competent technical supervision teams and rigorous DED compliance audit systems is a profoundly effective cost control strategy, demonstrating that quality assurance provides a demonstrable financial return by avoiding expensive system failures and subsequent legal disputes.

a) Influence of Quality Control and Field Inspection on Costs

Quality Control (QC) data and field inspection records demonstrated that projects which consistently implemented rigorous material verification and testing procedures exhibited lower cost overruns. A t-test was conducted comparing the Mean Cost Overrun of projects with Stringent QC versus those with Weak QC (using a binary grouping variable).

$$t = \frac{\bar{x}_{\text{Stringent QC}} - \bar{x}_{\text{Weak QC}}}{S_{\bar{x}_{\text{diff}}}}$$

The t-test yielded a coefficient of t(38) = 3.12 (p = 0.004) with a large effect size (Cohen's d) of 0.88. This signifies that stringent quality control measures are notably effective in mitigating cost escalation. The Cohen's d = 0.88 effect size indicates that the difference in cost overruns between the two groups has a large practical impact. The significant t-test coefficient convincingly proves that stringent QC is an investment that yields substantial savings on cost overruns.

3. Impact of Field Condition Risk Factors and Design Changes on Cost Overruns

Risks stemming from unforeseen site conditions, such as undetected soil inadequacies during initial surveys, were found to be a substantial contributor to cost overruns. Quantitative findings indicate that these geotechnical risks alone increased project costs by approximately 8.3% of the total budget, while subsequent design modifications necessitated by field discoveries accounted for a 9.7% cost increase (Yescombe, 2021; Suhendra & Satrio, 2020). The 8.3% cost overrun contribution from undetected geotechnical risks statistically justifies the necessity for a significantly larger and more comprehensive investment in initial geotechnical and topographical surveys. The finding that design modifications (9.7%) have a cost contribution almost equal to the site risk suggests a reciprocal relationship: unpredicted site risks directly necessitate design changes, which then trigger the cost increase. This highlights that design risk and site risk cannot be treated as separate entities. A failure to rapidly and accurately update the DED once site risks are identified becomes the starting point for contractual disputes and poorly managed *change order* costs, demanding a seamless process for design-construction feedback loops to minimize this budgetary exposure.

Structural Equation Modeling (SEM) analysis confirmed the simultaneous impact of field-related risks on cost overruns, showing a standardized path coefficient of β_{Risk}0.45 at the significance level p < 0.01 (Hair et al., 2021). The interrelationship between design risk and construction management was found to moderate the cost overrun magnitude, underscoring the imperative for integrated mitigation strategies that combine early risk evaluation with responsive control planning (Ameyaw et al., 2022). The standardized path coefficient of 0.45from the SEM provides strong causal evidence that risks originating from site conditions have a direct and significant influence on cost overruns. The finding

regarding construction management's moderating effect is a critical insight: even when site risk is high, projects with effective construction management are better equipped to absorb and manage its impact, such as by responding to soil changes with rapid schedule adjustments rather than costly claims. This suggests that effective construction management acts as a buffer against technical uncertainty, emphasizing that an adaptive, integrated response, not just static planning, is key to successful PPP cost control, advocating for agile project management principles in infrastructure.

Table 1. Correlation and Statistical Metrics for Cost Overruns in PPP Water Supply Projects

Variable	Correlation (r)	p-value	Effect Size / Coefficient
Construction Management Effectiveness	-0.632	<0.01	-
Hydraulic Design Compliance	-0.527	<0.05	-
Quality Control	-	$p = 0.004$	t=3.12,d=0.88
Field Condition Risk	-	< 0.01	Path Coef β_{Risk}= 0.45

The core statistical symbols are interpreted as follows:

Pearson Correlation Coefficient (r) = measures the strength and direction of the linear relationship between two variables.

p-value = indicates the statistical significance of the results.

t-test Coefficient (t) = is used for comparing the average outcomes of two distinct groups.

Cohen's d (Effect Size) = measures the practical magnitude of the difference between groups.

Standardized Path Coefficient (β) = measures the direct causal strength of one variable on another within the Structural Equation Model.

These results affirm that both the effectiveness of construction management and rigorous adherence to hydraulic design specifications significantly influence cost overruns in PPP water supply projects. Furthermore, external factors such as site risk and necessary design amendments emerged as key triggers for budgetary escalation, necessitating optimal management. These findings are congruent with previous research emphasizing the vital need for integrating risk management with technical and managerial quality controls to effectively curb cost overruns (Nguyen & Zhang, 2023; Ameyaw et al., 2022). Collectively, the correlation and regression analyses comprehensively support an integrated risk management framework that encompasses both managerial aspects (scope control, coordination) and technical aspects (DED compliance, material QC).

This study provides specific quantitative empirical evidence from Indonesia reinforcing the theoretical argument that cost overruns are a result of systemic failure, not just isolated errors. The practical implication is that PPP projects must adopt a unified reporting system that compares cost and schedule performance in real-time with technical compliance metrics, enabling management teams to

identify and correct hydraulic design non-conformance before they trigger significant rework and associated additional expenditures, promoting a holistic view of project health.

DISCUSSION

1. Interpretation of Findings in the Context of Theory and Previous Research

The results of this study validate the hypothesis that construction management efficacy bears a significant inverse correlation with cost overruns in PPP water supply projects. This finding is highly consistent with established classical project management theory, which posits that superior coordination, rigorous planning, and proactive risk control are foundational to preventing budget escalations (Ervianto, 2002; Suhendra & Satrio, 2020). Effective construction management functions fundamentally as a risk mitigant, thereby minimizing managerial errors, reducing necessary rework, and accelerating material delivery timelines. Earlier literature has pointed out that these managerial components are often less than optimal, particularly in large-scale, high-complexity projects (Nguyen & Zhang, 2023). This research robustly supports this contention with empirical data sourced from Indonesian projects, where demonstrably better quality construction management translates directly into a tangible reduction in cost deviations. This consistency with classical project management theory provides a strong foundation for policy recommendations. The statistically significant correlation ($r = -0.632$) suggests that variations in managerial capability such as skill in negotiating change orders and efficiency in the supply chain are the primary differentiating factors in project cost outcomes. Theoretically, construction management failures in PPPs are often linked to principal-agent problems, where the incentives of the private partner may not fully align with the public's long-term cost-saving objectives. The empirical data from this study underlines the necessity for contract designs that explicitly incentivize the private partner to invest in superior construction management and stringent QC systems, making it not just a best practice but an auditable contractual requirement backed by performance penalties for non-compliance.

Furthermore, compliance with hydraulic design specifications was unequivocally demonstrated to be a critical determinant in cost control. Non-compliance that necessitates rework and subsequent structural modifications not only results in schedule delays but also imposes an unnecessary financial burden (He et al., 2020). This underscores the absolute necessity for stringent technical supervision and adherence to strict working standards to ensure that technical implementation aligns perfectly with the designed plans. This implication aligns seamlessly with construction management literature emphasizing the integration of quality control and technical standards as a vital component for overall project success (Bui & Nguyen, 2022). The significant impact of hydraulic design non-compliance, causing an average 12.1% cost overrun, statistically justifies that the technical aspect is of equivalent importance to the managerial aspect. Technical failures on site, such as using pipes with a different roughness coefficient than specified in the DED, can affect the system's long-term hydraulic parameters, potentially triggering system failure or lower efficiency, which requires massive cost interventions later. This research reinforces the argument that continuous technical due diligence and audits of compliance by an independent third party should not be optional but a compulsory operational standard for all PPP water infrastructure projects, ensuring that the initial investment in quality prevents far greater costs of failure over the project's operational lifespan, thereby protecting public funds.

Risk factors linked to unforeseen site conditions and scope changes emerged as additional variables that significantly moderate cost overruns. Unidentified site risks, such as geotechnical mismatches not detected during initial surveys, and sudden design changes frequently trigger substantial budget escalations (Yescombe, 2021). This discovery advocates for an integrated risk

management methodology within PPP projects that is not solely focused on preliminary planning but also on rapid adaptation to dynamic field conditions (Ameyaw et al., 2022). Moreover, the interaction observed between site-specific risks and construction management effectiveness suggests that these two elements must be managed concurrently to successfully suppress the adverse impact of cost overruns. The finding on moderation by construction management is a key discussion point, indicating that the project's vulnerability to site risk can be significantly mitigated by the managerial capacity for rapid adaptation and mitigation. Theoretically, this supports the Dynamic Capabilities model in project management, where an organization's ability to sense, reshape, and reconfigure resources (including design plans and schedules) under field uncertainty becomes the primary determinant of cost outcomes. Policy recommendations should, therefore, encourage the establishment of a joint Managed Risk Contingency Fund within the PPP contract, allocated specifically to respond to unavoidable site risks and associated design changes, which is governed through a transparent and efficient process to prevent discretionary spending.

2. Managerial Implications for Cost Control: Construction Management and Hydraulic Design Standards

The study unequivocally proves that effective construction management is fundamental to controlling excessive costs. The consistent implementation of proper risk management practices, realistic scheduling, rigorous quality control, and streamlined cross-functional communication are key control levers at the site level. Integrating risk protocols from the planning stage through execution, alongside continuous monitoring, enhances responsiveness to deviations, consequently enabling cost savings (Jasri et al., 2020). The primary managerial implication is that construction management must be positioned as a value-creating function rather than merely an oversight function. This requires a shift from a reactive to a proactive culture, where risk surveillance and claim management are at the core of the project manager's duties. The use of digital tools, such as real-time performance dashboards that integrate cost, schedule, and QC compliance data, empowers managers to make data-driven decisions. Intensive training in contract management for on-site staff is crucial to minimize the financial impact of change orders and disputes arising from hydraulic design non-conformance, ensuring that every financial decision is contractually auditable.

Rigid hydraulic design standards must be rigorously enforced as the definitive technical reference to ensure field execution is in lockstep with the planned design. Implementing stringent systems for monitoring raw material quality and technical installation, which includes mandatory workforce training and periodic audits, is crucial for preventing costly rework. The practical implication highlights that close collaboration among the design, construction, and site supervision teams significantly boosts both compliance and the final quality of the project outcome (He et al., 2020). The strict enforcement of hydraulic design standards necessitates the creation of a Technical Compliance Unit independent of the construction team. This unit should be responsible for pre-installation material audits, hydrostatic testing, and verifying the calibration of critical equipment. Close collaboration demands the use of a shared design-construction collaboration platform, such as BIM, which allows the design team to resolve hydraulic design clashes instantly as they arise in the field. This technical compliance is, essentially, a cost insurance policy an investment in technical quality that guarantees the water system will operate to specification without premature failures that trigger expensive operational and maintenance costs later, solidifying technical integrity as a non-negotiable project metric.

3. Recommendations for Cost Overrun Risk Mitigation

Based on the empirical findings, several key recommendations for mitigating cost overrun risk in PPP water supply projects are proposed:

a. Strengthening Construction Management Effectiveness: Optimizing planning, contract administration, risk governance, and establishing robust communication channels among stakeholders to enhance coordination and accelerate problem resolution (Nguyen & Zhang, 2023).
b. Enhancing Hydraulic Design Compliance: Establishing strict working protocols, conducting routine technical audits, and providing targeted workforce training to ensure execution aligns precisely with design specifications (He et al., 2020).
c. Integrated Risk Management: Implementing a comprehensive risk framework that systematically combines identification, analysis, evaluation, and control of risks with the mandatory involvement of all relevant parties from the earliest stages (Ameyaw et al., 2022).
d. Adoption of Monitoring Technology: Utilizing digital technologies and real-time monitoring tools to ensure transparent project oversight and rapid responsiveness to potential cost escalation factors (Hair et al., 2021).

4. Limitations and Future Research Directions

A limitation of this study lies in its reliance on official secondary data, which, despite its formal nature, may possess inherent constraints in capturing the granular detail of day-to-day operational decisions. Furthermore, the use of statistical models based on historical data may not fully capture dynamic phenomena and the human factors involved in on-site decision-making.

Future research is recommended to incorporate a longitudinal approach combined with in-depth case studies to better understand the daily dynamics and the influence of organizational culture on construction management. Studies could also expand the geographical scope to compare PPP projects across various nations to achieve broader generalizability. Finally, the application of information technology and the digitalization of project management processes present a key area for innovation-focused research to achieve more effective cost control.

CONCLUSIONS

This research definitively affirms a statistically significant correlation between the efficacy of construction management and adherence to hydraulic design compliance with cost overruns in Public-Private Partnership (PPP) water supply projects across Indonesia. Enhanced construction management effectiveness, encompassing meticulous planning, proactive risk governance, diligent project scope control, and strong inter-party coordination, was statistically proven to substantially mitigate cost escalation. This provides robust empirical confirmation for classic project management theory, which stresses the pivotal role of managerial controls in ensuring projects remain within their initial budgetary constraints (Suhendra & Satrio, 2020; Nguyen & Zhang, 2023).

Furthermore, strict fidelity to hydraulic design standards was established as having a crucial impact on preventing budget overruns. Discrepancies between technical field execution and the approved design documentation invariably led to increased rework, thereby significantly augmenting project cost escalation. Consequently, stringent technical supervision, the mandatory application of quality material standards, and specialized field labor training are paramount to guarantee that the final project output aligns with the original design specifications, thus suppressing the risk of both technical and financial failure (He et al., 2020).

External variables, specifically unforeseen site conditions and scope changes, also contribute substantially to budgetary increases. Risks arising from site inconsistencies that are not adequately detected during initial phases necessitate adjustments to the design and execution methodology, which automatically drives up project expenses. This investigation underscores the imperative need for integrating site condition risk management into the planning and execution processes of PPP projects. This flexibility in design adaptation must be balanced with strict managerial controls to minimize cost deviations (Ameyaw et al., 2022; Yescombe, 2021).

The practical applicability of these research findings is extensive, particularly for policymakers and practitioners involved in water infrastructure projects. By clearly understanding the correlation and influence of construction management factors, hydraulic design compliance, and field risks on cost overruns, project executives are better equipped to develop more efficacious mitigation strategies. Such strategies can encompass refining risk management systems, improving cross-sectoral coordination, and implementing more disciplined technical oversight. This is highly pertinent for maximizing the efficiency of public and private funding and ensuring the sustainable and high-quality delivery of essential infrastructure projects (Nguyen & Zhang, 2023).

Moreover, this study paves the way for the advancement of future research examining organizational culture, the social dynamics within project teams, and the utilization of digital technologies for more integrated project governance. A longitudinal approach utilizing real-time data would offer deeper insights into the dynamic nature of project management and the human factors that impact cost overruns. Comparative, cross-country studies can also provide global perspectives and actionable best practices suitable for adaptation within the national context (Hair et al., 2021; Creswell & Creswell, 2018).

In summary, this research strengthens the comprehension that the success of PPP water supply projects is profoundly dependent on the synergy between effective construction management and technical adherence to hydraulic design in controlling cost overruns. Developing relevant policies, standardizing technical procedures, and implementing comprehensive risk management practices will be essential in realizing efficient and sustainable water infrastructure projects to meet the ever-growing needs of the population.

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