Enhancing Constructability through Construction-Phase Design Adaptations: The Case Study of the Jenelata Dam Project

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ABSTRACT

This study explores how construction-phase design changes affect constructability performance in large-scale dam projects, using the Jenelata Dam Project in Indonesia as a case study. Three questions are tackled: (1) how design process factors relate to constructability, (2) how much these factors impact constructability performance, and (3) how design adaptations during construction influence time, cost, and constructability. A mixed-method approach was used, combining a survey of 32 project stakeholders (owners, consultants, and contractors), field observations, and document analysis. Quantitative analysis included Pearson correlation and multiple linear regression, with an R^2 of 0.786, showing strong explanatory power of design process variables. The results indicate that all design process factors are positively and significantly related to constructability, with Iterative and Adaptive Design being the most influential ($\beta = 0.408$). Qualitative validation shows that early and systematic design adaptations, such as replacing frame beams and hydroseeding with Geomat Type III for slope protection, and changing foundation treatment from vertical to rim grouting, led to significant improvements, including a 70% reduction in construction time and cost savings up to 61.3%. These findings provide empirical evidence that well-managed construction-phase design changes can improve constructability when coordinated and driven by data. The study offers practical insights for better integration of design and construction, and for managing design changes adaptively in complex dam projects.

Keywords- design process; constructability; design changes; Dam Project; construction efficiency

I. INTRODUCTION

In dam construction projects, design is a determinant of technical performance, cost efficiency, project duration, and work quality. However, discrepancies between design assumptions and actual site conditions frequently trigger project changes that affect constructability and overall performance. Construction-phase changes are often driven by contractual structures, implementation timing, stakeholder roles, and resource availability, all of which shape the extent and severity of project impacts [1]. In large-scale infrastructure systems, decision-making under uncertainty further complicates design implementation, as projects must accommodate evolving technical, environmental, and stakeholder conditions over their lifecycle [2]. This highlights the importance of flexibility and adaptability in infrastructure design and management. Moreover, advances in BIM-based construction management demonstrate that the implications of design changes on time and cost can be predicted earlier through integrated digital and analytical approaches, enabling more informed decision-making and improved coordination among stakeholders [3]. These challenges are particularly relevant in dam projects, where their high technical complexity and geotechnical uncertainty demand strong integration between design and construction processes to ensure that design solutions are practical to implement. This need becomes more significant when design detailing occurs concurrently with construction activities, as decisions made during this stage directly influence constructability and project control. Such conditions were evident in the Jenelata Dam Project, where design detailing was conducted in parallel with construction under a unit price contract scheme, resulting in adaptive design changes in response to field-based technical, geotechnical, and operational requirements.

The complexity of projects is increasing as multinational stakeholders with different technical standards, design practices, and communication patterns are involved, making coordination and design clarification during construction implementation a challenge. The importance of synergy between design and construction in achieving project success has been emphasized. Authors in [4] stated that contractor involvement from the design stage can reduce conflicts, revisions, and project delays. Authors in [5] showed that iterative and collaborative design can improve constructability and maintainability. Authors in [6, 7] emphasized the concept of design partnering, which combines collaboration between project owners, planning consultants, and contractors from the early design stage to achieve efficiency and adaptability in implementation. Authors in [8] revealed that the application of Building Information Modeling (BIM) can detect design clashes early on and facilitate cross-party coordination. Although previous studies have extensively discussed constructability and design–construction integration, most of them emphasize the negative impacts of design changes, such as delays and cost overruns. Limited empirical evidence exists on how early, systematic construction-phase design adaptations can enhance constructability performance, particularly in dam projects. Furthermore, few studies integrate quantitative analysis of design process factors with qualitative validation based on real construction-phase adaptations. This study addresses these gaps through a case study of the Jenelata Dam Project, combining statistical analysis with field-based evaluation. Based on the limitations identified in the existing literature, there is a need for empirical investigation into how construction-phase design processes influence constructability performance in complex dam projects. Accordingly, this study formulates the following research objectives.

This study addresses the following research questions:

- RQ1: What is the relationship between construction-phase design adaptations and constructability performance in the Jenelata Dam Project?
- RQ2: To what extent do construction-phase design adaptations influence constructability performance?
- RQ3: How do slope protection and foundation grouting design adaptations affect constructability, time efficiency, and cost performance?

Therefore, this study aims to analyze the relationship between the design process and constructability through a case study of the Jenelata Dam Project, focusing on design changes to slope protection and foundation grouting works. These findings provide empirical evidence that construction-phase design adaptations, when implemented in a coordinated and data-driven manner, can enhance design–construction integration and improve constructability performance in complex dam infrastructure projects.

II. METHODOLOGY

A. *Research Location and Time*

The research timeframe provides a picture of the duration required to complete each activity, ensuring that the research can be completed on time according to the predetermined schedule. This research is planned to last for five months. The former uses a quantitative approach supported by qualitative and comparative analysis. Quantitative analysis is conducted to assess the relationship and influence of the design process on constructability using questionnaires and statistical tests. Qualitative and comparative analysis is employed to evaluate the impact of design changes through case studies of slope protection and foundation grouting works. The research was conducted at the Jenelata Dam Project in Gowa Regency, South Sulawesi Province, during five months in the active construction phase. The location was selected based on the project's characteristics, and the work underwent detailed design in parallel with construction under a unit price contract. Figure 1 shows the research location.

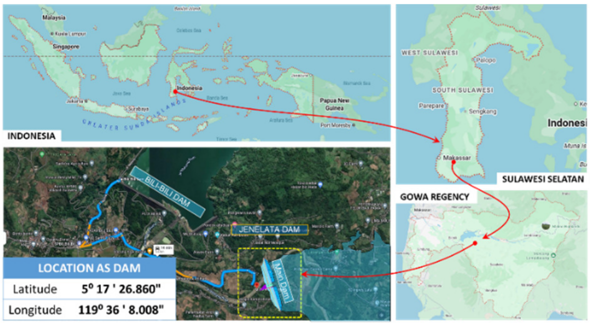

Fig. 1. Research location.

Figure 2 illustrates the research methodology using the Input–Process–Output (IPO) framework. The study deploys mixed methods to address three research questions. RQ1 employs validity, reliability, classical assumption tests, and Pearson correlation to examine relationships between design factors and constructability. RQ2 uses multiple linear regression to assess the magnitude and significance of the design factor's influence. RQ3 applies a comparative case study based on project documents, interviews, and field observations to evaluate the impacts of design changes on constructability, cost, and time performance. This framework ensures systematic and rigorous analysis.

B. *Data Collection Methods*

This study involved 32 expert respondents (N = 32) directly engaged in the Jenelata Dam Project, representing the project owner, planning consultants, supervision consultants, and the main contractor. The respondent distribution consisted of 18.75% owners, 15.63% planning consultants, 15.63% supervision consultants, and 50% contractor personnel. In terms of educational background, 59.38% held a bachelor's degree (BSc), 34.38% a master's degree (MSc), and 6.25% a PhD, primarily in Civil or Geotechnical Engineering. Additionally, most respondents (81.25%) had more than 10 years of professional experience. Given the case study approach and the limited number of qualified professionals involved in the project, the sample represents the accessible expert population rather than a probabilistic sample. While this ensures relevance to the specific project context, the relatively small sample size may limit the generalizability of the findings.

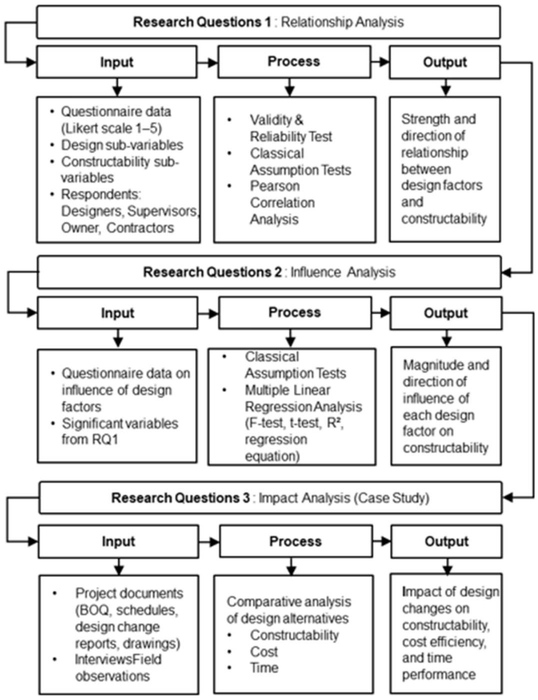

Fig. 2. Research flowchart based on IPO framework.

The study utilized both primary and secondary data sources. Primary data were collected through questionnaire surveys distributed to key stakeholders, including the owner, consultants, and contractor. These data were used to address RQ1, which examines the relationship between design process factors and constructability, and RQ2, which evaluates the extent of their influence on constructability performance. To address RQ3, which focuses on the impact of construction-phase design adaptations on time, cost, and constructability, interviews and direct field observations were conducted. Secondary data were obtained from relevant literature and official project documentation, including initial and revised bills of quantities, planned and actual schedules, design change reports, and technical drawings. These sources supported both the quantitative and qualitative analyses. The research instrument consisted of a 1–5 Likert-scale questionnaire designed to measure design process and constructability variables [9]. Instrument validity was assessed using the Pearson Product-Moment method, while reliability was evaluated using Cronbach's Alpha. Statistical analysis included classical assumption tests, Pearson correlation to examine relationships between variables (RQ1), and multiple linear regression to assess the influence of design process factors on constructability (RQ2). All quantitative analyses were conducted using SPSS software [10]. The research variables and their corresponding sub-variables are presented in Table I.

TABLE I. RESEARCH VARIABLES

Code	Variable	Sub-variable	Source
X1	Design process	Stakeholder involvement	[1, 3, 4]
X2	Design process	Design time planning	[10, 11]
X3	Design process	BIM	[5, 12, 13]
X4	Design process	Design documentation and clarity	[10, 11]
X5	Design process	Standardization and modularization	[14]
X6	Design process	Iterative and adaptive design	[2, 15]
X7	Design process	Interdisciplinary collaboration	[3, 4, 14]
X8	Design process	Project objective clarity	[15]
X9	Design process	Sustainable design	[16, 17]
X10	Design process	Modular design	[14]
Y1	Constructability	Implementation feasibility	[1, 2]
Y2	Constructability	Interdisciplinary coordination	[3, 4]
Y3	Constructability	Specification quality and accuracy	[10, 11]
Y4	Constructability	Early construction involvement	[1, 3]
Y5	Constructability	Design time and risk management	[10, 18]
Y6	Constructability	Tolerance to site conditions	[15]
Y7	Constructability	Design re-evaluation during the project	[2, 13]

The Y1–Y7 factors serve as constructability indicators and collectively constitute the dependent variable (Y) in the statistical analysis. To answer RQ3, a comparative analysis was conducted between the initial and revised designs for slope protection and foundation grouting, focusing on technical aspects, cost, time, and constructability. The comparison was based on BoQ data and actual productivity to evaluate the effectiveness of the design changes in improving field implementation.

C. Relationship between the Design Process and Constructability

To examine the linear relationship between the design process variable (X) and constructability (Y), Pearson correlation analysis was employed. This analysis determines the direction and strength of the relationship, whether positive, negative, or insignificant. The hypotheses were formulated as:

- H_0: There is no significant relationship between variable X and variable Y.
- H_1: There is a significant relationship between variable X and variable Y.

The decision criterion was established at a significance level of $\alpha = 0.05$. If the p-value exceeds 0.05, the null hypothesis (H_0) is not rejected. Conversely, if the p-value is less than 0.05, the null hypothesis is rejected in favor of the alternative hypothesis (H_1). The strength of the relationship is evaluated using the Pearson correlation coefficient (r), with interpretation guidelines adapted from [10], as presented in Table II.

TABLE II. INTERPRETATION OF PEARSON CORRELATION VALUES

Pearson correlation coefficient (r)	Level of relationship
0 – 0.19	Very weak
0.2 – 0.39	Weak
0.4 – 0.59	Fair
0.6 – 0.79	Strong
0.8 – 1	Very strong

This analysis is used to address RQ1, which examines the relationship between design process factors and the level of constructability.

D. Influence of Design Process on Constructability

To examine the influence of design process variables on constructability, multiple linear regression analysis was employed, as expressed in:

$$Y = \alpha + \beta\_1\, X\_1 + \beta\_2\, X\_2 + \cdots + \beta\_n\, X\_n + \epsilon \qquad (1)$$

where Y represents constructability (dependent variable), X_1–X_n denote the design sub-variables (independent variables), α is the constant, β_1–β_n are the regression coefficients indicating the contribution of each design variable, and ε is the error term. The F-test was used to evaluate the simultaneous effect of all independent variables, while the t-test assessed the partial effect of each sub-variable. The coefficient of determination (R^2) measures the proportion of variation in constructability explained by the design variables. This analysis addresses RQ2 by determining the extent to which design factors influence constructability improvement.

E. Impact of Changes in the Design of Slope Protection and Foundation Grouting

The impact of design changes in the Jenelata Dam Project was analyzed to address Research Question 3 (RQ3), which evaluates how construction-phase design modifications affected technical performance, cost, time, and constructability. The two primary changes examined were the slope protection method and the foundation grouting system, both of which directly influence implementation efficiency and ease of construction. A comparative analysis was conducted by evaluating the initial and revised designs to assess their relative effectiveness and efficiency. The analysis involved the following stages:

1) Identification of Work Items from the Contract, Design Drawings, and Bill of Quantities

The slope protection design was modified from a frame beam with hydroseeding to a Type III geomat to improve implementation efficiency. Although structurally adequate, the initial method required complex reinforcement, formwork, casting, and vegetation maintenance. Steep and uneven slope conditions further complicated formwork installation and equipment mobilization. The revised method used a lighter, more flexible Type III geomat system, comprising synthetic geomat installation, anchoring, and vegetation cover, enabling better adaptation to slope contours.

2) Data Collection

Technical performance was evaluated based on equipment production capacity, calculated from cycle capacity (V), efficiency factor (Fa), and cycle time (Ts). Cost data were obtained from the Bill of Quantities (BoQ) to determine total method costs. Constructability aspects were assessed using design drawings, implementation methods, technical specifications, field observations (accessibility, topography, slope conditions), and interviews with contractors and consultants to evaluate complexity, equipment requirements, flexibility, and coordination.

3) Time Calculation

Production capacity is calculated using:

$$Q = \frac{V \times Fa \times 60}{Ts} \qquad (2)$$

From the Q value, the daily production capacity was calculated, and then the total duration of each work item was determined by:

Duration (days) = Volume / (Daily Productivity).

The total duration of the method was calculated based on the sequence of work, not just the sum, to represent the actual conditions in the field.

4) Cost Calculation

The total cost of each work item was determined by multiplying the volume by the respective unit price. The overall cost of each method was then calculated by aggregating all relevant items, and the difference between methods was evaluated in absolute (IDR) and percentage terms to assess cost efficiency.

5) Constructability Analysis

The qualitative analysis was conducted using a structured comparative framework. Each design alternative (initial and revised) was evaluated based on three predefined criteria: (1) number of work items, (2) level of specialized equipment requirements, and (3) flexibility to site conditions. The comparison was supported by project documentation, field observations, and interview data to ensure an objective assessment. This structured approach reduces subjectivity and strengthens the validity of the qualitative findings.

III. RESULTS AND DISCUSSION

A. Instrument Testing Results

The validity test was conducted using the Pearson Product-Moment method in SPSS version 27, based on 32 respondents. An item was considered valid if the calculated correlation coefficient (r-value) exceeded the critical r-table value (0.349; n = 32; α = 0.05). The results indicate that all questionnaire items have r-values greater than 0.349 with significance levels below 0.05. The correlation coefficients range from 0.42 to 0.963, confirming that all indicators are statistically valid. These findings demonstrate that each item adequately represents its respective theoretical construct and is suitable for further analysis. Reliability was assessed using Cronbach's Alpha, with α > 0.7 indicating acceptable reliability and α > 0.8 indicating high reliability. The results show that the Design Process variable (X) achieved a Cronbach's Alpha value of 0.883, indicating high internal consistency. The Constructability variable (Y) had a Cronbach's alpha value of 0.956, indicating excellent reliability. Since both variables exceed the threshold of 0.7, the research instrument is considered reliable and appropriate for subsequent statistical analysis.

B. Correlation between Design Process and Constructability

Before conducting the Pearson correlation analysis, a multicollinearity test was performed to ensure that the independent variables were not highly correlated, as highly correlated variables can distort statistical interpretation. The test was conducted using Tolerance and Variance Inflation Factor (VIF) values obtained from SPSS version 27. The detailed results of the multicollinearity test are presented in Table III. The results show that all variables have Tolerance values greater than 0.1 and VIF values below 10, indicating that no serious multicollinearity problem exists in the regression model. The highest VIF value (6.501) was found in the Sustainable Design variable (X9), which remains below the commonly accepted threshold. Therefore, no serious multicollinearity problem was detected, and the regression model is considered statistically valid for further analysis.

TABLE III. MULTICOLLINEARITY TEST RESULTS

Model	Collinearity statistics	
	Tolerance	VIF
X1	0.263	3.802
X2	0.338	2.959
X3	0.482	2.076
X4	0.295	3.388
X5	0.268	3.733
X6	0.285	3.513
X7	0.344	2.907
X8	0.203	4.932
X9	0.154	6.501
X10	0.205	4.872
a dependent variable: constructability_Y		

The Pearson correlation analysis (Table IV) shows that all 10 design process variables (X_1–X_{10}) are positively and significantly related to constructability (Sig. < 0.05). This indicates that improved design management is consistently associated with enhanced constructability performance. The strongest correlation was found for Iterative and Adaptive Design (r = 0.795), followed by Interdisciplinary Collaboration (r = 0.706) and Design Technology Integration (r = 0.626). These findings highlight the importance of adaptive and collaborative design approaches for improving the effectiveness of construction implementation.

TABLE IV. PEARSON CORRELATION RESULTS

Code	Design process sub-variable	r	Sig.	Relationship strength	Significance
X1	Stakeholder involvement	0.417	0.018	Moderate	Significant
X2	Design time planning	0.412	0.019	Moderate	Significant
X3	BIM	0.626	0	Strong	Significant
X4	Design documentation and clarity	0.542	0.001	Moderate	Significant
X5	Standardization and modularization	0.589	0	Moderate–strong	Significant
X6	Iterative and adaptive design	0.795	0	Very strong	Significant
X7	Interdisciplinary collaboration	0.706	0	Strong	Significant
X8	Project objective clarity	0.613	0	Strong	Significant
X9	Sustainable sesign	0.62	0	Strong	Significant
X10	Modular design	0.611	0	Strong	Significant

C. Influence of the Design Process on Constructability

The regression model indicates a very strong influence of design process variables on constructability, with R = 0.887 and $R^2 = 0.786$, indicating that design process factors explain 78.6% of the variation in constructability. Table V presents the statistical results of the multiple linear regression analysis.

TABLE V. REGRESSION MODEL SUMMARY

Model	R	R-square	Adjusted R-square	Std. error of the estimate
1	0.887a	0.786	0.684	0.25113
a. Predictors: (constant), X10, X1, X3, X8, X4, X7, X2, X6, X5, X9				

The partial test (Table VI) identifies Iterative and Adaptive Design (X6) as the most significant variable (β = 0.408; Sig. = 0.043), followed by Technology Integration (X3) and Interdisciplinary Collaboration (X7) with positive effects.

TABLE VI. PARTIAL REGRESSION COEFFICIENTS

Variable	β (Beta)	Sig.	Interpretation
Iterative and adaptive design (X6)	0.408	0.043	Significant & most influential
Technology integration (X3)	0.205	0.173	Positive influence
Interdisciplinary collaboration (X7)	0.126	0.474	Positive influence

Design process variables collectively have a significant and positive impact on constructability ($R^2 = 0.786$). The dominant factor is Iterative and Adaptive Design, confirming that flexible, responsive design management improves constructability efficiency, as demonstrated by the Jenelata Dam Project.

D. Impact of Slope Protection Design Changes

The design changes that occurred in the Jenelata Dam Project are concrete manifestations of the application of the Iterative and Adaptive Design principle to improve constructability. The design revision process was carried out based on field conditions and technical input from field implementers to achieve easier, more efficient, and safer implementation. The two main cases studied were changes to slope protection and foundation grouting works.

E. Changes in Slope Protection Design

During direct observation in the field at the Jenelata Dam construction project, specifically during the implementation of slope-protection work, the slope-protection method design changed. Initially, frame beams + hydroseeding were used, but these were later replaced with type III geomats. Therefore, a comparative analysis was conducted to assess the differences between the two methods in terms of constructability, cost, and implementation time. The slope protection works on the left side of the dam have been completed. The implementation stages of slope protection using the Geomat Type III method are illustrated in Figure 3, based on official project documentation from the Jenelata Dam Project.

Fig. 3. Implementation of slope protection.

The following is an analysis of the productivity of the main items for slope protection work using frame beams, hydroseeding, and type III geomat, carried out by the contractor, as displayed in Table VII.

TABLE VII. PRODUCTIVITY OF EACH ITEM WORK

No	Work item	Capacity/ cycle (V)	Efficiency factor (Fa)	Cycle time (Ts) [minutes]	Production capacity (Q) [per h]	Note
A	**Frame beam and hydroseeding**					
1	Reinforcement	0.5	0.83	50	0.5	Tonnes/h
2	Formwork	1	0.83	15	3.32	m^2/h
3	Concrete	3	0.83	21.61	6.91	m^3/h
4	Anchor	60	0.83	11.5	34.64	m/h
5	3D mesh with seed spraying and grass planting	1	0.83	2	24.90	m^2/h
B	**Geomat type III**					
1	Geomat installation and vegetation	10	0.83	45	11.07	m^2/h
2	Anchor	60	0.83	11.5	34.64	m/h

The analysis of the time required to complete the work is presented in Table VIII. This indicates that the frame beam and hydroseeding method requires a substantially longer implementation time than the geomat type III method. The frame beam approach involves sequential stages, including reinforcement, formwork, casting, and hydroseeding, resulting in an estimated duration of approximately 42 days. In contrast, the geomat method consists mainly of geomat installation and vegetation planting, with a total duration of approximately 11 days, making it about 70% faster. From a constructability perspective, the geomat system is simpler, more flexible in adapting to slope contours, and requires fewer pieces of equipment and labor. Conversely, the frame beam method requires heavy equipment, multi-stage coordination, and strict quality control, increasing implementation complexity and the risk of delays. Cost analysis based on contracted unit prices further supports these findings. The frame beam and hydroseeding method resulted in a total cost of IDR 1754218253.03, largely driven by structural components, such as hydroseeding mesh (36.3%), formwork (23.2%), reinforcement (16.7%), and concrete (17.7%). In contrast, the geomat type III method required only IDR 679075420.72, representing approximately 38.7% of the frame beam cost. The primary cost component was geomat and vegetation installation (98.5%), with minimal anchorage cost (1.5%). Overall, the geomat method achieved savings of IDR 1075142832.31, or approximately 61.3% compared to the frame beam approach. From a constructability and value engineering perspective, these results demonstrate that the geomat type III method is more efficient in terms of cost, time, and ease of implementation. Given the relatively stable slope conditions at the Jenelata Dam, the geomat system provides adequate protection without requiring additional structural reinforcement. Table IX summarizes the comparative evaluation of complexity, flexibility, and resource requirements, confirming the overall superiority of the geomat method.

TABLE VIII. EVALUATION OF WORK PRODUCTIVITY PROTECTION

No	Work item	Sat	Volume	Hourly production capacity	Daily production capacity	Total duration (Days)
A	**Frame beam and hydroseeding**					
1	Reinforcement	t	11.87	0.50	3.98	3
2	Formwork	m^2	778.74	3.32	26.56	30
3	Concrete	m^2	186.13	6.91	55.31	4
4	Anchor	T	154.35	34.64	277.15	1
5	3D mesh with seed spraying and grass planting	m^2	742.21	24.90	199.2	4
B	**Geomat type III**					
1	Installation geomat and vegetation	m^2	850.75	11.07	88.53	10
2	Anchor	t	0.4	34.64	277.15	1

With a shorter duration (approximately 11 days compared to 42 days) and significantly lower costs (IDR 679 million versus IDR 1.75 billion), the geomat type III method demonstrates substantial efficiency gains without compromising slope protection performance. In contrast, the frame beam and hydroseeding method, despite offering certain structural advantages, is more complex, costly, and time-consuming to implement. Table X presents a comparative evaluation of both methods, highlighting differences in constructability, time performance, cost efficiency, and implementation flexibility.

TABLE IX. COMPARISON OF PROTECTION WORK COSTS ON THE SLOPE

No	Work item	Unit	Volume	Unit price	Total price
A	**Frame beam and hydroseeding**				
1	Reinforcement	t	11.87	24607010	292131218.13
2	Formwork	m^2	778.74	522940	407234098.56
3	Concrete	m^2	186.13	1673200	311437844.86
4	Anchor	pcs	154.35	686800	106007580
5	3D mesh with seed spraying and grass planting	m^2	742.21	858796	637407511.48
				TOTAL	1754218253.03
B	**Geomat type III**				
1	Installation of geomat and vegetation	m^2	850.75	786559	669165069.25
2	Anchor	t	0.4	24607010	9910351.47
				Total	679075420.72

TABLE X. COMPARISON BETWEEN THE GEOMAT METHOD TYPE III AND FRAME BEAM

Aspect	Frame beam and hydroseeding	Geomat type III
Application	Requires reinforcement, formwork, concrete grid casting, followed by hydroseeding between the grid.	The geomat is laid out along the existing contour, covered with topsoil, and then planted by hand.
Speed	Longer concrete curing: approximately 7–14 days per segment, total duration.	Faster installation of geomat rolls ± 500–700 m²/day/team + planting manual placement.
Effectiveness	Highly effective in preventing erosion, provides a permanent concrete framework.	Effective for erosion control, accelerating vegetation growth, and sufficient strength, as the existing slope is already stable.
Flexibility	Limited, must adjust the grid to the artificial slope ratio of 1:1.25.	Highly flexible, follows existing contours without significant additional work.
Cost	Total IDR 1754218253.03, high cost due to the dominance of concrete work, formwork, and hydroseeding.	Total IDR 679075420.72, approximately 61.3% cheaper due to the (geomat + vegetation + anchors).
Duration	±42 days (reinforcement, formwork, casting, curing, hydroseeding).	±11 days (installation of geomat + vegetation + anchors), approximately 70% faster.
Strength	Provides a structural grid, but its main function is surface control.	Both are structurally adequate because the slope, its primary function, is erosion control and vegetation.
Ease	Complex, involving numerous components and requiring heavy machinery.	Simple, can be done manually by a small team.
Maintenance	Requires checking for concrete cracks; vegetation often fails to grow after hydroseeding.	Light maintenance is required, primarily limited to ensuring proper vegetation growth.

F. Changes in Foundation Grouting

The modification of the foundation grouting method was evaluated by comparing the productivity and cost performance between the vertical grouting pattern and the rim grouting pattern. The comparative analysis results are presented in Tables XI and XII.

TABLE XI. EVALUATION OF WORK PRODUCTIVITY FOUNDATION GROUTING

No	Work item	Sat	Volume	Hourly production capacity	Daily production capacity	Total duration (days)
1	Vertical grouting pattern	m	1250.38	0.2	1.63	110
2	Rim grouting pattern	m	840	0.52	4.19	29

TABLE XII. COMPARISON OF PROTECTION WORK COSTS GROUTING

No	Work item	Unit	Volume	Unit price	Total price
1	Vertical grouting pattern	m	11.87	24607010	292131218.13
2	Rim grouting pattern	m	850.75	786559	669165069.25

The analysis results show that the rim grouting pattern is approximately 74% faster than the vertical pattern. Work duration is reduced from 110 days to 29 days due to reduced equipment movement and the absence of scaffolding installation in steep areas. The vertical method has a longer cycle time because each drilling point requires scaffolding installation, equipment position adjustment, and difficult equipment movement on steep terrain. Conversely, the rim pattern allows work to be carried out from a flat platform at the top of the slope, without additional scaffolding, making the time per point more efficient.

Based on the cost analysis, the design modification resulted in savings of IDR 336339240.4, equivalent to approximately 32.8% of the total project cost. These savings were primarily achieved through reduced material quantities, simplified installation procedures, lower equipment requirements, improved productivity, and better adaptability to actual field conditions. In addition, the modification minimized rework and optimized resource allocation, further enhancing overall cost efficiency without compromising technical performance. Key contributing factors included a reduction in the number of drilling points and injection volume, elimination of manual labor on steep slopes, and a shorter construction duration, which collectively reduced equipment and labor operational costs. The analysis shows that the rim grouting pattern provides significant improvements in terms of constructability, time efficiency, and work safety. With a shorter implementation duration (29 days compared to 110 days) and a cost efficiency of ±33%, this method has proven more suitable for field conditions with steep slopes, such as those found in the Jenelata Dam Project. Although design changes are often associated with delays and cost overruns in general construction literature, the findings of this study reflect a project-specific condition. In the Jenelata Dam Project, design adaptations were implemented early and in a coordinated manner during the construction phase to address actual site constraints. Unlike late or unplanned design changes, these adaptive modifications improved constructability and resulted in time and cost efficiencies.

Previous studies indicate that inadequate planning is a major contributor to project delays, as reflected by a high

Relative Importance Index (RII) value of 0.93 [11]. In contrast, strategic design decisions, such as prioritizing controlled blasting over hydraulic breakers, have been shown to significantly increase productivity, from 729.1 to 875.95 m³/day. These findings are consistent with the results of the present study, which demonstrate that adaptive and well-coordinated design decisions during construction can enhance constructability under site-specific conditions. In this study, the importance of Iterative and Adaptive Design (X6) is evidenced through field-based design revisions and effective coordination between design and supervision teams. A key example is the transition from vertical to rim grouting patterns, which proved more suitable for actual foundation conditions. This modification resulted in improved time efficiency, reduced costs, and enhanced construction safety, without compromising seepage control performance. The findings of this study provide a different perspective from previous research, which mainly linked design changes to poor project performance. Previous studies have identified design changes and change orders as significant contributors to cost overruns and delays [12–14], while inadequate strategic planning and weak coordination are reported as dominant causes [18]. In dam infrastructure contexts, design-phase success factors are also important determinants of overall project performance [13]. Improvement-oriented approaches, such as Lean Design Management [16], BIM integration in hydropower infrastructure [17], and flexible planning–design–operation frameworks [15], emphasize integration, adaptability, and coordination as performance enhancers. In contrast to research that frames design changes primarily as disruption factors, this research demonstrates that systematically managed construction-phase design adaptations, supported by strong statistical explanatory power ($R^2 = 0.786$), can significantly enhance constructability, achieving time reductions of up to 70% and cost savings of 61.3%. These results suggest that, in large-scale dam infrastructure projects, design changes can serve not only as risk drivers but also as structured optimization strategies when implemented through coordinated, data-driven management practices. This study is based on a single dam project; therefore, the applicability of the findings may vary depending on geological conditions, construction methods, and logistical constraints. The results are most relevant to projects with similar geotechnical characteristics and construction-phase design coordination practices.

IV. CONCLUSIONS

Based on the qualitative and quantitative analyses of the Jenelata Dam Project, this study concludes that construction-phase design processes play a substantial role in enhancing constructability in complex dam infrastructure projects. All design process factors were found to have positive and statistically significant relationships with constructability. Among these, Iterative and Adaptive Design and Interdisciplinary Collaboration emerged as the most influential contributors. The regression results further indicate that design process variables explain a substantial proportion of the variation in constructability performance, underscoring the importance of design flexibility and coordinated decision-making during construction. The case study demonstrates that well-managed design adaptations, such as the implementation of geomat type III for slope protection and rim grouting for foundation treatment, can significantly improve time efficiency, reduce costs, and enhance construction safety when applied early and are aligned with actual site conditions. Overall, the findings suggest that adaptive and collaborative design management during the construction phase should not be viewed as a deviation from conventional construction practices, but rather as a context-specific strategy for improving constructability. When supported by field validation and interdisciplinary coordination, construction-phase design adaptations can function as proactive optimization mechanisms rather than reactive corrections. This study contributes to the advancement of constructability theory by reframing design changes as performance-enhancing interventions. It also provides practical insights for improving design–construction integration and guiding decision-making in the management of adaptive design processes in complex dam projects.

REFERENCES

[1] J. Smith, D. J. Edwards, I. Martek, N. Chileshe, S. Hayhow, and C. J. Roberts, "The antecedents of construction project change: an analysis of design and build procurement application," *Journal of Engineering, Design and Technology*, vol. 21, no. 3, pp. 655–689, May 2023, https://doi.org/10.1108/JEDT-12-2020-0507.

[2] M. Sánchez-Silva and W. Calderón-Guevara, "Flexibility and adaptability within the context of decision-making in infrastructure management," *Structure and Infrastructure Engineering*, vol. 18, no. 7, pp. 950–966, July 2022, https://doi.org/10.1080/15732479.2022.2038642.

[3] B. S. Abdulfattah *et al.*, "Predicting implications of design changes in BIM-based construction projects through machine learning," *Automation in Construction*, vol. 155, Nov. 2023, Art. no. 105057, https://doi.org/10.1016/j.autcon.2023.105057.

[4] B. Trigunarsyah, "Constructability Practices among Construction Contractors in Indonesia," *Journal of Construction Engineering and Management*, vol. 130, no. 5, pp. 656–669, Oct. 2004, https://doi.org/10.1061/(ASCE)0733-9364(2004)130:5(656).

[5] R. A. Apriliani, "Pemodelan hubungan proses desain terhadap peningkatan constructability dan maintainability pada proyek konstruksi berbasis sistem dinamik," 2017.

[6] Y. Liu *et al.*, "Improving Design by Partnering in Engineering–Procurement–Construction (EPC) Hydropower Projects: A Case Study of a Large-Scale Hydropower Project in China," *Water*, vol. 13, no. 23, Jan. 2021, Art. no. 3410, https://doi.org/10.3390/w13233410.

[7] T. Wang, W. Tang, D. Qi, W. Shen, and M. Huang, "Enhancing Design Management by Partnering in Delivery of International EPC Projects: Evidence from Chinese Construction Companies," *Journal of Construction Engineering and Management*, vol. 142, no. 4, Apr. 2016, Art. no. 04015099, https://doi.org/10.1061/(ASCE)CO.1943-7862.0001082.

[8] M. W. Suminto, "Analisa Penerapan Building Information Modelling (BIM) Terhadap Peningkatan Constructability Pada Proyek Konstruksi Dengan Metode Sistem Dinamik," M.S. Thesis, s2, Universitas Mercu Buana Jakarta, 2020.

[9] Sugiyono, *Metode Penelitian Kuantitatif, Kualitatif DAN R&D.* Indonesia: Penerbit Alfabeta Bandung, 2013.

[10] A. Rustam, E. D. Sari, and L. Yunita, Statistika dan pengukuran pendidikan: analisis menggunakan SPSS, Iteman dan Lisrel. PT. Ilham Sejahtera Persada, 2018.

[11] S. A. Toresa, R. Arifuddin, and S. Hamzah, "An Analysis of Miscommunication Factors Affecting Time Delays and Quality Degradation in Construction Projects in Makassar City," *Engineering, Technology & Applied Science Research*, vol. 15, no. 6, pp. 29180–29185, Dec. 2025, https://doi.org/10.48084/etasr.12987.

[12] M. Aslam, E. Baffoe-Twum, and F. Saleem, "Design Changes in Construction Projects – Causes and Impact on the Cost," *Civil Engineering Journal*, vol. 5, no. 7, pp. 1647–1655, July 2019, https://doi.org/10.28991/cej-2019-03091360.

[13] P. Amies, X. Jin, and S. Senaratne, "Achieving Design-Phase Success in Dam Construction: An Exploration of Project Success Elements Through Factor Analysis and Structural Equation Modeling," *International Journal of Construction Education and Research*, vol. 21, no. 4, pp. 554–584, Oct. 2025, https://doi.org/10.1080/15578771.2025.2450309.

[14] J. S. Ramadhan and M. Waty, "Impact of Change Orders on Cost Overruns and Delays in Large-Scale Construction Projects," *Engineering, Technology & Applied Science Research*, vol. 15, no. 1, pp. 20291–20299, Feb. 2025, https://doi.org/10.48084/etasr.9449.

[15] K. Willebrand, M. Zaniolo, J. Skerker, and S. Fletcher, "Valuing Combinations of Flexible Planning, Design, and Operations in Water Supply Infrastructure," *Water Resources Research*, vol. 60, no. 3, 2024, Art. no. e2023WR036048, https://doi.org/10.1029/2023WR036048.

[16] B. Mota, C. Biotto, A. Choudhury, S. Abley, and M. Kagioglou, "Lean Design Management in a Major Infrastructure Project in UK," presented at the 27th Annual Conference of the International Group for Lean Construction (IGLC), Dublin, Ireland, July 2019, pp. 37–48, https://doi.org/10.24928/2019/0251.

[17] J. Wangchuk, S. Banihashemi, H. Abbasianjahromi, and M. F. Antwi-Afari, "Building Information Modelling in Hydropower Infrastructures: Design, Engineering and Management Perspectives," *Infrastructures*, vol. 9, no. 7, July 2024, Art. no. 98, https://doi.org/10.3390/infrastructures9070098.

[18] R. Wang, D. A. S. Samarasinghe, L. Skelton, and J. O. B. Rotimi, "A Study of Design Change Management for Infrastructure Development Projects in New Zealand," *Buildings*, vol. 12, no. 9, Sept. 2022, Art. no. 1486, https://doi.org/10.3390/buildings12091486.