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# A Quantitative Analysis of Cost, Time, and Construction Risk of Underground Construction Methods for A Lifting Pump Station in A Constrained Site: A Case Study of the Jakarta Sewerage Development Project (JSDP) Zone 1 Package 1

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**Abstract**

The construction of Lifting Pump Stations (LPS) in urban infrastructure projects on limited land has high technical and managerial challenges, especially due to structural depth, saturated soft soil conditions, high groundwater levels, and limited workspace. This study aims to analyze and determine the most suitable underground construction method in the construction of the Jakarta Sewerage Development Project (JSDP) Zone 1 Package 1 LPS based on the aspects of cost, time, and implementation risk. The research was carried out through the identification of alternative construction methods, screening using the Zero-One Matrix, cost analysis, time analysis, risk register-based risk analysis, and decision-making using AHP Direct Measurement. The screening results show that the Top-Down Construction and Pneumatic Caisson methods are worthy of further analysis. The results of the cost analysis show that Top-Down Construction is more economical, with a cost of about 32.93% lower than Pneumatic Caisson. However, in terms of time, Pneumatic Caisson has an implementation duration of about 11 months shorter than Top-Down Construction. Risk analysis showed that the two methods had different risk characteristics, but after mitigation most of the residual risk was at an acceptable level. Based on AHP Direct Measurement, the risk aspect gets the highest weight, followed by time and cost. The final results show that the Pneumatic Caisson obtained the highest priority and is therefore recommended as the most suitable construction method for LPS projects with soft soil conditions, high ground water levels, large structural depths, and limited land.

## INTRODUCTION

The development of urban wastewater management infrastructure is one of the strategic efforts to improve the quality of the environment and public health in metropolitan areas. One of the important components in the system is the Lifting Pump Station (LPS), which serves to drain wastewater from low elevations to higher elevations before further processing. In the Jakarta Sewerage Development Project (JSDP) Zone 1 Package 1 project, LPS construction is carried out in urban areas with limited land, density of existing activities, and water-saturated soft soil conditions, thus demanding appropriate and reliable underground construction methods. The construction of this facility is generally carried out underground, so it has a higher level of complexity than construction work above ground level.

The implementation of underground construction in limited land conditions has complex challenges, both from technical and managerial aspects. Confined workspaces, significant excavation depths, soil and groundwater stability control, and high occupational safety demands can have a direct impact on implementation time, project costs, and construction risk levels. Therefore, the selection of underground construction methods is a key factor that determines the overall success of the project.

Theoretically and practically, there are various alternative underground construction methods that can be applied to the construction of structures such as LPS, including open cut, top-down, contiguous bored pile, and pneumatic caisson methods. Each method has different implementation characteristics, resource requirements, and implications for the duration of the work, construction costs, and implementation risks. However, not all of these methods are always suitable for specific project conditions, especially in areas with very limited land and complex geotechnical conditions.

In construction project practice, method selection is often based on prior experience or specific preferences, potentially ignoring comprehensive comparative evaluation. In fact, differences in construction methods can produce significant differences in terms of time efficiency, cost, and risk exposure, both technical risks, occupational safety risks, and project delay risks. Therefore, an analytical approach is needed that is able to identify, filter, and evaluate alternative construction methods systematically and based on data.

Previous studies have evaluated underground construction methods based on cost, schedule, or geotechnical performance individually. However, limited studies have integrated cost, construction time, construction risk, and multi-criteria decision making into a unified framework for selecting underground construction methods in constrained urban environments.

Therefore, this study proposes an integrated framework combining Zero-One Matrix, quantitative cost analysis, schedule analysis, risk assessment, and AHP Direct Measurement to support construction method selection.

Based on the characteristics of the LPS project in JSDP Zone 1 Package 1, this study begins with the process of identifying and filtering alternative underground construction methods that are technically possible to be applied to limited land conditions and water-saturated soft soils. Through this process, the most relevant alternative methods are obtained for further analysis. Furthermore, the selected alternative method was analyzed quantitatively by comparing its performance in terms of implementation time, construction costs, and project risks, in order to obtain the construction method that best suits the conditions and needs of the project.

Thus, this research is expected to provide an academic contribution in the form of a systematic and quantitative analysis framework for the selection of underground construction methods, as well as practical contributions for construction industry players in decision-making on the method of implementing underground infrastructure projects in limited land conditions.

## RESEARCH METHOD

### Data Analysis Techniques

This study adopted a quantitative comparative approach to evaluate alternative underground construction methods for the Lifting Pump Station (LPS) of the Jakarta Sewerage Development Project (JSDP) Zone 1 Package 1. The evaluation was carried out by comparing the construction methods from the perspectives of cost, implementation time, and construction risk in order to determine the most appropriate method for the project.

The research was conducted through several sequential stages. First, potential underground construction methods were identified based on the project characteristics, including limited working space, saturated soft soil conditions, high groundwater levels, and deep excavation requirements. Four construction methods were initially considered, namely Open Cut, Top-Down Construction, Contiguous Bored Pile (CBP), and Pneumatic Caisson (PCM). These alternatives were then screened using the Zero-One Matrix to identify the methods that were technically feasible for further evaluation.

The selected construction methods were subsequently evaluated in terms of construction cost. Cost analysis was performed using the project Cost Budget Plan (RAB), unit price analysis, work quantities, material requirements, labour, equipment, and other supporting costs obtained from the project documents. The analysis included both direct and indirect construction costs to determine the total implementation cost of each construction method.

Schedule analysis was carried out to estimate the implementation duration of each construction method based on the project work sequence and construction activities. The results were used to compare the implementation time required by each alternative under the same project conditions.

Construction risks associated with each alternative were identified using a project Risk Register developed from project documents and expert judgement. Each risk was evaluated based on its probability and impact to determine the level of risk exposure. Appropriate mitigation measures were then developed for the identified risks, followed by residual risk assessment to evaluate the effectiveness of the proposed mitigation strategies.

Finally, the results of the cost, schedule, and risk analyses were integrated and used as the basis for decision-making using the AHP Direct Measurement method. At this stage, experts assigned importance weights to the evaluation criteria and assessed each construction alternative based on the quantitative analysis results. The weighted scores obtained from the AHP Direct Measurement analysis were then used to determine the most appropriate underground construction method for the construction of the Lifting Pump Station.

## RESULTS AND DISCUSSION

### Alternative Construction Method Screening

**Table 1. Zero-One Matrix Screening Results**

| Construction Method | Screening Result | Decision |
|---|---|---|
| Open Cut | Not feasible | Eliminated |
| Contiguous Bored Pile | Not feasible | Eliminated |
| Top-Down Construction | Feasible | Selected |
| Pneumatic Caisson | Feasible | Selected |

The initial stage of the study involved identifying underground construction methods that were technically feasible for the construction of the Lifting Pump Station (LPS) in the Jakarta Sewerage Development Project (JSDP) Zone 1 Package 1. Four construction alternatives were initially considered, namely Open Cut, Contiguous Bored Pile (CBP), Top-Down Construction, and Pneumatic Caisson.

A preliminary screening was conducted using the Zero-One Matrix to evaluate the compatibility of each method with the project constraints, including limited workspace, saturated soft soil, high groundwater levels, and deep excavation requirements. The evaluation showed that Open Cut and Contiguous Bored Pile did not adequately satisfy the technical requirements of the project and were therefore excluded from further evaluation. Conversely, Top-Down Construction and Pneumatic Caisson demonstrated sufficient technical feasibility and were selected for quantitative assessment.

This screening stage ensured that subsequent analyses focused only on alternatives capable of meeting the project's technical requirements before considering economic, scheduling, and risk-related aspects.

**Construction Cost Analysis**

**Table 2. Comparison of Construction Cost**

| Method | Total Cost | Comparison |
|---|---|---|
| Top-Down | IDR 329,19 Billion | Lower |
| Pneumatic Caisson | IDR 490,78 Billion | Higher |

The implementation cost analysis demonstrates that the Top-Down Construction method provides a clear economic advantage over the Pneumatic Caisson method. Based on the project cost estimation, the total construction cost of the Top-Down method is approximately 32.93% lower than that of Pneumatic Caisson. This difference is primarily attributed to the additional equipment, compressed-air system, and operational requirements associated with Pneumatic Caisson construction.

**Schedule Analysis**

**Table 3. Comparison of Construction Duration**

| Method | Duration |
|---|---|
| Top Down | 34 months |
| PCM | 23 months |

The schedule analysis indicates that Pneumatic Caisson provides superior time performance compared with Top-Down Construction. The estimated implementation period is approximately 11 months shorter, mainly because excavation and sinking operations are performed continuously inside the pressurised caisson without being interrupted by staged slab construction.

In contrast, the Top-Down method requires sequential coordination between excavation and structural works. Each excavation stage depends on the completion of the structural slab above, resulting in a longer overall implementation period.

The findings suggest that while Top-Down Construction is more economical, Pneumatic Caisson offers a significant advantage for projects with strict completion targets.

**Construction Risk Analysis**

**Pneumatic Caisson Construction Risk**

**Table Top Five Risk PCM**

| Risk | Category |
|---|---|
| Loss of Air Pressure | High |
| Working Chamber Safety | High |
| Productivity | High |
| Equipment Failure | Moderate |
| Worker Health | Moderate |

The risk analysis of the Pneumatic Caisson method indicates that the dominant risks are primarily associated with operational reliability and occupational safety. The highest exposure originates from loss of air pressure, which may interrupt the sinking process, reduce productivity, and endanger workers operating inside the pressurised chamber.

Unlike conventional underground construction methods, Pneumatic Caisson relies heavily on specialised equipment and continuous compressed-air operation. Consequently, the success of this method is strongly influenced by equipment reliability, emergency preparedness, and strict occupational safety management.

The heat map demonstrates that several operational risks initially fall within the High category, highlighting the importance of implementing preventive control measures before construction begins.

**Top-Down Construction Risk**

**Table Top Five Risk Top Down**

| Risk | Category |
|---|---|
| Diaphragm Wall Failure | High |
| Excavation Stability | High |
| Settlement | High |
| Work Coordination | Moderate |
| Limited Workspace | Moderate |

The Top-Down Construction method exhibits a different risk profile from Pneumatic Caisson. The dominant risks are mainly related to geotechnical stability and construction sequencing. Diaphragm wall failure represents the highest-risk event because it directly affects groundwater control and excavation stability. Other significant risks include excessive wall deformation, surrounding ground settlement, and conflicts between excavation and structural activities. These risks are characteristic of staged excavation in confined urban environments where structural and excavation works must proceed simultaneously.

The risk heat map confirms that geotechnical and coordination-related risks dominate the implementation of the Top-Down method.

**Comparison of Risk Characteristics**

| Aspect | PCM | Top Down |
|---|---|---|
| Dominant Risk | Operational | Geotechnical |
| Safety | High | Moderate |
| Structural Stability | Moderate | High |
| Groundwater | Low | High |

Although both construction methods are applicable to underground LPS construction, they present distinctly different risk characteristics. Pneumatic Caisson is dominated by operational and occupational safety risks associated with compressed-air systems, whereas Top-Down Construction is primarily influenced by excavation stability, retaining structure performance, and construction sequencing. These findings indicate that the choice of construction method should consider not only the magnitude of risk but also the nature of the dominant risks and the capability of the project team to control them.

**Risk Mitigation and Residual Risk**


Gambar Residual Heatmap PCM


Gambar Residual Heatmap Top Down

Risk mitigation strategies were developed based on the identified dominant risks for each construction method. The proposed control measures focus on reducing both the probability and impact of risk events through quality assurance, geotechnical monitoring, operational control, construction sequencing, and occupational safety management.

Following the implementation of mitigation measures, both construction methods showed a substantial reduction in risk exposure. The residual heat maps illustrate that the majority of risk events shifted from the High category to the Low or Moderate category, indicating that the proposed mitigation strategies are effective in improving overall project risk control.

**Integrated Evaluation**

| Evaluation Aspect | Pneumatic Caisson | Top-Down Construction | Comparison Result |
|---|---|---|---|
| Construction Cost | Higher implementation cost | Lower implementation cost | Top-Down is more cost-efficient |
| Construction Duration | Shorter implementation duration | Longer implementation duration | Pneumatic Caisson provides better schedule performance |
| Dominant Risk | Compressed-air system failure, occupational safety hazards, and sinking productivity | Diaphragm wall failure, ground deformation, construction sequencing | Different dominant risk characteristics |
| Residual Risk | Predominantly Low after implementing mitigation measures | Predominantly Low after implementing mitigation measures | Both methods achieve acceptable residual risk levels |

| Evaluation Aspect | Pneumatic Caisson | Top-Down Construction | Comparison Result |
|---|---|---|---|
| Construction Complexity | High | Moderate | Top-Down is less complex |
| Special Equipment Requirement | High | Moderate | Top-Down requires less specialized equipment |
| Geotechnical Control | Excellent | Good | Pneumatic Caisson provides better geotechnical control |

The integrated evaluation indicates that neither construction method consistently outperforms the other across all evaluation criteria. Each method demonstrates distinct advantages depending on the aspect being evaluated. Top-Down Construction offers greater cost efficiency, whereas Pneumatic Caisson performs better in terms of implementation duration and geotechnical control.

Therefore, construction method selection should be based on a balanced evaluation of cost, implementation duration, and construction risk rather than a single performance criterion.

**Decision Analysis Using AHP Direct Measurement**

Table Summary of Analysis Results Provided to the Experts

| Criterion | Pneumatic Caisson (PCM) | Top-Down Construction |
|---|---:|---:|
| Construction Cost | IDR 490.78 billion | IDR 329.19 billion |
| Construction Duration | 23 months | 34 months |
| Residual Construction Risk | Predominantly Low | Predominantly Low |

Table Expert Judgment Results for Criteria Weights

| Criterion | Expert 1 (%) | Expert 2 (%) | Expert 3 (%) | Average (%) |
|---|---:|---:|---:|---:|
| Cost | 20 | 25 | 20 | **21.7** |
| Time | 35 | 35 | 30 | **33.3** |
| Risk | 45 | 40 | 50 | **45.0** |
| **Total** | **100** | **100** | **100** | **100** |

Table Evaluation of Construction Method Alternatives Based on Research Findings

| Criterion | Weight | Pneumatic Caisson (PCM) | Top-Down Construction | Evaluation Basis |
|---|---:|---:|---:|---|
| Construction Cost | 0.217 | 3 | 5 | Top-Down Construction has a lower implementation cost. |
| Construction Duration | 0.333 | 5 | 3 | Pneumatic Caisson has a shorter implementation duration. |

| Criterion | Weight | Pneumatic Caisson (PCM) | Top-Down Construction | Evaluation Basis |
|---|---|---|---|---|
| Construction Risk | 0.450 | 5 | 4 | Pneumatic Caisson has a lower residual construction risk. |

Table Final Ranking of Construction Method Alternatives

| Criterion | Weight | PCM Score | PCM Weighted Score | Top-Down Score | Top-Down Weighted Score |
|---|---|---|---|---|---|
| Construction Cost | 0.217 | 3 | 0.651 | 5 | 1.085 |
| Construction Duration | 0.333 | 5 | 1.665 | 3 | 0.999 |
| Construction Risk | 0.450 | 5 | 2.250 | 4 | 1.800 |
| **Total** | | | **4.566** | | **3.884** |

| Construction Method | Final Score | Rank |
|---|---|---|
| Pneumatic Caisson (PCM) | 4.566 | 1 |
| Top-Down Construction | 3.884 | 2 |

The integrated analysis was subsequently evaluated using the AHP Direct Measurement approach to determine the most appropriate construction method. Expert judgement assigned the highest importance to construction risk (45.0%), followed by implementation time (33.3%) and construction cost (21.7%). These weightings reflect the critical influence of geotechnical uncertainty and project safety on underground construction under constrained urban conditions.

The final evaluation produced an AHP score of 4.566 for Pneumatic Caisson and 3.884 for Top-Down Construction. Although Top-Down demonstrated better cost efficiency, Pneumatic Caisson achieved a higher overall score because of its superior performance in schedule and risk control, particularly under soft soil and high groundwater conditions. Consequently, Pneumatic Caisson was identified as the preferred construction method for the LPS project.

**Managerial Implications**

The findings highlight that construction method selection for deep underground infrastructure should be based on a balanced evaluation of technical feasibility, implementation cost, construction duration, and project risk. Projects with challenging geotechnical conditions and strict schedule requirements may benefit from Pneumatic Caisson despite its higher initial investment, whereas Top-Down Construction remains an attractive alternative for projects where cost efficiency is the primary objective.

The integrated evaluation framework developed in this study provides a practical decision-support tool for project owners, contractors, and consultants when selecting underground construction methods under constrained site conditions.

## Generalisability of the Research Findings

The findings of this study demonstrate that the integrated evaluation of construction cost, implementation duration, construction risk, and AHP Direct Measurement provides a systematic approach for selecting underground construction methods under constrained urban conditions. Rather than relying on a single evaluation criterion, the proposed framework enables construction alternatives to be assessed from both technical and managerial perspectives.

Although this study was conducted using the Lifting Pump Station (LPS) of the Jakarta Sewerage Development Project (JSDP) Zone 1 Package 1 as a case study, the evaluation procedure may also be applied to other underground infrastructure projects with similar geotechnical characteristics, such as soft soil, high groundwater levels, deep excavation, and limited working space. However, the selection of construction methods should always consider project-specific conditions, including structural requirements, construction constraints, available resources, and project objectives.

Overall, the proposed evaluation framework provides practical support for project owners, consultants, and contractors in selecting underground construction methods by balancing construction cost, implementation duration, and construction risk. The framework may therefore serve as a decision-support tool for projects with comparable technical characteristics rather than as a universal recommendation for all underground construction projects.

## CONCLUSION

This study evaluated alternative underground construction methods for the Lifting Pump Station (LPS) of the Jakarta Sewerage Development Project (JSDP) Zone 1 Package 1 by integrating technical feasibility assessment, construction cost, implementation duration, construction risk, and AHP Direct Measurement into a systematic decision-making framework.

The Zero-One Matrix screening identified Top-Down Construction and Pneumatic Caisson as the two technically feasible alternatives for further evaluation, while the Open Cut and Contiguous Bored Pile methods were excluded because they did not adequately satisfy the project constraints related to limited working space, saturated soft soil, and high groundwater conditions.

The comparative analysis demonstrated that each construction method has different advantages. Top-Down Construction provides better cost efficiency, with an implementation cost approximately 32.93% lower than Pneumatic Caisson. Conversely, Pneumatic Caisson offers superior schedule performance by reducing the construction duration by approximately 11 months compared with the Top-Down method.

Risk analysis revealed different dominant risk characteristics for the two alternatives. Pneumatic Caisson is primarily influenced by operational and occupational safety risks associated with compressed-air excavation, whereas Top-Down Construction is dominated by geotechnical risks related to diaphragm wall performance, excavation stability, and construction sequencing. The implementation of risk mitigation measures successfully reduced the dominant risks of both methods to acceptable residual risk levels.

The integrated evaluation using AHP Direct Measurement assigned the highest decision weight to construction risk (45.0%), followed by implementation duration (33.3%) and construction cost (21.7%). Based on these criteria, Pneumatic Caisson achieved the highest overall score and was identified as the preferred underground construction method for the LPS project. These findings demonstrate that construction method selection should not rely solely on construction cost but should consider cost, implementation duration, and construction risk simultaneously to support more reliable decision-making for underground construction projects.

**Future Research**

Although the proposed evaluation framework has been demonstrated through the Lifting Pump Station (LPS) of the Jakarta Sewerage Development Project (JSDP) Zone 1 Package 1, its application should be further validated using underground construction projects with different geotechnical conditions, structural configurations, and project characteristics. Future studies are encouraged to evaluate additional construction alternatives and to involve a larger number of experts in the decision-making process to improve the robustness of the evaluation results.

Furthermore, the proposed framework may be expanded by incorporating additional decision criteria, such as environmental sustainability, life-cycle cost, constructability, carbon emissions, and operational performance. The integration of these aspects with construction cost, implementation duration, and construction risk is expected to provide a more comprehensive decision-support framework for selecting underground construction methods under various project conditions.

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