Vilventhan, A., Rajadurai, R. and Vishwakarma, P., 2022. Value engineering for the selection of a suitable type of foundation in metro rail projects: A case study from India. In: Sandanayake, Y.G., Gunatilake, S. and Waidyasekara, K.G.A.S. (eds). *Proceedings of the 10th World Construction Symposium*, 24-26 June 2022, Sri Lanka. [Online]. pp. 949-959. DOI: https://doi.org/10.31705/WCS.2022.76. Available from: https://ciobwcs.com/2022-papers/

VALUE ENGINEERING FOR THE SELECTION OF A SUITABLE TYPE OF FOUNDATION IN METRO RAIL PROJECTS: A CASE STUDY FROM INDIA

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ABSTRACT

The design and construction of foundation systems for metro rail projects require effective planning and performing analysis over various alternatives in achieving a suitable cost-effective solution. Often the foundation system is selected based on the Soil Bearing Capacity (SBC) and other onsite constraints are left unconsidered. This results in costly design changes during the execution stages and incurs severe delays in the project. This demands the application of advanced managerial techniques to select cost-effective solutions during the design stages of metro rail projects. Value Engineering is one such function-oriented approach used in analyzing the functions of a product or a process and selecting a suitable solution that achieves all the required functions at the lowest possible cost. The application of the value engineering concept in metro rail projects would enable identifying suitable solutions while considering different alternatives over several criteria. Hence, this paper applies value engineering technique for selecting the suitable foundation type for the construction of metro rail projects. A case study of an ongoing metro rail project was considered and three foundation alternative types and nine significant selection criteria were identified. The foundation alternatives were quantitatively analyzed using the weighted evaluation technique. The results indicate that for limited availability of Right of Way (ROW), the foundation with Controlled Low Strength Mortar (CLSM) is highly suitable. In scenarios of limited ROW with less SBC use of pile foundation is identified as a suitable cost-effective foundation type.

Keywords: *Foundation Type; Metrorail Projects; Value Engineering; Weighted Evaluation Technique.*

1. INTRODUCTION

Metro rail projects comprise massive structures that necessitate immense amounts of expenditure, materials, skilled laborers, engineers, and heavy machinery for the construction. Unlike conventional railway systems, metro rail projects are unique, and grade-separated from traffic and other existing urban transportation systems (Sharma, et al., 2013). They are mostly constructed in the middle of the Right of Way (ROW) of the

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roads as elevated structures and partly as underground structures depending on the site conditions. Several considerations are made during the planning and design stages of the metro projects. They include consideration of the type of structure (underground or elevated), impact over the surrounding environment, passenger traffic, land acquisition, issues in construction and maintenance of the structures (Sharma, et al., 2013). Over the number of considerations, the selection over the type of foundation is often less emphasized in current practice.

The foundation of metro rail projects plays a crucial role in confirming the stability of the entire structure. In practice, the selection of the type of foundation is made based on the nature of the soil, type of loads, and the type of proposed structure. However, other critical factors like the surrounding environment, the existence of sub-surface utilities, and the availability of land for construction are not considered during the planning and designing stages of metro rail projects. Often design changes were made during the execution phases of metro projects due to unfavorable site constraints and resulting in cost and schedule overruns in the project.

Value Engineering is a systematic procedure that employs various techniques over a product or a facility to analyze its existing functions, aiming to propose the best suitable alternative at the lowest possible cost without sacrificing the function or quality (Assaf, et al., 1996; Yanita and Mochtar, 2021). They are used in various manufacturing and construction industries in maximizing the value aiming at a lower lifecycle cost of the product or the project (Liu and Shen, 2005). However, in the Architecture Engineering Construction (AEC) industry, their applications are fairly limited to buildings (Lee, 2018; Berawi, et al., 2021), highway infrastructure projects (Kim, et al., 2016; Mousakhani, et al., 2017), and their application on other infrastructural projects such as metro rail projects are left unattended. The application of systematic value engineering can provide a cost and time-effective solution for the construction of a foundation in metro rail projects that can improve the value of the project without reducing its intended function. Hence, the paper aims to fulfill this gap through the application of the Value Engineering (VE) process in metro rail projects and develop a solution for the selection of a suitable type of foundation.

The structure of the paper is organized as follows: The next section describes the literature review on VE and their applications over different phases of the construction project. Then, the research methodology adopted in the paper is discussed. In the later sections, the application of VE for selecting a suitable foundation type for the case study is discussed and the results are evaluated. Lastly, the conclusion of the paper is provided.

2. LITERATURE REVIEW

2.1 APPLICATIONS OF VALUE ENGINEERING

The VE in the construction industry has been used for various applications such as project conceptualization, site selection, feasibility of design proposal, selection of construction material, method, and facility maintenance (Atabay and Galipogullari, 2013). The application of VE in construction projects enabled cost reduction, functional enhancement, time shortening, and improvements in constructability, quality, and sustainability (Shen and Liu, 2004; Shen and Yu, 2012; Atabay and Galipogullari, 2013; Salmi, 2017; Gunarathne, et al., 2020). The VE process was found applied at various stages of the project lifecycle such as planning and analysis, schematic design, design development, construction documentation, construction and operation, and maintenance stages (Danso and Kwadwo, 2019).

2.1.1 VE during Pre-Construction Stages

During the pre-construction stages, the VE process was mainly applied for conducting feasibility analysis of road network design (Chen and Hsu, 2011) and selecting suitable project design alternatives of highway construction (Kim, et al., 2016; Mousakhani, et al., 2017) and pipeline water supply system (Shahhosseini, et al., 2018).

The application of the VE process was also used in selecting suitable material types for construction such as optimal building façade material (Lee, 2018) and drainage pipeline material for a highway construction project (Atabay and Galipogullari, 2013).

The application of VE also extends to green construction (Li, et al., 2019) and sustainability projects (Gunarathne, et al., 2020; Berawi, et al., 2021). The VE process was used in creating a green construction evaluation system and used in identifying suitable construction schemes with maximum green construction co-efficient value. This enabled maintaining the balance between the cost implications and green construction effect on the project.

2.1.2 VE during Construction Stages

The application of VE during the construction stages of the project was used in reducing project lifecycle costs and in preventing project delays. In a highway construction project, VE was applied for cost and time optimization through selecting suitable construction methods such as in-situ construction and prefabricated construction for the selected project (Atabay and Galipogullari, 2013). In a similar study, VE was applied to evaluate and identify the most suitable construction system for bridge construction projects, thereby the cost of the project was reduced and the constructability of the project was improved (Basha and Gab-Allah, 1991).

The application of VE was also used in addressing various onsite challenges and used in deciding on suitable cost-effective management approaches for the project (Tang and Bittner, 2014). Thompson, et al., (2009) applied VE, considering site complexities to select a suitable type of embankment stabilization system. VE was also applied for identifying suitable cost-effective temporary facilities such as selecting the sources of electricity supply for the mobility phases of the project (Trigunarsyah and Hamzeh, 2017).

2.1.3 VE in Post-Construction Stage

Limited research efforts were identified on applying VE for the operation and maintenance stages of construction projects. The VE methodology was mainly used in evaluating the performance of the water distribution system and used for decision-making in renewal and rehabilitation processes (Cuimei and Suiqing, 2008).

The VE practices for construction were found applied for various buildings (Lee, 2018; Berawi, et al., 2021), and infrastructure projects such as highways (Atabay and Galipogullari, 2013; Kim, et al., 2016; Mousakhani, et al., 2017), bridges (Basha and Gab-Allah, 1991; Tang and Bittner, 2014), power stations (Trigunarsyah and Hamzeh, 2017; Li, et al., 2019) and other utility projects (Cuimei and Suiqing, 2008). However, their application specific to the construction of metro rail infrastructure projects are seldom targeted. The VE practices were used for the selection of a suitable type of material (Atabay and Galipogullari, 2013), selection of design, construction methodology (Kim, et al., 2016; Mousakhani, et al., 2017), and selection of green construction schemes (Li, et al., 2019) in infrastructure projects. However, their application for the selection of a suitable type of foundation system is left unattended. To fill the above gap in the literature, this paper applies systematic VE to select the suitable type of foundation system for the construction of the metro rail projects in India.

3. RESEARCH METHODOLOGY

A case study research methodology was used for applying VE for selecting the suitable type of foundation for the construction of metro rail projects. A case study research methodology allows collecting and analyzing empirical evidence and establishing a practical understanding of the contemporary phenomenon in a real-life context (Yin, 2018). A reliable case study involves the collection of various sources of information such as interviews, observations, documents, archival records, physical artifacts, which converge to the same set of facts resulting in triangulation (Yin, 2018). In this study, data were collected through participant observation, interviews, questionnaire and referring project documents.

The applied VE study adopts the following phases: information, creative, evaluation and development phase. In the information phase, required information about the project is collected through participant observation, conducting semi-structured interviews with the project team, and referring project documents. Relevant data such as project type, technical specifications, and issues with the construction of the foundation were obtained. In the creative phase, foundation alternative types that solve the identified problems and support the required basic function were determined through brainstorming technique. A purposeful sampling of 30 professionals from the case study (comprising of owner, designers, consultants, and contractors), were selected to form a VE team. The professionals were selected based on their profound knowledge and experience (minimum of six years) in the design and construction of metro rail projects. The professionals held positions such as Chief Engineer, Project Manager, Site Engineer, Design Engineer, and Coordinator. Two brainstorming sessions were conducted with the VE team and three suitable foundation alternatives were determined. In the evaluation and development phase, individual foundation alternatives were quantitatively analyzed using the weighted evaluation technique and suitable alternative was identified. The weighted evaluation technique allows considering both the economic and functional factors of alternatives (Dell'Isola, 1997; Basha and Gab-Allah, 1991) and enables better decision-making over the best suitable foundation type for the selected site condition. The technique involves identifying evaluation criteria and determining their relative weights or degree of importance. Semi-structured interviews were conducted with the VE team to identify evaluation criteria for the considered project. Further, a questionnaire was developed and individual criteria were ranked on a scale of 1 to 5 (varying from poor to best preference) based on the degree of importance and criteria weights were determined. Also, the foundation alternatives were ranked on a similar scale of 1 to 5 against individual criteria for each possible scenario. Finally, an analysis matrix was developed by multiplying the criteria weights and obtained foundation alternatives rank for each possible scenario and a suitable foundation type was determined.

4. CASE STUDY DESCRIPTION

The construction of the Hyderabad metro rail project was considered as a case study in this paper. The project is located in Telangana, India. It was executed in Design Build Finance Operate Transfer (DBFOT) model. It consists of 3 elevated corridors with a total length of 72 Km and the stations were constructed in the middle of the road with an elevated concourse. The construction of foundation systems for the elevated structure is affected by onsite issues such as limited availability of right of way and the presence of uncharted underground utilities. During the excavation process, many underground utilities were found in the construction area and were required to be relocated. Often delays were encountered during relocation and caused significant delays to the project. In cases, where shifting or repositioning of utilities is not possible, design changes of the footing and the super-structure were made. This escalated project completion time and increased the total lifecycle cost of the project.

Based on the onsite observation, the construction site location was categorized into 3 possible scenarios depending on the availability of the area and bearing capacity of the soil. Case 1 represents the site location with sufficient load carrying capacity and sufficient ROW is available for construction of the foundation. Case 2 represents the site location with sufficient load carrying capacity and limited ROW for construction and Case 3 represents site location with limited load carrying capacity and limited ROW for construction of the foundation.

5. TYPES OF FOUNDATION SYSTEMS

Selection over a type of foundation is mainly based on the type of load and the Soil Bearing Capacity (SBC) of the soil. Pile foundations are preferred for heavy/medium loads with loose/soft soil strata, and open foundations are preferred for site locations where hard strata or rock is available nearer to the ground level. However, the consideration of the above two criteria is not sufficient for the selection of foundation types for metro rail projects. Hence, brainstorming activities were conducted and foundation alternatives were identified and categorized into three types such as A (open foundation with square footing), B (pile foundation), and C (open foundation with Controlled Low Strength Mortar (CLSM)).

6. SELECTION CRITERIA

To evaluate the different design alternatives, suitable criteria for analysis are required. Several selection criteria were used in the extant literature for the selection of design alternatives in infrastructure projects. In a roadway expansion project five factors such as safety, constructability, maintenance, environment, and cost were considered as evaluation criteria for design alternate evaluation (Kim, et al., 2016). Similarly, for construction of bridges, eight types of criteria such as construction cost, maintenance, durability, service life, resource availability, ease of construction, construction progress rate, and design efficiency were considered (Basha and Gab-Allah, 1991). The identified criteria were limited to road and bridge construction projects. Criteria for the construction of metro rail projects are not established in the literature. Though the criteria used in the studies were similar, they vary with the project type, size, and location. Hence, to identify selection criteria impacting the selection of foundation types for metro rail projects, a semi-structured interview was conducted with the VE team. Nine evaluation criteria such as construction cost, time taken for foundation, constructability, presence of utilities, design efficiency, safety, resource availability, the service life of the structure, and construction progress rate was identified and used for the evaluation of individual foundation alternatives.

7. CRITERIA WEIGHTING

The criteria weighting identifies important individual evaluation criteria and establishes ranks or relative importance. The relative weights (raw weight) of identified criteria were obtained through the questionnaire and further normalized and presented in Table 1. The normalized weight percentage was obtained by taking the average raw weight for individual criteria and multiplying it by 100. It can be observed that construction cost and safety were considered highly important on comparing with other criteria such as the presence of utilities and ease of construction.

Table 1. Evaluation criteria along with their raw and normalized weight

Criteria	Raw weight	Normalized weight (%)
Construction cost	106	12.33
Safety	106	12.33
Service life	100	11.63
Time	97	11.28
Construction progress rate	97	11.28
Design efficiency	95	10.05
Ease of construction	91	10.58
Resource availability	85	9.88
Utilities	83	9.65
Total	860	100

8. EVALUATION OF FOUNDATION ALTERNATIVES

The analysis matrix for the foundation type was developed for the considered three case scenarios as follows.

8.1 CASE 1: WHEN SUFFICIENT SOIL BEARING CAPACITY IS AVAILABLE AND NO CONSTRAIN IN RIGHT OF WAY

In Case1, the considered site location has sufficient soil bearing capacity to transfer loads of the super-structure and hard strata with a safe bearing capacity of 45 t/m^2 to 75 t/m^2, obtained at a depth of 3m and 5m respectively. Similarly, the selected site location has no constrain in the right of way and the selected site is free from existing underground utilities or any irremovable structures like the foundation of other existing structures. Through questionnaire (as discussed in research methodology) foundation alternatives were ranked on a scale of 1 to 5 against individual criteria for the considered scenario as shown in Table 2. The obtained rank in Table 2 and the corresponding criteria weight obtained (Table 1) were multiplied to obtain a total score of individual alternatives. The resulting analysis matrix is shown in Table 3 and the foundation type with the highest score was considered as the suitable alternative.

Table 2. Ranking for the type of foundation

Type of foundation	A*	B*	C*
Construction cost	4.14	2.28	4.0
Time of construction	4.3	2.2	3.5
Ease of construction	4.1	2.4	4.0
Utilities	2.5	4.2	3.9
Design efficiency	3.7	3.6	3.0
Safety	4.5	3.3	3.4
Resource availability	4.4	2.6	3.4
Service life	3.7	4.3	3.3
Construction progress rate	4.4	2.6	3.7

*Ranking performance: best = 5; very good = 4; good = 3; fair = 2; poor = 1.

Table 3. Analysis matrix when piers on the right of way

Criteria	Normalized weight	A		B		C	
		Rank	Score	Rank	Score	Rank	Score
Construction cost	12.33	4.14	51.08	2.28	28.18	4.00	49.32
Time	11.28	4.30	48.50	2.20	24.816	3.50	39.48
Ease of construction	10.58	4.10	43.38	2.40	25.392	4.00	42.32
Utilities	9.65	2.50	24.13	4.20	40.53	3.90	37.635
Design efficiency	10.05	3.70	37.18	3.60	36.18	3.00	30.15
Safety	12.33	4.50	55.48	3.30	40.689	3.40	41.922
Resource availability	9.88	4.40	43.47	2.60	25.688	3.40	33.592
Service life	11.63	3.70	43.03	4.30	50.009	3.30	38.379
Construction progress rate	11.28	4.40	49.63	2.60	29.328	3.70	41.736
Total score			**395.89**		300.814		354.534

8.2 CASE 2: WHEN SUFFICIENT SOIL BEARING CAPACITY IS AVAILABLE AND CONSTRAIN IN THE RIGHT OF WAY

In Case 2, the considered site location has sufficient soil bearing capacity to transfer loads of the super-structure and hard strata with a safe bearing capacity of 45 t/m^2 to 75 t/m^2 are obtained at a depth of 3m and 5m respectively. However, the selected site is identified with the presence of multiple utilities that are difficult to relocate. In such a case, the alignment of the metro corridor has to be modified, which is more complex and cumbersome, or an alternate solution has to be made. The alternative foundation types were ranked against each criterion and were multiplied with their corresponding normalized weight. The obtained analysis matrix for Case 2 is shown in Table 4.

Table 4. Analysis matrix when piers do not fall on right of way for case 2

Criteria	Normalized weight	A		B		C	
		Rank	Score*	Rank	Score*	Rank	Score*
Construction cost	12.33	2.9	35.757	3.9	48.087	4.3	53.019
Time	11.28	3.4	38.352	3.8	42.864	4.2	47.376
Ease of construction	10.58	3.6	38.088	3.5	37.03	4.4	46.552
Utilities	9.65	3.3	31.845	4.7	45.355	4.1	39.565
Design efficiency	10.05	3.4	34.17	4.5	45.225	3.5	35.175
Safety	12.33	3.4	41.922	4.6	56.718	3.5	43.155
Resource availability	9.88	3.8	37.544	3.4	33.592	4.2	41.496
Service life	11.63	3.6	41.868	4.1	47.683	3.9	45.357
Construction progress rate	11.28	3.8	42.864	3.2	36.096	4.3	48.504
Total score			342.41		392.65		400.2

8.3 CASE 3: WHEN BOTH SOIL BEARING CAPACITY AND RIGHT OF WAY IS NOT SUFFICIENT

In Case 3, the selected site location is not sufficient to transfer the load of the superstructure, and no hard strata are found to a depth of 5m below the ground surface. Similarly, the selected site is identified with the presence of multiple utilities, hindering the construction of the foundation. For the considered case, the alternative foundation types are ranked and scored against individual selection criteria. The obtained analysis matrix is shown in Table 5.

Table 5. Analysis matrix when piers do not fall on right of way for case 3

Criteria	Normalized weight	A		B		C	
		Rank	Score*	Rank	Score*	Rank	Score*
Construction cost	12.33	2.00	24.66	4.60	56.718	2.70	33.29
Time	11.28	3.50	39.48	3.30	37.224	4.30	48.50
Ease of construction	10.58	3.80	40.204	3.40	35.972	3.80	40.20
Utilities	9.65	2.50	24.125	4.70	45.355	3.40	32.81
Design efficiency	10.05	2.90	29.145	4.60	46.23	3.10	31.16
Safety	12.33	3.10	38.223	4.40	54.252	3.00	36.99
Resource availability	9.88	3.80	37.544	3.60	35.568	3.60	35.57
Service life	11.63	3.70	43.031	4.60	53.498	3.70	43.03

Criteria	Normalized weight	A		B		C	
		Rank	Score*	Rank	Score*	Rank	Score*
Construction progress rate	11.28	3.40	38.352	3.90	43.992	3.60	40.61
Total score			314.764		**408.809**		342.16

9. DISCUSSION

Referring to Table 3, for Case 1, foundation type A (Open - Raft foundation) obtained a higher score of 395.89 in comparison with the other type of foundations. Compared to the type A foundation, type B has 44.82% higher construction cost, 48.83% higher erection time, 41.46% more difficult for construction. Therefore, for Case 1, type (B) is not suitable. Hence foundation type A is most suitable for cases where SBC is sufficiently high and no constraint is present in occupying the right of way of the road.

Referring to Table 4, foundation type C (foundation with CLSM) obtained a higher score of 400.2 in comparison with the other type of foundations B and C. Type C is 9.3%, and 32.56% is more profitable in terms of cost than type B and type A respectively. In terms of construction time-saving type C is 9.52% and 19.05% more efficient than type B and type A respectively. The overall score shows that under this case type C is the most suitable choice for a case concerning sufficient SBC and where constraint in occupying the right of the road prevails.

Referring to Table 5, foundation type B (Pile foundation), obtained a higher score of 400.8 on comparing with other types of foundations. The foundation type B scores a high rank of 4.7 as a suitable alternative when multiple utilities are encountered at the site. On comparing with the other alternatives in terms of ease of construction and time taken for construction, foundation type B scores low by 39.3% and 23.26%. However, in terms of safety criteria, type B scores 42% more compared with the other type of alternatives, and the safety criterion is considered critical (with normalized rank 12.33) when compared with other selection criteria. Hence, in cases where sufficient SBC and the availability of the right of way of the road are limited, foundation type B provides the best suitable choice as a foundation system.

10. CONCLUSION

The design and selection of a foundation type for construction are based on the type of loading and the bearing capacity of the soil. However, during the execution stages, the preferred original design or selected foundation type may not be suitable due to existing on-site conditions such as less availability of construction space or the presence of unmovable structures or facilities. Often less consideration was given to these factors while selecting the foundation type and changes in the original design were made during the construction stages of the project. This results in overall project delays and increases the lifecycle cost of the project. Hence it is required to identify the best suitable cost-effective foundation type while ensuring its basic intended function and value are not compromised. Hence, VE concepts were applied for the selection of suitable foundation types for the construction of metro rail projects.

A practical case study was presented in this paper and VE is applied as a decision-making tool in selecting a suitable type of foundation system. Based on the analysis, it was determined that foundation type A (open foundation with square footing) provides a suitable solution when sufficient SBC and ROW are available. In scenarios of sufficient SBC with limited ROW, the foundation type C (open foundation with CLSM) was identified as suitable. In scenarios of limited SBC and limited ROW, foundation type B (Pile foundation) was identified as suitable. It was observed that, the selection over a foundation type varied with the availability of ROW even when sufficient SBC is available. This infers that the availability of ROW impacts the selection type of foundation. Thus, the application of VE in metro rail projects enabled selecting suitable foundation type for different on site scenario.

The current study has the following limitations. The findings and the conclusion presented in the paper are project-specific and the results obtained may vary with other transportation infrastructure projects as the different project uses different selection criteria with different weights and requires different VE techniques to determine the best possible alternatives. However, the methodology adopted in this paper can be applied for any metro rail project for the selection of foundation type. Also, the current study can be extended to include cost-benefit analysis in the future.

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