DEVELOPMENT OF A FRAMEWORK FOR SELECTION OF A TUNNEL LINING FORMWORK SYSTEM

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Tunnels are considered special structures because of their uniqueness in analysis, design, and construction. During the construction of the tunnels, it is desirable to optimise the lining formwork system for the rapidity with quality, safety, and economy. The requirement of the tunnel leads to the change in the structure of the lining formwork system. However, the selection of lining formwork system is comprehensive and requires years of experience. This necessitates the development of a novel framework to select a lining formwork system for tunnelling projects. Therefore, this study attempts to develop a framework for selecting a lining formwork system using the Delphi method. For this purpose, guidelines of the Delphi Method are modified to select the experts based on their qualifications and experience. Then, ten experts are elected as a panellist. Subsequently, a total of 11 factors and 43 sub-factors are identified from the existing literature. Out of these, eight factors with their sub-factors are shortlisted using the Delphi method. Afterwards, Cronbach's alpha is determined for the remaining eight factors to test reliability. The proposed framework can help practising engineers to select and optimise the lining formwork system.

Keywords: tunnel; lining formwork; Delphi; geometry; quality; safety; economy

INTRODUCTION

Tunnels are different and special from any other civil engineering structures, as they are structures that are not worked out in typical day to day constructions. Tunnels serve numerous functions in civil engineering constructions like road and rail networks, hydropower generators, mass rapid transit systems, crude oil storage, water supply systems, and sewage systems. For example, India has been making a huge investment in various infrastructure construction projects, which involve numerous tunnel construction (Sharma 2021). Further, Sharma (2021) presented the number of tunnelling projects proposed or in various construction phases in India. The number of tunnels is 1641 spanning 3445 km long pipeline construction project, 30 for the Siang hydropower project, and seven major tunnels on different highway projects. Moreover, India's upcoming metro rail project has 10% of its construction work is underground. In this connection, engineers and practitioners in India have the challenging task of ensuring the stability of tunnel construction.

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Generally, the construction of the tunnel consists of reinforced concrete (RC) lining works, which mainly comprise formwork, rebar, and cast in situ concrete. However, out of these three-element, formwork is considered the most important because its structure changes with the change in the tunnel requirements (Jha 2012). The formwork of the tunnel project is generally called a tunnel lining formwork system. A formwork system is an essential non-standard component for the secondary lining during tunnel construction. Markewitz *et al.,* (1972) stated that non-standard components include a horizontal formwork component and two vertical formwork sections that are both bending resistant, with the vertical formwork portions moveable relative to the horizontal formwork portion.

In this connection, Pintado and Barragán (2009), Huang *et al.,* (2011), Peng *et al.,* (2011), Jha (2012), and Gaofei Group (2019) have respectively described the four types of tunnel lining formwork: (1) Simple lining Trolley/ formwork loop wheel machine (Double arch Tunnel); (2) Modular Tunnel Deck formwork; (3) Fully Hydraulic Automatic Walking Lining Trolley (Arch and Floor-to-arch transition formwork); (4) Truss Frame Lining Trolley (Universal-Rod Steel-Shuttering Jumbo for Tunnel Lining). Thus, selecting the tunnel lining formwork system is essential, as it fulfils various aspects such as quality, safety, productivity, and economy of the tunnel construction. However, selecting an appropriate tunnel lining formwork from the four types is a comprehensive and challenging process and requires years of experience.

Furthermore, there are no such studies available in the literature in order to identify the influencing factors. Therefore, this necessitates the development of a novel framework to select a lining formwork system for tunnelling projects. In this regard, the research sets the objectives to; (1) identify the potential factors and sub-factors that are required to be considered for the selection of a lining formwork system and (2) develop a hierarchical framework for selecting an optimized lining formwork system. To achieve these objectives, the paper proceeds with the following section. The paper first summarizes the literature review to understand better the formwork selection process used in different construction projects. Then, sections include the research methodology and data collection and analysis. Finally, the last section presents the concluding remarks.

LITERATURE REVIEW

Formwork is a structure whose aim is to stand on its weights and support the freshly placed concrete and live load, including material, equipment, and workers. Therefore, selecting an appropriate formwork system is critical in any construction project. In the last four decades, several studies have explored the selection of formwork systems for construction projects. Hanna (1989) identified 38 factors prompting the selection of formwork systems for building construction projects, and then, based on expert opinions, those identified factors were grouped into four categories. He also proposed selection criteria for formwork alternatives like a conventional column or wall form, ganged form, slip form etc. Further, Hanna and Sanvido (1990) proposed a methodology to select a vertical formwork system using a knowledge base experts' opinion. Hanna *et al.,* (1992) developed a rule-based system to guide practitioners in selecting the most appropriate formwork system for building projects. Further, Hanna (1999) integrated the additional factors, such as labour force and labour productivity, into the relevant literature. Proverb *et al.,* (1999) evaluated the critical factors affecting formwork selection and evaluated the degree of association between the selection factors for contractors from the UK, France, and Germany. In addition to the above-selected factors, Krawczyńska-Piechna (2016, 2017) added new factors such as flexibility, durability, compatibility, safety, and weights for the formwork selection in building construction projects. Some studies in the Indian construction industry (Loganathan and Viswanathan 2016; Pawar *et al.,* 2018; Lohana 2018; Rajeshkumar and Sreevidya 2019; Rajeshkumar *et al.,* 2021) have identified the factors influencing the selection of formwork in building projects.

In the tunnel lining formwork system, Pintado and Barragán (2009) have explained the importance of self-compacting concrete (particularity of mix design) and floor to arch transition gantry for tunnel lining work. Huang *et al.,* (2011) have considered the lining formwork design criteria to use the formwork system with required security arrangements so that the project is done with quality and speed for improving construction efficiency. Peng *et al.,* (2011) designed Universal-Rod Steel-Shuttering Jumbo (URSSJ) to customise the tunnel's shape and size with less repair and maintenance. Eventually, the literature explores that most of the studies mentioned above have identified the factors for selecting formwork systems for residential, commercial and industrial construction. Further, most of these studies (Hanna 1989; Hanna and Sanvido 1990; Hanna *et al.,* (1992); Proverb *et al.,* 1999; Loganathan and Viswanathan 2016) have used the knowledge acquisition process to select the formwork based on the identified factors for selecting horizontal and vertical formwork for building projects. However, no such studies are available on identifying the factors affecting the selection of the tunnel lining formwork. Therefore, there is a need to identify factors and develop a framework that can help to select an appropriate tunnel lining formwork system.

METHOD

Based on the review of literature, the research methodology is framed to identify and shortlist the factors influencing the selection of tunnel lining formwork systems using the Delphi method. Hallowell and Gambatese (2010) described the Delphi method as a "well-designed research technique used to acquire the opinion of independent experts on a specific topic". The Delphi method is more precise than other standard simple survey methods, as it allows users to keep control over biased feedback acquired from competent experts (Hallowell and Gambatese 2010). Owing to these, controlled feedbacks found during multiple rounds can help to accomplish consensus among the experts. Thus, to achieve this study's objectives, the procedure of the Delphi method is outlined in seven steps, and it is shown in Figure 1. A brief description of these steps is as follows.

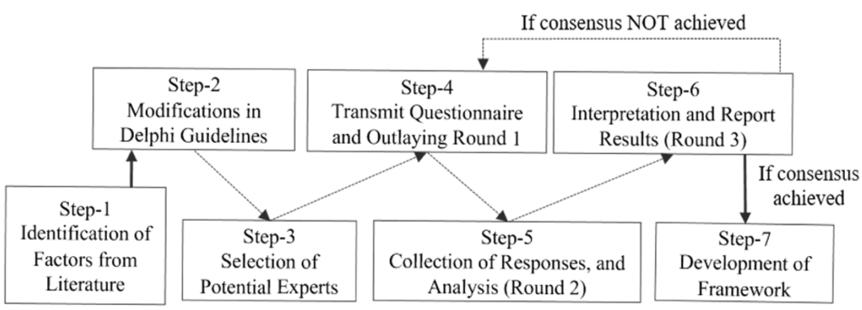

Figure 1: Research Method

In step 1, potential factors influencing the selection of tunnel lining formwork systems are identified from the literature. In step 2, guidelines are required to define for selection and certification of the respondents as experts (panellists'). In this connection, Hallowell and Gambatese (2010) have already presented the sample guidelines and recommend to modified them based on the requirement of the studies. Therefore, the present study modifies the guidelines as described in Table 1.

Table 1: Modified guidelines for the Delphi method

Characteristics	Minimum requirement adopted in this study
Identifying potential experts	Experts must satisfy at least one of the following criteria:
	1. Member or chair of a nationally recognized committee.
	2. Participated in expert-based research studies on tunnelling systems.
	3. The person with the number of handling projects and publications in the relevant field.
	4. Person in charge of design and Fabrication of Tunnel lining formwork system
Qualifying panellists as experts	Experts must satisfy at least three of the following criteria:
	1. Minimum three years of work experience in tunnelling or academics.
	2. Minimum four years of B.E./B.Tech. Civil Engineering degree from a renowned University/Institute OR Advanced or Master's degree in CEM, Structural Engineering, Tunnel Engineering or any related course to Formwork System.
	3. Professional registration such as Registered Engineer, Licensed Engineer
	4. Primary or secondary writer of at least three peer-reviewed journal articles.
	5. Invited to present at a conference or training program.
	6. Member or chair of a nationally recognized committee, society/council
Number of panellists	10
Number of rounds	3
Feedback for each round	Round 1: Data from existing literature, personal judgment, interview with experts, or archived data (if available).
	Round 2: Median response from Round 1.
	Round 3: Median response from Round 2 and reasons for outlier responses.
Measuring consensus	Absolute deviation (median) (AD), coefficient of variance (CV), range of data

Note: B.E./B.Tech. = Bachelor of Civil Engineering; CEM = construction engineering and management;

This modification is based on the requirement of Indian tunnel engineering. In step 3, the modified guidelines are used to select and certify the qualified experts in the panel. In step 4, the first round of the questionnaire survey is performed using a two-point Likert scale where 1 for satisfaction and 0 for un-satisfaction. The questionnaire is used to verify the factors identified in step 1 with the help of the panellists' responses.

In step 5, second round of the questionnaire survey is conducted using a six-point Likert scale where, extremely unimportant = 1, unimportant = 2, somewhat unimportant =3, somewhat important =4, important = 5, and extremely important = 6. However, Lad *et al.,* (2021) supported that the 'Neutral' should not be considered in the Likert scale to have a convenient response without cognitive efforts. Further, to judge whether experts have reached the required consensus, the statistical parameters such as mean, median, standard deviation (SD), absolute deviation (AD)-mean, AD-median, coefficient of variation (CV), and range of data are computed. Cut-off values for these statistical parameters can be set as per the requirement of the study in order to shortlist the factors (Patel and Jha 2017). In step 6, the third round of the Delphi method is conducted, wherein experts are asked to observe the results of the second round and shortlisted factors in order to develop the required framework. However, if an expert is not satisfied with the results, then the expert is asked for its justification. If other experts are satisfied with the justification given by that expert, then all three rounds are to be performed again. Finally, in step 7, if all the experts agree with the result of the second round, then the framework is developed that helps to select an appropriate tunnel lining formwork system.

FINDINGS

Data collection and analysis of the different steps of the research method are as follows:

First, as per the process described in step 1 of the research method, a total of 11 factors with 44 sub-factors, essential for selecting the tunnel lining formwork, were identified from the existing literature (Hanna 1989; Hanna *et al.,* 1992; Pintado and Barragán 2009; Huang *et al.,* 2011; Peng *et al.,* 2011; Jha 2012; Krawczyńska-Piechna 2016, 2017; Rajeshkumar and Sreevidya 2019). Then, 15 probable respondents were identified, and out of them, 10 potential experts were selected as the panellist based on the modified guidelines (Table 1). Of these 10 experts: three are from metro rail corporations; two are consultants; one is a private contractor; four are academicians/researchers. The average experience of the 10 experts in tunnelling projects/ research is approximately 13 years. Then, the first round of the survey was performed with the questionnaire as mentioned in step 4 of the research methodology. The four experts suggested to remove the sub-factors, namely: (1) Salvage Value, (2) Dewatering Time, and (3) Ventilation, as these factors were not required in the selection of the lining formwork system. In contrast, some experts advised to add the sub-factors: (1) Uplift of Form and (2) Contract Administration. Hence, a total of 11 factors and 43 sub-factors are finalized in the first round of the Delphi method, and they are described in Table 2.

After that, the second round of the Delphi method was performed with the questionnaire as described in step 5 of the research methodology. The responses obtained in the second round of the Delphi method are then analysed, and their statistical parameters are determined and shown in Table 3. Subsequently, the cut-off values for the parameters AD- Median, CV, and Range of data were set to be less than 0.75, 0.249, and 3, respectively. The criteria were decided on variations in data and previous studies (Hallowell and Gambatese 2010; Patel and Jha 2017). Three factors: (1) Cycle Time (F6), (2) Dewatering (F9), and (3) Construction Sequence (F10), exceeding the limit stated for AD- Median, CV, and Range of data (Table 3). Therefore, these three factors and their respective sub-factors were eliminated from further study. The eight factors and their corresponding 32 sub-factors were shortlisted, and then they were taken for validation using a reliability test. For this, Cronbach's alpha was calculated for the shortlisted 11 factors, and their values are shown in Table 4. Hair *et al.,* (2018) advocated that the value of Cronbach's alpha should be greater than 0.6 to have better reliability and internal consistency among the factors and their sub-factors. Thus, Table 4 shows that the value of Cronbach's alpha value of the "Organisational Support (F11)" factor was 0.147. However, Hair *et al.,* (2018) recommended that one can improve the value of Cronbach's alpha by eliminating irrelevant sub-factors. Therefore, the factor "Troubleshooting Experience (F11.4)" was eliminated from the study, and the improved Cronbach's alpha is recalculated and shown in Table 4 (in the bracket).

In the third round of the Delphi method, all experts were asked to observe the results of the second round and confirm their consensus on the results. Thus, all the experts agreed with the second-round results; therefore, no further modification was required for the shortlisted factors and their corresponding sub-factors.

Table 2: List of factors and sub-factors for selecting tunnel lining formwork

Factors	Sub-factors
F1 Geometry	F1.1 Shape of Tunnel, F1.2 Crown Height, F1.3 Thickness of Lining, F1.4 Tunnel Length and Alignment
F2 Economy	F2.1 Initial Investment, F2.2 Repair and Maintenance, F2.3 Stripping Cost, F2.4 Reusability
F3 Quality	F3.1 Mix Ratio of Concrete, F3.2 Compaction of Concrete, F3.3 Surface Finishing, F3.4 Cold Joints/Combing Defects
F4 Work Safety	F4.1 Safety Induction, F4.2 Risk Assessment, F4.3 Primary Lining, F4.4 Working Environment, F4.5 Degree of Supervision
F5 Project Complexity	F5.1 Company Practices, F5.2 Uplift of Formwork, F5.3 Site Characteristics, F5.4 Flexibility in Design, F5.5 Formwork Expertise
F6 Cycle Time	F6.1 Installation Time, F6.2 Crane Time, F6.3 Speed of Construction, F6.4 Stripping Time
F7 Labour Management	F7.1 Resource Requirement, F7.2 Resource Available, F7.3 Scheduling and Controlling
F8 Geological Conditions	F8.1 Topography, F8.2 Geology of Soil and Rock Mass, F8.3 Engineering Behaviour of Soil and Rock
F9 Dewatering	F9.1 Dewatering Technique, F9.3 Dewatering Time, F9.3 Seepage and Drainage Control, F9.4 Freeing and Thaw
F10 Construction Sequence	F10.1 Method of Construction, F10.2 Exposure to Dust, F10.3 Tunnel Monitoring
F11 Organizational Support	F11.1 Available Capital, F11.2 Contract Administration, F11.3 Hoisting Equipment, F11.4 Troubleshooting Experience

Table 3: Results of statistical parameters in the second round of the Delphi method

Factors	M	SD	Med	CV	Max.	Min.	R	ADM	AD Med.	V
F1	5.8	0.42	6	0.073	6	5	1	0.32	0.00	0.16
F2	5	0.47	5	0.094	6	4	2	0.2	0.00	0.2
F3	5.6	0.52	6	0.092	6	5	1	0.48	0.00	0.24
F4	5.2	1.14	6	0.218	6	3	3	0.96	0.00	1.16
F5	5.1	1.10	5.5	0.216	6	3	3	0.9	0.50	1.09
F6 *	4.8	1.23	5	0.256	6	2	4	0.88	1.00	1.36
F7	4.7	0.82	5	0.175	6	3	3	0.62	0.00	0.61
F8	5.4	0.70	5.5	0.129	6	4	2	0.6	0.50	0.44
F9 *	4.5	1.65	5	0.367	6	1	5	1.3	1.00	2.45
F10 *	3.9	1.37	4	0.351	6	2	4	1.12	1.00	1.69
F11	4.8	0.63	5	0.132	6	4	2	0.48	0.00	0.36

*Note: (1) For the name of factors F1 to F11, refer to Table 2. (2) M-Mean, SD-Standard Deviation, Med.-Median, CV-Coefficient of Variance, R-Range of Data (Max.-Min.), ADM-Absolute deviation (Mean), AD Med.- Absolute Deviation (Median), V-Variance. (3) * symbol indicates that factors are eliminated from the study.*

Finally, the results from the Delphi method were utilised to develop a hierarchical framework, where eight main factors and 31 sub-factors were shortlisted. The hierarchical framework is shown in Figure 2. Thus, the shortlisted eight factors are discussed as follows: (1) Geometry primarily indicates the different shapes of the tunnel-like circular, oval, rectangular, etc. With it, the shape of tunnel lining formwork is required to mould. (2) Economy is one of the vital factors because the experts stated that the selected formwork system incurs approximately 60-65% cost in the tunnel construction.

Table 4: Cronbach's alpha of factors

Factors and Sub-factors	Cronbach's Alpha
F1 Geometry	0.744
F1.1 Shape of Tunnel, F1.2 Crown Height, F1.3 Thickness of Lining, F1.4 Tunnel Length and Alignment	
F2 Economy	0.747
F2.1 Initial Investment, F2.2 Repair and Maintenance, F2.3 Stripping Cost, F2.4 Reusability	
F3 Quality	0.693
F3.1 Mix Ratio of Concrete, F3.2 Compaction of Concrete, F3.3 Surface Finishing, F3.4 Cold Joints/Combing Defect	
F4 Work Safety	0.829
F4.1 Safety Induction, F4.2 Risk Assessment, F4.3 Primary Lining, F4.4 Working Environment, F4.5 Degree of Supervision	
F5 Project Complexity	0.716
F5.1 Company Practices, F5.2 Uplift of Formwork, F5.3 Site Characteristics, F5.4 Flexibility in Design, F5.5 Formwork Expertise	
F7 Labour Management	0.885
F7.1 Resource Requirement, F7.2 Resource available, F7.3 Scheduling and Controlling	
F8 Geological Conditions	0.971
F8.1 Topography, F8.2 Geology of Soil and Rock Mass, F8.3 Engineering Behaviour of Soil and Rock	
F11 Organizational Support	0.147 (0.8)
F11.1 Available Capital, F11.2 Contract Administration, F11.3 Hoisting Equipment, F11.4 Troubleshooting Experience*	

Note: *symbol indicates that factors or sub-factors are eliminated from the study

Therefore, the selected tunnel lining formwork system look for less initial cost, minimum repairs and a high reuse cycle. (3) Quality of formwork impacts the quality of the tunnel structure. (4) Safety during the moulding of the formwork system can reduce the hazards and risks associated with the progress of the tunnel lining work. (5) Project complexity of constructing tunnel also creates a challenge for the moulding formwork system too, as it is based on various aspects such as company practices, site characteristics, etc. (6) Labour management is decisive in terms of resource identification, resource requirement, resource availability, and resource control through its staffing and levelling. The lining formwork requires special attention and skilled labour (Jha 2012); therefore, the availability of necessary labour and their staffing is crucial in selecting the lining formwork system. (7) Geological factors, such as ground conditions, location of the water table, soil bearing capacity, and rock strength, decide the suitable module of formwork. These sub-factors play a vital role in designing and fabricating the heavy parts of the tunnel lining formwork system. (8)

Organisation support is essential to sustain financial investment for the tunnel lining formwork from the initial to the completion stage of the project. Therefore, the proposed three-level hierarchy structured framework qualitatively helps the tunnel engineers and practitioners in selecting an appropriate tunnel lining formwork system.

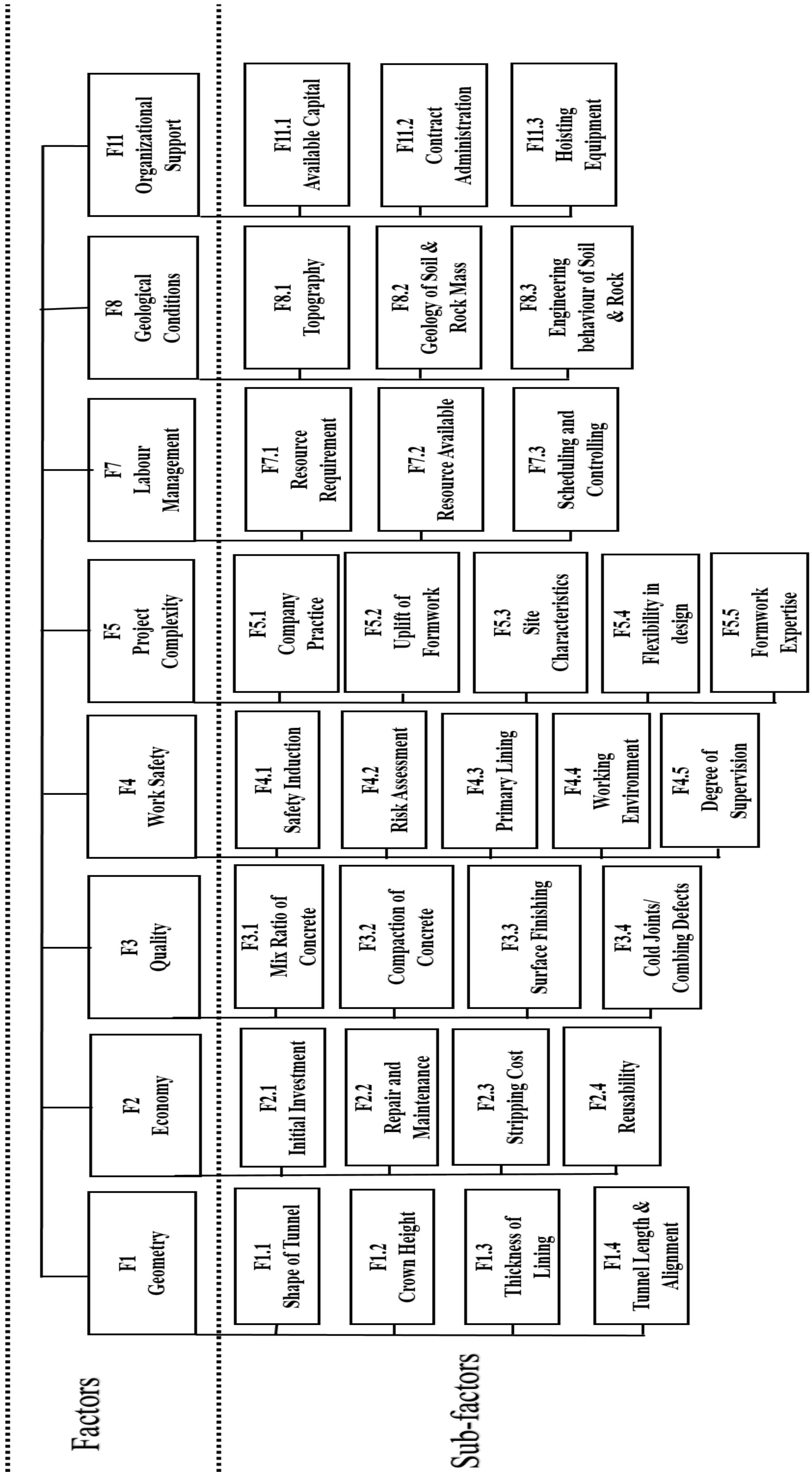

Figure 2. Framework for selecting tunnel lining formwork system

CONCLUSIONS

The proposed study aims to develop the framework for selecting the tunnel lining formwork system using the Delphi method.

First, the existing literature was used to identify factors and their sub-factors affecting the selection of tunnel lining formwork. Then, in the first round of the Delphi method, the experts' opinions were taken to confirm the identified factors and sub-factors. For shortlisting, the statistical parameters, AD-median, CV, and Range of Data, were determined, and their limits were set to be less than 0.75, 0.249, and 3, respectively.

Based on these statistical parameters and their limits, eight factors and their corresponding 32 sub-factors were shortlisted in the second round of the Delphi method. The consent was taken from all experts for agreement on the results of the second round. Then, the value of Cronbach's alpha is determined for each factor, which shows that one of the factors, "Organisational Support", had less value than the required (i.e., 0.6). Thus, the sub-factor, 'Troubleshooting Experience', was eliminated to have better reliability and internal consistency for this factor. Therefore, the final eight factors and their corresponding 31 sub-factors were used to develop a framework for selecting an appropriate tunnel lining formwork system.

The proposed framework represents the potential factors and sub-factors that can be used for selecting the formwork system. The limitation of the present study is that the developed framework is only applicable to tunnel construction. Before the framework could be used to assess and select the formwork system quantitatively, it is essential to determine the relative weights of the eight factors and their sub-factors.

For this, further research is required to propose a quantitative approach for selecting the formwork system for the tunnel lining work. An index can be developed in order to rank the factors and sub-factors.

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