INTEGRATION OF DELPHI TECHNIQUE AND ANALYTICAL HIERARCHY PROCESS IN SELECTING THE TYPE OF DAM: A CASE STUDY OF BUNGOH CATCHMENT IN SARAWAK, MALAYSIA

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ABSTRACT

Dams are built ancient structures, which serve to retain, collect, and store water. Over the years, the function of dams has been diversified to flood prevention, water level regulation, and even recreational purposes. However, selecting a suitable type of dam based on the characteristics of a potential dam site is consistently a concern in the preliminary construction stage. Therefore, this study attempts to integrate the Delphi technique and Analytical Hierarchy Process (D-AHP) to develop a set of influential attributes, which assists in the selection of a suitable type of dam for the potential dam site. These influential attributes are determined based on comprehensive literature reviews and corroborated by twelve experts from relevant fields through three rounds of interviews. Using the Delphi technique, 9 important criteria and 25 sub-criteria are finalized. Expert’s judgments are measured through pairwise comparisons to derive eigenvectors. Based on prioritisation of AHP, the gravity dam scores the highest total weight, and is selected as the optimal type of dam for Bungoh catchment. The selection of the gravity dam is quantified based on the developed influential attributes, which include environmental criteria, social criteria, and engineering criteria. Essentially, the selection takes the characteristics of the potential dam site into account during the pairwise comparison process. In this context, the developed set of influential attributes could objectively assist related organizations in their decision making process. These attributes are also applicable in the preliminary stage of any dam development project.[1]

Keywords: Analytical Hierarchy Process (AHP); Delphi technique; Multi-criteria decision making (MCDM); type of dam

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1. Introduction

Dams are structures that impound water or underground streams. They serve the purpose of retaining, collecting and storing water, which is then evenly diverted between locations (Beck et al., 2013). Dams have been constructed for centuries globally to provide water for agricultural and municipal uses (Azami et al., 2012). However, the suitability of a constructed dam type in a potential dam site is consistently questioned. Moreover, the decision making process over the suitability of a dam type typically involves a trade-off from among many intangibles (Saaty, 2008). Therefore, this study attempts to integrate both the Delphi technique and Analytical Hierarchy Process (D-AHP) to develop a set of influential attributes in selecting a suitable type of dam for the potential dam site.

Based on expert's judgments over a scale of absolute judgments, AHP assists the measurement of each attribute through pairwise comparisons to derive priority scales (Saaty, 2008). The priority scales are synthesized by multiplying them with the priority of their parent nodes and adding all such nodes (Saaty, 2008). In recent years, the integration of the Delphi technique and AHP method (D-AHP) has been employed to further refine the attributes used in the decision making process (Arof, 2015). In fact, the integration of D-AHP itself is academically recognized (Arof, 2015). In developing a decision making model, the Delphi technique is typically utilized in the preliminary research stage to identify prominent variables for selection, which is subsequently followed by the AHP method to determine the weight of selected variables (Chung & Her, 2013; Da Cruz et al., 2013; Lee et al., 2014; Moradi et al., 2014; Sayareh & Alimini, 2014).

The Delphi technique is a widely used method to achieve convergence of opinion in relation to the real-world knowledge, solicited from experts within specific areas (Hsu & Sandford, 2007). During the 1950s, the Delphi technique was developed by the Rand Corporation in the United States to support military strategic-oriented surveys (Chaves et al., 2012). It was later applied externally by Dalkey & Helmer (1963), where the Delphi technique was specifically defined by means of obtaining the most reliable collective opinion from a group of specialists, subjected to a combination of questionnaires and/or interviews and controlled feedback in a series of cycles (Chaves et al., 2012). Theoretically, the Delphi technique could be continuously iterated until a consensus is achieved (Hsu & Sandford, 2007). Nevertheless, three iterations are often sufficient to collect the required information before achieving a consensus in most cases (Cyphert & Gant, 1971; Brooks, 1979; Ludwig, 1997; Custer et al., 1999).

Meanwhile, AHP is a multi-criteria decision making (MCDM) method, which principally consists of three levels, namely the main goal, criteria, and alternatives (Adamcsek, 2008; Gawlik, 2008; Yau, 2009). AHP is a decision support tool to solve complex problems, in which the main goal level could be extended into forces and actors influencing the decision making process; the criteria level could be divided into both criteria and sub-criteria; and the alternatives could be treated as action scenarios and prognostics of their effects (Gawlik, 2008). The number of criteria to be taken into account could be rather extensive in a strategic decision making process particularly in a disorderly environment of actual economic reality. Theoretically, more determinants at the preparatory stage are associated with improved decision making. However, multiplying the number of factors obfuscates the main goal and potentially affects the final decision (Saaty, 1990; Gawlik, 2008). Thus, a certain number of criteria are necessary to mitigate the problem. According to Saaty (2003), the number of analyzed criteria and alternatives in a decision making process should

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not exceed 7 (+/- 2), which gives a maximum of 9 criteria/alternatives to ensure appropriate precision in the obtained results.

2. Methodology

The AHP method involves six essential steps, which are in the following order: (1) define the main goal or objective, (2) structure the AHP hierarchy, (3) conduct pairwise comparisons, (4) calculate the eigenvectors, (5) evaluate the consistency, and (6) obtain the total weights and overall ranking of the alternatives (Safari et al., 2010; Yasser et al., 2013). For this study, the main goal is to select a suitable type of dam for a potential dam site. Subsequently, the Delphi technique is integrated into the AHP to obtain the necessary data from participants within their domain of expertise and gather their opinion specifically on the influential criteria in selecting the optimal type of dam alternative (Hsu & Sandford, 2007). The data collection stage proceeds as follows:

First round: A structured questionnaire is developed based on extensive reviews of related literature, which serves as the cornerstone of soliciting important criteria in determining the optimal type of dam (Custer et al., 1999). According to Hsu & Sandford (2007), utilizing a structured questionnaire in the preliminary round is acceptable and considered a common modification in the Delphi process format. After obtaining responses from all twelve experts, the gathered information is then converted into a revised questionnaire, which is utilized in the second round of data collection.

Second round: The revised questionnaire is distributed to each selected expert and these experts are required to rank the criteria as well as the sub-criteria to establish preliminary priorities, in which areas of agreement and disagreement are identified (Ludwig, 1994). In some cases, Delphi panellists are required to state the rationale concerning their ranking priorities among the provided items (Jacobs, 1996). In this round, initial consensus is obtained and the actual outcomes are presented based on the expert’s responses.

Third round: The revised questionnaire is redistributed among experts with a summary from the previous round. In this round, experts are required to refine their judgments regarding the relative importance of these items. Consequently, a finalized questionnaire containing influential attributes (criteria and sub-criteria) is developed to structure the AHP hierarchy in selecting the optimal type of dam. Nevertheless, a slight increase in the degree of consensus between the final two rounds is typically expected (Weaver, 1971; Dalkey & Rourke, 1972; Anglin, 1991; Jacobs, 1996).

With the developed hierarchy structure, pairwise comparisons are conducted at each level, namely goal, criteria, sub-criteria, and alternatives. Experts are required to determine the relative preference for the elements in each level using an underlying semantic 9-point scale, representing different intensities of importance, which was developed by Thomas Saaty (Table 1).

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Table 1
Saaty's scale of preferences in the pairwise comparison process (Saaty, 1990)

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favour one activity over another
5	Strong importance	Experience and judgment strongly favour one activity over another
7	Very strong or demonstrated importance	An activity is favoured very strongly over another; its dominance is demonstrated in practice
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation.
2,4,6,8	Intermediate values between adjacent scale values	When compromise is needed

All the attributes in the hierarchy are compared in the pairwise comparison matrix as shown in Equation 1, where A is the pairwise comparison matrix, w_1 represents the weight of element 1, w_2 represents the weight of element 2, and w_n represents the weight of element n (Saaty, 1990; Yasser et al., 2013):

$$A = \begin{bmatrix} \frac{w_1}{w_1} & \frac{w_1}{w_2} & \cdots & \frac{w_1}{w_n} \\ \frac{w_2}{w_1} & \frac{w_2}{w_2} & \cdots & \frac{w_2}{w_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & \cdots & \frac{w_n}{w_n} \end{bmatrix} \quad (1)$$

As pairwise comparisons are conducted by experts, eigenvectors or relative weights of the attributes are calculated using Equation 2. Following that, the eigenvalues of matrix A are obtained using simultaneous solutions of Equation 3 and Equation 5, where λ_{max} is the principal eigenvalue of matrix A, W (Equation 4) is the eigenvectors, and I is the unit matrix (Yasser et al., 2013):

$$A \, x \, W = \lambda \, x \, W \quad (2)$$

$$(A - \lambda_{max} I) \, x \, W = 0 \quad (3)$$

$$W = (w_1, w_2, w_3, \dots, w_n) \quad (4)$$

$$\sum_{i=1}^{n} w_i = 1 \quad (5)$$

Once the eigenvectors are obtained, they are subjected to consistency checking. This is an important step to evaluate the degree of reasonability of expert's judgments (Saaty, 2008). Therefore, a Consistency Index (CI) (Equation 6) is used, where n is the dimension of the pairwise comparison matrix (Yasser et al., 2013).

$$\text{Consistency Index} = \frac{\lambda max - n}{n-1} \quad (6)$$

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The value of the CI is calculated with random numbers using a Random Consistency Index (RCI). Table 2 shows the values of RCI for (1–10) dimensional matrices. For each matrix, a Consistency Ratio (CR) (Equation 7) is calculated by dividing CI with RCI. CR is an appropriate index for consistency judgment (Yasser et al., 2013). When CR exceeds 0.1, the judgments are considered untrustworthy because they are too close for comfort to randomness and the process is valueless or must be repeated (Teknomo, 2006).

Table 2
Random Consistency Index (RCI) (Saaty, 1980)

n	1	2	3	4	5	6	7	8	9	10
R.C.I	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

$$\text{Consistency ratio} = \frac{\text{Consistency Index}}{\text{Random Consistency Index}} \quad (7)$$

The final stage of AHP is to obtain the total weights and overall ranking of the alternatives for the type of dam. The eigenvector (relative weight) of each criteria and sub-criteria (attribute) as well as the eigenvectors of alternatives are combined based on Equation 8, where *Wi* is the total weight of alternative *i*, w_{ij}^{a} is the eigenvector of alternative *i* with respect to attribute *j*, w_{ij}^{c} is the eigenvector of criterion *j*, *m* is the number of criteria, and *n* is the number of alternatives (Yasser et al., 2013):

$$W_i = \sum_{j=1}^{m} (w_{ij}^{a}) \left(w_j^{c}\right) \quad (i = 1, 2, \ldots, n) \quad (8)$$

3. Results and discussion

3.1 Developing the D-AHP hierarchical structure for dam type selection

The integration of D-AHP selects the most influential attributes in determining the suitable type of dam. Twelve experts are selected from the fields of ecological studies, socio-economic, biodiversity conservation, water quality, biology conservation, environmental impact assessment, environmental management, forest hydrology, wildlife ecology, and engineering to participate in this study. The years of experience among these selected experts in their respective field range from 3 to 10 years.

Table 3 shows 9 important criteria and 25 sub-criteria, which are selected by these experts after three iterations of a questionnaire survey. These attributes are used during the decision making process. The influential attributes are represented with abbreviations of C_1 to C_9 and SC_1 to SC_{25} respectively, while the four alternatives are assigned with 'A', 'B', 'C' and 'D'. These attributes are then used to form the hierarchy structure as shown in Figure 1.

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Table 3
The most influential attributes in selecting the type of dam

Criteria	**Definition**	**Sub-criteria**	**Definition**
C_1	Topography	SC_1	Valley shape
		SC_2	Accessibility
		SC_3	Valley cross section
		SC_4	River plan
C_2	Hydrology	SC_5	River catchment
		SC_6	Average runoff
		SC_7	Daily flow
		SC_8	Groundwater
		SC_9	Flood regime
C_3	Water quality		
C_4	Geology	SC_{10}	Foundation type
		SC_{11}	Bearing capacity
		SC_{12}	Foundation thickness
		SC_{13}	Foundation dip
		SC_{14}	Foundation jointing
		SC_{15}	Foundation permeability
		SC_{16}	Seismicity
		SC_{17}	Safety
C_5	Climate	SC_{18}	Climate type
		SC_{19}	Rainfall
		SC_{20}	Temperature
		SC_{21}	Evaporation
		SC_{22}	Humidity
C_6	Flora & fauna		
C_7	Land use		
C_8	Economical condition	SC_{23}	Material supply
		SC_{24}	New technology
		SC_{25}	Skilled contractor
C_9	Local community		

The hierarchy structure consists of four levels. The first level is the objective (goal) of D-AHP, which is to select the optimal type of dam. The second level is the criteria, which consists of 9 criteria: (1) topography, (2) hydrology, (3) water quality, (4) geology, (5) climate, (6) flora & fauna, (7) land use, (8) economical condition and (9) local community. Meanwhile, the third level consists of 25 sub-criteria, namely (1) valley shape, (2) dam site accessibility, (3) changes in valley cross section, (4) condition of the river in plan, (5) river catchment, (6) average runoff, (7) daily flow, (8) groundwater, (9) flood regime, (10) foundation type, (11) foundation bearing capacity, (12) foundation thickness, (13) foundation dip, (14) foundation joint, (15) foundation permeability, (16) seismicity, (17) safety, (18) climate type, (19) rainfall, (20) temperature, (21) evaporation rate, (22) humidity, (23) supply of the manufactured materials, (24) application of new technology and (25) skilled contractors. The fourth level is the type of dam, specifically embankment dam, gravity dam, arch dam, and buttress dam.

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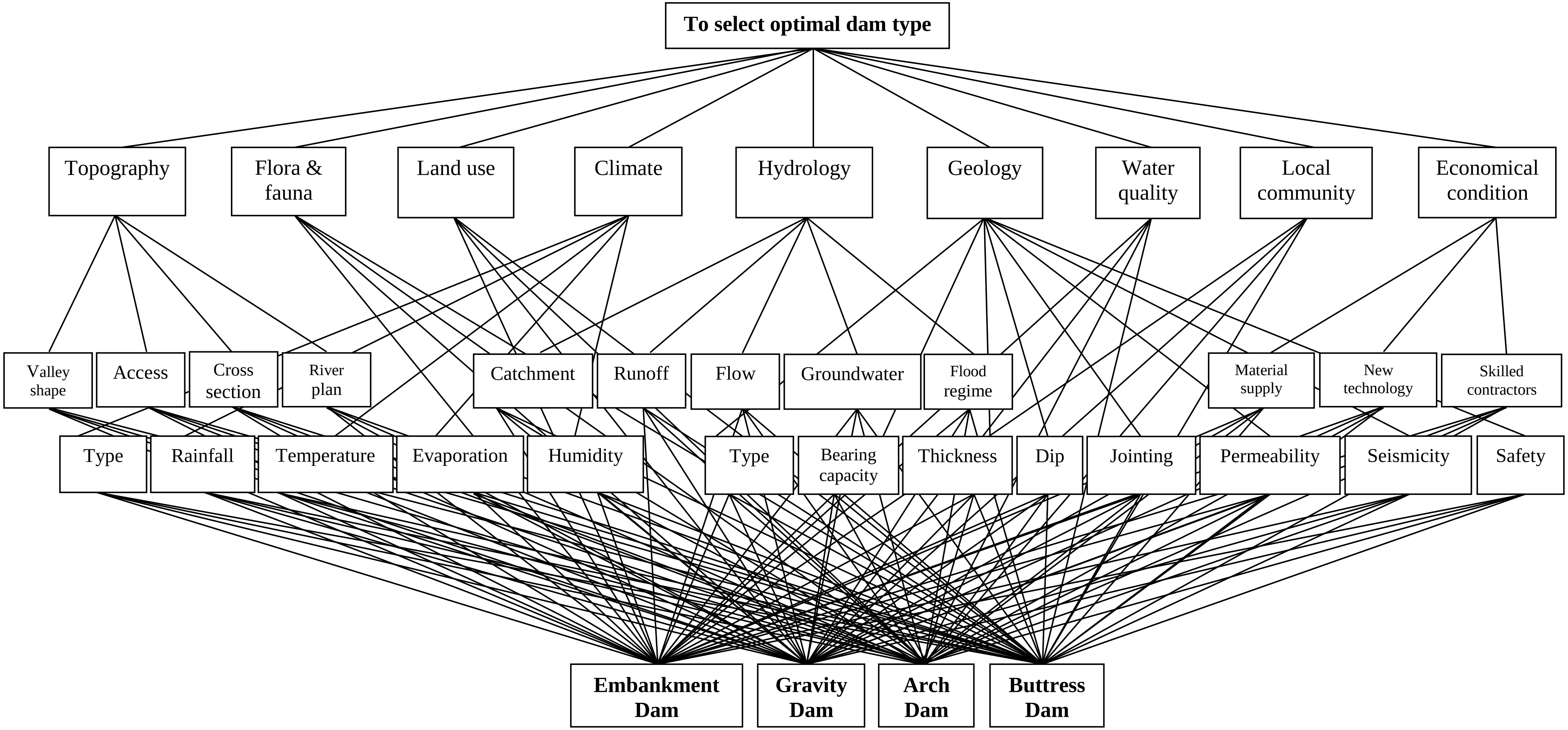

Figure 1 D-AHP hierarchy structure in selecting the type of dam

Brief explanations about the selected attributes are provided below:

Topography: In general, topography dictates the first choice in selecting the type of dam. The topographic considerations include surface configuration (such as valley shape, condition of the river in plan, changes in valley cross section) and accessibility to the potential dam construction site (Walters, 1962; Sherard et al., 1963; Thomas, 1976; Emiroglu, 2008).

Hydrology: This attribute includes the existence of river catchment and groundwater, the level of average runoff, daily flow, and flood regime at the potential dam site. The proposed type of dam depends on the purpose the dam serves.

Water quality: The effects of aggressive water on a dam may influence the type of dam; stored water in a reservoir might contain dissolved chemicals (such as acids) that are harmful for concrete (Mason, 1990; Emiroglu, 2008).

Geology: The type, bearing capacity, thickness, dip, jointing, and permeability of the geological foundations at the potential dam site are a set of decisive factors in selecting the type of dam (Deere, 1976; Soderberg, 1979; Bureau of Reclamation, 1987; Bell, 1993; Becue et al., 2002). However, the foundation limits the type of dam to a certain extent, which could be modified by considering the height of a proposed dam (Emiroglu, 2008).

Climate: This attribute comprises climate types, rainfall, temperature, evaporation rate, and humidity, where the design of a dam could be considerably affected as the weather plays an essential role during the dam construction period (Sherard et al., 1963; Armstrong, 1977).

Flora & fauna: The existence of exotic flora and fauna at a dam site has an influence on the selection of dam type. The principal influence of environmental laws and regulations in selecting the type of dam is necessary to consider optimum environmental protection, in which the type of dam, size of dam, locations, and other aspects could be influenced (Emiroglu, 2008).

Land use: It is recognized that a dam is a large artificial structure in regards to its height and type. Thus, the location and natural environment should be taken into account when a potential dam site is selected (Arai et al., 2009). If the constructed dam affects land use of the selected dam site, mitigation plans or other potential dam sites should be considered to preserve the existing settlements, arable land, and pastures in that site.

Economic condition of a country: A country's economic condition plays an important role in influencing the type of dam as the dam construction depends heavily on the supply of manufactured material such as cementitious materials, steel, asphalt, and others (Sherard et al., 1963). The application of new technology for dam construction may be deployed if a country is economically strong, which enables an intricate dam framework with the assistance of skilled personnel (Emiroglu, 2008).

Local community: Local community refers to the villagers near the potential dam site. This attribute might seem to have no direct influence to the selection of dam type. However, with this large artificial structure at the potential site, the displacement of neighbouring settlements should be taken into consideration as they could potentially lose their source of income. Forest or arable land nearby is typically

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used to grow crops, which is the local community's source of income. While the construction of a dam is meant to bring comfort and contribute to human development, the natural environment is also a source of income for the local community; a balance between a manmade environment and a natural environment should exist for environmental preservation.

3.2 Pairwise comparison and calculations

The hierarchy structure (Figure 1) is utilized to conduct pairwise comparison to obtain the final ranking of the type of dam for the case study of Bungoh catchment in Sarawak, Malaysia. The Bungoh catchment is located between 1.184° and 1.296° latitude and between 110.106° and 110.242° longitude (Latifah et al., 2014).

Pairwise comparison is an important component, where expert's judgments are recoded based on Saaty's scale of preference, as previously shown in Table 1. Referring to the developed hierarchy structure (Figure 1), experts work together as a unit to aggregate their judgements for the comparison matrices according to their knowledge, experience, and expertise (Forman & Peniwati, 1998). A group interview with twelve experts was conducted to discuss and come up with an agreement regarding the intensity of importance for each comparison matrix. The pairwise comparison of D-AHP is conducted by comparing each level - [1] criteria towards goal, [2] sub-criteria towards criteria, and [3] alternatives towards criteria and sub-criteria. Table 4 shows the comparison matrix of criteria towards the goal.

Using Equations 2-5, the eigenvectors (relative weights) of the attributes and alternatives are obtained and provided in the final column, as shown in Table 4. The sum of the relative weights equals1, as these relative weights are normalized. Relative weights indicate the priority of each criterion in this pairwise comparison. C_1 has the highest priority with the highest relative weight (0.271), followed by C_4 (0.202), C_8 (0.142), C_9 (0.122), C_6 (0.113), C_7 (0.076), C_2 (0.028), C_3 (0.024), and C_5 (0.022). Referring to Table 2, the principle eigenvalue (λmax) for this pairwise comparison matrix is 9.66 while RCI is 1.45 for 9 criteria. CI (0.083) and CR (0.057) are calculated using Equations 6 and 7 respectively. Based on Table 4, CR is less than 0.1, which indicates an acceptable and consistent decision. This process is repeated with all pairwise comparisons to obtain respective eigenvectors.

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Table 4
Pairwise comparison of criteria towards goal

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	Weight
C_1	1	9	8	2	5	2	3	3	5	0.271
C_2	1/9	1	1	1/7	2	1/4	1/3	1/4	1/8	0.028
C_3	1/8	1	1	1/7	2	1/6	1/5	1/6	1/9	0.024
C_4	1/2	7	7	1	8	2	3	2	2	0.202
C_5	1/5	1/2	1/2	1/8	1	1/2	1/5	1/8	1/7	0.022
C_6	1/2	4	6	1/2	2	1	2	1	1	0.113
C_7	1/3	3	5	1/3	5	1/2	1	1/3	1/2	0.076
C_8	1/3	4	6	1/2	8	1	3	1	2	0.142
C_9	1/5	8	9	1/2	7	1	2	1/2	1	0.122

Principle Eigen Value (λmax)	Consistency Index (CI)	Random Consistency Index (RCI)	Consistency Ratio (CR)
9.66	0.083	1.45	0.057

3.3 Priority analysis and overall ranking

Priority analysis lists the calculated eigenvectors (relative weights) for three levels of pairwise comparison matrices. The first column in Table 5 reveals the eigenvectors of criteria with respect to the specified objective (goal). The second column reveals the eigenvectors of sub-criteria towards criteria, and the final four columns reveal the eigenvectors of alternatives towards criteria and sub-criteria. The total weight of each alternative is calculated using Equation 8, as tabulated in the final row of Table 5.

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Table 5
The total weight of each type of dam

Criteria	**Sub-criteria**	**Alternatives**			
		A	**B**	**C**	**D**
C_1 (0.271)	SC_1 (0.711)	0.047	0.413	0.238	0.302
	SC_2 (0.154)	0.593	0.208	0.081	0.118
	SC_3 (0.068)	0.445	0.360	0.127	0.069
	SC_4 (0.068)	0.505	0.308	0.091	0.096
C_2 (0.028)	SC_5 (0.522)	0.422	0.327	0.106	0.124
	SC_6 (0.071)	0.579	0.202	0.104	0.115
	SC_7 (0.071)	0.662	0.116	0.090	0.132
	SC_8 (0.062)	0.076	0.318	0.080	0.526
	SC_9 (0.274)	0.087	0.525	0.218	0.171
C_3 (0.024)		0.066	0.277	0.315	0.342
C_4 (0.202)	SC_{10} (0.272)	0.074	0.072	0.481	0.372
	SC_{11} (0.199)	0.052	0.223	0.419	0.306
	SC_{12} (0.044)	0.472	0.315	0.122	0.091
	SC_{13} (0.106)	0.064	0.255	0.450	0.231
	SC_{14} (0.113)	0.628	0.180	0.091	0.101
	SC_{15} (0.025)	0.627	0.213	0.077	0.083
	SC_{16} (0.052)	0.077	0.376	0.404	0.143
	SC_{17} (0.189)	0.062	0.210	0.506	0.222
C_5 (0.022)	SC_{18} (0.063)	0.498	0.197	0.139	0.166
	SC_{19} (0.408)	0.498	0.197	0.139	0.166
	SC_{20} (0.094)	0.498	0.197	0.139	0.166
	SC_{21} (0.372)	0.498	0.197	0.139	0.166
	SC_{22} (0.062)	0.498	0.197	0.139	0.166
C_6 (0.113)		0.176	0.231	0.430	0.163
C_7 (0.076)		0.389	0.079	0.170	0.362
C_8 (0.142)	SC_{23} (0.548)	0.058	0.380	0.305	0.257
	SC_{24} (0.241)	0.129	0.125	0.340	0.405
	SC_{25} (0.210)	0.095	0.089	0.265	0.551
C_9 (0.122)		0.103	0.395	0.135	0.367
Total weight		0.176	0.277	0.272	0.275

The total weight for alternatives A, B, C, and D is 0.176, 0.277, 0.272, and 0.275 respectively. As a result, alternative B, which is the gravity dam, has the highest total weight; hence, it is considered the optimal dam type for the selected site, which is the Bungoh catchment.

The selection of a dam type is quantified based on the developed influential attributes, which include environmental criteria, social criteria, and engineering criteria. Essentially, the selection takes the characteristics of a potential dam site into account during the pairwise comparison process. According to Singh & Sharma (1976), the type of dam is typically dictated by the foundation (geology) and valley shape (topography). The foundation and valley shape at the Bungoh catchment is a rock foundation and a narrow U-shaped valley respectively. The selection of a gravity dam for Bungoh catchment satisfied both of the fundamental attributes, as a gravity dam is to be constructed on a sound rock foundation with a narrow shaped valley to ensure it is seismically safe. Although the total weights of both alternative C and alternative D are slightly lower than alternative B, experts suggested that alternative B is a more suitable type of dam for Bungoh catchment.

4. Conclusion

The selection of a dam type is influenced by various factors, which may not be well-documented. This complicates the decision making process and the decision made may be rather subjective since a set of systematic processes does not exist. Therefore, a type of multi-criteria decision making (MCDM) method is utilized to address this problem. In this study, the integration of Delphi-Analytical Hierarchy Process (D-AHP) develops a set of influential attributes (9 criteria and 25 sub-criteria), which assists in selecting the type of dam for a potential dam site. Through the developed hierarchy structure, a complicated decision making process is simplified and could be performed objectively, as it takes three fundamental elements into account, namely environmental criteria, social criteria, and engineering criteria, rather than focusing on one specific criterion. The outcome of this study is proven effective as it is in line with the selected type of dam for Bungoh catchment, which is the gravity dam. In addition, the developed AHP hierarchy structure, not only could be employed for Bungoh catchment, but it is also applicable in the preliminary stage of any dam development project.

APPENDIX

Example of pairwise comparison matrix calculation

Comparison of alternatives with respect to valley shape sub-criterion

The pairwise comparison matrix in Table 6 shows that gravity dam and arch dam are of "very strong importance" to embankment dam, with the intensity of importance of 7. Both of the judgement values are in reciprocal values (1/7). This is due to both the pairwise comparison between embankment dam and gravity dam and the pairwise comparison between embankment dam and arch dam favouring the gravity dam and arch dam over embankment dam. Meanwhile, buttress dam is of "strong importance" compared to an embankment dam, with the intensity of importance of 6. The selection of intensity importance of 6, which is the intermediate value between the intensity of importance of 5 and 7, signifies the need of compromising, as revealed in Table 1. The judgement value is in reciprocal values (1/6) as the pairwise comparison between embankment dam and buttress dam favours a buttress dam over an embankment dam. The pairwise comparison value equals 1 when an embankment dam is compared to itself. On the other hand, a gravity dam is of "moderate importance" compared to an arch dam, with the intensity of importance of 3. This signifies that the judgement slightly favours a gravity dam over an arch dam. Gravity dam is of "equal importance" compared to buttress dam, with the intensity of importance of 1. This represents that the comparison between a gravity dam and a buttress dam contributes equally to the objective. Arch dam has "equal importance" compared to buttress dam, with the intensity of importance of 1. This means that the comparison between arch dam and buttress dam contributes equally to the objective as well. The reciprocal matrix value is used to complete the comparison. For example, the pairwise comparison value for embankment dam with respect to gravity dam equals to 1/7; thus, the pairwise comparison value for gravity dam with respect to embankment dam equals to 7.

The subsequent step after pairwise comparison is the calculation of eigenvectors. There are several methods to calculate the eigenvectors. One of the methods, which gives a very good approximation, is to multiply the entries in each row of the matrix and then take the n^{th} root of that product (Coyle, 2004). The n^{th} root is summed and that value is used to normalize the eigenvectors. The summed eigenvectors is equivalent to 1.00. In the following matrix, the 4^{th} root for the first row is 0.242 and this value is divided by 5.184, which equals 0.047, as the first element in the eigenvector. The eigenvector for gravity dam, arch dam and buttress dam is 0.413, 0.238 and 0.302 respectively.

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Table 6
Pairwise comparison and calculation of eigenvectors

	Embankment Dam	Gravity Dam	Arch Dam	Buttress Dam	n^{th} root of product of values	Eigen vectors
Embankment Dam	1	1/7	1/7	1/6	0.242	0.047
Gravity Dam	7	1	3	1	2.141	0.413
Arch Dam	7	1/3	1	1	1.236	0.238
Buttress Dam	6	1	1	1	1.565	0.302
Total					5.184	1.000

Calculation of principle eigenvalue

The following step is the calculation of the principle eigenvalue (λ_{max}). The matrix of judgments is multiplied by the calculated eigenvectors to obtain a new vector, as shown in the following calculation:

Embankment dam = 1*0.047 + 1/7*0.413 + 1/7*0.238 + 1/6*0.302 = 0.190
Gravity dam = 7*0.047 + 1*0.413 + 3*0.238 + 1*0.302 = 1.758
Arch dam = 7*0.047 + 1/3*0.413 + 1*0.238 + 1*0.302 = 1.007
Buttress dam = 6*0.047 + 1*0.413 + 1*0.238 + 1*0.302 = 1.235

These vectors of four elements (0.190, 1.758, 1.007, and 1.235) are the product of *A* x *W* (Equation 2) and the theory of AHP stated in Equation 3 and Equation 5, where λ_{max} is determined by dividing each component with the corresponding eigenvector:

Embankment dam = 0.190/0.047 = 4.043
Gravity dam = 1.758/0.413 = 4.257
Arch dam = 1.007/0.238 = 4.231
Buttress dam = 1.235/0.302 = 4.089

The mean of these values equals 4.155 and this value is λ_{max} of the matrix. If any of the estimated λ_{max} is less than n or in this case, n = 4, this denotes that there is an error in the calculation. This serves as a useful sanity check (Coyle, 2004).

Testing of the consistency ratio

Next, the CI is determined through Equation 6 and since n = 4 for this matrix, the CI is:

CI = (4.155 - 4) / (4 - 1) = 0.052

The final step is the calculation of CR. For this set of judgments, referring to Table 2 for RCI value, using the obtained CI as the corresponding value, CR is calculated (Saaty, 1980; Coyle, 2004). Therefore, CR (Equation 7) for this matrix is:

CR = 0.052 / 0.90 = 0.058

Calculation of total weight

Using Equation 8, the total weight of each dam type alternative is calculated. The following is an example of the calculation to obtain total weight for the embankment dam, which is by integrating the eigenvectors of decision elements:

W_A = (0.271*0.711*0.047) + (0.271*0.154*0.593) + (0.271*0.068*0.445) + (0.271*0.068*0.505) + (0.113*0.176) + (0.076*0.389) + (0.022*0.063*0.498) + (0.022*0.408*0.498) + (0.022*0.094*0.498) +

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(0.022*0.372*0.498) + (0.022*0.062*0.498) + (0.028*0.522*0.442) +
(0.028*0.071*0.579) + (0.028*0.071*0.662) + (0.028*0.062*0.076) +
(0.028*0.274*0.087) + (0.202*0.272*0.074) + (0.202*0.199*0.052) +
(0.202*0.044*0.472) + (0.202*0.106*0.064) + (0.202*0.113*0.628) +
(0.202*0.025*0.627) + (0.202*0.052*0.077) + (0.202*0.189*0.062) +
(0.024*0.066) + (0.122*0.103) + (0.142*0.548*0.058) +
(0.142*0.241*0.129) + (0.142*0.210*0.095)
= 0.176

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