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# Optimal monitoring instruments selection using innovative decision support system framework

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**Abstract.** Structural monitoring is the most important part of the construction and operation of the embankment dams. Appropriate instruments selection for dams is vital, as inappropriate selection causes irreparable loss in critical condition. Due to the lack of a systematic approach to determine adequate instruments, a framework based on three comparable Multi-Attribute Decision Making (MADM) methods, which are VIKOR, technique of order preference by similarity to ideal solution (TOPSIS) and Preference ranking organization method for enrichment evaluation (PROMETHEE), has been developed. MADM techniques have been widely used for optimizing priorities and determination of the most suitable alternatives. However, the results of the different methods of MADM have indicated inconsistency in ranking alternatives due to closeness of judgements from decision makers. In this study, 9 criteria and 42 geotechnical instruments have been applied. A new method has been developed to determine the decision makers' importance weights and an aggregation method has been introduced to optimally select the most suitable instruments. Consequently, the outcomes of the aggregation ranking correlate about 94% with TOPSIS and VIKOR, and 83% with PROMETHEE methods' results providing remarkably appropriate prioritisation of instruments for embankment dams.

**Keywords:** management; embankment dam; field instrumentation; geotechnical engineering; structural monitoring; decision making

## 1. Introduction

Concerning level of accuracy in the modelling and analysing of embankment dams and its comparability to field stresses, deformations, seepage pattern and etc., design and construction of embankment dams usually are along with uncertainties (Milligan 2003). Therefore, embankment dams' monitoring is a critical part all over the project management plan. When the project is in operation, observations, investigations and evaluations become necessary for satisfying operational objectives. The economic well-being and safety are the two most important goals in the dams designing and construction (Bassett 2012).

The instrumentation and monitoring project of an embankment dam affects quality and safety of the plan. Undesirable instrumentation causes irreparable problems. Safety of structures needs applying effective instruments, which means those should be selected based on special condition of the projects with appropriate compatibility of expectations. Adaptability and effectivity of the instrumentation plan have been considered as one of the main topics among researchers' interest (Teng *et al.* 2015). Furthermore, assessing dam performance by experts needs appropriately gained data from adaptable instruments (Curt and Talon 2013). Adequate instrument selection needs evaluation of different criteria for the projects. There are diverse type of instruments which are applied in structures such as dams. Every instruments include specific features which makes them unique. Installation, data transferring, transducer, data acquisition and structure of the instruments are different which form various types of instruments as decision alternatives. On the other hand, selection of appropriate instruments is one of the most important stage of a monitoring plan (Dunnicliff 1993, Kong 2003, Eberhardt and Stead 2011). The instruments should be selected based on various criteria which complicated the selection. These factors are, but not limited to, reliability, cost, accessibility, installation condition, accuracy level, lifetime and etc. (Andersen *et al.* 1999, Mauriya 2010).

In most studies, instruments selection were based on experimental tables and even there were not any framework to prioritise the instruments based on decision making methods (Naterop 2002, Novak *et al.* 2007, Dunnicliff 1993). Therefore, in this study a framework proposed to select the reliable instruments based on Multi-Attribute Decision Making (MADM) techniques. There are several decision making methods which have known as subgroups of MADM and the MADM itself is one of the subgroups of Multi-Criteria Decision Making (MCDM).

Nowadays, the use of the MADM techniques is increasing in decision-making processes and different areas. It is because of the simplicity and understandability of these

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techniques for various users (Behzadian *et al.* 2012, Behzadian *et al.* 2010, Gul *et al*. 2016).

Regarding the importance of instruments selection, three MADM methods have been employed. Multi criteria optimisation and compromise solution (VIKOR), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and Preference Ranking Organization METHod for Enrichment of Evaluations (PROMETHEE) have been applied. The main idea of TOPSIS came from the concept of the compromise solution to choose the best alternative nearest to the positive ideal solution and farthest from the negative ideal solution (Tzeng and Huang 2011). VIKOR is well-known MADM technique which emphasized on select and rank of alternatives sets of conflicting criteria. While TOPSIS and VIKOR calculate distances to ideal or reference points, these methods have been applied for comparison because they have the same input and both rely on a normalization process. However, some differences exist between both methods (Cristobal 2012). Besides, PROMETHEE is an outranking method which is quite simple in conception and application compared to other methods for multi-attribute analysis (Cristobal 2013). It is well adapted to problems where selection of a finite number of alternatives are to be ranked considering several, sometimes conflicting, attributes (Goumas and Lygero 2000).

The main idea was to compare the results of decision making using three different method. The group decision making have been applied and the correlation among the answers have been investigated and the best alternative has been introduced. Besides, a method has been generated to calculate the decision makers' (DMs) importance weights. Therefore, a new framework to prioritise the geotechnical instruments has been developed in this study based on decision making methods. However, sometimes it is complicated to aggregate the results of methods when three different methods are applied. Hence, a new method has been applied based on defuzzification to introduce the optimal alternative and to prioritise the alternatives.

Hence the correlation among answers will be investigated and the best alternative will be introduced.

## 2. Development of decision framework

MADM techniques have not been unusual in dam engineering field. Fu (2008) employed multicriteria decision making approach to assess the reservoir flood. Minatour *et al*. (2013) applied analytic hierarchy process (AHP) to select the earth dam site which was based on 9 attributes and 11 sub-attributes and analysed 4 alternatives of dam location. Also, land ownership plan and relocation during construction of a new dam for more water resources was proposed by Kurniati *et al*. (2013). To overcome the uncertainties of decision making, three MADM methods, which are VIKOR, TOPSIS and PROMETHEE, will be used for proposed study. Then, the results and ranking of these method will be compared and the most suitable alternatives and their ranking will be introduced. The outcomes of the MADM methods are not always compatible (Taal *et al.* 2016). Hence, an aggregation technique will be introduced to overcome this inconsistency.

DMs in these problems try to find the best option among the existing and countable ones. Usually, many criteria are applied for decision making, hence DMs encounter with MCDMs problems (Tzeng and Huang 2011). In fact, decision making problem can be shown as Eq. (1)

$$D = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \dots & C_n \end{array} \\ \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2n} \\ \vdots & \vdots & x_{ij} & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \end{array} \tag{1}$$

Where $A_1, A_2, \dots A_m$ are possible decision making alternatives, $C_1, C_2, \dots C_n$ are decision making criteria and $X_{ij}$ is $i^{th}$ alternative importance against $j^{th}$ criterion, $i$=1, 2, …, $m$ and $j$=1, 2, …, $n$. The matrix $D$ is the fundamental inputs for the MCDM methods that will consider here. Also, Table 1 represents the scale system which has been used for evaluating the decision matrix by experts considering the instruments and dam information.

### 2.1 TOPSIS method

The TOPSIS method was developed by Hwang and Yoon in 1981 (Masoumi *et al.* 2014). TOPSIS is a popular MADM method, because of its simple and mathematically programmable structure (Tansel İç 2016). It is an attractive ranking technique requiring a limited subjective input. It selects the best alternative as the one nearest to the positive ideal solution and farthest away from the negative ideal solution (Cristobal 2012). TOPSIS is composed by the following steps based on Eq. (1):

The first step is to calculate normalized matrix.

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \tag{2}$$

Where $r_{ij}$ is the normalized matrix. The next step is to calculate the weighted normalized matrix ($V_{ij}$) which is computed by multiplying importance vector to normalized matrix

$$V_{ij} = r_{ij} \times w_j \tag{3}$$

Table 1 Scale of decision matrix evaluations

| Linguistic variable | Extremely poor | Very poor | Poor | Medium-poor | Fair | Medium-good | Good | Very good | Extremely good |
|---|---|---|---|---|---|---|---|---|---|
| Corresponding value | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |

Where $w_j$ is the criteria importance weights vector which is calculated using AHP method for all MADM techniques in this research. The next step is to calculate the positive ideal solution (PIS), $A+$, and the negative ideal solution (NIS), $A-$, as follows

$$A^+ = \{V_1^+, V_2^+, \cdots, V_j^+, \cdots, V_n^+\} \tag{4}$$

$$A^- = \{V_1^-, V_2^-, \cdots, V_j^-, \cdots, V_n^-\} \tag{5}$$

Where $V_j^+ = \max i\ (V_{ij})$ and $V_j^- = \min i\ (V_{ij})$ if the $j^{th}$ criterion is benefit; and $V_j^+ = \min i\ (V_{ij})$ and $V_j^- = \max i\ (V_{ij})$ if the $j^{th}$ criterion is cost. The distances of $j^{th}$ alternative from PIS and NIS are then calculated by Eqs. (6) and (7).

$$d_i^+ = \sqrt{\sum_{j=1}^{n} (V_{ij} - V_j^+)^2} \tag{6}$$

$$d_i^- = \sqrt{\sum_{j=1}^{n} (V_{ij} - V_j^-)^2} \tag{7}$$

The next step is to calculate the relative closeness to both ideal solutions as following

$$C_i = \frac{d_i^-}{d_i^+ - d_i^-} \tag{8}$$

Finally, the preferred orders can be obtained according to the similarities to the PIS in descending order to choose the best alternatives.

### *2.2 PROMETHEE method*

The PROMETHEE method was first introduced by Brans and then developed by Brans *et al*. (Brans and Vincke 1985). It is an outranking method quite simple in conception and application compared to other methods for multi-attribute analysis (Masoumi and Rashidinejad 2011). In this research PROMETHEE I and PROMETHEE II are employed to rank the alternatives (Brans and Smet 2016). Assume that the decision matrix is same as Eq. (1), the PROMETHEE method consists of the following steps:

The first step is to calculate deviation amplitudes by Eq. (9).

$$d_j(a, b) = x_{aj} - x_{bj};\ \ a, b = 1,2,3, \dots, m;\ j = 1,2,3, \dots, n \tag{9}$$

Where $d_j(a, b)$ denotes the difference between the evaluations of alternatives $a$ and $b$ on each criterion. The next step is to calculate preference function. Brans and Smet (2016) proposed 6 types of preference function. There are not any limitation to use each of them. The Gaussian criteria were used in this paper. In case of a Gaussian criterion the preference function remains increasing for all deviations and has no discontinuities, neither in its shape, nor in its derivatives. The Gaussian preference function has been chosen to be used for criteria because this criterion has been proved to be the least sensitive to small variations of the PROMETHEE input values (Soltanmohammadi *et al.* 2009). Therefore, the preference function corresponding to Gaussian criteria computes by Eq. (10).

$$p_j(d) = \begin{cases} 0 & d \le 0 \\ 1 - e^{-d^2/2\delta^2} & d > 0 \end{cases} \tag{10}$$

Where $\delta$ is an intermediate value between threshold of indifference and threshold of strict preference. A parameter $\delta$ has to be selected, it defines the inflection point of the preference function (Brans and Smet 2016). Soltanmohammadi *et al*. (2009) proposed Eq. (11) to calculate $\delta$.

$$\delta_j = \frac{\sum_{a,b=1,\ a\neq b}^{a,b=m} |d_j(a, b)|}{m(m-1)};\ j = 1, 2, \dots, n\ ;\ a, b = 1, 2, \dots, m \tag{11}$$

The Gaussian preference function represented in Fig. 1.

The next step is to calculate the preference index $(\pi(a, b))$ between alternatives according to Eq. (12).

$$\pi(a, b) = \sum_{j=1}^{m} w_j . p_j(a, b) \tag{12}$$

The $w_j$ is the importance weights of attributes which is calculated by AHP. Eq. (13) computes the outranking flows and the PROMETHEE I partial ranking are obtained from Eq. (14).

$$\emptyset^-(a) = \frac{1}{m-1} \sum_{x \in A} \pi(x, a)\ \ and\ \ \emptyset^+(a) = \frac{1}{m-1} \sum_{x \in A} \pi(a, x) \tag{13}$$

$$\begin{cases} aP^I x & if & \begin{cases} \emptyset^+(a) > \emptyset^+(x) \text{ and } \emptyset^-(a) < \emptyset^-(x), \text{or} \\ \emptyset^+(a) = \emptyset^+(x) \text{ and } \emptyset^-(a) < \emptyset^-(x), \text{or} \\ \emptyset^+(a) > \emptyset^+(x) \text{ and } \emptyset^-(a) = \emptyset^-(x), \end{cases} \\ aI^I x & if & \{\emptyset^+(a) = \emptyset^+(x) \text{ and } \emptyset^-(a) = \emptyset^-(x) \\ aR^I x & if & \begin{cases} \emptyset^+(a) > \emptyset^+(x) \text{ and } \emptyset^-(a) > \emptyset^-(x), \text{or} \\ \emptyset^+(a) < \emptyset^+(x) \text{ and } \emptyset^-(a) < \emptyset^-(x), \end{cases} \end{cases} \tag{14}$$

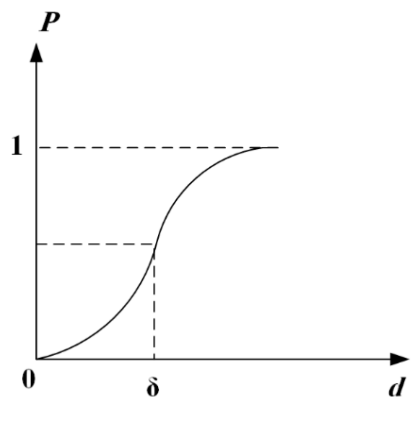



Fig. 1 Gaussian preference function

Where $\emptyset^{-}$ is negative and $\emptyset^{+}$ is the positive flows. $aP^{I}x$ , $aI^{I}x$ and $aR^{I}x$ are respectively stand for preference, indifference and incomparability. PROMETHEE II consists of the complete ranking. The net outranking flow can then be calculated (Eq. (15)). It is the balance between the positive and the negative outranking flows. The higher net flows, the better alternative.

$$\emptyset^{net}(a) = \emptyset^{+}(a) - \emptyset^{-}(a) \tag{15}$$

### 2.3 VIKOR method

VIKOR method was firstly proposed by Yu (1973) and then by Zeleny (1982). In recent years, Opricovic and Tzeng (2007) developed this method. Main idea of compromise solution has derived from compromise planning based on $L_p$-metric standard and it can be obtained by the following equation (Zeleny 1982)

$$L_{p,i} = \left\{ \sum_{j=1}^{n} \left[ \frac{w_j\left(f_j^{*} - f_{ij}\right)}{\left(f_j^{*} - f_j^{-}\right)} \right]^{p} \right\}^{1/p} \quad ; 1 \le p \le \infty ; j = 1,2,\dots,n \tag{16}$$

Where $w_j$ is $j^{th}$ attribute importance weight, $f_j^{*}$ is the highest value of $j^{th}$ attribute regarding to decision making alternatives and $f_j^{-}$ is the lowest value of $j^{th}$ attribute regarding to decision making alternatives. In VIKOR method, $P$ should be equal to one and infinity in order to rank alternatives or in the other words, calculate $L_{1,i}$ and $L_{\infty,i}$ values which have been shown using variables $S_i and\ R_i$. The main process of VIKOR method regarding to Eq. (1), for ranking the alternatives will be as follows (Opricovic and Tzeng 2007):

Step 1: In benefit attributes, the greatest and the fewest value of any attribute will be calculated with Eqs. (17) and (18) which are shown by $f_j^{*}$ and $f_j^{-}$, respectively.

$$f_j^{*} = \max_{j} f_{ij} \tag{17}$$

$$f_j^{-} = \min_{j} f_{ij} \tag{18}$$

Step 2: Calculation of $S_i$ and $R_i$

$$S_i = \sum_{j=1}^{n} w_j \left( \frac{\left[f_j^{*} - f_{ij}\right]}{\left[f_j^{*} - f_j^{-}\right]} \right); i = 1,2,\dots,m , j = 1,2,\dots,n \tag{19}$$

$$R_i = \max_{i} \left[ w_j \left( \frac{\left[f_j^{*} - f_{ij}\right]}{\left[f_j^{*} - f_j^{-}\right]} \right) \right]; \ j = 1,2,\dots,n \tag{20}$$

Step 3: Determination of $Q_i$ with following equation

$$Q_i = v\left(\frac{(S_i - S^{-})}{(S^{*} - S^{-})}\right) + (1 - v)\left(\frac{(R_i - R^{-})}{(R^{*} - R^{-})}\right) \tag{21}$$

Where $S^{*}$ = min $i$ $(S_i)$, $S^{-}$ = max $i$ $(S_i)$, $R^{*}$ = min $i$ $(R_i)$, $R^{-}$ = max $i$ $(R_i)$, and $v \in [0, 1]$. Parameter $v$ balances the relative importance of indexes $S$ and $R$ and usually equal to *0.5* (Jing, Niu and Chang 2015).

Step 4: Sorting $Q$ in increasing order: The best-ranked alternative is the one with the lowest value of $Q$.

Step 5: Compromise solution: the so-called compromise solution is the alternative $A_1$ which is the best ranked according to $Q$ (minimum) if the following two conditions are satisfied:

Condition 1: Acceptable advantage. $Q(A_2) - Q(A_1) \ge DQ$ where $A_2$ is the best second alternative according to $Q$ and $DQ = 1/(m-1)$ ($m$ is the number of alternatives).

Condition 2: Acceptable stability in decision-making. Alternative $A_1$ must be also the best ranked according to $S$ and/or $R$ (the alternative with the lowest value). If one of the conditions is not satisfied, then a set of compromise solutions is proposed, which consists of:

- The alternatives $A_1$ and $A_2$ if condition 1 is true and condition 2 is false, or
- The set of alternatives $A_1, A_2, \dots, A_m$ if condition 1 is false; $A_m$ being the position in the ranking of the alternative that verifying $Q(A_m) - Q(A_1) < DQ$. The best alternative, ranked by $Q$, is the one with the minimum value of $Q$.

VIKOR method is a very useful method for MADM problems, especially in some cases that DMs have not ability or knowledge about priorities importance in the first step of design. The compromise solution results is acceptable for DMs because it has the highest amount of group utility $S^{-}$ and also the least rate of individual regret $R$.

### 2.4 Decision makers' importance weight

Human errors should be reduced in engineering judgments to improve structural safety (Brown and Elms 2015). Since the team of the DMs have different mental, experimental and scientific skills, it is likely to have some disagreements in the surveys. Thus, each expert can make a different influence on the decision making. To increase the accuracy of the decision making, some measures were proposed to determine the importance weight among DMs.

To do so, firstly, three criteria were defined to represent the educational level, related working experience and the number of publications in embankment dams and monitoring them. The matrix to determine the priority weights of the experts are composed of columns of criteria and rows of experts. The matrix will then be normalized using Eq. (22).

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{n} x_{ij}^{2}}} \tag{22}$$

Where $r_{ij}$ is the normalized values of decision matrix, $x_{ij}$ is the value of $i^{th}$ alternative from $j^{th}$ criteria. $i$ is the rows and $j$ is the columns. The importance weights of the DMs then calculate with Eq. (23).

$$DM_i' = \sum_{j=1}^{m} r_{ij} \tag{23}$$

Where $DM_i'$ is the importance weights matrix of DMs which includes one columns and $i$ rows. $j$ is the columns so $m$ is the number of criteria which are three in this case and $i$

is the rows or DMs. The normalized importance weights of DMs then obtain by Eq. (24).

$$DM_i = \frac{W_i'}{\sum_{i=1}^{n} W_i'} \tag{24}$$

These importance weights then multiply to each specific DMs' matrix before aggregation of group judgments.

### 2.5 Aggregation technique to prioritize alternatives

In order to use MADM techniques to select appropriate alternative, there is a risk employing just one particular method (Hodgett 2016). Due to overcome the risk of using single method, in this study, three MADM techniques have been introduced and employed to develop the decision framework. The ranking resulted from different MADM techniques are not always the same (Shahdany and Roozbahani 2016). Therefore, following aggregation technique is developed to optimally prioritise the alternatives which have been ranked incompatible by different method. Assume that the ranking of $z$ alternatives resulting from three MADM methods are as Table 2.

From Table 2, *Alt.* is an alternative and $x_{ij}$ represents the ranking of them. The first step is to normalize the ranking values by cost vector normalization using Eq. (25).

$$R_{ij} = \frac{(\frac{1}{x_{ij}})}{\sqrt{\sum_{i=1}^{m}(1/x_{ij}^2)}} \tag{25}$$

Where $R_{ij}$ is the normalized matrix, $i$=1, 2, …, $m$ or rows and $j$=1, 2, …, $n$ or columns. Then, there are 3 normalized values from three methods. These values can be considered as a lower, mean and upper bonds of a triangular fuzzy number (TFN) for each individual alternative. Therefore, the corresponding membership function of each TFN can be considered as 0, 1 and 0 for lower, mean and upper values, respectively. These values should be drawn as a triangle on a chart which consists of membership function as its vertical axis and normalized values as its horizontal axis.

The next step is to calculate the priorities of the alternatives which will be implemented by centre of gravity (COG) defuzzification method for a single fuzzy number (Wierman 1997). It can be calculated by Eq. (26).

$$C = \frac{(u-l)+(m-l)}{3} + l \tag{26}$$

Where $C$ is the defuzzified value of the TFN, and $l$, $m$ and $u$ are the lower and mean as well as upper bonds of the TFN, respectively.

Table 2 Example of ranking of alternatives from different MADM techniques

| | Ranking of alternatives | | |
|---|---|---|---|
| | *Alt.1* | *Alt.2* | *Alt.z* |
| TOPSIS | $x_{11}$ | $x_{12}$ | $x_{1m}$ |
| VIKOR | $x_{21}$ | $x_{22}$ | $x_{2m}$ |
| PROMETHEE | $x_{31}$ | $x_{32}$ | $x_{nm}$ |

### 2.6 Optimal instruments selection framework

The process of the model for determining reliable instruments is shown in Fig. 2. The first phase of the model includes identifying the criteria which affect the selection of measurement devices as attributes and categorizing geotechnical instruments as alternatives for embankment dams, which will be specified in next section. Then, it is essential collecting dam data and the preparation of the questionnaires which should be provided for DMs. The next step will be using decision framework which has been developed previously.

## 3. Identifying effective attributes and geotechnical instruments in embankment dams

Decision making procedure consists of development and design of alternatives and attributes (Laufer 1990). Concerning appropriate instrument selection, the first phase of the problem is to identify the effective attributes, which influence the decision making process, and classifying the instruments as possible alternatives. Instrument adequacy and the optimal selection must be analysed based on the effective criteria. By evaluating the existing alternatives, the priority of the instruments will be determined.

Fig. 3 shows the typical monitoring instruments which should be installed in embankment dams. However, embankment dams' instruments are not limited to those in Fig. 3. For instance, a comparison among piezometers are represented in Table 3. Consequently, it implies that the selection of the most consistent instrument is a complicated task. To ensure the operation safety of an embankment, a reliable safety monitoring system is usually required (Li *et al.* 2015). The main issue is how to choose the most adequate instrument type which is reliable for safety inspection of the dam.

It is very important to employ reliable attributes for investigating the alternatives. Appropriate instrument selection is a complex task, especially, in relation to in situ measurements in large engineering structures. As the instruments are available with different specialities, making the suitable selection is difficult (Barai and Pandey 2004).

Reliability is one of the main considerations related to the instrument selection, which is consisted of the various factors including simplicity, accuracy, conformance, precision, stability and etc. Other factors can be implied as lifelong and its proportion to the instruments efficiency and cost (Dunnicliff 1993). The importance of each factor is depend on the applied goals for using instruments. Data acquisition mode, manual or automatic, must be considered during instrument selection (Shrive, Brown and Shrive 2009). Automated data acquisition system should not be used until the explanation is not available for using electrical transducers (Bassett 2012). Transducers which are available for calibration or replacement should be used everywhere it is possible. For instance, vibrating wire piezometers should not be used instead of standpipe piezometers only due to their superiority for automatic data acquisition. For difficult conditions of accessibility (e.g.,

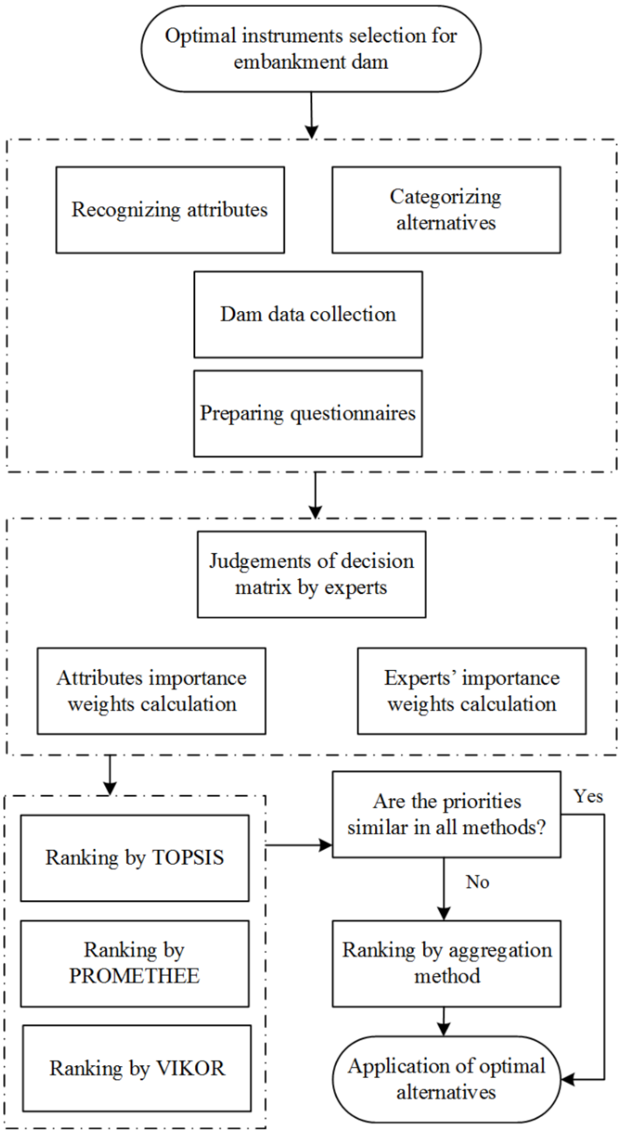



Fig. 2 Optimal instruments selection framework

increasing pressure during a flood) using instruments with remote readout unit is considered (FERC 1994).

Total cost must be considered in the comparison of instruments systems or alternative instruments, which is consisted of the instrument, installation, maintenance, monitoring, operation longevity, and data analysis process costs. The cheapest instrument, necessarily do not prepare the least cost of lifelong, especially, when replacement instruments need to be installed (FERC 1994).

Instruments accessibility must be considered commercially and historically. An inseparable risk exists in any electronic instrument without satisfying history. Instruments simplicity will be an important factor in making decisions. The instrument installation is very important, which can cause a discontinuity in a foundation or embankment dams due to weak consolidation of surrounding area. Geotechnical experts should employ an adequate level of knowledge in order to select the instruments and consider advantages and limitations regarding to the environmental condition (USACE 1995).

One of the most important criteria that should be considered for selecting an instrument is its ability to being a complementary instrument (Pehlivan and Bayata 2016). In addition, instruments technology, accessibility and also experts' availability are the other factors of instrument selection, which are considered as the monitoring plan steps (Negro *et al.* 2009). Instruments selection and installation should be considered based on the environmental compatibility and instrument component consistency (Bukenya *et al.* 2014). The installation of instrument is designed to conform to the surrounding ground or structure. The type of casing and backfill can affect the ability of the instrument to accurately detect the deflections (Machan and Bennett 2008). Ideally, applied instruments in a certain condition in embankment dams must have specified features (e.g., acceptable degree of correctness, long-term reliability, less requirements of maintenance, compatibility with structuring techniques, low cost and simplicity) (Bartholomew *et al.* 1987, Patjawit and Chinnarasri 2014).

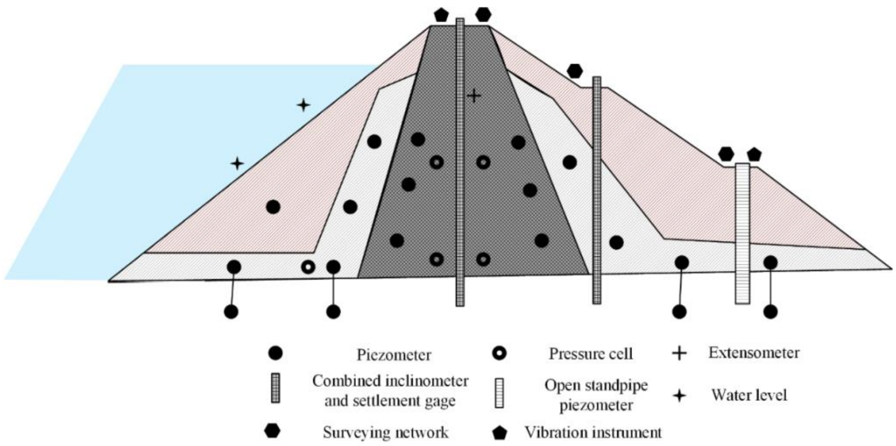



Fig. 3 Typical embankment dam monitoring instruments (Masoumi *et al.* 2017)

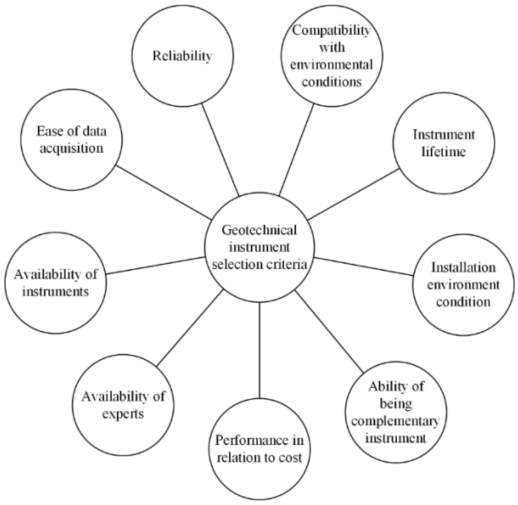



Fig. 4 Geotechnical instruments selection criteria

Table 3 Comparison of some of characteristics of different piezometers (Bartholomew *et al.* 1987, FERC 1994, USACE 1995)

| Characteristic | Standpipe | Pneumatic | Hydraulic | Vibrating wire | Electrical |
|---|---|---|---|---|---|
| Precision of data | Moderate | Low | Low | Very high | High |
| Cost | Inexpensive | Expensive | Moderately expensive | Very expensive | expensive |
| Complexity of installation | Very simple | Complex | Moderate | Moderate | Moderately complex |
| Problem with installation | Fairly low | High | High (problem develop with age) | Very low | Moderate |
| Environmental condition | Freezing problem | Must prevent humid air from entering tubing | Readout location must be protected from freezing | Sensitive to temperature changes | Voltage or current output signal sensitive to cable length, splices, moisture, etc. |
| Lifetime | Long successful performance record | fairly long experience record | long experience record | Long term stability | Not recommended for long-term monitoring |
| Expertise | Simple to monitor and maintain | Moderately complex monitoring and maintenance | Moderately complex monitoring and maintenance | Simple to monitor | Simple to monitor |


Fig. 5 Classified geotechnical instruments of embankment dams

The significant attributes which affect optimal instruments selection have been collected that encompass different sides of suitable instruments selection. These criteria are illustrated in Fig. 4.

The criteria to assess the priority of instruments are: reliability (REL), system or instrument lifetime (INL), ease of data acquisition (EDA), installation environment condition (IEC) (e.g., standpipe piezometers are suitable in high permeable soil materials but diaphragmatic piezometers are more efficient in low permeable soil materials), ability of being complementary instrument (ACI) (e.g., it is possible to confirm displacement in inclinometers by interpretation of changes in pore water pressure in piezometers, and/or accessibility of at least one instrument when unable to gain data from the other ones due to deterioration or loss of it.), compatibility with environmental conditions (CEC) (such as instrument performance in frost, heat, moisture and etc.), availability of experts (AVE), availability of instruments (AVI) and performance in relation to cost (PRC).

Also, general classification of instruments has performed which specifically consists of all various type of geotechnical instruments for embankment dams. Subgroups have been classified based on their general applications. It is necessary to mention that the rotational and axial displacements have been considered as instruments in subsurface displacement measurement subgroups (Masoumi, Ahangari and Noorzad 2017). Fig. 5 represents the classified geotechnical instruments of embankment dams.

## 4. Application of decision framework to optimally select geotechnical instruments

In this study, a rock fill with clay core which has constructed in Khuzestan province located in southern Iran used as case study. This dam has 3634 $km^2$ watershed area with 175 m height from the foundation and length of 345 m and considered as one of the biggest storage dam in Khuzestan province. The area of dam reservoir is 25 $km^2$ and its volume is $12 \times 10^8 m^3$.

Considered volume for sediments is $160 \times 10^6 m^3$ during 50 years and the dam body has the total volume of $8.59 \times 10^6 m^3$. This dam has semi-underground power station with 150 MW installed capacity. Average annual energy production the dam is currently 190 GW and it is working with 85% efficiency.

By collecting the embankment dam information consisting of dam's geometry, field geology, risk acceptability of predicted problems, weather, dam's structure material, local downstream condition and etc., one can provide questionnaire for experts to evaluate the decision matrices.

In the present project, 13 experts have been employed for the survey. In decision-making problems, judging decision matrix by DMs is one of the most important process and level of reliability in designated comparisons should be essentially high (Balali *et al*. 2014). In order to increase decision making quality level, a process has been developed for determining the DMs' importance weights.

The DMs have been compared together based on 3 criteria. The criteria are educational level, the number of related scientific publications and also work experience in this field. An importance weight have been consequently allocated to all DMs based on Eqs. (22) to (24).

Table 4 represents the normalised decision matrix of 13 experts based on 3 introduced factors. The education level was a qualitative factor that has been scaling from 1 to 9. The two other factors were quantitative. The final importance weights of experts considered in the last column of Table 4. Therefore, these DMs' importance weight have an effects on the decision matrices resulting from each DM's judgement. Then, the averaging of this group decision making will provide the final results.

Regarding to solve the problem, attributes' importance weights have to be obtained for 9 effective attributes. In this study the AHP method has been applied for producing attributes' importance weights.

Table 4 Normalised matrix of DMs' importance weights and their final weights

| Decision makers | Education level | Work experience | Number of publications | Final importance weights |
|---|---|---|---|---|
| DM1 | 0.316 | 0.284 | 0.403 | 0.098 |
| DM2 | 0.316 | 0.114 | 0.201 | 0.062 |
| DM3 | 0.316 | 0.284 | 0.403 | 0.098 |
| DM4 | 0.246 | 0.190 | 0.523 | 0.094 |
| DM5 | 0.316 | 0.360 | 0.282 | 0.094 |
| DM6 | 0.316 | 0.379 | 0.403 | 0.107 |
| DM7 | 0.316 | 0.246 | 0.161 | 0.071 |
| DM8 | 0.246 | 0.531 | 0.000 | 0.076 |
| DM9 | 0.246 | 0.000 | 0.282 | 0.052 |
| DM10 | 0.316 | 0.227 | 0.121 | 0.065 |
| DM11 | 0.246 | 0.322 | 0.000 | 0.056 |
| DM12 | 0.246 | 0.133 | 0.000 | 0.037 |
| DM13 | 0.316 | 0.284 | 0.322 | 0.090 |

In this case, 13 pair-wise comparison matrices have been employed which have been rated by DMs. The attributes' importance weights results represent in Table 5. The AHP is widely used method to obtain attributes importance weights. The procedure of method can be found at following references (Saaty 1990).

After determination of experts and attributes final importance weights, the next step is to solve the main decision matrices of 13 experts. Table 1 has represented the scoring system which has been used for evaluating the decision matrix by experts. All individual decision making matrix has been taken effect by multiplying its expert's importance weight. Finally, geometrical averaging has been applied to generate the main decision matrix from 13 experts. Since geotechnical instruments for embankment dams had been categorised in 8 groups, there were 8 main matrices for solving by VIKOR, TOPSIS and PROMETHEE methods.

For instance, the main averaged decision matrix of the instruments in pore water pressure category has been represented as Table 6.

In this manner, eight groups of decision matrix have been weighted by experts' importance weights and then they have been averaged until just one main decision matrix has remained for every groups. These main decision matrices for each group of instruments have been solved by the three MADM techniques. First of all, VIKOR method has been performed. Table 7 shows the calculation results for the pore water pressure instruments category using Eqs. (17) to (21). As it can be seen from Table 7, the second condition of compromise solution has not satisfied according to the conditions of VIKOR method in step 5.

Therefore, vibrating wire and electrical resistance piezometers considered as superior alternatives and introduced as decision making choices, respectively. These instruments have selected based on the technical efficiency by VIKOR. Other alternatives have been brought on their final ranks in the last column of Table 7. Whereas, two instruments have been recognised most suitable for monitoring based on the $Q$ rank and the conditions of VIKOR method. These two instruments were vibrating wireand electrical resistance piezometers.

Table 5 Final importance weights of attributes

| Attributes | Importance weights |
|---|---|
| Instrument lifetime | 0.12144 |
| Reliability | 0.07450 |
| Ease of data acquisition | 0.13922 |
| Installation environment condition | 0.14199 |
| Ability of being complementary instrument | 0.07768 |
| Compatibility with Environmental condition | 0.13145 |
| Availability of expert | 0.10373 |
| Availability of instrument | 0.11209 |
| Performance in relation to cost | 0.09790 |

Table 6 Final averaged decision matrix for pore water pressure instruments

| Decision making matrix | INL | REL | EDA | IEC | ACI | CEC | AVE | AVI | PRC |
|---|---|---|---|---|---|---|---|---|---|
| Observation well | 5.12 | 4.47 | 2.55 | 3.28 | 4.84 | 4.97 | 5.82 | 6.65 | 6.34 |
| Open standpipe piezometer | 4.72 | 4.32 | 4.64 | 5.94 | 4.07 | 5.55 | 6.24 | 6.58 | 5.99 |
| Pneumatic piezometer | 5.35 | 4.79 | 3.12 | 5.48 | 4.83 | 3.38 | 5.48 | 4.85 | 6.00 |
| Twin tube hydraulic piezometer | 5.27 | 4.68 | 5.21 | 4.44 | 4.37 | 4.46 | 6.58 | 5.79 | 5.01 |
| Electrical resistance piezometer | 6.11 | 6.32 | 5.89 | 5.62 | 5.72 | 4.26 | 4.71 | 5.29 | 5.02 |
| Vibrating wire piezometer | 6.01 | 6.66 | 6.15 | 4.40 | 4.07 | 4.81 | 5.10 | 5.23 | 5.87 |

Table 7 Pore water pressure instrument selection results by VIKOR

| Alternatives | S | Rank | R | Rank | Q | Rank |
|---|---|---|---|---|---|---|
| Observation well | 0.5569 | 5 | 0.1420 | 6 | 0.8406 | 5 |
| Open standpipe piezometer | 0.3810 | 1 | 0.1214 | 4 | 0.3069 | 3 |
| Pneumatic piezometer | 0.6392 | 6 | 0.1315 | 5 | 0.9009 | 6 |
| Twin tube hydraulic piezometer | 0.5343 | 4 | 0.0979 | 2 | 0.3826 | 4 |
| Electrical resistance piezometer | 0.4016 | 2 | 0.1037 | 3 | *0.1805* | 2 |
| Vibrating wire piezometer | 0.4196 | 3 | 0.0888 | 1 | *0.0748* | 1 |

Table 8 Pore water pressure instrument selection results by PROMETHEE

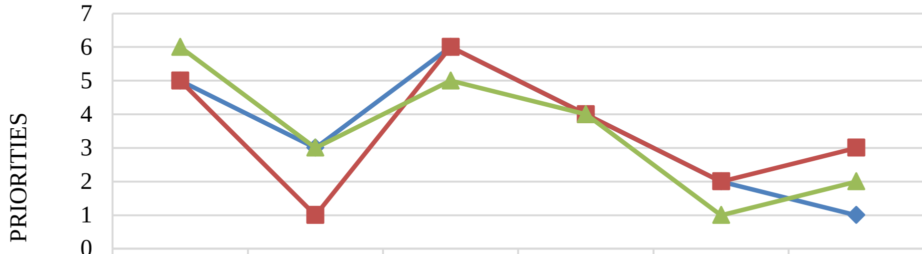
| Alternatives | $\emptyset^{net}$ | Rank |
|---|---|---|
| Observation well | -0.0759 | 5 |
| Open standpipe piezometer | 0.1693 | 1 |
| Pneumatic piezometer | -0.2131 | 6 |
| Twin tube hydraulic piezometer | -0.0486 | 4 |
| Electrical resistance piezometer | 0.1136 | 2 |
| Vibrating wire piezometer | 0.0546 | 3 |

Table 9 Pore water pressure instrument selection results by TOPSIS

| Alternatives | $C_i$ | Rank |
|---|---|---|
| Observation well | 0.326 | 6 |
| Open standpipe piezometer | 0.643 | 3 |
| Pneumatic piezometer | 0.372 | 5 |
| Twin tube hydraulic piezometer | 0.560 | 4 |
| Electrical resistance piezometer | 0.677 | 1 |
| Vibrating wire piezometer | 0.647 | 2 |

Secondly, PROMETHEE method has been used to solve the Table 6. In order for PROMETHEE to be solved, one needs to calculate the Gaussian preference function by Eq. (11). The results of the Gaussian preference function and also final ranking of the instruments, which had been computed by Eqs. (9) to (15), have been indicated in Table 8.

Finally, the TOPSIS method have been employed as third option for ranking the alternatives; as a result, Table 9 shows the priorities of TOPSIS, which has been determined




| | Observation well | Open standpipe piezometer | Pneumatic piezometer | Twin tube hydraulic piezometer | Electrical resistance piezometer | Vibrating wire piezometer |
|---|---|---|---|---|---|---|
| VIKOR | 5 | 3 | 6 | 4 | 2 | 1 |
| PROMETHEE | 5 | 1 | 6 | 4 | 2 | 3 |
| TOPSIS | 6 | 3 | 5 | 4 | 1 | 2 |

Fig. 6 The comparison of the ranking of the three MADM methods

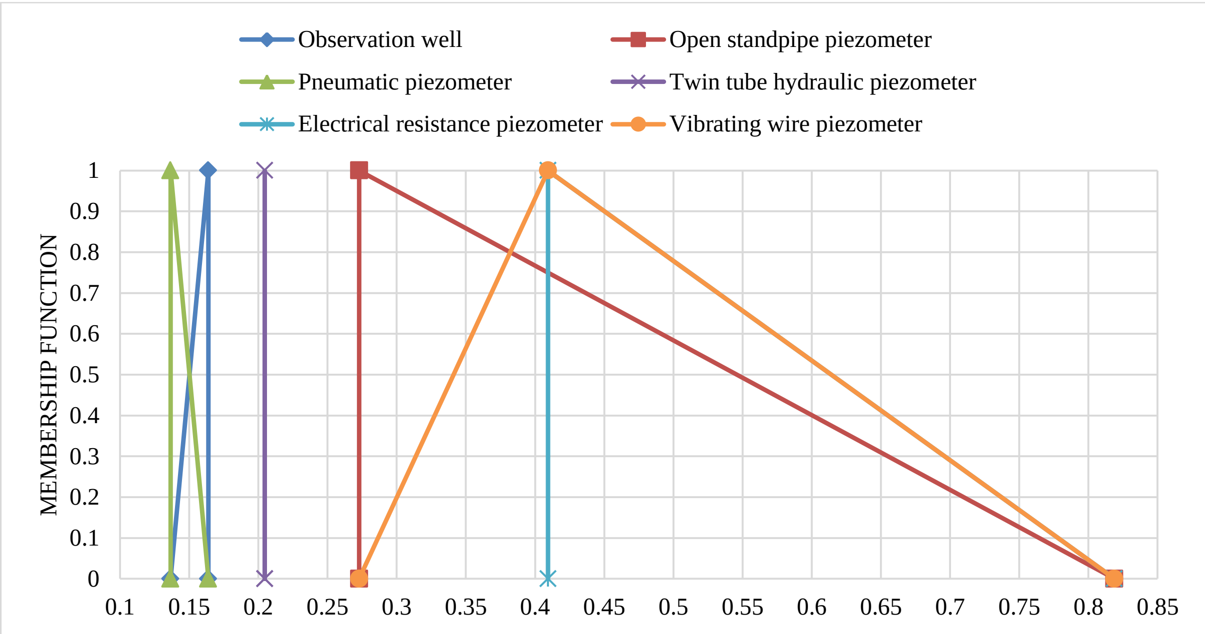



Fig. 7 Ranking of alternatives as a TFN

Table 10 The correlations of the results of MADM methods

| | VIKOR | PROMETHEE | TOPSIS |
|---|---|---|---|
| VIKOR | 1 | | |
| PROMETHEE | 0.77 | 1 | |
| TOPSIS | 0.89 | 0.77 | 1 |

by Eqs. (2) to (8). Similarly, the judgments from Table 6 have been used to implement the method.

As it can be seen, the best alternative is different in each method. The PROMETHEE, VIKOR and TOPSIS methods have proposed Open standpipe, Vibrating wire and Electrical piezometer as the optimally selected alternative, respectively.

Not only are instruments important for dam health monitoring assessment, but also instrumentation data are critical in order to risk assessment of embankment dams (Gulgec *et al.* 2016). Thus, it is essential to use most compatible instrument as measurement device. Fig. 6 represents the comparison of the three MADM techniques in which the preference orders of alternatives are shown.

Table 11 The normalized values of three MADM methods priorities

| | Observation well | Open standpipe piezometer | Pneumatic piezometer | Twin tube hydraulic piezometer | Electrical resistance piezometer | Vibrating wire piezometer |
|---|---|---|---|---|---|---|
| VIKOR | 0.1638 | 0.2730 | 0.1365 | 0.2047 | 0.4094 | 0.8189 |
| PROMETHEE | 0.1638 | 0.8189 | 0.1365 | 0.2047 | 0.4094 | 0.2730 |
| TOPSIS | 0.1365 | 0.2730 | 0.1638 | 0.2047 | 0.8189 | 0.4094 |

Table 12 Comparison of the ranking results of three MADM methods with aggregated method

| | VIKOR | PROMETHEE | TOPSIS | Aggregated | |
|---|---|---|---|---|---|
| | | | | Rank | Final values |
| Observation well | 5 | 5 | 6 | 5 | 0.1547 |
| Open standpipe piezometer | 3 | 1 | 3 | 3 | 0.4549 |
| Pneumatic piezometer | 6 | 6 | 5 | 6 | 0.1456 |
| Twin tube hydraulic piezometer | 4 | 4 | 4 | 4 | 0.2047 |
| Electrical resistance piezometer | 2 | 2 | 1 | 1 | 0.5459 |
| Vibrating wire piezometer | 1 | 3 | 2 | 2 | 0.5004 |

Table 13 Correlations among VIKOR, PROMETHEE, TOPSIS and the aggregation method

| | *VIKOR* | *PROMETHEE* | *TOPSIS* | *Aggregated* |
|---|---|---|---|---|
| VIKOR | 1 | | | |
| PROMETHEE | 0.77 | 1 | | |
| TOPSIS | 0.89 | 0.77 | 1 | |
| Aggregated | 0.94 | 0.83 | 0.94 | 1 |

In this case, the problem is that it is difficult to find out best alternative and their ranking. The ranking of different methods needs to be aggregated to recognise the most suitable preference order of alternatives. Table 10 indicates the correlations among the three methods.

It can be seen that the correlations of the results are lower than 80% between PROMETHEE-VIKOR and TOPSIS-PROMETHEE, and it is 89% in case of TOPSIS-VIKOR. Regarding the priorities of the alternatives from each method, it is difficult to determine the exact ranking of the alternatives; therefore, an aggregation should be applied introducing the optimal alternative and ranking them. Since three MADM methods have been employed in the present study, the results of them can be considered as a triangular fuzzy number for each specific alternative.

The ranking of alternatives in Fig. 6 should be normalized by vector normalization using Eq. (25). The normalized matrix represents in Table 11.

These values can be considered as a lower, mean and upper bonds of a triangular fuzzy number (TFN) for each individual alternative. Therefore, the corresponding membership function of each TFN can be considered as 0, 1 and 0 for lower, mean and upper values, respectively. The results, then, are shown in Fig. 7.

Fig. 7 implies that only twin tube hydraulic piezometer has the exact ranking which situates at 4$^{th}$ place among other alternatives by all three methods. In case when the alternatives are much more and the judgments for the main decision matrix are so closer than this procedure, it will be more difficult to aggregate the priorities. Moreover, above condition will result in different ranking from various MADM techniques.

The next step is to calculate the priorities of the alternatives from Fig. 7 which will be implemented by Eq. (26).

The results of this calculation are shown in the last column of Table 12 and also the comparison among alternatives ranking are demonstrated in this table.

The correlations among different methods are represented by Table 13 where the aggregation method remarkably shows a significant improvement regarding relevance of the optimal ranking of the alternatives to other methods.

It can be seen that, the aggregation method correlates about 94% to VIKOR and TOPSIS methods and about 83% to PROMETHEE method. This increase in correlation will improve the decision making outcomes and enhance the priorities which should be used as optimal alternative.

Table 14 Final selected instruments and their priorities based on decision making framework

| Priority | Temperature | Seepage and water level | Vibration | Subsurface vertical displacement | Subsurface horizontal displacement | Surface displacement | Stress |
|---|---|---|---|---|---|---|---|
| 1 | Resistance temperature device | Weirs | Accelerometer | Rod settlement gage | Combined inclinometer and settlement points | Micro geodesy and surveying network | Hydraulic pressure cell with vibrating wire transducer |
| 2 | Thermocouple | Parshall flumes | Geophone | Combined inclinometer and settlement point | In place inclinometer | Mechanical crack meter | Hydraulic pressure cell with resistance strain gage transducer |
| 3 | Bimetal thermometer | Velocity meter | Seismograph | Settlement gage with casing and probe | Probe inclinometer | Tape extensometer | Strain resistance diaphragm pressure cell |
| 4 | Mercury thermometer | Calibrated catch container | | Fixed borehole extensometer | Soil strain gage | Vibrating wire crack meter | Hydraulic pressure cell with pneumatic transducer |
| 5 | Thermistor | Water level gage | | Probe extensometer | | Electrical crack meter | Diaphragm pressure cell with vibrating wire transducer |
| 6 | | Thermotic survey/Thermal monitoring | | Settlement cell or platform | | | |
| 7 | | | | Horizontal inclinometer | | | |
| 8 | | | | Soil strain gage | | | |

Since the alternatives are geotechnical instruments in this study, it is very important to employ the best possible measurement device because of the significance of structural health monitoring which should be reliable and accurate.

Finally, Table 14 indicates all the optimal selected alternatives for each category by aggregation method and their ranking. These alternatives have been prioritised based on group decision making. Their technical efficiency have analysed based on 9 involving attributes which have affected the decision making procedure.

## 5. Conclusions

The geotechnical instruments are vital devices for dam safety monitoring. Every dam requires specific type of instruments which need to be logically selected. The lack of a method to select adequate instruments has been the reason to develop the present study. The selection of monitoring device by MADM method has a very good ability to analyse the alternatives and to introduce the optimal alternatives. This method can prioritize the alternatives and ranking them. Since there are several MADM techniques, three methods have been used to enhance the reliability of the model and to compare the results of each method for introducing the optimal ranking of the alternatives.

The result of each method is not always similar to others, especially when the judging scores by DMs are so close together; therefore, using an aggregation technique to optimally prioritize the alternative is inevitable. In this study the aggregation method has been introduced determining the best ranking of alternatives which have been calculated by TOPSIS, PROMETHEE and VIKOR methods. By using aggregation method, the results are well-distributed and the ranking of the alternatives is on their optimal point while the correlation among these methods are about 94%.

Every embankment dam's conditions are different; therefore, it is logical fact that every embankment dam should be limited for monitoring with a special type of instruments only. Using MADM method when instruments are categorized, DMs able to decide what categories should be applied.

Considering dam features, experts can neglect judging one category to limit that type of instruments. Besides, it is possible adding new attributes and other instruments alternatives that might not be inserted in this framework.

The other benefit of this method is considering experts' subjective ambiguities in determining the appropriate instruments. For example it can introduce just one instrument as a best alternative or proposed more than one while optimally ranking them. That means of DMs priorities have included in decision making process.

Application of experts' importance weights also increased the level of reliability and scoring acceptance of the decision making framework. The results show a higher confidence to the main decision making matrix due to more knowledge of the expert.

It is possible to investigate different embankment dams and suitable selection of instruments based on the structured framework. Also, the framework is able to be applied in other geotechnical structures for selecting of their proper instruments by means of changing instrument categories and influencing attributes. On the other hand, the aggregation technique can be used in managerial decision makings when the priorities of different methods are not compatible.

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