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Reliable monitoring of embankment dams with optimal selection of geotechnical instruments

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Abstract. Monitoring is the most important part of the construction and operation of the embankment dams. Applied instruments in these dams should be determined based on dam requirements and specifications. Instruments selection considered as one of the most important steps of monitoring plan. Competent instruments selection for dams is very important, as inappropriate selection causes irreparable loss in critical condition. Lack of a systematic method for determining instruments has been considered as a problem for creating an efficient selection. Nowadays, decision making methods have been used widely in different sciences for optimal determination and selection. In this study, the Multi-Attribute Decision Making is applied by considering 9 criteria and categorisation of 8 groups of geotechnical instruments. Therefore, the Analytic Hierarchy Process and Multi-Criteria Optimisation and Compromise Solution methods are employed in order to determine the attributes' importance weights and to prioritise of instruments for embankment dams, respectively. This framework was applied for a rock fill with clay core dam. The results indicated that group decision making optimizes the selection and prioritisation of monitoring instruments for embankment dams, and selected instruments are reliable based on the dam specifications.

Keywords: risk management; decision analysis; embankments dams; geotechnical instrument; monitoring; multi-attribute decision making; Analytic Hierarchy Process; Multi-Criteria Optimisation and Compromise Solution

1. Introduction

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 correct observation of the interaction between dam body, dam foundation and external environment, the dam structural behavior is very important for dam safety control (Ashtankar and Chore 2015, Su *et al*. 2016). Besides, application of appropriate instruments is a must to validate the dam design assumptions and models (Colombo *et al*. 2016).

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Past dam failure disasters showed that the loss of life in the event of a dam failure is directly related to the warning time available to evacuate the population at risk downstream of the dam (Fell *et al.* 2014, Paté-Cornell and Tagaras1986). Improperly monitoring program was reported as one the dam failure causes (Sharma and Kumar 2013). Any instrument selected should target specific items to be evaluated, establish critical thresholds that suggest the need for a specific action, and establish the details of the monitoring programs (Chavan and Valunjkar 2015). One of the most important issues in structural health monitoring is to reduce errors in application of measurement devices which is accessible by choosing compatible type of instruments (Kim *et al.* 2016, Li *et al*. 2014). Appropriate instrument selection is the most difficult stages of instrumentation and monitoring plan. The number of installed instruments has less importance against competent selection, suitable installation on critical points and smart interpretation of obtained data in total monitoring plan (Novak *et al.* 2007). The economic well-being and safety are the two most important goals in the dams designing and construction (Basset 2012). Undesirable instrumentation causes irreparable problems. Safety which implied in the structures have supplied by using competent instrumentation that needs using effective instruments technically, which means those should be selected based on special condition of the projects with appropriate compatibility of expectations. Appropriate instrument selection needs evaluation of different criteria for the projects.

Reliable monitoring of complex structures has been the topics of engineers which goal is to enhance the instrumentation plan of these structures (Yi *et al*. 2015). Dunnicliff (1993) explained instruments in different structures such as dams, mines and other geotechnical structures. In his point of view appropriate instrument selection is one of the most important steps of the monitoring plan. He believed that the most important factor in selecting instruments is reliability. Although, simplicity is inseparable part of instrument selection. Anderson *et al.* (1999) defined a multistep strategy for ranking of repair funds for the monitoring of embankment dams. Anderson *et al.* (2001) implied that the dam maintenance operation procedures can be done by utilising the appropriate selected monitoring systems. Naterop (2002) proposed that it is very important to respond questions about accuracy level, cost, accessibility, reliability, installation condition and installation place in order to select the appropriate instruments.

Kong (2003) suggested that selection of accurate and appropriate instruments in order to provide the required information for engineers is very important in structures monitoring, which is very necessary for increasing structural safety.

Mauriya (2010) investigated the geotechnical instruments, which are used within the earthen and the rock fill dam construction. In his point of view, dam projects consist of unique specifications that cause necessity of special instruments for monitoring each of them. There is usually an unnecessary tendency to high accuracy but in his opinion accuracy must be sacrificed by reliability when they should be chosen. Eberhardt and stead (2011) introduced instrumentation and monitoring planning trend. In their opinion, one of the steps of a suitable and measured plan is appropriate selection of geotechnical instruments. To design a monitoring plan, there should be an opportunity reducing cost of maintenance while safety of the structures during its lifecycle should be considered (Kim *et al.* 2016).

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. Nowadays, the use of the Multi-Attribute Decision Making (MADM) techniques is increasing in decision-making processes and different areas. It is because of the simplicity and understandability of these techniques for various users (Gul *et al.* 2016). In this study, the Analytic Hierarchy Process (AHP) and Multi-Criteria Optimisation and Compromise Solution (VIKOR) methods are utilised in order to obtain the attributes' importance weights and ranking the alternatives, respectively; consequently, the suitable instrument selection will be implemented. The main advantages of the AHP method are that it provides a hierarchical segmentation of a decision, which helps to better understand the overall process of decision making, it incorporates both quantitative and qualitative criteria and it is relatively easy for the researcher to use (Samaras *et al.* 2014). The AHP and fuzzy logic have been advanced as a formal means to deal with implicit imprecision in a wide range of problems (Masoumi and Rashidinejad 2011). The VIKOR (Vlse Kriterijumska Optimizacija I Kompromisno Resenje in Serbian) method is an effective tool in MADM. The VIKOR method introduces an aggregating function representing the distance from the ideal solution. This ranking index is an aggregation of all criteria, the relative importance of the criteria, and a balance between total and individual satisfaction (San Cristóbal Mateo 2012). The VIKOR method is a remarkable multi-attribute group-based decision making analysis method that can be widely used to solve many practical problems (Jing *et al.* 2015). There are many effective factors such as reliability, availability, system life, impact of installation on the structure, transducer type, readout unit and etc. in selecting the type of the instruments. Thus, using decision making method based on mathematical planning can help the selection process.

2. Identifying effective attributes and geotechnical instruments

Geotechnical structures should be equipped structural monitoring systems because unpredicted structural failure may cause economic, catastrophic, and human life loss. An effective and reliable monitoring system is crucial to maintain safety and integrity of structures (Li *et al.* 2016).

Fig. 1 represents the instruments selection procedure for geotechnical structures. It has been designed for all geotechnical structures such as dams, tunnels, slopes, etc. but it should be considered that the present study is about embankment dams and for other structures the data, the attributes and the alternatives should be recognised consistently. As shown in Fig. 1, the first phase of the problem solution is to collect the embankment dam information which are consist of dams geometry, field geology, risk acceptability of predicted problems, weather, material applied in dams structure, local downstream condition and etc. On the other hand, the next step is to identify the effective attributes which influence the decision making 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.

Once the problem procedure is clarified, it is very important to employ reliable attributes for investigating the alternatives. All the attributes and geotechnical instruments are listed below. Where, all have been collected from following researches. In each case, the most important part of their findings are discussed and the effective attributes and instruments were extracted.

Fig. 2 shows the typical monitoring instruments which should be installed in embankment dams. However, embankment dams' instruments are not limited to those in Fig. 2. The main issue is how to choose the most adequate instrument type which is reliable for safety monitoring of the dam.

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).

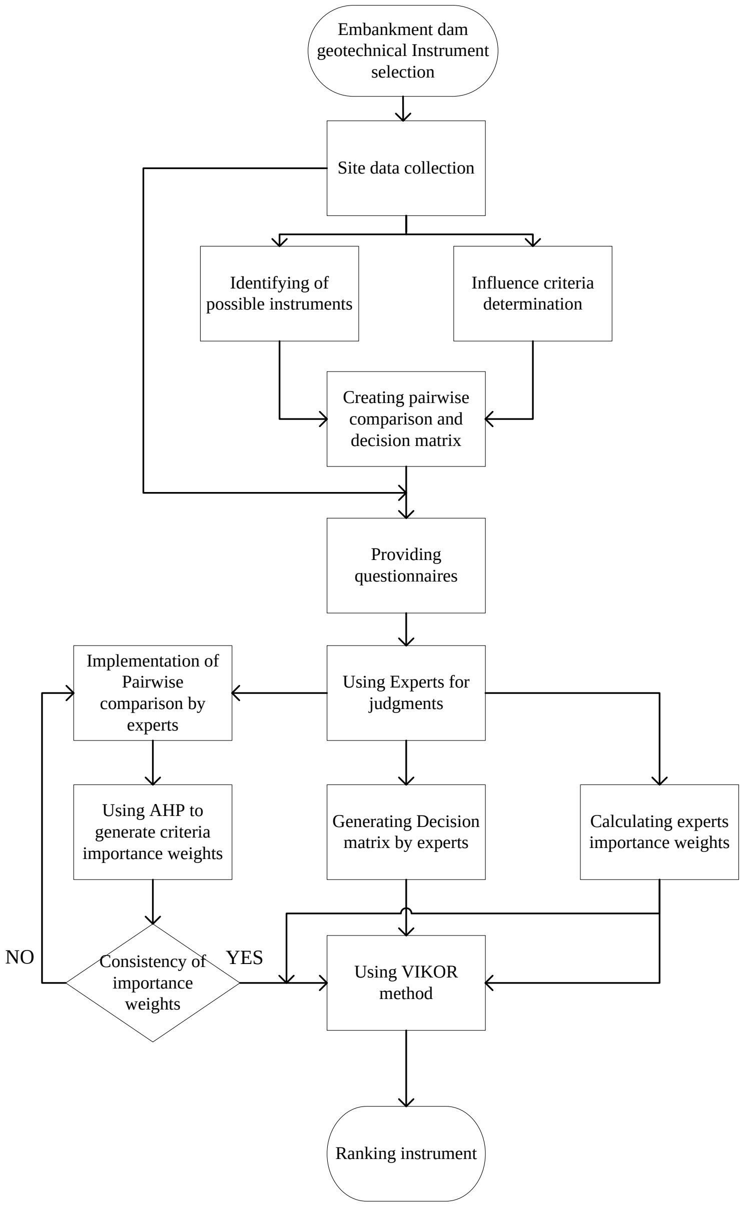

Fig. 1 Optimal instruments selection procedure for geotechnical structures

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 lifetime and its proportion to the instruments efficiency and cost (Nagarajaiah and Erazo 2016). 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. Automated data acquisition system should not be used until the explanation is not available for using electrical transducers. Transducers which are available for

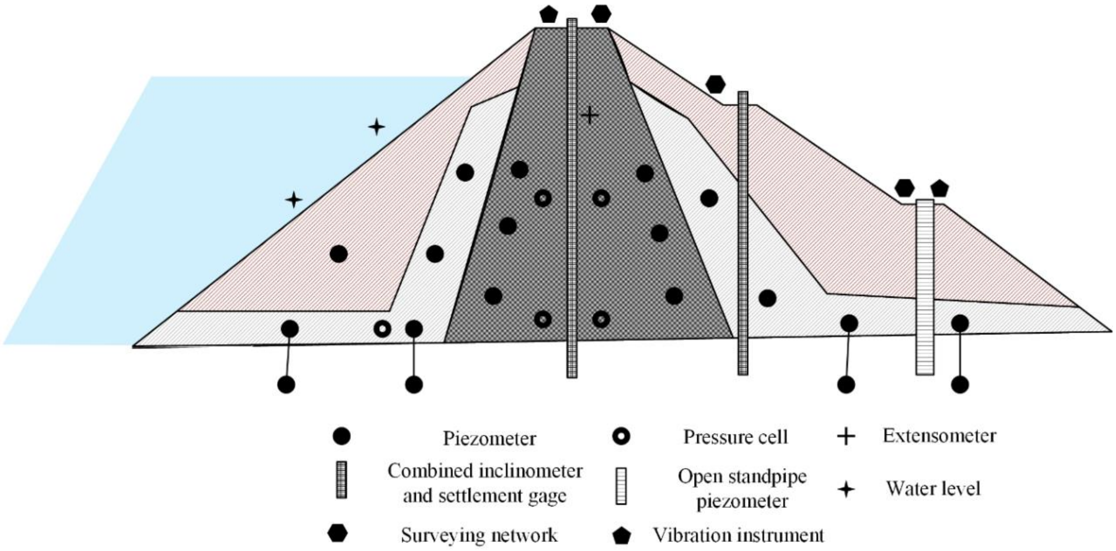

Fig. 2 Typical embankment dam monitoring instruments

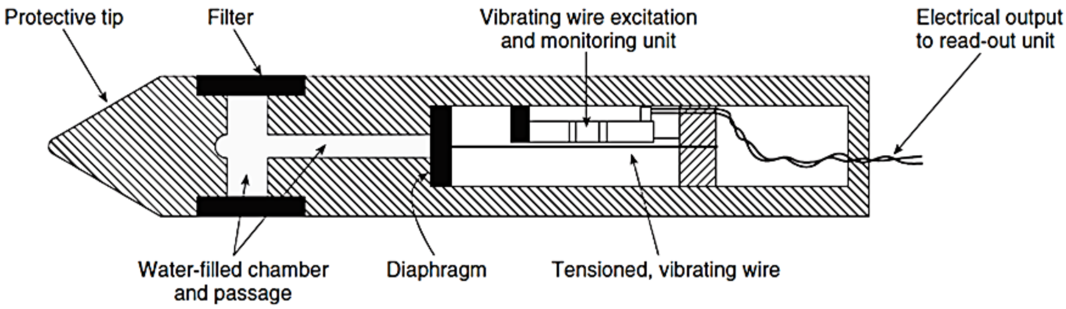

Fig. 3 Typical section of vibrating wire piezometer (Sarsby 2013)

calibration or replacement should be used everywhere it is possible. For instance, vibrating wire piezometers (Fig. 3) should not be used instead of standpipe piezometers (Fig. 4) only due to their superiority for automatic data acquisition. For difficult conditions of accessibility (e.g., 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 instruments and consider advantages and limitations regarding to the environmental condition (USACE 1995).

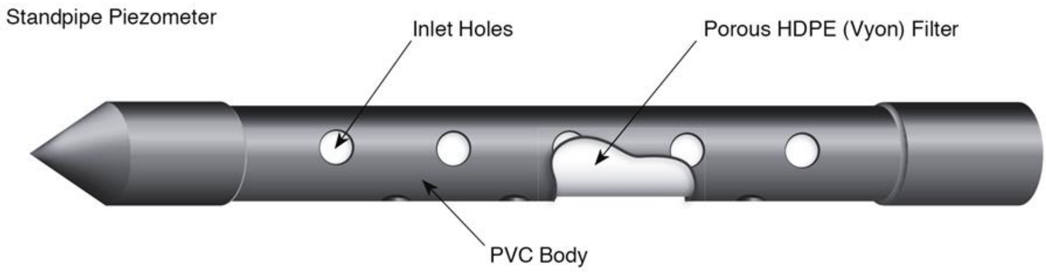

Fig. 4 Typical standpipe piezometer (Solinst® 2013)

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. 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).

The significant attributes which are effective in optimal instruments selection have been collected that encompass different sides of suitable instruments selection. These criteria consist of:

- Reliability
- System or instrument lifetime
- Ease of data acquisition
- Installation environment condition (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 (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 (such as instrument performance in frost, heat, moisture and etc.)
- Availability of experts
- Availability of instruments
- Performance in relation to cost

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. Table 1 represents the classified geotechnical instruments of embankment dams.

Table 1 Classification of geotechnical instruments of embankment dam

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

3. Integrated decision making framework

Although the importance of instrument selection has been reported in many researches, there are not determinable methods presented yet. Applicable problems commonly are investigated by several incommensurable and conflicting criteria and maybe there is no solution to satisfy all criteria at the same time. Therefore, solution is set of compatible responses according to decision makers priorities (Opricovic and Tzeng 2004).

Decision makers in these problems try to find the best option among the existing and countable ones. Usually, many criteria are applied for decision making, hence decision makers encounter with multi criteria decision making problems (Hwang and Yoon 1981). In fact, decision making problem can be shown as Eq. (1)

$$D = \begin{matrix} \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{matrix} \begin{matrix} C_1 & C_2 & \dots & C_n \\ \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2n} \\ \vdots & \vdots & x_{ij} & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \end{matrix} \quad (1)$$

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. VIKOR method is one of the most applicable MADM methods in different fields and has been used widely (Zeng *et al.* 2013). VIKOR method has been developed as a multi-criteria decision making (MCDM) to solve discrete problems with conflicting and incommensurate criteria. This method concentrates on ranking and selecting a set of alternatives and determines compromise solution for conflicting criteria. This advantage helps to decision makers reaching final decision (Opricovic and Tzeng 2007).

MADM methods require importance weight determination of criteria. AHP is one of the MADM methods which is able to determine importance weights of attributes in addition to decision making alternatives priority. Investigation of consistency ratio of pair-wise comparison is one of the most important advantage of this method which causes that error decreases in criteria importance weights determination (Yavuz *et al.* 2008, Singh *et al.* 2015).

Also, this method has been used in many different dam engineering researches such as Yasser *et al.* (2013) who determined embankment dams' optimal location with 9 attributes and 11 sub-attributes and analysed 4 alternatives of dam location. Shayesteh *et al.* (2015) employed this method for environmental risk assessment of constructed dams. In this way, based on the earthquake occurrence risk, possible solution for encountering these conditions was studied and the best one was proposed. Also, land ownership plan and relocation during construction of a new dam for more water resources was proposed by Kurniati *et al.* (2013). The combination of AHP and VIKOR methods will be used for proposed study. So that, the AHP method and VIKOR method utilises to assign criteria importance weights and to determine the instruments final priority.

3.1 AHP method

Subjective judgements of decision makers are quantified by means of the assigning correspondent numerical values to components relative importance. This method was founded and was developed by Saaty (1980, 1990) and Saaty and Vargas (1994) which is the most known of MADM (Masoumi *et al.* 2014). In order to determine importance weights, this method is summarising in to 4 steps:

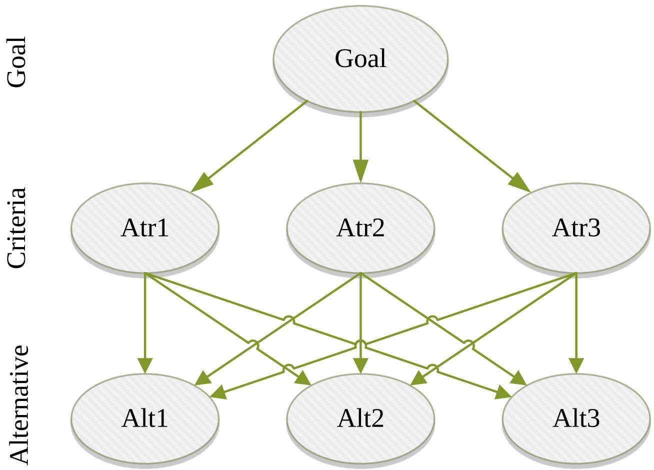

Fig. 5 Hierarchy structure of AHP

• Step 1: Developing the AHP hierarchy

Decision making problem should become as a decision making tree in which general goal locate on the highest level and attributes and sub-attributes (if any) locate on the lower levels and alternatives place on the lowest level of hierarchy (in this case, this method only uses for determining the importance weights of attributes, so there is no need for formulating alternative level) (Safari *et al.* 2010). Fig. 5 indicates a simple hierarchy structure which consists of three levels: goal and criteria as well as alternatives. *Atr1*, *Atr2* and *Atr3* are 3 attributes applying for creation of pair-wise comparison matrix towards Goal level. *Alt1*, *Alt2* and *Alt3* show the alternatives.

• Step 2: Pair-wise comparison

Decision matrix is formed with pair-wise comparison through decision makers as it can be seen in Eq. (2). In this equation, the rows and columns consist of attributes and compare against each other. Pair-wise comparison is based on 9-points scale (Table 2). In this scale, values 1 to 9 present the relative superiority of two attributes (Lee *et al.* 2008)

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix}, a_{ij}=\frac{1}{a_{ji}}, a_{ii}=1 \tag{2}$$

Where a_{ij} showed superiority degree of i^{th} attribute over j^{th} attribute and reverse.

Assume that a pair-wise comparison matrix based on Fig. 5 has been done by an expert and it generates Table 3 as a result of expert's judgements according to Table 2.

• Step 3: Importance weights calculation

Averaging over normalised columns is known as a simple method proposed for this scope. At the first must be calculated the sum of the columns in the comparisons matrix and the next, divided each element in the matrix to the sum of the column (the element is a member). Then, normalise the sum of the rows. The results of this computation are referred to as the criteria comparison normalised vector. The vector can be called as the priority matrix or importance weights (Bascetin 2007). The results for the example in Table 3 is shown in Table 4.

Table 2 Scales for pair-wise comparison (Lee *et al.* 2008)

Preferences expressed in numeric variable	**Preferences expressed in linguistic variable**
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance
2, 4, 6, 8	Intermediate values between adjacent scale values

Table 3 Example of a pair-wise comparison matrix between attributes

Goal	*Alt1*	*Alt2*	*Alt3*
Alt1	1	1/5	3
Alt2	5	1	7
Alt3	1/3	1/7	1

Table 4 Attributes importance weights calculation

Goal	*Alt1*	*Alt2*	*Alt3*	Importance weights
Alt1	0.158	0.149	0.273	0.1932
Alt2	0.789	0.745	0.636	0.7235
Alt3	0.053	0.106	0.091	0.0833

• Step 4: Inconsistency ratio calculation

Inconsistency ratio is calculated to reflect consistency ratio of decision makers' judgement in pair-wise comparison stage. It is obtaining with Eq. (3)

$$IR = \frac{II}{RII} \tag{3}$$

Where II is Inconsistency Index that calculated using Eqs. (4) and (5) and RII is Random Inconsistency Index which extracted from Table 5. Whatever inconsistency ratio approached is zero, the greater consistency value and generally its value must be less than 0.1 until AHP results will be acceptable

$$A * W = \lambda\ * W \tag{4}$$

Where W is relative weights vector from step 3, λ is eigenvalues matrix and A is pair-wise comparison matrix. With averaging eigenvalues matrix, $\lambda_{\max}$ will be calculated; consequently, II will be obtained as follow

$$II = \frac{\lambda_{max} - n}{n-1} \tag{5}$$

Where n is existing matrix dimension in the problem (Saaty, 1980). The procedures for calculating inconsistency ratio of above numerical example is illustrated in the following. Firstly, λ matrix should be calculated by Eq. (4) as it shows by Eq. (6). Then, $\lambda_{\max}$, which is a number,

Table 5 Random inconsistency index (Saaty 1980)

n	1	2	3	4	5	6	7	8	9	10
RII	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.51

computes by Eq. (7). Finally, based on Eqs. (5) and (3) as well as Table 5, the *IR* equals to 0.057 as it can be seen in Eq. (8)

$$\begin{bmatrix} 1 & 1/5 & 3 \\ 5 & 1 & 7 \\ 1/3 & 1/7 & 1 \end{bmatrix} \times \begin{bmatrix} 0.193 \\ 0.724 \\ 0.083 \end{bmatrix} = \lambda \times \begin{bmatrix} 0.193 \\ 0.724 \\ 0.083 \end{bmatrix} \Rightarrow \lambda = \begin{bmatrix} \frac{0.588}{0.193} \\ \frac{2.273}{0.724} \\ \frac{0.251}{0.083} \end{bmatrix} = \begin{bmatrix} 3.043 \\ 3.141 \\ 3.014 \end{bmatrix} \tag{6}$$

$$\lambda_{max} = \frac{3.043+3.141+3.014}{3} = 3.066 \tag{7}$$

$$II = \frac{3.066-3}{3-1} = 0.033 \; and \; RII = 0.58 \; \Rightarrow IR = 0.057 \tag{8}$$

Since 0.057 is less than 0.1, the results of AHP is acceptable in this example.

3.2 VIKOR method

VIKOR method was firstly proposed by Yu (1973) and then by Zeleny (1982). In recent years, Opricovic and Tzeng (2002, 2003, and 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)

$$L_{p,i} = \left\{ \sum_{j=1}^{n} \left[\frac{w_j\left(f_j^* - f_{ij}\right)}{\left(f_j^* - f_j^-\right)} \right]^p \right\}^{1/p}, 1 \leq p \leq \infty \; ; j = 1,2, \dots, n \tag{9}$$

Where w_j is jth attribute importance weight, f_j^* is the highest value of jth attribute regarding to decision making alternatives and f_j^- is the lowest value of jth 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 variable $S_i and\ R_i$. The main process of VIKOR method regarding to Eq. (1), for ranking the alternatives will be as follows (Opricovic and Tzeng 2002, 2007):

- Step 1: After formulating decision making matrix, the first step is to normalize the decision matrix which has been done by Eq. (10). Then, in benefit attributes, the greatest and the fewest value of any attribute will be calculated by Eqs. (11) and (12) which are shown by f_j^* and f_j^-, respectively

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \tag{10}$$

$$f_j^* = \max_j f_{ij} \tag{11}$$

Table 6 Example of decision matrix

	Atr1	*Atr2*	*Atr3*
Alt1	4	6	3
Alt2	5	8	7
Alt3	3	4	4

Table 7 Normalized decision matrix and related parameters

	Atr1	*Atr2*	*Atr3*
Alt1	0.5657	0.5571	0.3487
Alt2	0.7071	0.7428	0.8137
Alt3	0.4243	0.3714	0.4650
f_j^*	0.7071	0.7428	0.8137
f_j^-	0.4243	0.3714	0.3487

$$f_j^- = \min_j f_{ij} \tag{12}$$

Based on Fig. 5, assume that a decision matrix is as Table 6 while *Alt* indicates alternatives and *Atr* shows attributes. It should be noted that it is possible to employ both quantitative and qualitative scales in order to investigate alternatives against attributes.

Therefore, normalized decision matrix's elements, which are called f_{ij}, f_j^* and f_j^- are equal to Table 7.

• Step 2: Calculation of S_i and R_i

$$S_i = \sum_{j=1}^{n} w_j \left(\frac{[f_j^* - f_{ij}]}{[f_j^* - f_j^-]} \right); i = 1,2,\dots,m\ , j = 1,2,\dots,n \tag{13}$$

$$R_i = \max_i \left[w_j \left(\frac{[f_j^* - f_{ij}]}{[f_j^* - f_j^-]} \right) \right];\ j = 1,2,\dots,n \tag{14}$$

Where W_j is the attributes' importance weights. Regarding above example, attributes' importance weights have been calculated by AHP method and they have been shown in Table 4; as a result, S_i and R_i have been obtained and they have been demonstrated in Table 8.

• Step 3: Determination of Q_i with following equation

$$Q_i = \nu \left(\frac{(S_i - S^-)}{(S^* - S^-)} \right) + (1-\nu) \left(\frac{(R_i - R^-)}{(R^* - R^-)} \right) \tag{15}$$

Where S^* = min*i* (S_i), S^- = max*i* (S_i), R^* = min*i* (R_i), R^- = max*i* (R_i), and $\nu \in [0, 1]$. Parameter ν balances the relative importance of indexes *S* and *R* and usually equal to 0.5. The results of Q_i for above numerical example are indicated in Table 8.

• 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. $Q(A_2) - Q(A_1) \geq DQ$ where A_2 is the best second

Table 8 Results of VIKOR method

	S_i	R_i	Q_i	Rank
Alt1	0.2966	0.1659	0.7550	2
Alt2	0.0000	0.0000	0.0000	1
Alt3	0.3859	0.2237	1.0000	3

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 $A_1, A_2, \ldots, A_m$ 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.

For instance, considering Table 8, condition 1: $0.755 - 0.00 \geq 1/2$ and Condition 2 are satisfied; therefore, the best-ranked alternative is *Alt2*, which is the one with the lowest value of Q.

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

4. Application of decision framework to 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 12×10^8 m^3.

Considered volume for sediments volume is 160×10^6 m^3 during 50 years and the dam body has the total volume of 8.59×10^6 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.

In the present project, 13 experts have been employed for the survey. In order to increase decision making quality level, a process has considered for determining of the decision makers' importance weights. The decision makers has compared together based on 3 criteria of education level, related scientific publications number and also work experience and each has been allocated an importance weights.

Table 9 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 are in the last column of Table 9.

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. (10). The importance weights of the decision makers (DMs) then calculate with Eq. (16)

$$DM_i' = \sum_{j=1}^{m} r_{ij} \tag{16}$$

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. (17)

$$DM_i = \frac{W_i'}{\sum_{i=1}^{n} W_i'} \tag{17}$$

Table 9 Normalised matrix of decision makers' 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

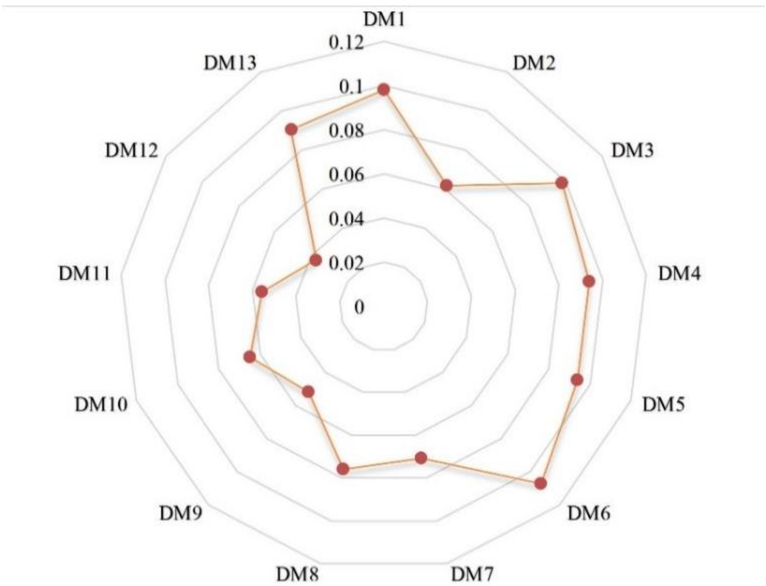

Fig. 6 Decision makers' importance weights

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

Also, Fig. 6 illustrates experts' importance weights visually. These decision makers' importance weight therefore, will take effect on the AHP and VIKOR results from each decision makers' judgement. Then, the averaging of this group decision making will provide the final results.

Regarding to solve the problem, attributes' importance weights have obtained for 9 effective attributes using AHP from every pair-wise comparison matrix which has been rated by decision makers. Then, every individual expert's importance weights have been multiplied to the result of attributes' importance weights from the same expert. Finally, the final importance weights of attributes have obtained using geometrical averaging method for VIKOR method.

Since, AHP method has a process for determining the inconsistency ratio, only consistent experts' pair-wise comparisons were counted in the attributes' importance weights determination process. The final pair-wise comparison matrix, which has been averaged of all DMs judgments, is

Table 10 final group averaged pair-wise comparison matrix

	Instrument lifetime	Reliability	Ease of data acquisition	Installation environment condition	Ability of being complementary instrument	Environmental compatibility	Availability of expert	Availability of instrument	Performance in relation to cost
Instrument lifetime	1.09	0.53	0.83	1.50	1.17	0.98	1.00	0.86	0.90
Reliability	2.21	1.09	2.32	2.57	2.45	1.87	2.14	2.08	2.14
Ease of data acquisition	1.41	0.51	1.09	2.10	1.35	1.35	1.78	1.40	1.18
Installation environment condition	0.79	0.46	0.56	1.09	0.98	0.87	0.80	0.61	0.53
Ability of being complementary instrument	1.01	0.48	0.87	1.20	1.09	0.93	1.33	0.85	1.02
Environmental compatibility	1.20	0.63	0.87	1.35	1.26	1.09	1.15	0.58	0.98
Availability of expert	1.18	0.55	0.66	1.47	0.88	1.02	1.09	0.79	0.88
Availability of instrument	1.36	0.57	0.84	1.94	1.38	2.02	1.50	1.09	1.68
Performance in relation to cost	1.30	0.55	1.00	2.22	1.15	1.20	1.33	0.70	1.09

Table 11 Final importance weights of attributes

Attributes	Importance weights	Rank
Instrument lifetime	0.094	6
Reliability	0.198	1
Ease of data acquisition	0.123	3
Installation environment condition	0.071	9
Ability of being complementary instrument	0.092	7
Environmental compatibility	0.098	5
Availability of expert	0.089	8
Availability of instrument	0.129	2
Performance in relation to cost	0.106	4

shown in Table 10. Again, it should be mentioned that all individual DM's pair-wise comparison matrix has been multiplied to DM's specific importance weights, which have been indicated in Fig. 6, prior to final pair-wise comparison matrix has been averaged. The attributes' importance weights results represent in Table 11 and Fig. 7.

After determination of experts and attributes' final importance weights, the next step is solving the main decision matrix which has been resulted from 13 experts' judgments. Fig. 8 represents the scoring system which has been used for evaluating the decision matrix by experts. All individual decision making matrix have been taken effect by multiplying its expert's importance weight as same as pair-wise comparison matrices. Finally, geometrical averaging has been applied to generate the main decision matrix from 13 experts. There were 8 main matrices for solving by VIKOR method since geotechnical instruments for embankment dams had been categorised in 8 groups.

For instance, the main averaged decision matrix of the instruments in pore water pressure category has been represented as Table 12.

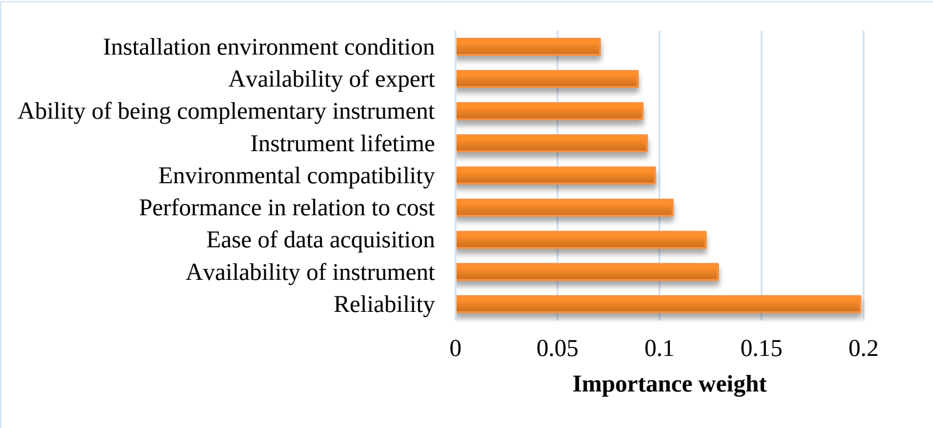

Fig. 7 Final ranking of attributes importance weights

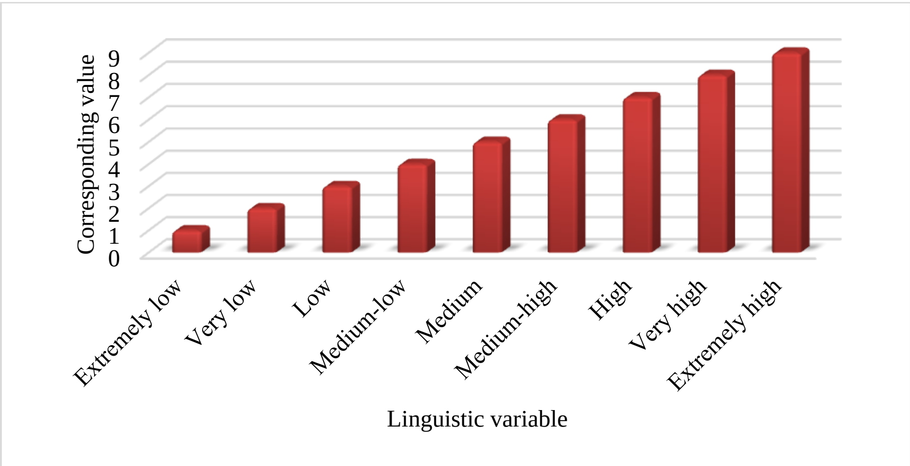

Fig. 8 Scale for VIKOR decision matrix evaluation

Table 12 Final group averaged decision matrix for pore water pressure to apply in VIKOR method

Main averaged decision making matrix	Instrument lifetime	Reliability	Ease of data acquisition	Installation environment condition	Ability of being complementary instrument	Environmental compatibility	Availability of expert	Availability of instrument	Performance in relation to cost
Observation well	0.443	0.473	0.087	0.380	0.283	0.276	0.399	0.540	0.344
Open standpipe piezometer	0.460	0.500	0.110	0.369	0.357	0.331	0.399	0.427	0.424
Pneumatic piezometer	0.291	0.388	0.325	0.382	0.429	0.405	0.352	0.205	0.273
Twin tube hydraulic piezometer	0.284	0.376	0.256	0.358	0.366	0.342	0.348	0.210	0.317
Electrical resistance piezometer	0.409	0.494	0.546	0.471	0.456	0.456	0.438	0.262	0.287
Vibrating wire piezometer	0.438	0.520	0.608	0.474	0.441	0.429	0.411	0.258	0.383

Table 13 Pore water pressure instrument selection results

Alternatives	S	rank	R	rank	Q	rank
Observation well	0.539	4	0.123	4	0.348	4
Open standpipe piezometer	0.410	3	0.117	3	0.220	3
Pneumatic piezometer	0.757	5	0.182	5	0.842	5
Twin tube hydraulic piezometer	0.847	6	0.198	6	1.000	6
Electrical resistance piezometer	0.284	2	0.107	1	0.067	2
Vibrating wire piezometer	0.198	1	0.108	2	0.008	1

In this manner, eight groups of decision matrix have been weighted with experts' importance weights and then have been averaged until just one main decision matrix remained for every groups. Table 13 shows the calculation results for the pore water pressure instruments category using VIKOR method.

As it can be seen from Table 13, 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. Other alternatives have been brought on their final ranks in the last column of Table 13. Whereas, only two instruments have been recognised suit for monitoring based on the *Q* rank and the conditions of VIKOR method. These two instruments were vibrating wire and electrical resistance piezometers and their cells are shaded in the Table 13. Also a comparison has been done among instruments of pore water pressure category and it is illustrated in Fig. 9.

Since the dam is a large one, the vibrating wire and electrical resistance piezometers are reliable choices. The performance of these instruments covers their cost in long-term monitoring. Both are able to be automated readout and availability of the experts is necessary in such a huge structures. Hence, the selected instruments are optimal relating to this case.

Table 14 indicates all the optimal selected alternatives for each category by VIKOR method. 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. All adequate alternatives have been selected and where there are another possible solution, they have been ranked.

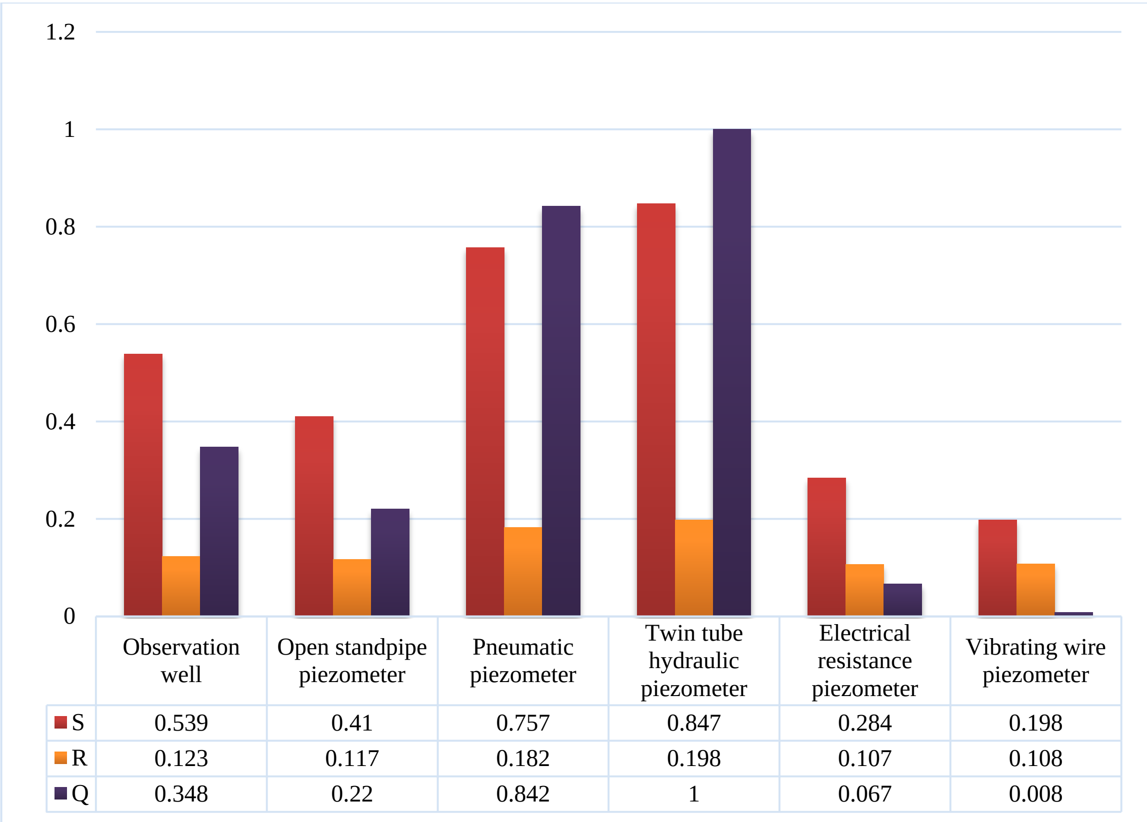

Fig. 9 Comparison of pore water pressure instruments

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	Strain resistance diaphragm pressure cell
2		Calibrated catch container	Geophone	Combined inclinometer and settlement point	In place inclinometer		Hydraulic pressure cell with resistance strain gage transducer
3		Velocity meter	Seismograph	Settlement gage with casing and probe	Probe inclinometer		
4		Parshall flumes		Fixed borehole extensometer			
5		Water level gage					

5. Conclusions

The geotechnical instruments selection method based on MADM has a very good ability to analyse the alternatives and to introduce the optimal alternatives with compromise solution. This method is able to use the next selected alternatives that was picked as appropriate alternative or to use all the acceptable prioritised options. Every embankment dams condition are different, therefore, it is logical fact that should be limited with the most consistent type of instruments for monitoring.

It is possible to not rating some cells by experts which are unfamiliar for them or their knowledge is not enough for the specific instrument. Besides, it is possible adding new attributes and other instruments alternatives that might not be inserted in this framework.

Most important categories of embankment dam instruments were collected in this research and introduces in Table 1. Besides, the most effective attribute were presented. Therefore, the framework is able to be applied to all types of embankment dams from small to large one and from earth to rock-fill dam.

The other benefit of this method is considering experts' subjective ambiguities in determining the appropriate instruments. For example it can introduce just one instrument (micro geodesy and surveying network) or proposed more than one (such as pore water pressure category). That means of decision makers priorities have included in decision making process.

Calculated inconsistency ratio in AHP method improves determination of attributes' importance weights. 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. The risk of unpredicted disasters will be reduced since the health monitoring of dam structure will be based on optimal selected instruments. 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.

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