The Effect of the Inclined Core of the Earth Fill Dam on the Settlement Rate

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ABSTRACT: Since the constituent material of the earth fill dams are granular, they have little resistance to tensile stresses and are undergoing deformations as settlement. A large number of parameters affect the performance of dams. The aim of this paper is to evaluate the effect of the inclined core of earth fill dam as a parameter that is less regarded for the dam settlement rate. Therefore, considering the different angles for the core (60°, 75°, and 90°), the dam settlement (Case Study: Sardasht dam) was investigated. In this study, numerical and statistical methods (fuzzy set) were used to analyze the results, first analyses were conducted by numerical modeling using PLAXIS software, and then a settlement criterion was obtained using existing techniques in statistics. Then, to obtain the considered relationship, the fuzzy linear regression model was used. Finally, after dynamic and static analysis with the mentioned methods, it was observed that with increasing core slope, the dam settlement decreases. The outcomes of fuzzy regression equations also confirm this issue.

KEYWORDS: Settlement rate, Inclined core, Body slope, Numerical modelling, PLAXIS, Fuzzy set regression.

1. INTRODUCTION

Safety is the first and most important reason for observing the settlement of dams. A secondary reason, of less immediate concern to the owner, but potentially great long-range significance to the engineering profession, is the need for a better understanding of basic design concepts, the settlement, and deformation of earth fill (Fell et al., 1992; Cooling, 1962; Marsel, 1963).

During dam or embankment construction, settlement takes place due to changes in total stresses, pore pressures, creep and secondary time effects. Foundation movements, load transfer between zones, and other factors have impact on the settlement (Bechtel, 1960).

The assessment of the settlement behavior of rock-fill dams has always been a challenge for dam designers and geotechnical engineers. Vassilis Gikas et al. in 2008 showed that the difference between the settlements predicted by the finite element model and monitoring results at cross-section locations adopted in the analysis for the entire lifetime of the Moreno's earth dam (Greece) and for the period for which monitoring data, is more than 0.03 centimeter (Vassilis, 2008). According to the research that Zhou et al. done on the settlement of Shubuta dam in 2011, the difference between the settlement predicted by the finite element model and monitoring data during the three years of operation is about 5 cm (Wei et al., 2011). Also, as Liang Pei et al. showed in 2016, the average absolute value of the relative error between the calculated settlements determined from the back analyzed parameters and the measured settlement is 6.8 percent (Liang, 2016).

During the first impounding of the central core rock-fill dams, the collapse settlement inside the upstream shell can increase the settlement of rock-fill shell relative to the core. For instance, during the first impounding of the Cherry Valley dam, the settlement of the upstream shell was four times greater than that of the central core, which consequently led to the formation of longitudinal cracks on the crest along the shell-core interface (Squier, 1970; Hunter, 2003). Nobary and Duncan proposed a technique for modeling this phenomenon (Nobari, 1972). This technique relies on the hyperbolic model presented by Duncan (Duncan, 1970) and is closely tied to the direct use of triaxial test results. Naylor et al. proposed another method, which combined the technique of Nobary and Duncan with a critical state elastoplastic model (Naylor et al., 1986). This method was used to simulate the collapse settlement of the rock-fill shell of the Beliche dam, located in Portugal (Alonso et al., 2005). Other researchers used porous media mechanics and unsaturated soil frameworks to develop other methods with similar objectives (Lioret, 1980; Oldecop, 2001; Oldecop, 2003). Recently, Mahinroosta (Mahinroosta, 2012) used a concept called "stress reduction factor" to develop a practical technique for modeling the collapse settlement incorporated with a hardening/softening constitutive model (Itasca Consulting Group, Inc. 2005) in the framework of saturated soil mechanics. This technique was used to simulate the collapse settlement of the rock-fill shell of the Gotland Dam, the highest rock-fill dam located in Iran (Mahinroosta et al., 2015). Soroush and Shyadeh in their research in 2008 investigated the extent of earth fill dam settlement by considering two dams with oblique and vertical cores. They also used FLAC software for modeling. The results of their modeling indicated that the rate of horizontal displacement and settlement in earthen dams with inclined core is higher than vertical core (Soroush, 2008). In 2011, Nayebzadeh and Mohammadi-Mirali dealt with the "effect of the shape of the dam core". The results of their research indicated that by using finite element analysis evaluated desired conditions from the point of view of stress, deformation and resistance against hydraulic fracturing for the same width of dam designs (Nayebzadeh, 2011).

Due to the fact that during the vertical core performance, the volume of the downstream, which is practically dry and without pore pressure, and the possibility of its sliding surface contact with the core on the downstream slope is very low, in permanent settlement conditions has higher reliability than the inclined core. Also, because the volume of downstream materials has increased, the thickness of the filter layers can be reduced and in case of cracks in the core, the dam will have a higher safety factor. However, the disadvantages of dams with inclined core can be the high volume of downstream materials and the phenomenon of arching that occurs due to the settlement difference between the core materials and the crust.

2. GENERAL DESCRIPTION OF SARDASHT DAM

Sardasht dam is an earth-fill dam with a wide central clay core and located on the Zabkouchak River about 13 km upstream from Sardasht city in East Kurdistan province of Iran. The crest is about 114 meters above the original stream bed, but alluvial sands, gravels and weathered rock were excavated under the core to an additional depth of about 30 m. The crest length is about 204 m and the toe width is about 445 m. The side slopes are 1.4:1 and 1.5:1 (H:V) in the upstream and downstream embankment faces, respectively. The following tables show the largest cross-section with different zones indicated. The Physical and mechanical characteristics of clay core and crust are shown in Table 1 and Table 2.

Construction of the dam started in 2009 and completed to design elevation in 2018. Filling of the reservoir commenced about four months before the completion of the dam. The present study is an assessment of settlement behavior by the effect of inclined core changes (60°, 75°, and 90°) using the numerical PLAXIS software. Since presenting a relationship between inclined core and settlement is of high prominence, the strong frequently used statistical linear regression analysis was used for this purpose. Linear regression is a technique used to explain the relation between (an) independent continuous variable(s) and dependent a continuous variable.

Table 1 Mechanical characteristics of clay core material (Final Technical Report Sardasht Earth Dam, 2003)

Unified Classification	W_{opt} (%)	γ_d (gr/cm^3)	C' (kg/cm^2)	φ' (°)	K (cm/s)
CL-CH	15 - 18	1.5 - 1.7	0.39	14 - 19	0.4 - 4×10^8

Table 2 Material and construction characteristics of crust material (Final Technical Report Sardasht Earth Dam, 2003)

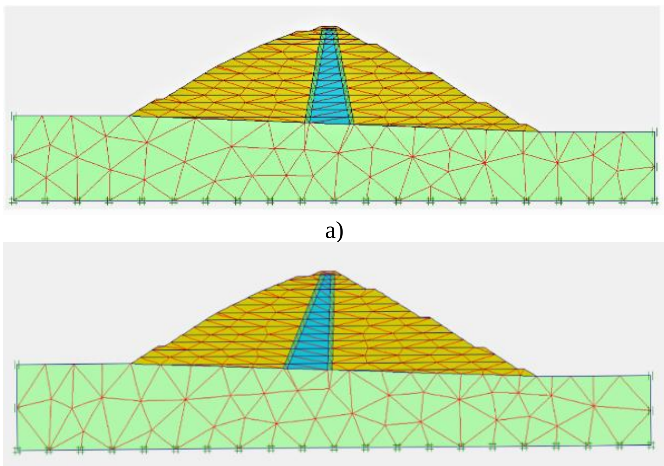
Zone		1A	1B	2A
Type		Impervious fill	Tuvenan alluvium	Sieved rock
Particle Sizes	D_{max} (mm)	50	380	150
	Sand (%)	> 70	-	35 - 50
	Fines (%)	> 35	< 20	3 - 10
Construction techniques	Layers (m)	0.60	0.60	0.40
	Compaction (10 roller)	5 passes (static)	5 passes	7 passes
Zone		**2AA**	**3A**	**3B**
Type		Filter	Selected rock	Quarry rockfill
Particle Sizes	D_{max} (mm)	20	300	600
	Sand (%)	70-100 40% < 0.5 mm	15 - 45	< 20
	Fines (%)	< 5	< 5	< 5
Construction techniques	Layers (m)	-	0.40	0.80
	Compaction (10 roller)	-	8 passes	4 passes
Zone		**3C**	**3D**	
Type		Quarry rock fill	Selected rock	
Particle Sizes	D_{max} (mm)	1000	2000	
	Sand (%)	-	-	
	Fines (%)	< 2	-	
Construction techniques	Layers (m)	1.20	Surface placed rocks	
	Compaction (10 roller)	6 passes	-	

The regression analysis is based on the assumption that variables (and other observations) are accurate numerical values. However, this assumption is not always true because in many cases the observations cannot be represented accurately. Such inaccurate values can be configured as fuzzy values. In this regard, fuzzy values provide very strong tools in regression analyses based on uncertain observations. Since the number of data for the slope angle and settlement is low and the values are inaccurate, fuzzy linear regression modeling is used in the present study. Through this approach, the observations made for each variable are presented as some generalized interval-valued intuitionistic fuzzy numbers. Our literature review shows that no study has been conducted on obtaining a settlement criterion using the linear regression model in a fuzzy medium. This modeling was originally presented by Taheri for estimating the unknowns of the model through linear programming. Numerous studies have been conducted on estimating coefficients of the linear regression model. Generally, these methods are classified into two groups of linear programming and the least square approaches. In the current research, the estimation method proposed by Torkian (Torkian et al., 2014), which is based upon the least square approach, is applied for the linear regression modeling in an environment with interval fuzzy numbers (Torkian et al., 2014).

3. FINITE ELEMENT MODEL

The analysis of the settlement behavior of the dam was carried out using a finite element program PLAXIS. Since soil and rock have a nonlinear behavior, different nonlinear behavior models were incorporated in PLAXIS. The behavior model considered in the present study is the hardening soil model. Since this model is an advanced elastoplastic model for simulating the behaviors of both soft and hard soils, the hyperbolic model was replaced by the hardening soil model using 1) the plasticity to elasticity theory, 2) incorporating soil dilation, and 3) introducing the flow cone.

The rock-fill embankment is modeled by 15-node triangular elements. These elements have 12 interior stress points located at different coordinates from the element nodes where displacements are output. These elements have 50 cm thicknesses and eight stress points. For a preliminary analysis, each construction stage was represented by a 10 m thick layer. It was observed that reducing the layer thickness renders the simulation better while extending the run time. Finally, a layer thickness of 7 m was decided as agreeable. The finite element mesh is shown in Figure 1. This mesh consists of 13,561 nodes and 22,744 stress points.



a)

b)

Figure 1 a) Mesh adopted for PLAXIS-vertical core of dam, and b) Mesh adopted for PLAXIS-inclined core of dam

3.1 Analysis Method

To perform the finite element analysis of a dam the following steps must be undertaken:

1) Selection of the model for the analysis (geometry, loading, and boundary conditions),
2) Selection of the material model (nonlinear),
3) Selection of geotechnical parameters of the materials.
4) The behavior of the earth material may be determined using the hyperbolic nonlinear model (Konner, 1963; Konner and Belasco, 1963).

As previously mentioned, the numerical and statistical methods were applied for stability analysis of the inclined core. The analysis output (settlement) produced by PLAXIS was then compared for all three dam body slopes (90°, 75°, and 60°). Finally, using the statistical method, an equation was developed between the slope and settlement values.

3.2 Settlement Calculation Using the Numerical Method

Numerical modeling is the mathematical simulation of a physical process that outperforms other methods because of its deformation analysis compatibility. Numerical methods are currently used in dynamic analysis to solve accurately advanced behavioral models with complicated equations. Numerical modeling analyzed under static conditions is used as the base of dynamic analysis. Next, by considering the seismicity of the study and design features, a suitable accelerograph is selected and the obtained deformations in different dam inclined core are compared. In the following, the maximum settlement plots of the studied dams obtained under seismic conditions for various inclined core are presented.

3.3 Assumptions of the Numerical Modeling

- Shell materials behavior is undrained; thus, no excess pore pressure is produced;
- Core and filter materials behavior is undrained;
- An earthquake occurs at the end of construction;
- Total stress analysis without pore pressure calculation is carried out;
- Before starting the dynamic analysis, all of the static deformations are reset to zero.

Consolidation analysis is incorporated into the boundary conditions added for the excess pore pressure. Since the right and left vertical boundaries are closed in such modeling, the horizontal flow does not occur; besides, the upper boundary is free.

In the dynamic analysis, absorbing boundaries are used to prevent wave reflection. For planar strain models (also used in the present study), the absorbing boundaries are developed in the right and left boundaries. Modeling and analysis of the dam are for the period before the impounding.

4. NUMERICAL ANALYSIS

4.1 During Construction

Figures 2, 3, and 4 indicate the settlement for the Sardasht dam at the end of construction. As it is shown in the following plots, the maximum settlement occurs above the middle of the dam height. The maximum pore water pressure at the end of construction for the three inclined cores (60°, 75°, and 90°) is shown in Figures 5 to 7. In the following, the values of settlement, horizontal displacement, and pore water pressure for all three inclined core (60°, 75°, and 90°) are presented in Table 3 and compared. As can be observed, the values of horizontal displacement and settlement increase with decreasing slope of the dam core, but the amount of pore water pressure decreases with decreasing slope.

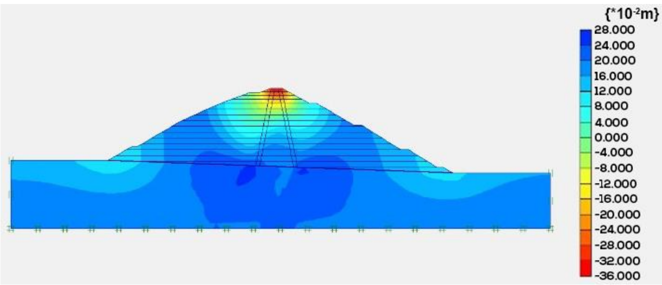


Figure 2 Settlement of dam with 90° slope

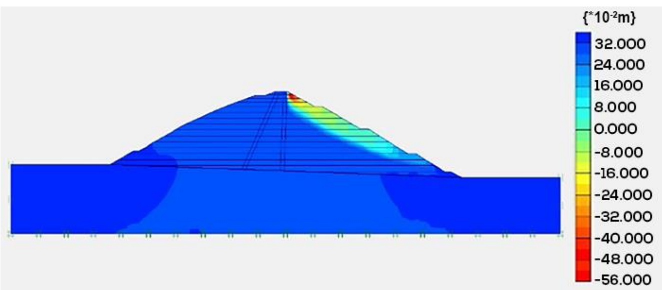


Figure 3 Settlement of dam with 75° slope

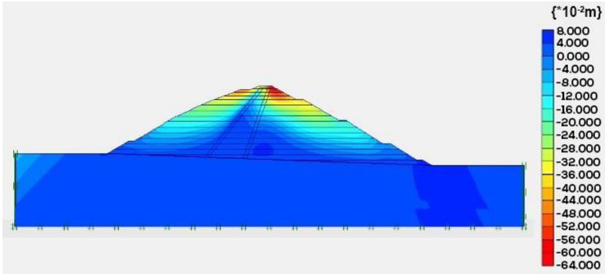


Figure 4 Settlement of dam with 60° slope

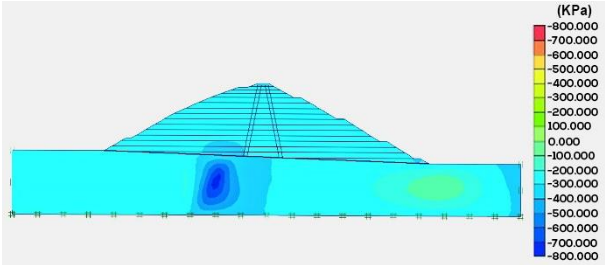


Figure 5 Excess pore pressure of dam with 90° slope

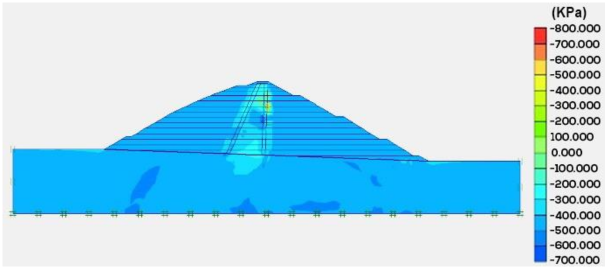


Figure 6 Excess pore pressure of dam with 75° slope

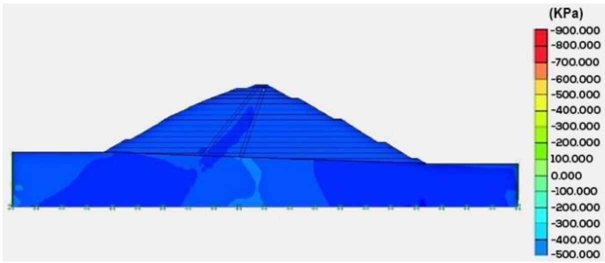


Figure 7 Excess pore pressure of dam with 60° slope

Table 3 Settlement values computed under the static mode analysis

Slope (°)	**90°**	**75°**	**60°**
Max Settlement (cm)	36	49	61
Max Horizontal displacement (cm)	23	41	55
Excess pore pressure (kPa)	725	670	406

4.2 During Earthquake

As for the earthquake input, the Bam earthquake is employed (Figure 8). For the stability analysis, the PGA is scaled to 0.4g.

After completing the dynamic analysis, we used the computed deformations for comparison of the behavior of the three dams body slopes. Figure 8 presents the time history of the dynamic horizontal and vertical displacements by using the SEISMOSIGNAL Software.

The sub-contour plots of the vertical and horizontal displacements under dynamic conditions for PGA = 0.4g for various inclined core (90°, 75°, and 60°) are presented in Figures 9 to 14. Generally, there is an obvious difference in the plots of displacements for the three dams.

It can be realized that rapid changes occur approximately at the time of 2 sec. The horizontal and settlement are 145 and 25 cm, respectively, in the inclined core dam with 750 slopes, and 240 and 66 cm in the inclined dam with 600 slopes; while, in the vertical-core dam, the horizontal and settlement are respectively 55 and 14 cm.

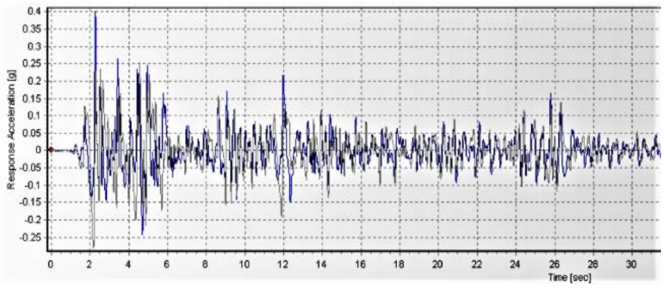


Figure 8 Dam horizontal Accelograph, PGA = 0.4g

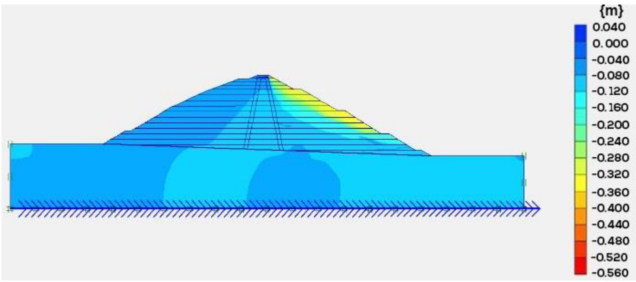


Figure 9 Settlement of dam with 90° slope

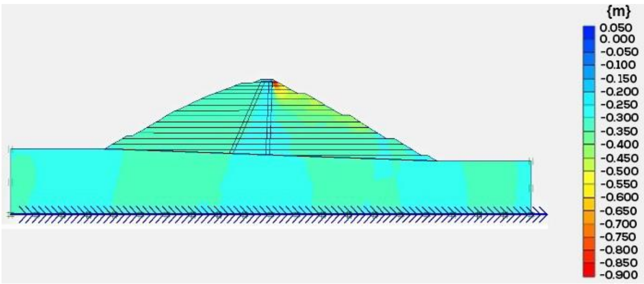


Figure 10 Settlement of dam with 75° slope

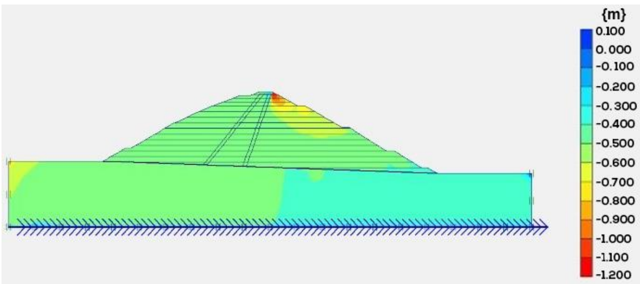


Figure 11 Settlement of dam with 60° slope

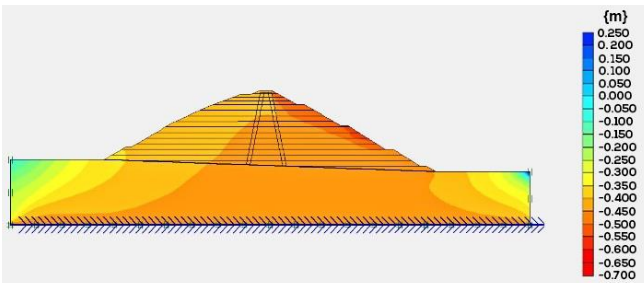


Figure 12 Horizontal displacement of dam with 90°slope

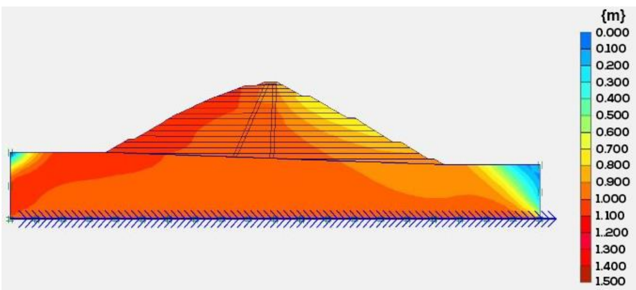


Figure 13 Horizontal displacement of dam with 75° slope

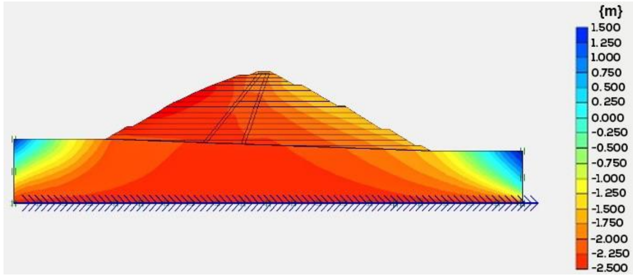


Figure 14 Horizontal displacement of dam with 60° slope

Table 4 illustrates the settlement and horizontal displacement values for various dam body slopes of Sardasht dam computed using PLAXIS for dynamic states.

Table 4 Settlement values computed under the dynamic analysis mode

Slope (°)	90°	75°	60°
Max Settlement (cm)	56	87	114
Max Horizontal displacement (cm)	66	145	240

4.3 Development of a Settlement Criterion Using the Fuzzy Set

In this part, first, the basic concepts of fuzzy set logic and a summary of Torkan's method are presented. First, regression equations in an interval intuitionistic fuzzy environment in two static and dynamic modes are extracted.

4.3.1 Interval Valued Intuitionistic Fuzzy Sets

Suppose that X is a given reference set. Each subgroup A of X is represented by a function of X as {0,1} called marker function:

$$I_A(x) = \begin{cases} 1, x \in A \\ 0, x \notin A \end{cases} \tag{1}$$

Now, if the range of marker function is extended from the binary {0,1} membership to the interval [0,1], we will have a function that assigns for each x a value within [0,1] from X. This function is called membership function μÃ (x). Thus, the fuzzy set of Ã is a set in which degrees of freedom (DOFs) of the members can be selected from a continuous range of [0,1]. The membership function μÃ (x) assigns a value for each element of X is a value within [0,1] as its DOF in the fuzzy set Ã. The proximity of μÃ (x) to 1 implies the higher belonging of x to the fuzzy set Ã. On the other hand, the proximity of it to 0 indicates it less belongs to Ã. According to the definition of a fuzzy set, the dismembership degree of x in fuzzy set Ã equals to 1 - μÃ (x); however, it is not in the reality. To deal with this problem, a different generalization of fuzzy sets has been defined. An interval-valued intuitionistic fuzzy membership degree is a well-known generalization of fuzzy sets. In a given interval intuitional fuzzy set, Ã from the reference set is expressed as:

$$\tilde{A} = \left\{ x, \mu_{\tilde{A}}(x), \nu_{\tilde{A}}(x) : x \in X \right\} \tag{2}$$

where $\mu_{\tilde{A}}(x)$:X→ [0,1] and $\nu_{\tilde{A}}(x)$:X → [0,1] present membership and dismembership degrees of x in Ã respectively providing that $x \in X$ is true in the condition that $0 \le \mu_{\tilde{A}}(x) + \nu_{\tilde{A}}(x) \le 1$. Therefore, the membership degree of x in the interval-valued Intuitionistic Fuzzy set Ã is represented as $[\mu_{\tilde{A}}(x), 1-\nu_{\tilde{A}}(x)]$ in [0,1], where $\mu_{\tilde{A}}(x)$ and $1-\nu_{\tilde{A}}(x)$ are the lower and upper membership boundaries of x in the interval-valued Intuitionistic Fuzzy set Ã, respectively.

If the reference set is the real numbers (R), the interval-valued intuitionistic fuzzy set Ã is called as an interval-valued intuitionistic fuzzy number (LR) when its membership functions are defined as ($l, r, l', r' \geq 0$):

$$\mu_{\tilde{A}}(x)=\begin{cases} L\left(\frac{m-x}{l}\right), m-l \leq x \leq m \\ 1, x=m \\ R\left(\frac{x-m}{r}\right), m \leq x \leq m+r \\ 0, o.w \end{cases} \tag{3}$$

$$1-\nu_{\tilde{A}}(x)=\begin{cases} L'\left(\frac{m-x}{l'}\right), m-l' \leq x \leq m \\ 1, x=m \\ R'\left(\frac{x-m}{r'}\right), m \leq x \leq m+r' \\ 0, o.w \end{cases} \tag{4}$$

where L(.), R(.), L′(.), and R′(.) are absolutely descending functions of R+ within [0,1] and L(0) = R(0) = 1 and L′(0) = R′(0) = 1.

The interval-valued intuitionistic fuzzy numbers of Ã = (m;l,r,l′,r′) are triangular fuzzy numbers if for every $x \in [0,1]$ we have $L'(x) = R'(x) = L(x) = R(x) = 1 - x$; which is presented as Ã = $(m; l, r, l', r')_T$; where l and r are respectively the left and right boundaries of $\mu_{\tilde{A}}(x)$ and l′ and r′ are respectively the left and right boundaries of $1-\nu_{\tilde{A}}(x)$. Figure 15 presents a triangular interval-valued intuitionistic fuzzy membership of a fuzzy number, which is equal to 30.

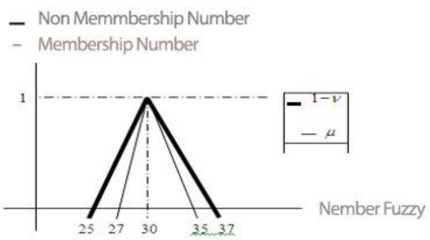


Figure 15 A triangular interval-valued intuitionistic fuzzy membership

4.3.2 Estimation Method of Torkian

In Torkian method defined an interval value between the interval fuzzy numbers that are a generalization of the signed distance function of Yao and Vio. This distance value for triangular distance values is expressed as follows (Torkian et al., 2014):

$$d\left(\tilde{A},\tilde{B}\right)=m-n+\frac{1}{8}\left[r_1-l_1+r_1'-l_1'\right]-\frac{1}{8}\left[r_2-l_2+r_2'-l_2'\right] \tag{5}$$

where, Ã = $(m; l_1, r_1, l_1', r_1')_T$ and $\tilde{B}$ = $(n; l_2, r_2, l_2', r_2')_T$ are triangular internal value fuzzy numbers.

Then, using this value, Tokrian et al. estimated the coefficients of fuzzy linear regression model using the method of least squares. The regression model used by the Torkian method is a fuzzy multiple linear regression presented as:

$$\tilde{y}_i = \beta_0 \oplus \beta_1 \otimes \tilde{x}_{i1} \oplus ... \oplus \beta_p \otimes \tilde{x}_{ip} \tag{6}$$

where $\tilde{y}_i = \left(y_i; l_{i1}, r_{i1}, l_{i1}', r_{i1}'\right)_T$, $\tilde{x}_{ij} = \left(x_{ij}; l_{ij2}, r_{ij2}, l_{ij2}', r_{ij2}'\right)_T$, $i = 1,...,n$ and $j = 1,..., p$

Thus, this equation presents the observations of dependent and independent variables in the form of triangular interval-valued numbers. The unknowns of the model (βj) are also non-fuzzy values that are estimated by minimizing the sum of squared error (SSE) as follows:

$$SSE=\sum_{i=1}^{n} d^2\left(\tilde{y}_i,\hat{\tilde{y}}_i\right)=\sum_{i=1}^{n} d^2\left(\tilde{y}_i,\beta_0+\beta_1\tilde{x}_{i1}+...+\beta_p\tilde{x}_{ip}\right) \tag{7}$$

where d is a generalization of Yao-Vio's singed distance for triangular interval-valued fuzzy numbers (5). Then, the model coefficients are estimated using the following matrix. For detailed information about the parameters of the matrix and their estimation, see Torkian et al. (2014).

4.3.3 Model Fitting Criterion

$$\hat{B}=\left[\left(X+\frac{S}{8}\right)'\left(X+\frac{S}{8}\right)\right]^{-1}\left[\left(X+\frac{S}{8}\right)'\left(Y+\frac{R}{8}\right)\right] \tag{8}$$

After the estimation of each prediction model, it is required to assess its prediction power. In this regard, there are various criteria for assessing the performance of different methods. To compare the prediction power of the model proposed in this work, we applied the coefficient of determination (R^2), which is defined as the ratio of the sum of squared regression to the total sum of squares (SST):

$$R^2=\frac{SSR}{SST}=\frac{\sum_{i=1}^{n} d^2\left(\hat{\tilde{y}}_i,\bar{\tilde{y}}\right)}{\sum_{i=1}^{n} d^2\left(\tilde{y}_i,\bar{\tilde{y}}\right)} \tag{9}$$

where d is a generalization of the signed distance of Yao-Vio for the triangular fuzzy interval-valued numbers (5).

4.3.4 Model Fitting

To extract the regression model, the core slope was considered as the independent fuzzy value (x) and the settlement was considered as the dependent fuzzy variable (y) and their relationship (model coefficients) were considered as non-fuzzy. The observations of each variable were considered as triangular interval-valued fuzzy numbers. Tables 5 and 6 present these observations in two static and dynamic modes, respectively.

Table 5 The fuzzy numbers of slope (inclined core) and settlement values in the static mode analysis

i	$\tilde{x} = x_i; 0.02x_i, 0.01x_i, 0.05x_i, 0.01x_i$
1	(90;1.8,0.9,4.5,0.9)
2	(75;1.5,0.75,3.75,0.75)
3	(60;1.2,0.6,3,0.6)
i	$\tilde{y} = y_i; 0.2y_i, 0.15y_i, 0.3y_i, 0.25y_i$
1	(36;7.2,5.4,10.8,9)
2	(49;9.8,7.35,14.7,12.25)
3	(61;12.2,9.15,18.3,15.25)

Table 6 The fuzzy numbers of slope (inclined core) and settlement values in the dynamic mode analysis

i	$\tilde{x} = x_i; 0.02x_i, 0.01x_i, 0.05x_i, 0.01x_i$
1	(90;1.8,0.9,4.5,0.9)
2	(75;1.5,0.75,3.75,0.75)
3	(60;1.2,0.6,3,0.6)
i	$\tilde{y} = y_i; 0.2y_i, 0.15y_i, 0.3y_i, 0.25y_i$
1	(56;11.2,8.4,16.8,14)
2	(87;17.4,13.05,26.1,21.75)
3	(114;22.8,17.1,1.34,28.5)

Proposed by the Torkian method, model coefficients under static and dynamic modes are determined as follows:

Static mode:

$$\hat{B} = \begin{pmatrix} 220.774 \\ -1.825 \end{pmatrix} \tag{10}$$

Dynamic mode:

$$\hat{B} = \begin{pmatrix} 104.512 \\ -0.758 \end{pmatrix} \tag{11}$$

Table 7 presents the fuzzy linear regression equations obtained based on the coefficient of determination (R^2) for the static and dynamic modes. Regarding the obtained R^2 values, the obtained regression models provide relatively high accuracy for estimating settlement using the core slope for both static and dynamic modes.

Table 7 The obtained fuzzy regression equations with their coefficient of determination

Mode	Static	Dynamic
The coefficient of determination (R^2)	0.841	0.893
Extracted fuzzy regression equation	$\hat{y}_i = 104.512 - 0.758\tilde{x}_i$	$\hat{y}_i = 220.774 - 1.825\tilde{x}_i$

Table 8 The settlement values obtained using the numerical (PLAXIS software) and statistical (the equation presented in Table 7) methods for static and dynamic modes

Dam body with a slope (inclined core) of 90° with the horizon		
Static model settlement (cm)	Numerical	36
	Statistical	(36.22; 0.68, 1.36, 0.68, 3.41)
Dynamic model settlement (cm)	Numerical	56
	Statistical	(56.44; 1.64, 3.29, 1.64, 8.22)
Dam body with a slope (inclined core) of 75° with the horizon		
Static model settlement (cm)	Numerical	49
	Statistical	(47.60; 0.57, 1.14, 0.57, 2.84)
Dynamic model settlement (cm)	Numerical	87
	Statistical	(83.83; 1.37, 2.74, 1.37, 6.85)
Dam body with a slope (inclined core) of 60° with the horizon		
Static model settlement (cm)	Numerical	61
	Statistical	(58.98; 0.45, 0.91, 0.45, 4.78)
Dynamic model settlement (cm)	Numerical	114
	Statistical	(111.22; 1.10, 2.19, 1.10, 11.50)

As shown in the following Figure 16 and Figure 17, to depict the settlement outputs obtained using the statistical method, the center of fuzzy numbers was used.

Using the graphs presented in Figure 16 and Figure 17, it can be stated that an increase in the inclined core of the dam results in a less dam settlement. In this regard, the comparison of results from the fuzzy regression model and numerical analysis shows satisfactory compliance.

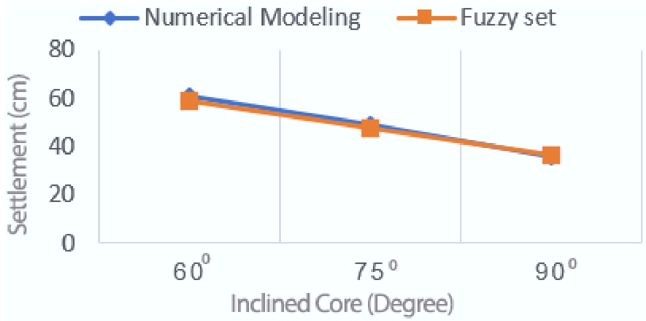


Figure 16 Dam settlement variations with the dam core changes in the static mode using both numerical and statistical approaches

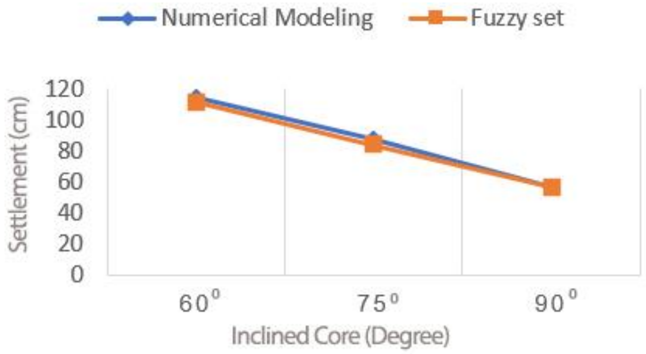


Figure 17 Dam settlement variations with the dam core changes in the dynamic mode using both numerical and statistical approaches

5. CONCLUSIONS

The purpose of this paper is to determine the criterion of the settlement of the inclined core of the earth fill dam, therefore numerical and fuzzy methods were used to obtain this criterion. In the numerical method, the static and seismic behavior of the Sardasht dam was studied considering three different angles for the slope of the core. PLAXIS software was used for dam analysis during construction and under earthquake load. To simulate the earthquake, the Bam earthquake accelerometer was used and scaled to PGA = 0.4g. The results of the analysis in both static and dynamic states are as follows.

Static analysis: The obtained plots using PLAXIS software indicate that the settlement rate has increased with a decreasing of inclined core, the obtained plots technically indicate that one-third of the height above the dam crest is more exposed to settlement. The results indicate that the subsidence rate with the core slope of 90° is lower than the settlement rate with the 60° slope. At the end of construction, the maximum pore water pressure value in the vertical core is greater than the associated value in the inclined core.

Dynamic analysis: The performed dynamic analysis with a PGA acceleration of 0.4 using the obtained plots indicates that the maximum settlement at the dam crest occurs near the core and decreases with the increasing slope of the core during an earthquake. Therefore, decreasing the settlement provides greater free height and consequently increases the dam's stability against earthquake and decreases the amount of settlement with increasing the slope of the dam core. Also, it is obvious that the maximum horizontal displacement occurs on the surface of the shell. The maximum horizontal displacement in the upstream shell in the dam with the inclined core is greater than the same value in the vertical core dam.

As can be seen in the figures, the modeling results were in good agreement with the results of other researchers who had performed numerical modeling in this field, such as Soroush and Shyadeh (2008) and Nayebzadeh and Mohammadi-Mirali (2011).

Fuzzy analysis with R coding: In the fuzzy method, the most valid and commonly used technique in statistics called linear regression analysis was proposed. Since the values related to the subsidence and slope are inaccurate, so these values are formatted as fuzzy numbers. Consequently, to obtain the relationship between slope and subsidence, a fuzzy linear regression model was used. Then, to ascertain the strength of the prediction of the model, the coefficient determination was used. Therefore, according to the estimated fuzzy regression equation in Table 7 and the obtained output of it in Table 8, it was also deduced from Figures 16 and 17 that the values correspond to the software output, and this model has relatively high accuracy in both static and dynamic states for representing the relationship between slope and subsidence.

It is necessary to explain that the accuracy of this equation can be checked through statistical hypothesis test. Also, through the correlation coefficient and using SPSS software, the effect of other variables (height and length of the dam crown) can be investigated. However, due to the difficulty and complexity of the problems in the fuzzy environment, its calculations were ignored.

6. REFERENCES

Alonso, E.E., Olivella, S., and Pinyol, N. M. (2005) "A review of Beliche Dam", Geotechnique, 55(4), pp267–285.

Bechtel Corporation. (1960) "Pore Pressure and Embankment Movement Measurements during Construction", Bechtel Corporation.

Cooling, L. F. (1962) "Field measurements in Soil Mechanics", Geotechnique Vol. XII, No. 2, London.

Duncan, J. M., Chang, C. Y., (1970) "Nonlinear analysis of stress and strain in soils", J. SMFD, ASCE 96 (5), pp1629- 1653.

Fell, R., Macgregor, P., Stapleton, D. (1992) "Geotechnical Engineering of Embankment", Taylor & Francis Group plc, London, UK, Alkema.

Final Technical Report., (2003) "second phase studies of Sardasht Earth Dam", Tehran, Consulting Engineering MAHAB QODS, pp50-442, Repot No. 19.

Hunter, G.J. (2003) "The Pre- and Post-failure Deformation Behavior of Soil Slopes", PhD Thesis, University of New South Wales, Australia.

Itasca Consulting Group, Inc. FLAC3D. (2012) "User's manuals", Minneapolis, Minnesota.

Liang, P., Qinqin, G. (2016) "Response surface and genetic method of deformation back analysis for high core rock-fill dams", Journal of Computers and Geotechnics vol. 74: pp132-140.

Lioret, A., and Alonso, E.E. (1980) "Consolidation of unsaturated soils including swelling and collapse behavior", Geotechnique, 30(4), pp449–477.

Mahinroosta, R., and Alizadeh, A. (2012) "Simulation of collapse settlement in rock-fill material due to saturation", Inter. J. Civ. Engin., 10(2), pp125-135.

Mahinroosta, R., Alizadeh, A., and Gatmiri, B. (2015) "Simulation of collapse settlement of first filling in a high rock-fill dam", Engineering Geology, 187, pp32-44.

Marsel, R.J., Ramirezde Arellano L. (1963) "Field Measurements in Rockfill Dams", Proc. 2nd PanAm. Conf. Soil Mech. Found. Eng., Vol.11, Brazil, pp87-96.

Nayebzadeh, R., Mohammadi, M. (2011) "The Effect of Impervious Clay Core Shape on the Stability of Embankment Dams", journal of Geotechnical and Geological Engineering, 29(4): pp627-635.

Naylor, D.J., Maranha, D., Neves, E., Mattar, J.D., and Veiga Pinto, A.A. (1986) "Prediction of construction performance of Beliche Dam", Geotechnique, 36 (3), pp359–376.

Nobari, E.S., and Duncan, J.M. (1972) "Effect of reservoir filling on stresses and movements in earth and rock-fill dams", Report TE-72-1. University of California, Department of Civil Engineering.

Oldecop, L.A. and Alonso, E.E. (2001) "A model for rock-fill compressibility", Geotechnique, 51(2), pp127–139.

Oldecop, L.A., and Alonso, E.E. (2003) "Suction effects on rock-fill compressibility", Geotechnique, 53(2), pp289–292.

Soroush, A., Shyadeh, H. (2008) "A Comparison between seismic behaviors of earth dam with inclined and vertical clay cores in numerical analysis approach", 14th world conference on earthquake engineering, October 12-17, Beijing, china, pp47-57.

Squier, L.R. (1970) "Load transfer in earth and rock-fill dams", J. Soil Mech. Found. Div. ASCE, 96 (SM1), pp213–233Vassilis, G., Sakellariou, M. (2008) "Settlement analysis of the Mornos earth dam (Greece): Evidence from numerical modeling and geodetic monitoring," Journal of Engineering Structures vol. 30, pp3074-3081.

Torkian, F., Arefi, M., Akbari M.G. (2014) "Multivariate least square regression using interval-valued fuzzy data and based on extended Yao-vu signed distance", International journal of computational intelligence systems, Vol. 7, Issue. 1, pp172-185.

Vassilis, G., Sakellariou, M. (2008) "Settlement analysis of the Mornos earth dam (Greece): Evidence from numerical modeling and geodetic monitoring," Journal of Engineering Structures vol. 30, pp3074-3081.

Wei, Z., Junjie. H.,and Xiaolin, C., Chuangbing, Z. (2011) "Settlement analysis of the Shuibuya concrete-face rock-fill dam," Journal of Computers and Geotechnics vol. 38: pp269-280.