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Stability Analysis of Upstream Slope of Earthen Dams Using the Finite Element method Against Sudden Change in the Water Surface of the Reservoir, Case Study: Ilam Earthen Dam in Ilam Province

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ABSTRACT

The goal of this study was stability analysis of the upstream slope of earthen dams using the finite element method against sudden change in the water surface of the reservoir in the case study of Ilam Earthen dam in Ilam Province. This research was of applied type and respecting the data analysis type, the field method is used for data collection. In this research using numerical modeling by the finite element method and applying the GEOSLOPE software, attempt is made to perform stability analysis of the earthen dams to overcome existing shortcomings present in the finite element methods. The results showed that at a discharge equal to 47.7 l/s, the piezometric pressures in the body, bed and within the dam which were considered to investigate the efficiency and upstream slope of Ilam Dam, we demonstrated that the amount of upstream slope of Ilam Dam for the piezometric pressures in the body, bed and within dam were better and showed a lower compressibility. The highest exerted pressures were related to the left section at the top and bottom of dam. At discharge of 69.175 l/s we demonstrated that the amount of upstream slope of Ilam Dam for the piezometric pressures in the body, bed and within the dam was better and showed a better compressibility. The highest pressures belonged to the left section at the top and bottom of dam. At discharge of 100.55 l/s we demonstrated that the amount of upstream slope for the highest exerted pressures corresponded to the left section at the top and right section at the bottom of dam. The results of numerical analysis showed that at the time of 0.2 seconds and for the five ramps of 1, 5, 10, 20, 40 degrees, the velocity (fluctuations) in axial direction, the kinetic energy of velocity turbulence (fluctuations) at the radial and axial axes increase with increase in the ramps slope. In other words the upstream slope at a ramp of 40 degrees and time of 0.2 seconds performs better for control of the sudden changes. At the time of 0.8 seconds by increase in the ramps slope, the above mentioned characteristics are first decreased and then increased. In other words the upstream slope has a better performance for control of the sudden changes for a ramp of 40 degrees and time of 0.8 seconds. For the time of 1 second, by increase in the ramps slope the above mentioned characteristics are first decreased and then increased, in other words for the ramp of 20 degrees and time of 1 second it has better performed for control of the sudden changes.

Key words: Upstream slope, Piezometric pressure, Numerical analysis, Finite element method, Dam reservoir.

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1. INTRODUCTION

Earthen dams are among the world important dams which have significant role in the control of water flow and its optimal use. Earthen dams due to their special design and their execution conditions have different characteristics with respect to the concrete dams or RCC dams. One of these characteristics is the high importance of the upstream slope and its stability against water level at the reservoir, and any disturbance in this respect could affect dam quality and disturb optimal use of its capacity (1-4). In earthen dams, the upstream slope is often taken as 1 to 1.5-3, although slopes up to 1 to 6 or milder ones are also taken for special conditions. In addition, design of the ramps with different slope degrees is very common and the upstream slope is taken steeper than the lower parts. One of the most important features of the long-term behavior of an earthen dam is its stability during the operation period. The dam stability is affected by the fluctuations of water surface level in the reservoir at the upstream slopes, especially during the reservoir emptying. Sudden change in the water surface level of the reservoirs in these dams could greatly affect their performance. One of the main strategies to alleviate rapid changes in the water flow in the reservoir is to build upstream slopes of the earthen dam to slow down changes in the water surface level in the reservoir. In spite of this, when the water surface level in the reservoirs of the earthen dams is not controlled it causes serious damages and economic losses and even dam break (5-7). The slope stability analysis during the rapid drawdown is of great importance in design of the earthen dams. During the rapid drawdown, the stabilizing effect of water on the upstream face is diminished and the pore water pressures are increased. As the result, the upstream face stability of dam is significantly reduced. Investigating the slope stability is performed usually using the limit equilibrium methods. In these methods the effective parameters like stress history in the soil, non-linear behavior of the inhomogeneous and anisotropic materials and other factors within and outside of the sliding mass which affect the effective stress distribution are not taken into account. Combining the assumptions of the limit equilibrium method and the numerical methods like the finite element method (FEM) and/or the finite difference method (FDM) a more suitable method is derived for the stability analysis which lacks the above mentioned limitations. The finite element method is a numerical method for approximate solution of the partial differential equations and also integral equations. The basis of this method is complete removal of differential equations or simplifying them into the ordinary differential equations which are solved by the numerical methods like the Euler method (8). In solution of the partial differential equations, it is important to obtain a simple equation which is numerically stable, i.e. the error in the initial data or during solution is not so much that might result into obscure responses (9). Hou (2012) computationally performed continuum analysis using the explicit finite difference method which is capable of analyzing linear and non-linear problems, permeability and water pressure in the static and dynamic cases (10). In this procedure, first the stresses and deformations are calculated using the explicit finite difference method and the factor of safety against stability of an assumed sliding surface is calculated from the results of the stress analysis. The developed program is able to analyze the circular surfaces, surfaces combined of circle and line, and broken surfaces. For investigating the slope stability, especially in earthen dams, there are various methods that generally are analyzed by the finite element method. According to this method first the surface corresponding to the change in slope stability is selected and the required shear strength against change in the stability at this surface is compared to the existing soil shear strength and the safety factor is obtained. The rapid drawdown of water surface in the reservoir of a dam is among the cases which might occur severally during the life time of a dam, so one of the main factors in the design of the upstream slope is the case of rapid drawdown in the reservoir (11). In this state, the upstream slope is in a critical condition and the slope might become unstable. When we have rapid drawdown in the reservoir of the dam, the water surface within the upstream shell (dam body) does not fall simultaneously with the reservoir water level and dissipation of the pore water pressure trapped in the upstream shell happens a while after fall of the water surface level in the reservoir. In this condition, the pore water pressure at the shell surface of the upstream slope is reduced and during the full emptying the balancing hydrostatic pressure within the dam body affects the upstream shell surface. These two factors cause reduction in the stability factor of the upstream slope. Concerning that what slope should be adopted as the standard slope of the ramps; various opinions have been expressed in the history of dam building. Fall of the water surface level is a classic scenario in the slope stability and occurs when the upstream slope that is fully or partially saturated experiences fall in the external water surface level. The vast and rapid fall in the water surface level in the discipline of analysis of dam processes is of great important as the water surface level could change many times due the operation reasons (12). In the investigations performed by Chen (2012), it was shown that fall in the water surface level was normally about 0.1m per day. Whereas an amount of 0.5m per day is significant and a fall of 1m in the water surface level could happen in exceptional conditions. In addition, creation of the reverse conditions during pumping in the storage projects could lead into rapid change in the water surface level of the dam reservoir (9). Sherard et al. (1963) in their book entitled relative strength of soil in the fluid movement have attributed control of the relative water level fall in the dam reservoir to the failure theory at the upstream slope (13).

2. SLOPE STABILITY ANALYSIS IN DAMS

Slope stabilization is among the most important problems in civil engineering practice. Any erroneous analysis could result into uncommendable damage. Selecting a proper slope stabilizing method is directly dependent on the environment, slope geomechanical parameters and also selection of a proper analysis method (14, 15). In analysis of the soil natural slope, the factor of stability (safety factor) in the general state is calculated as follows:

$$\text{Stability factor} = \frac{\text{Shear stress}}{\text{shear strength}} \qquad (1)$$

Up to now, many methods have been proposed for the slope stability analysis depending on the soil type and condition. Among these, the most important one is the Bishop method. This method is utilized in the form of a software package named Stabel for evaluation of the soil stability in sloped areas against landslide. In this method, the stability factor is calculated using the following formula:

$$F = \frac{L}{\sum w.\sin\square} . \sum \left\{ \left[c.b + (w - u.b)\tan\square \right] . \frac{\sec\square}{L + \frac{\tan\square . \tan\square}{F}} \right\}$$

(2)

Where:

F = Slope stability factor (safety factor)	L =Length of each chord or arc in m
□ =Angle of the segment surface with respect to horizon in degrees	u = Pore water pressure in KN/ m^2
w =Weight of each segment in N	b =Horizontal width of each segment in m
c = Cohesion coefficient of the soil mass in KN/ m^2	□ =Internal friction angle of the soil particles in degrees

For the physical characteristic of the soil, use has been made of the soil mechanics tests. For this purpose the triaxial shear test was performed to determine the soil mechanical properties including the internal friction angle of the soil particles (□), cohesion coefficient (c) and pore water pressure (u). To determine the role of variation in the relative water surface level in preventing sliding of the soil mass through increase in the soil stability factor use has been made of the bioengineering calculations. In this procedure variation in the relative water surface level behind dam is taken as the main factor in increasing the stability of the soil mass in sloped areas and is calculated based on the internal friction angle of the soil particles (□), and in the presence of variation in the relative water surface level of the dam. The increase in the shear strength due to the variation in the relative water surface level in the dam is:

$$\Delta SR = \sum 1.15 TR \frac{AR}{A} \qquad (3)$$

Where: TR= tensile strength of variation in the relative water surface level in dam

$\frac{AR}{A}$= Ratio of the dam area to the total soil area

To determine the amount of increase in the stability, by lining of variation in the relative water surface level in dam, in addition to determining the number and the area of dam per unit area for different dams, the diametric tension of variation in the relative water surface level of dams in Kg per square centimeters should be determined at diameter distributions of 1, 0.8 and 0.4 cm. For this purpose, the diametric tensile device was utilized (16). In addition to the internal friction angle of the soil particles, soil cohesion and the soil pore water pressure other factors such as the depth, soil density, earth slope, length and width of the soil mass, number of the roots per various diameter distributions and per unit area were also determined. These were done using the field operations and excavation of the soil profile at each study area (17-20).

3. METHOD OF PERFORMING THE RESEARCH

In the present research, the stability analysis of the upstream slope of the earthen dams against sudden change of the water surface level at the dam reservoir is investigated for the case study of Ilam Dam in Ilam Province. This research was of applied research type and regarding the type of data analysis, the field method is adopted for data collection. In this method, the information corresponding to the investigation and stability analysis of the upstream slope of Ilam Dam including the slope angle, distance of the slope to the dam reservoir, annual water level fluctuations in the reservoir, drain thickness, rate of rise and fall of water level and other factors related to the stability measurement would be evaluated (10, 21).

Analysis and investigating stability of the earthen dam against loss in water level or intense water volume in the reservoir are among the worked out research where their results could be utilized in the dam operation. There are various methods for investigating stability of the earthen dams against sliding, especially in the framework of the finite element methods which among them the limit equilibrium method due to its simplicity and time and cost effectiveness has been more utilized. In these methods using the static equilibrium for the sliding mass, the forces and pressures are obtained for the bottom of the segments. But as the overall stability of dams is dependent on the stress distribution in the dam body which is due to the arching phenomenon and also forces due to the core percolation occurring at different loading conditions, here by the numerical modeling using the GEOSLOPE software attempt is made to perform stability analysis of the earthen dams and remove shortcomings of the finite element method.

4. FINDINGS OF THE RESEARCH

The descriptive and analytic findings obtained from the information analysis corresponding to this research, which include investigation and analysis of the statistics of obtained data from the analysis of upstream slope of Ilam Dam, in terms of performance comprise investigation of data corresponding to the annual water transport, quantitative seasonal changes, water piezometric pressures, BOD level, and other bedding factors in relation to the slope stability analysis of Ilam Dam. The period investigated in this research is one year and the periods adopted for compatibility studies and examining changes in the bedding in the upstream slope stability analysis of Ilam Dam is a period of 4 years which deals with the performance and investigating its corresponding trend.

4.1. Data collected from various regional water authorities

The most important data from these regional water authorities are: sum of annual water transport, daily statistics of water transport, seasonal water transport, monthly water transport, maximum water transport,… and also data corresponding to bedding of the upstream slope stability analysis of Ilam Dam in terms of performance and with respect to the effective climatic factors that are derived from the station at Ilam Dam.

4.2. Geographic situation of the study area

For stability analysis of the upstream slope of Ilam Dam in terms of performance, the available data at the department of measurement of Ilam Dam data have been utilized. The investigated stations at the upstream slope of Ilam Dam were located at 50m distance from each other (Figure 1, Table 1 and Table 2).

Table 1. Location of the studied stations at the bottom of Ilam Dam in intervals of 8m

Soil type	Slope	Water height from the bottom to the highest point of the upstream slope	Stations	
Loamy clay	141	13	1	Ilam Dam stations
	141	41	2	
	0	50	3	

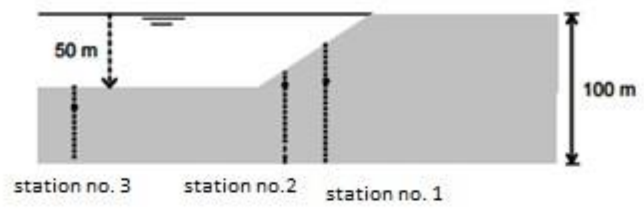

Figure 1. Changes in the general characteristics of the stations in terms of Ilam Dam width

Table 2. Locations of the studied stations in terms of the annual discharge from 2012 to 2015

Present Year (2012-2015) Exiting from the station (Million cubic meters)	Stations
2778	Highest sudden increase in the water volume entered at the upstream slope
1887	Water volume being discharged to the upstream slope
2123	Mean water volume entered at the upstream slope

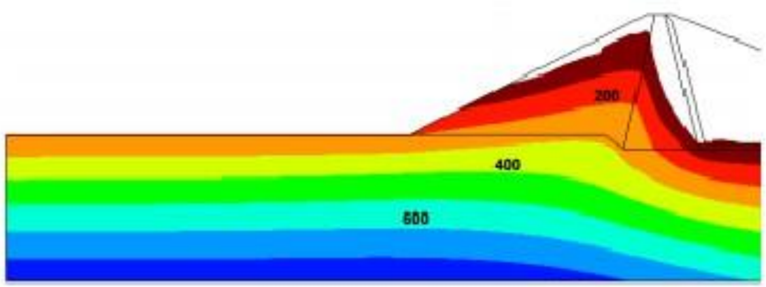

Figure 2. Changes in the volume of sudden annual water

As is seen in the statistical investigation, in this section we have statistically investigated the exit volume (millions of cubic meters) and also the exit discharge (cubic meters per second) (Figure 2). In the investigation, it is shown that the highest increase in the sudden water volume entered to the upstream slope is 2778 million cubic meters, where this value in the normal case is equal to 2123 million cubic meters and in the decreasing case and discharging to the upstream slope is equal to 1887 million cubic meters. In this research, the researcher is after investigating the effect of increase in the water volume and/or sudden discharge of the dam reservoir and its impact on the stability level of the upstream slope of Ilam earthen dam. For this purpose, we are after investigating the physical characteristics of the dam and effect of sudden change in the water level on the upstream slope stability level.

4.2. Investigating the upstream slope compressibility

In order to investigate the physical conditions of the upstream slope and examine the extend of being affected by the probable water volume entered to the slope surface and the impact of the pressure exerted by the high volume of water, we have investigated the physical characteristics at different sections of the upstream slope of Ilam Dam (Data corresponding to the hydraulic jump at the stations in the instability conditions and in the case of sudden change in the water volume entering the upstream slope; Table 3, Table 4 and Table 5).

Table 3. Station far from the slope

Piezometric pressures of the body (cm)	Sub-Basin	
0.70	1	Ilam Dam
0.70	2	
0.70	3	
0.80	4	
0.80	5	
0.9	6	

Table 4. Data corresponding to the station at the beginning of the upstream slope

Piezo metric pressures of the body (cm)	Sub-Basin	
0.03	1	Ilam Dam No. 1
0.03	2	
0.04	3	
0.04	4	
0.04	5	
0.05	6	

Table 5. Data corresponding to the station at the end of the upstream slope

Piezometric pressures of the body (cm)	Sub-Basin	
0.01	1	Ilam Dam No. 1
0.02	2	
0.03	3	
0.03	4	
0.04	5	
0.04	6	

4.3. Analysis of the upstream slope against sudden change in the water surface level in reservoir

Below the results of numerical analysis corresponding to calculation of the slope length for different flow parameters, especially the turbulent flow characteristics are given. The first characteristics studied are the main flow velocity. Regarding that the general trend of change in the main velocity is approximately the same in terms of different times, in Table 6, Table 7, Table 8 and Table 9 the slope length for various characteristics and per different acceleration periods are compared to expression.

Table 6. Slope length (m) at t*=0

Ramp up Time[s]	*U [m/s]*	☐ *[m^2/s^2]*	*u'v' [(m/s)^2]*	*μt [kg/m.s]*
All	1.49	1.78	1.55	1.98
Relation	Constant and equal to 0.98			

Table 7. Slope length (m) at t*=0.2

Ramp up Time[s]	*U [m/s]*	☐ *[m^2/s^2]*	*u'v' [(m/s)^2]*	*μt [kg/m.s]*
1	1.49	1.60	1.57	2.00
5	2.27	1.73	1.66	2.05
10	1.67	1.86	1.03	2.70
20	1.62	1.84	1.73	2.68
40	2.11	1.86	1.73	2.75
Relation	Constant and equal to 1.11			

At time of 0.2 seconds and for five ramps of 1, 5, 10, 20 and 40 degrees, the velocity (fluctuations) at the axial direction, kinetic energy of turbulent velocity (fluctuations) at radial and axial axes are increased with increase in the ramp angles. In other words, the upstream slope has better performed for control of sudden changes at a ramp of 40 degrees and time of 0.2 seconds.

Table 8. Slope length (m) at t*=0.8

Ramp up Time[s]	*U [m/s]*	□ *[m^2/s^2]*	*u'v' [(m/s)^2]*	*μt [kg/m.s]*
1	2.20	1.36	2.77	2.27
5	2.72	2.27	1.17	3.26
10	1.94	2.25	1.12	3.24
20	1.92	2.68	1.94	3.15
40	2.79	2.70	2.11	3.19
Relation	Constant and equal to 1.29			

At time of 0.8 seconds and for five ramps of 1, 5, 10, 20 and 40 degrees, the velocity (fluctuations) at the axial direction, kinetic energy of turbulent velocity (fluctuations) at radial and axial axes are first decreased with increase in the ramp angles and then are increased. In other words the upstream slope has better performed for control of sudden changes at a ramp of 40 degrees and time of 0.8 seconds.

Table 9. Slope length (m) at t*=1

Ramp up Time[s]	*U [m/s]*	□ *[m^2/s^2]*	*u'v' [(m/s)^2]*	*μt [kg/m.s]*
1	2.34	1.54	2.09	2.43
5	2.07	2.39	1.18	3.40
10	2.90	2.73	1.16	3.30
20	2.50	2.75	1.99	3.24
40	1.96	72.	1.87	3.11
Relation	Constant and equal to 1.33			

At time of 1 second and for five ramps of 1, 5, 10, 20 and 40 degrees, the velocity (fluctuations) at the axial direction, kinetic energy of turbulent velocity (fluctuations) at radial and axial axes are first decreased with increase in the ramp angles and then are increased. In other words the upstream slope has better performed for control of sudden changes at a ramp of 20 degrees and time of 1 second.

Legend of descriptions:

number of changes in the reservoir water level, [-]	Re
Time-time (dimensionless of acceleration) , [s]- [*]	t
time of acceleration period [s]	T
Velocity (fluctuations) at the axial direction, [m/s]	u
Velocity (fluctuations) at the radial direction, [m/s]	v
،flow field velocity, [m/s]	U
Turbulence kinetic energy of, [m^2/s^2]	κ
Density, kg/m^3	□
Fluid viscosity, kg/m.s	μ

5. CONCLUSION

In this research, we investigated and numerically analyzed the upstream slope. Here by simulation of the water movement in Ilam Dam located in Ilam Province, we demonstrated that at a discharge equal to 47.7 l/s, the piezometric pressures in the body, bed and within the dam which were considered to investigate the efficiency and upstream slope of Ilam Dam, we demonstrated that the amount of upstream slope of Ilam Dam for the piezometric pressures in the body, bed and within dam were better and showed a lower compressibility. The highest exerted pressures were related to the left section at the top and bottom of dam. At discharge of 69.175 l/s we demonstrated that the amount of upstream slope of Ilam Dam for the piezometric pressures in the body, bed and within the dam was better and showed a better compressibility. The highest pressures belonged to the left section at the top and bottom of dam. At discharge of 100.55 l/s we demonstrated that the amount of upstream slope for the highest exerted pressures corresponded to the left section at the top and right section at the bottom of dam. The results of numerical analysis showed that at the time of 0.2 seconds and for the five ramps of 1, 5, 10, 20, 40 degrees, the velocity (fluctuations) in axial direction, the kinetic energy of velocity turbulence (fluctuations) at the radial and axial axes increase with increase in the ramps slope. In other words the upstream slope at a ramp of 40 degrees and time of 0.2 seconds performs better for control of the sudden changes. At the time of 0.8 seconds, by increase in the ramps slope the above mentioned characteristics are first decreased and then increased. In other words, the upstream slope has a better performance for control of the sudden changes for a ramp of 40 degrees and the time of 0.8 seconds. For the time of 1 second, by increase in the ramps slope the sudden changes are first decreased and then increased, in other words for the ramp of 20 degrees and time of 1 second it has better performed for control of the sudden changes .

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AUTHORS CONTRIBUTION

This work was carried out in collaboration among all authors.

CONFLICT OF INTEREST

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