The Effect of Grout Curtain Efficiency on Abutments Stability of an Arch Dam

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Abstract

Abutment stability analysis of arch dams is one of the most challenging aspects in dam stability field of study. Generally, the rigid block model which has been presented by Londe is used to evaluate the stability of foundation wedges. In this paper the rock wedge in the left abutment of Luzzone dam has been studied. For this purpose, three components of unit-g acceleration are applied to the dam-reservoir-foundation finite element model. The safety factors are calculated due to different distribution of uplift pressure on the planes based on the extent of damages presumed for the grout curtain. The obtained results indicate that the uplift pressure can strongly affect the foundation stability and may lead to the wedge movement.

Keywords: Abutment Stability Analysis, Wedge, Arch Dams, Uplift Pressure.

1. INTRODUCTION

The safety of concrete dams is a major challenge for the owners due to their possible failure consequences when subjected to severe earthquake ground motions. One of the most important aspects in the stability of arch dams which have been encountered is the abutment stability. Failure of concrete arch dams showed that the main cause of the destruction of concrete arch dams is due to the rock mass instability in the abutments. In this regard, it is completely necessary to have proper and thorough analysis in order to evaluate stability of abutments for the purpose of dam safety. Yet it is not exclusively academic, as amply evidenced by disasters such as the Malapasset dam abutment failure and the Vajont rock slide [1, 2]. Because of scale effect, stability of the abutment varies generally with the wedge size and laws governing this variation are unknown. The rock slopes usually consists of discontinuities such as faults, joints and layering that must be considered in the abutment analysis.

Stability analysis of arch dam abutments was the topic of many studies. U.S. Army Corps of Engineering emphasize that the analysis of abutment stability requires very careful application of both engineering geology and rock mechanics and analytical techniques. The corresponding stability criteria have been recommended for different load case. Sohrabi et al. studied the stability of dam abutment including seismic loading. Time histories of safety factors as well as corresponding wedge displacement have been presented in their study[3]. Zenz et al. investigated seismic abutment stability of concrete arch dams. Accordingly they found that more sophisticated, realistic models show higher margins to entire system failure, which anticipates, that the existing model assumptions are conservative – as it is assumed[4]. In this paper, the abutment stability of Luzzone arch dam due to static and seismic loadings has been investigated. In order to calculate the thrust forces, a three dimensional finite element model of dam-foundation-reservoir has been developed and all three components of Kobe earthquake ground motions are applied to the model simultaneously. The safety factors are obtained for different scenarios of uplift pressure.

2. STABILITY ANALYSIS

In order to assess the stability of rock wedges, Londe method has been used by many researchers. In this method the wedges are defined by three probable sliding planes which have been shown by P1 (O, B, C), P2 (O, A, C) and P3 (O, A, B) in figure 1.

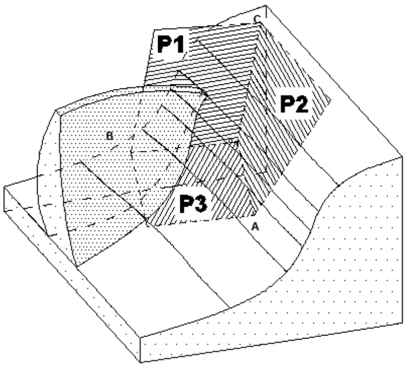

Figure 1. The geometry of plane

The geometry of each plane is characterized by its area and orientations (Dip and Dip direction). In this method the wedge is considered to be rigid and tensile strength on contact surfaces of the wedge are neglected. The cohesion and friction angel of each plane have profound effects on the wedge stability and should be estimated by the geology and rock mechanics studies. The moments of the forces are assumed negligible and their corresponding effects on the equilibrium equations are ignored. The wedge failure occurs only in the case of its movement on one or two of its supporting surfaces in the direction opposite to the wedge corner[3].

3. APPLIED FORCES

The dead load is encapsulated in the weight of the wedge. The weight of the wedge as a dead load can be calculated by the wedge volume time the specific weight of the rock. The uplift pressure on each plane can be determined due to the water level, geometry and area of the plane and the performance of grout certain. In spite of these two forces which are constant during the analysis, the inertia and thrust forces are time dependent and their magnitudes and directions will change during earthquakes. It should be mentioned that the thrust forces which are applied by the dam to the wedge include the weight of the dam, hydrostatic, hydrodynamic and seismic loads based on the considered load combinations. The resultant of the applied forces can be calculated as:

$$F_{\mathrm{Res}}^{W} = F_{W}^{W} + F_{Up}^{W} + F_{EQ}^{W} + F_{TH}^{D} \quad (1)$$

Where F_{W}^{W} , F_{Up}^{W} , F_{EQ}^{W} and F_{TH}^{D} are weight of the wedge, total uplift forces on planes, inertia force on wedge and the thrust force of the dam, respectively. Considering coordinate system that z-component corresponds to the vertical direction, the applied forces are represented in vector notation as follow:

$$F_{W}^{W} = \begin{bmatrix} 0 \\ 0 \\ -m^{W} \times g \end{bmatrix} \quad (2)$$

$$F_{UP}^{W} = \begin{bmatrix} U_X^1 \\ U_Y^1 \\ U_Z^1 \end{bmatrix} + \begin{bmatrix} U_X^2 \\ U_Y^2 \\ U_Z^2 \end{bmatrix} + \begin{bmatrix} U_X^3 \\ U_Y^3 \\ U_Z^3 \end{bmatrix} \quad (3)$$

$$F_{EQ}^{W} = (-m^{W}) \times \begin{bmatrix} \ddot{u}_x \\ \ddot{u}_y \\ \ddot{u}_z \end{bmatrix} \quad (4)$$

$$F_{EQ}^{W}=\begin{bmatrix}F_{TH-x}^{D}\\F_{TH-y}^{D}\\F_{TH-z}^{D}\end{bmatrix} \quad (5)$$

Where m^W ,U^1, U^2 and U^3 are mass of the wedge and the uplift forces on planes P_1 , P_2 and P_3 respectively. Also $\ddot{u}_x$,$\ddot{u}_y$,$\ddot{u}_z$ and F_{TH}^{D} are three components of ground acceleration time histories and the thrust force due to static and seismic loadings.

4. EQUILIBRIUM EQUATION AND SLIDING

Equilibrium equations are used to obtain three corresponding reaction forces on the planes (N_1 , N_2 and N_3). Due to the fact that planes are sole compressive, tensile normal forces mean that the planes are opened. When a plane is open it conclude that the considered sliding mode is not appropriate and will lead to the other different sliding modes excluding this plane. Eight possible separations or sliding modes which are likely to happen are listed in Table 1.

Table 1- Possible separation or sliding modes

Separation or Sliding Index	*Definition*	*Nature of Sliding Vector*
1	*All the plane are compressive*	*Stable*
2	*N1 is compressive*	*Sliding on Plane P1*
3	*N2 is compressive*	*Sliding on Plane P2*
4	*N3 is compressive*	*Sliding on Plane P3*
5	*N1 and N2 are compressive*	*Sliding on intersectionP1,P2*
6	*N1 and N3 are compressive*	*Sliding on intersectionP1,P3*
7	*N2 and N3 are compressive*	*Sliding on intersectionP2,P3*
8	*All the plane reactions are tensile*	*Unstable*

The sliding modes are described briefly in the following:

- Case 1: The planes normal reaction forces are compressive which means that all planes are in contact. So, the wedge is perfectly stable.

- Case 2: The normal force on plane P1 is compressive but, the reactions of planes P2 and P3 are in tension. By ignoring the planes P2 and P3 and solving the equilibrium equations the normal and shear forces on plane P1 are obtained. If the obtained normal force on P1 is compressive it means that the assumption is verified and sliding occurs on plane 1. The safety factor is obtained as follow:

$$SF=\frac{N_1\times\tan(\varphi_1)+c_1\times A_1}{Shear\ force\ on\ plane\ P1} \quad (6)$$

- Case 3: The reaction of plane P2 is compressive and reactions of planes P1 and P3 are in tension. This case is similar to case 2.

- Case 4: The reaction of plane P3 is compressive and reactions of plane P1 and P2 are in tension. This case is similar to case 2.

- Case 5: The normal forces on planes P1 and P2 are compressive and the reaction of plane P3 is in tension. In other word plane P3 is open and planes P1 and P2 are still in contact. To check the movement along the intersection line of planes P1 and P2, the force in this direction should be calculated. By solving the equilibrium equation and ignoring the plane P3, the values of normal forces on planes P1 and P2 and the corresponding shear force are obtained. The safety factor is calculated as follow:

$$SF = \frac{N_1 \times \tan(\varphi_1) + c_1 \times A_1 + N_2 \times \tan(\varphi_2) + c_2 \times A_2}{Shear\ force\ in\ direction\ of\ \text{intersection}\ P1\ P2} \qquad (7)$$

- Case 6: The reactions of planes P1 and P3 are compressive and normal force of plane P2 is in tension. This case is similar to case 5.

- Case 7: The reactions of planes P2 and P3 are compressive and normal force of plane P1 is in tension. This case is similar to case 5.

- Case 8: All the reactions are in tension and the wedge is detached from all its three supporting planes. In this case, the other sliding modes should be checked and if the assumption that all planes are in tension has been verified it means that the wedge is completely unstable.

4. CASE STUDY

This study is aimed to investigate the abutment stability of an arch dams due to seismic loading. For this purpose, Luzzone dam is selected. The Luzzone dam is a double curved concrete dam completed in 1963. The dam elevation heightened 17m between 1997 and 1998 and so the total height of dam is receipted 225m (Sohrabi Gilani, et al., 2009). Figure 2 shows a view of Luzzone dam [5].

Figure 2. Luzzone dam

5. FINITE ELEMENT MODEL

Figures 3 and 4 shows the provided finite element model of Luzzone dam. 332 and 2984 eight nodes brick elements including 249 and 3797 nodes are used to model the dam body and foundation, respectively. For modeling the reservoir 1080 eight nodes fluid elements are used. The reservoir is truncated at a distance from the upstream face which is about two times of the dam height.

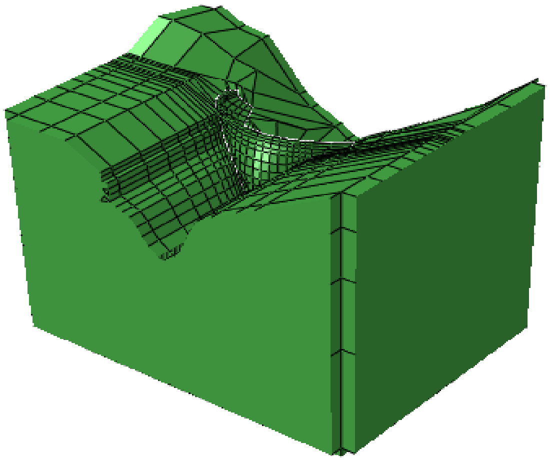

Figure 3. Finite element model of Luzzone dam

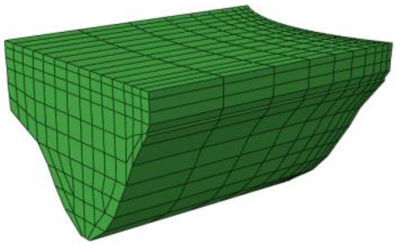

Figure 4. Reservoir finite element model

The material properties of the concrete and rock foundation are presented in table 2. The damping of the material considered to be five percent.

Table 2- Material properties of the dam concrete and the foundation rock

Materials	Elastic modulus (GPa)	Poisson's ratio	Density $(\frac{kg}{m^3})$
Concrete	27	0.167	2400
Foundation rock	25	0.2	2600

6. WEDGE DEFINITION

A unit-g acceleration is excited in each of three global directions for the purpose of seismic analysis. The accelerations are scaled according to the peak ground acceleration to 0.30g.

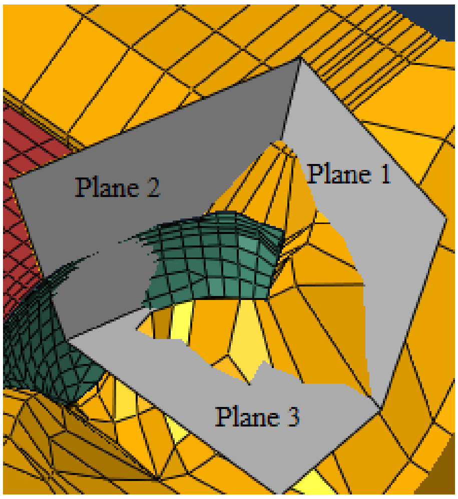

Figure 5. Geometry of the wedge

Table 3- Characteristic of the wedge

Plane	Friction degree	Cohesion	Area (m^2)	Dip Angle	Dip Direction
Plane1	35	-	23300	65	5
Plane2	35	-	7200	76	280
Plane3	35	-	28650	0	0

7. Seismic Loads

The ground acceleration time history of the Kobe earthquake is considered for the purpose of seismic analysis. The accelerations are scaled according to the peak ground acceleration to 0.40g. The ground acceleration earthquakes are applied in stream (x-direction), cross-stream (y-direction) and vertically upward (z-direction) directions, simultaneously.

8. Uplift Pressure Effects

In order to investigate the uplift pressure effects on the wedge stability, as indicated in table 4, six load combinations were considered based on damage of the grout curtain.

Table 4- Load combination

	Load			
Combination	Weight	Uplift	EQ	Thrust Force
Combo1	□	**0%**	□	□
Combo2	□	**20%**	□	□
Combo3	□	**40%**	□	□
Combo4	□	**60%**	□	□
Combo5	□	**80%**	□	□
Combo6	□	**100%**	□	□

By rotating the applied horizontal acceleration, the safety factor varies from 0.98(θ=320) to 1.49(θ=170). Figure 6 indicate the minimum safety factors for all load combinations. The obtained results show that when the uplift forces increase, the safety factors significantly decrease and even for the full uplift condition, the safety factor is less than one. This means that the wedge moves and seriously jeopardize the dam safety[6].

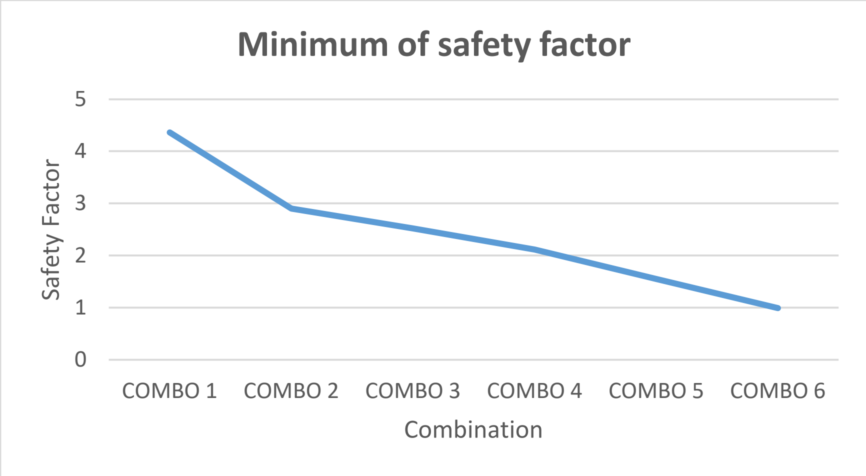

Figure 6. The minimum of safety factor of wedge for different load combination

9. CONCLUSIONS

The stability analysis of the left abutment of Luzzone dam was carried out to investigate the effect of uplift pressure on the wedge stability. In this study the Londe method is used and the safety factors are calculated for different distribution of uplift pressure based on the extent of damages of the grout curtain. The obtained results indicate that the uplift pressure can strongly affect the foundation stability and may even lead to wedge movement. So, the probability of the grout curtain failure during severe ground motions should be considered as a post-earthquake load combination. The monitoring of drainage system can play a significant role to assure the owner of the dam safety and help them to take the proper measures in critical conditions.

10. REFERENCES

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