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# Evaluation of Hydraulic Fracturing Potential in the Inclined Clay Core Dams Constructed in Narrow Valleys

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**ABSTRACT:**
One of the important phenomena that can occur specially in first filling of a clay core earth dam is possibility of crack formation. Stresses increase in some areas in the body of an earth dam, and decrease in other areas, due to ununiform strain and stress distribution. In first filling when the water level rises above areas with low minimum principal stresses, it can penetrate into cracks. Higher water level means more pressure on the surface of cracks and possibility of developing more cracks and concentrated leakage. In this study, stress-strain analysis has been performed on "BIDWAZ DAM" in 3D, using FLAC3D software and possibility of hydraulic fracturing in the core has been evaluated with "Normal stress" and "Mohr-Coulomb" Criteria. The dam is inclined clay core type dam under operation in the northwest of Iran. It has a height of about 66 meters constructed in a narrow valley with very steep abutments. The analysis results have been approved by instrument data. The results show that in the first filling minimal stresses in the clay core near the abutments could be reduced due to arching effect so hydraulic fracturing could be expected.

*Keywords: Inclined clay core earth dam, Hydraulic fracturing, 3D numerical analysis, Instrument results, Narrow valleys*

## 1. INTRODUCTION

In a clay core earth dam, stress transfer that is known as "Arching" phenomenon, can occur in two directions. The first type is in the upstream-downstream direction between shells and the clay core and the second type is arching between dam body and rock abutments. Core inclination can cause decreasing in the stress transfer in the up-down direction but it has no significant effect on the dam-abutment stress transfer. For the dams constructed in narrow valleys the second type of arching has a significant importance and it should be noticed by 3D numerical analysis. Because excessive reduction in the principal stresses in the face of the core, lead to "Hydraulic Fracturing"; where the stresses in the face of the core are less than the reservoir water pressure; it can penetrate into cracks. The water pressure deforms the crack face and concentrated leakage towards the downstream filter is possible.

There are some criteria to evaluate hydraulic fracturing potential. All of them are based on the stresses on the upstream face of the clay core, so numerical modeling techniques and instrument results can be use for estimation of these stresses.

In this study, possibility of hydraulic fracturing for the "BIDWAZ" dam has been evaluated using 3D numerical modeling verified by instrument results. Two known "Normal stress" and "Mohr-Coulomb" criteria are used for this purpose.

## 2. THE "BIDWAZ" INCLINED CLAY CORE EARTH DAM

"BIDWAZ" dam is an inclined clay core earth dam, located in the Khorasan province in northwest of Iran. Typical cross section of the dam and instrumentation including total pressure cells and inclinometers are shown in fig.1. Also the main materials and geometrical specifications are presented in Table 1. The dam has been constructed on a dense gravelly alluvium with a maximum depth of 23 m. A plastic concrete cut-off wall provides water sealing of the alluvium foundation. It is located in a narrow valley with the ratio of crest length to height of 1.6. Figure 2 illustrates longitudinal cross section of the dam and valley.

**Table1.**Materials and geometrical specifications of the dam

| | |
|---|---|
| *Geometry* | Max height: 66m, Crest Length 104m, Total Fill Volume 2.2 million m3, Crest Elev. +1534 |
| *Dam Material* | Core: CL, Ave. Plasticity 15, Opt. W.C. 15%<br>Shell: Well Graded River Gravel, F.C <5%<br>Rockfill: Limestone, Uni. Strength>50 MPa |

After finishing the cut-off wall, the main dam fill placement started in May 2003 and finished in Mar 2004 (Toosab 2003).

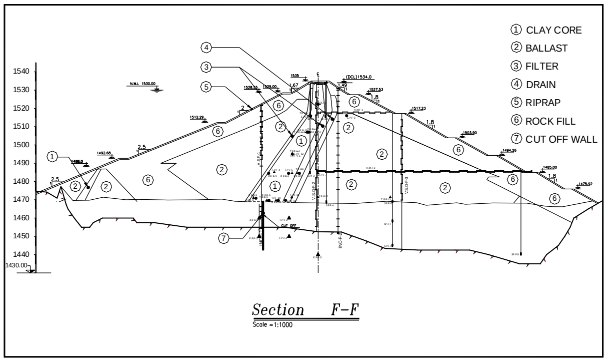


**Figure 1.** Typical cross section of the "BIDWAZ" dam

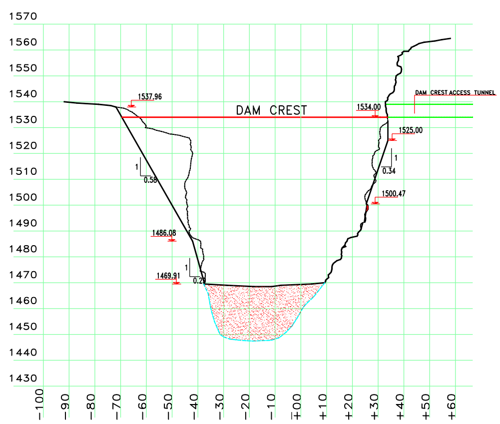


**Figure 2.** Longitudinal section of the dam and valley

## 3. NUMERICAL MODELING METHOD

Three dimensional, static deformation analysis of the "BIDWAZ" dam was performed using FLAC3D program and its built-in elastic-plastic model of Mohr-Coulomb (Itasca 1998, Vermeer 1984). The software is based on finite difference method.

### 3.1. Geometry of the Model

The simplified embankment model and the finite difference mesh used in 3 Dimensional analyses are shown in Fig. 3.

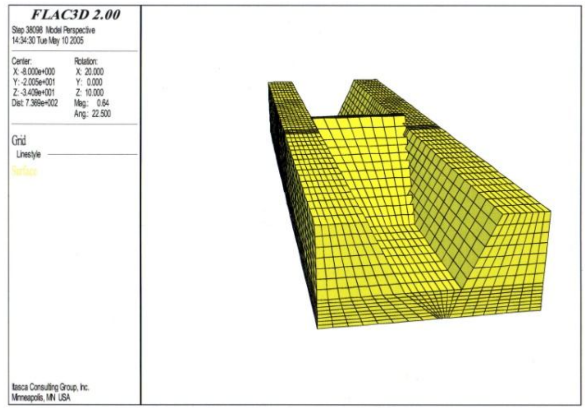


**Figure 3.** 3D Finite Difference Grid Generation

### 3.2. Material Properties

It should be noticed that the main purpose of the numerical modeling is to estimate the stresses in the clay core in the first impounding. Furthermore steep rock abutments cause some regions of the dam body to reach their plastic state so the constitutive model should be capable to model this behavior. The known "Mohr-Coulomb" elastic-plastic model seems to have an adequate accuracy for this purpose.

The material properties were selected based on the experimental tests and back-analysis of the end of construction stage deformations. Table 2 shows the material parameters.

**Table 2.** Mohr-Coulomb Properties for the dam and foundation

| Material | Wet Density | Saturated Density | E (KPa) | υ | φ | C KPa | ψ |
|---|---|---|---|---|---|---|---|
| Core | 20 | 21 | 4000 | 0.4 | 16 | 10 | 0 |
| Shell | 21 | 22 | 50000 | 0.3 | 38 | 0 | 8 |
| Alluvium | 19.5 | 20 | 50000 | 0.33 | 38 | 0 | 8 |

### 3.3. Analysis Stages

As it is known, final stress and strains state in an elastic-plastic material depends on the stress paths. So a comprehensive analysis should include different stages of loading. Analysis stages used for modeling were as below:

- Initial stress generation in the foundation
- Coffer dam construction
- Main dam fill placement in 14 layers
- First impoundment modeling including hydrostatic pressure on the upstream face of the core and Appling buoyancy forces to the upstream shell in 3 stages

## 4. ANALYSIS RESULTS

### 4.1. Stress and Deformation

Figure 4 illustrates vertical deformations and fig. 5 shows total vertical stresses in a section across the center of the valley. Comparison of the vertical stresses from 3D analysis with the previous 2D numerical modeling [Toosab 2003] indicated that stress reduction in the center of the dam is about 35%, this is due to longitudinal stress transferring in the 3D analyses.

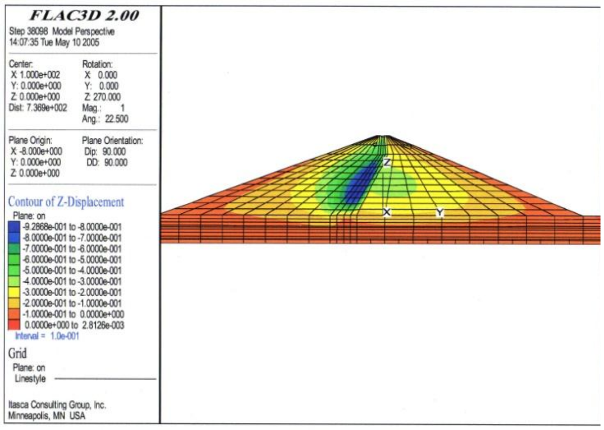


**Figure 4.** Vertical Displacements at the highest section of dam

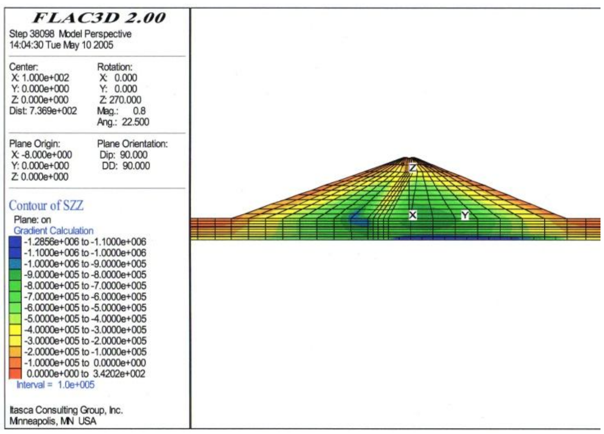


**Figure 5.** Total vertical stresses at the highest section of dam

Figures 6 to 8 show major, intermediate and minor principal stresses on the inclined clay core upstream face after applying hydrostatic water pressure due to impounding. The figures show that the minor and intermediate stresses in the contact region of the core with rock abutments, significantly decrease, while the major principal stresses increase. This is due to significant shear stresses in the abutment neighbors. Significant difference between rigidity of the rock abutments and dam material together with the steep abutments are the main reason for this phenomenon. At the bottom of clay core more reduction in minor stresses can be seen so it is more critical from hydraulic fracturing viewpoint.

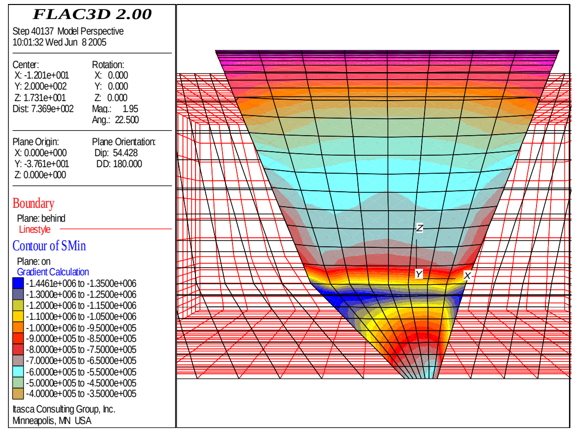


**Figure 6.** Maximum principal stresses at the upstream face of the core

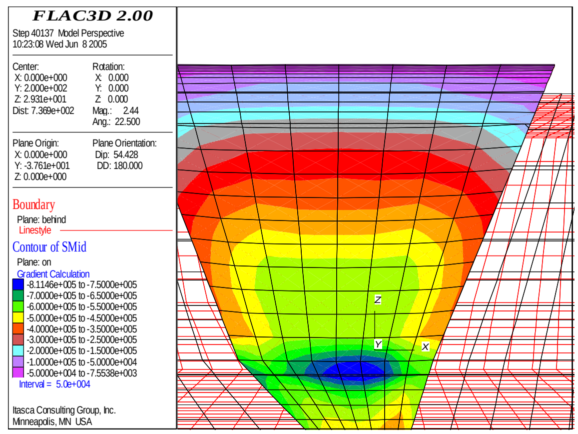


**Figure 7.** Intermediate principal stresses at the upstream face of the core

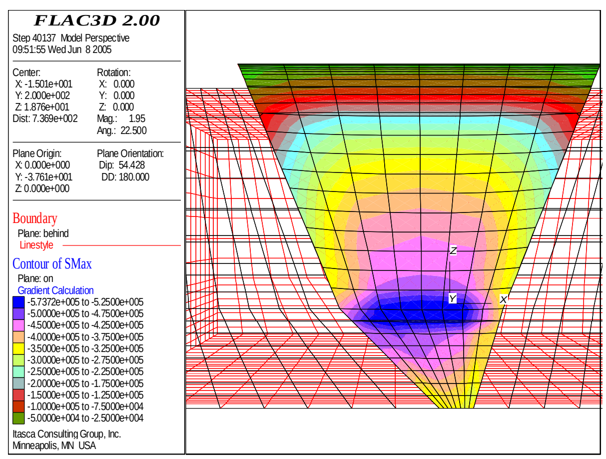


**Figure 8.** Minimum principal stresses at the upstream face of the core

### 4. 2. Instrumentation Data

Although in this research, comprehensive evaluation of dam behavior and monitoring is not the final goal but to

verify and caliber the numerical model, a brief comparison of the numerical results with a few installed instrument results, has been notified.
As an example, figures 9 and 10 show total vertical stresses from instruments and analysis together with the overburden weight (γh). Also embankment elevation rising in the construction time can be seen from right axis.

Two pressure cells (TPF-6 and TPF-5) have been installed in the centeral section of the dam (highest section, elevation +1484.5) at the clay core.

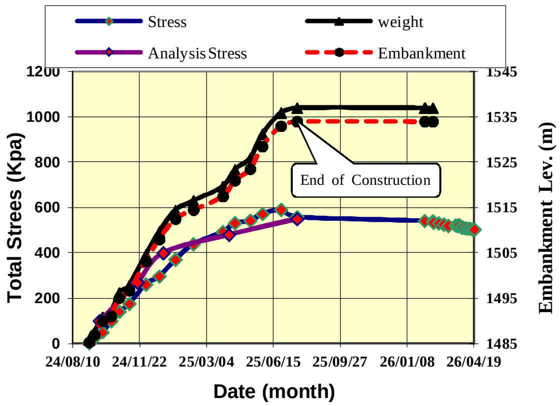


**Figure 9.** Total vertical stresses from numerical modeling and pressure cell (TPF-6)

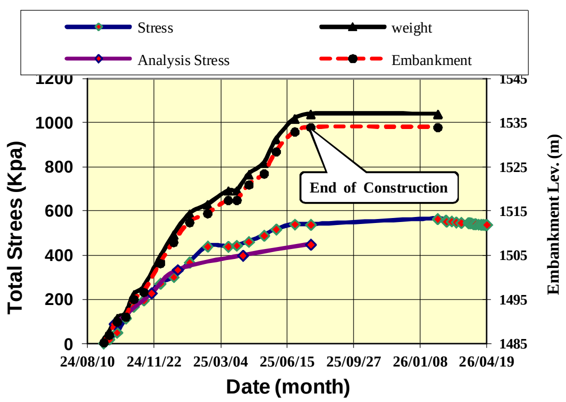


**Figure 10.** Total vertical stresses from numerical modeling and pressure cell (TPF-5)

Total vertical stresses from instruments, are in a good agreement with the numerical results but they are significantly different from overburden weight (γh).
Stress transferring (arching) is the main reason for these disconfirmations.

This comparison performed for some other instrument; however numerical results were in good agreement with the instrument readings. So numerical modeling is verified with adequate accuracy and it can be used to evaluate hydraulic fracturing potential.

## 5. HYDRAULIC FRACTURING

### 5.1. "Normal Stress" Criteria

Based on the "Normal Stress" theory, hydraulic fracturing phenomenon can occurs where the hydrostatic reservoir water pressure were higher than the normal stress in an existing crack. For a horizontal crack, vertical stress $\sigma_y$ should be higher than the hydrostatic water pressure to avoid crack opening and hydraulic fracturing. Nobari et al. (1973) showed that the major principal stress $\sigma_1$ in a clay core is approximately parallel to the clay core face so in that case intermediate principal stress $\sigma_2$ can be used to estimate if the hydraulic fracturing can be probable. It should be noted that in this theory, tensile strength of the soil is eliminated so generally it leads to a conservative estimation.

It is common to show the values of principal stresses together with vertical stress and hydrostatic water pressure on a chart. Figures 11 and 12 show these stresses for the right abutment and the center of the dam (highest section) respectively. To have a better judgment, overburden weight (γh) is also illustrated in the charts.
It is evidence from fig. 11 that minor stress and mid stress are less than hydrostatic water pressure at elevations lower than +1520 and +1497 for each case respectively. While, major stresses and vertical stresses are higher than the hydrostatic water pressure at the height of the dam core, so hydraulic fracturing at the dam abutments is possible.

At the dam center (fig. 12) all the stresses except, min stress at the lower elevation +1488, are higher than reservoir water pressure in the first impoundment so there is no probability of hydraulic fracturing in the dam center based on the "Normal Stress" criteria.
In these charts, the difference between overburden weight (γh) and total vertical stress ($\sigma_y$) shows arching phenomenon.

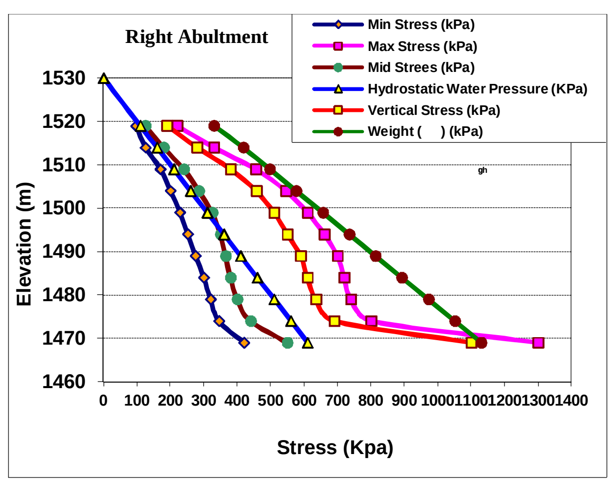


**Figure 11.** Principal stresses, total vertical stress, overburden weight and reservoir water pressure (Right Abutment)

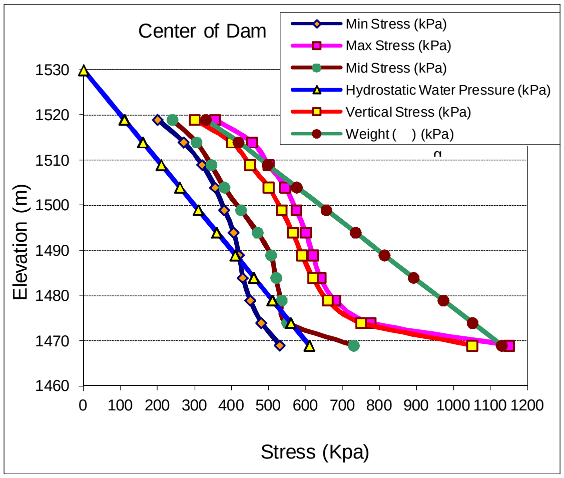


**Figure 12.** Principal stresses, total vertical stress, overburden weight and reservoir water pressure (Valley Center)

### 5.1. "Mohr-Coulomb" Criteria

Yanagisawa & Komak Panah (1994) offered a criterion based on the Mohr-Coulomb failure relation. Based on this criterion, pressure causes hydraulic fracturing ($P_f$) is a function of major principal stress; minor principal stress and undrained shear strength parameters of the soil (Medeirosetal. 1996). They developed an equation as below:

$$P_f = (1.5\sigma_3 - 0.5\sigma_1) \times (1 + \sin\phi_u) + C_u \cos\phi_u \qquad (1)$$

Where, $P_f$ is the water pressure causes fracturing based on the shear failure mode. In this criterion, the difference between major and minor stress (shear stress) has a significant influence on the hydraulic fracturing pressure ($P_f$). The experimental triaxial tests on the clay core material of the dam showed that undrained shear strength parameters are as below:

$C_{uu}$ = 1.0 Kg/cm$^2$
$\varphi_{uu}$ = 4°

The ratio of $P_f$ to water pressure can be defined as safety factor. Figures 13 and 14 present the value of $P_f$ and the water pressure (in the bottom axis) for the center and right abutment respectively. Also safety factor for each case has been calculated and presented in these figures (in the top axis).

The safety factor against hydraulic fracturing at the dam center (Fig. 13) is more than 1.0 in the much of the height except in elevations lower than +1484 but in the neighbor of rock abutments, situations are too different. In that case (Fig. 14), safety factor is less than unity in the height of the core face below elevation +1517. It is due to significant difference between major and minor stresses in the abutment neighborhood as a result of high shear stresses. The safety factor is less in the low elevations because of increase in longitudinal stress transferring (arching), as it is about 0.4 in the elevations from +1474 to +1504, reaching to 0.13 at the foundation elevation.

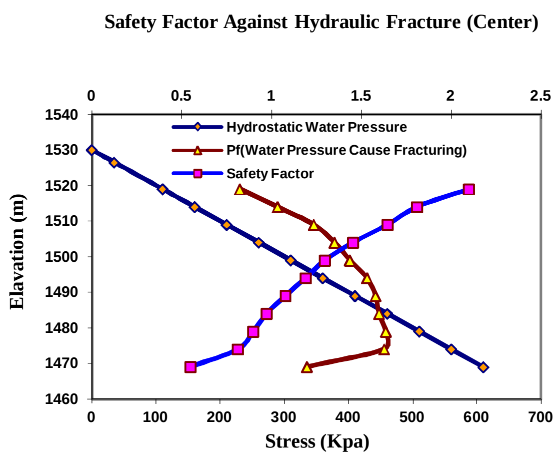


**Figure 13.** $P_f$, hydrostatic water pressure and safety against hydraulic fracturing (Center)

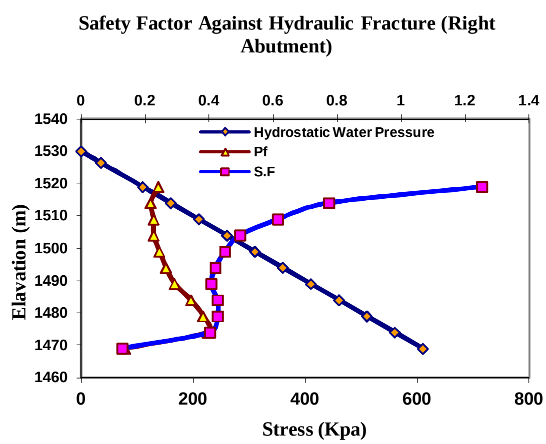


**Figure 14.** $P_f$, hydrostatic water pressure and safety against hydraulic fracturing (Right Abutment)

## 6. SUMMARY AND CONCLUTIONS

In this research, risk of hydraulic fracturing in the inclined clay core of the "BIDWAZ" dam, has been evaluated using 3D numerical modeling and verified by instrument results. Investigations were based on two criteria, "Normal stress" and "Mohr-Coulomb". 3D numerical modeling showed that stress transferring in the longitudinal direction has a significant influence on the stress distribution in the dam body. In the abutment neighbors, shear stress significantly increases and the dam material reaches its plastic state. Also stresses decrease, especially minor stresses, in the abutment contact region. This causes the risk of hydraulic fracturing to increase.

This phenomenon has been identified since the design stage, and some precautions taken in the design and construction stages by the consulting engineers (Toosab Consulting Eng. 2003). Some of these are summarized below:

- The standard proctor compaction method was used for clay core material placement, water content was in the optimum wet side, to increase flexibility and decrease cracking possibility.
- There was a special attention on the rock foundation treatment under the core to reduce stress concentration which can be occurs by local anomalies in geometry ; also the contact clay has the plasticity more than 20% and the water content about 3 to 4 % more than optimum. It can increase lateral stresses and decrease cracking possibility.
- Impounding was done very slowly and dam monitoring together with the visual inspections scheduled regularly during impounding stage.
- Comprehensive investigation on the filter material was performed. A series of NEF (No Erosion Filter) tests showed that the filter performance were successful to prevent erosion through concentrated leaks in cracked dam core (Tarbiat Modarres 2004).
- Even in case of cracking, the high velocity flow exerts shear stress capable of dislodging and carrying particles towards the filter. In this condition, clogging of the filter face is expected. However, the water pressure significantly rises, causing high seepage gradients in short paths adjacent to the filter. The successful critical filter should also prevent particle erosion under the action of these intense hydraulic gradients (Soroush et al. 2009).

For the time being, the dam is under operation and no partial or complete failure is reported. The seepage flow is relatively high but it is clean and no any containment can be seen. Furthermore, based on the investigations, most of water is leaking from jointed abutment limestone rock. However, the dam body participation in leakage is much smaller.

**AKNOWLEDGMENT**
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