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A DISCONTINUUM ANALYSIS ON THE EFFECT OF SHEAR SEAM ON AN INTACT DAM FOUNDATION

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ABSTRACT

As dams are large structures often constructed on rock formations exhibiting material non-homogeneity, anisotropy and non-linear behavior, a complete stress-deformation analysis is required to arrive at a proper design. Shear zones and seams encountered in the rock foundation of these structures are responsible for undesirable deformations and stress concentrations in the dam-foundation system. The presence of shear seam at any location and inclinations weakens the dam-foundation system. As the deformations and stress distribution in the foundation are highly influenced by the locations and inclinations of shear seam, intensive analysis of each cases need to be carried out. The paper presents a discontinuum analysis of a dam-foundation system under the influence of shear seam originating at heel and toe of the dam has been carried out using distinct element method. The inclination of the seam is considered as a critical parameter in defining the stress-deformation response of a dam-foundation system. The paper focuses on the stress-deformation analysis of a dam-foundation system carried out using UDEC.

KEYWORDS: Dam Foundation System, Shear Seam, Intact Rock, Deformations, Major Principal Stress

INTRODUCTION

Large surface structures, such as dam apply significant loads to the underlying geologic media and disturb the pre-existing natural conditions. Despite the apparent favorable stability conditions for the structures founded on the strong rock, there are unfortunately instances of the foundation failures. Failures may include excessive settlements due to the presence of undetected weak seams or deterioration of rock with time. Faults or seams not only change the physical properties of the rock in and near the discontinuous zone, but they substantially affect the distribution of stresses and the overall stability of the dam-foundation system. Because of low modulus values, these geological complexities may create zones of stress concentration and also become potential sliding paths. Numerical models, particularly finite element models, are routinely used in the analysis of the global mechanical and hydraulic behavior of dam-foundation systems under normal operating conditions. However, in case of foundations with weak zones, discrete element models are preferable, since structural behavior may be strongly influenced by the rock mass deformability and discrete element models have the capability of handling large displacement regime. The paper focuses on the stress-deformation analysis of a dam-foundation system carried out using UDEC.

INTACT ROCK

Intact rock refers to the unfractured blocks between discontinuities in a typical rock mass. These blocks may range from a few millimetres to several meters in size (Hoek, 1994). The properties of intact rock are governed by the physical properties of the minerals of which it is composed. The parameters which may be used in a description of intact rock include petrological name, colour, texture, grain size, minor lithological characteristics, density, porosity, strength, hardness and deformability.

DAM-FOUNDATION INTERACTION

For centuries, the dam engineer has been designing dams on the basis of past success and more importantly, past failures. Concrete dams are however less prone to failures. ICOLD (1995) reported failure of a total of 178 concrete, masonry and earth dams in 31 countries and shows that 25, or 14%, of these failures occurred as the result of deterioration of rock foundations. Today with the advancement in technology, engineers are gaining confidence in the design and construction of dams and it is possible to make use of almost any site. However, every project's behaviour is basically dependent on the supporting ground.

CONVENTIONAL METHOD FOR DAM FOUNDATION ANALYSIS

The design requirements for stability of concrete gravity dams as per IS:6512 (1984) are:

- The dam shall be safe against sliding on any plane or combination of planes within the dam, at the foundation or within the foundation;
- The dam shall be safe against overturning at any plane within the dam, at the base, or at any plane below the base; and
- The safe unit stresses in the concrete or masonry of the dam or in the foundation material shall not be exceeded.

Depending upon the scope and details of the various project components, site conditions and construction programme, one or more of the following loading conditions may be applicable and may need suitable modifications. The seven types of load combinations are (IS: 6512):

1. Load combination A (construction condition): Dam completed but no water in reservoir or tail water;
2. Load combination B (normal operating conditions): Full reservoir elevation, normal dry weather tail water, normal uplift, ice and silt (if applicable);
3. Load combination C: (Flood discharge condition) - Reservoir at maximum flood pool elevation, all gates open, tail water at flood elevation, normal uplift, and silt (if applicable);
4. Load combination D: Combination of A with earthquake;
5. Load combination E: Combination B, with earthquake but no ice;
6. Load combination F: Combination C, but with extreme uplift, assuming the drainage holes to be inoperative;
7. Load combination G: Combination E but with extreme uplift (drains inoperative).

The characteristics of a dam foundation are analysed with respect to their effects on (ICOLD, 2005): i) Stability of the foundation, including abutments and adjacent slopes; ii) Deformation of the foundation, such as differential settlement and distortions causing cracks and concentrated leaks; and; iii) Uplift, hydraulic gradient, internal erosion and piping.

COMPUTATIONAL METHODS FOR DAM FOUNDATION ANALYSIS

A number of computational methods of analysis have been developed over the past five decades. They have become popular due to rapid advancements in computer technology. Before the advent of computers, the structures were designed largely using analytical methods or rules of thumb. The increased consciousness amongst the public regarding the safety and economy has led the engineers to seek more rational solutions to the problems. Two approaches to model the dam-foundation system can be identified, both recognizing geological structures as being discontinuous due to joints, faults and bedding planes. A continuum approach treats the rock mass as an equivalent continuum, while a discontinuum approach views the rock mass as an assemblage of independent blocks. For dams on rock foundations, a critical requirement in the stability analysis is the localization of planes of weakness or discontinuities that combine to give a kinematically possible sliding block mechanism (ICOLD, 2005). Discontinuum models feature numerical procedures involving the equations of blocks rather than continuum. Cundall (1971) was among the first to implement the discrete element method (DEM), also called as distinct element method, to represent rock mass as an assembly of discrete blocks where joints/discontinuities are viewed as interfaces between distinct bodies.

DISTINCT ELEMENT ANALYSIS

A jointed rock mass is better modelled by a discontinuum approach using a distinct element method for discontinuum modelling. Here the discontinuous medium is represented as an assemblage of discrete blocks. By modelling the actual structure of rock mass made up of individual blocks, it simulates the real conditions in a satisfactory manner (Lin and Fairhurst, 1988). Cundall originated the distinct element codes (UDEC in 2-D and more recently 3DEC in 3-D), which analyse both small strain conditions and large displacements (Hart et al., 1988).

THE DAM-FOUNDATION SYSTEM

A concrete gravity dam, 82 m high and 72 m base width is founded on 400 m wide and 200 m deep rock foundation. The upstream face of the dam is vertical. The foundation is considered to have a shear seam of 1/10th of the base width of the dam originating at the toe of the dam. The strength properties of the seam are taken as 1/5th the strength of the intact rock mass. A free board of about 2 m is also considered. Different inclinations of shear seams in the foundation have been considered for the study. Figure 1 presents the problem geometry considered for the present study.

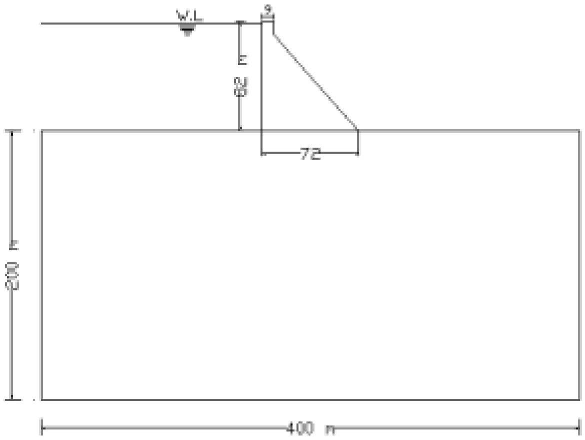

Figure 1 Problem Geometry

MATERIAL PROPERTIES

The dam foundation is considered to consist of quartz mica schist with the following properties of the rock mass. (Varadarajan et. al., 2002).

Intact Rock: Unit weight=27.2 kN/m^3, Bulk modulus=4780 MPa, Shear Modulus=3580 MPa

Concrete: Young's Modulus=2.1 x 10^4 MPa, Poisson's ratio=0.15 Unit weight of concrete=24 kN/m^3

Seam: Unit weight=26.5 kN/m^3, Bulk modulus=956 MPa, Shear Modulus=716 MPa, Joint normal stiffness=100 MPa/m, Joint shear stiffness=100 MPa/m, friction angle=16°, cohesion=0

Concrete and Rock Interface: Joint normal stiffness=1200 MPa/m, Joint shear stiffness=1000 MPa/m, friction angle=45°, cohesion=0.1 MPa

SOFTWARE USED

The analysis has been carried out using the software UDEC (Universal Distinct Element Code) which is a two-dimensional numerical program based on the distinct element method for discontinuum modelling. It simulates the response of discontinuous media subjected to either static or dynamic loading. The software is primarily intended for analysis in rock engineering problems, ranging from studies of the progressive failure of rock slopes to evaluations of the influence of rock joints, faults, bedding planes, etc. on underground excavations and rock foundations.

ANALYSIS OF DAM-FOUNDATION SYSTEM

The dam-foundation system has been analyzed with a loading condition of self-weight of dam and weight of water at full reservoir level. The shear seam is assumed to exhibit 1/5th the strength properties of the intact rock mass. Further, the width of the seam is taken as 1/10th the width of the dam. A uniform water load is also applied on the upstream face of the foundation. The concrete and intact rock is assumed to exhibit linear elastic behavior, whereas joints are assumed to exhibit nonlinear elasto-plastic behavior. The loading condition B of self weight of the dam plus full reservoir level as per IS-6512 (1984) has been considered. Two different case with the shear seam assumed to be originated at the heel and toe of the dam with inclination varying from 30° to 150° degree with an increment of 30° are analysed.

Dam Foundation with Shear Seam at Heel

In-depth analysis has been carried out considering two major aspects namely the deformations and the major principal stresses at some critical locations viz. a) Along dam foundation interface – 10 cm below the dam base, b) Along the depth at the heel – 20 cm inside from the heel of dam, c) Along the depth at the toe - 20 cm inside from the toe of dam, d) Along the upstream face of the dam – 20 cm inside. The magnified deformed shape (magnified 500 times) and the deformations at selected critical locations for all the cases analyzed are presented in Figures 2 to 13.

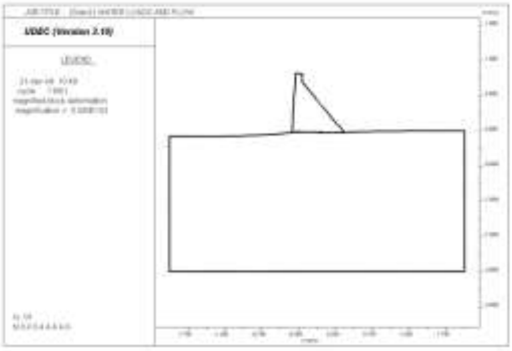

Figure 2 Deformed Shape of Intact Rock

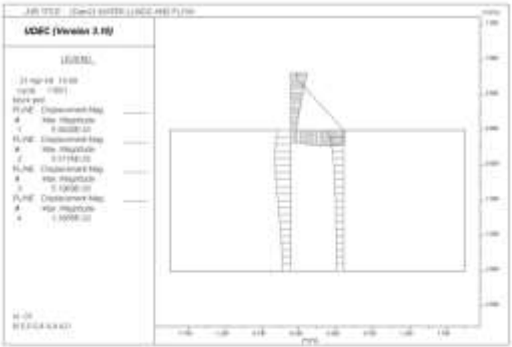

Figure 3 Deformations – Intact Rock

The magnified deformed shapes of dam-foundation system show that in all cases the seam is behaving as a discrete boundary and has divided the foundation in two blocks. It can be noted from the figures depicting the deformations along critical locations that generally the deformations are maximum at the crest, heel and the toe of the dam. The deformations recorded at these locations in respect of various shear seam inclinations are presented in Table 1. From this table it may be noted that the deformation is maximum at the crest irrespective of the inclinations and is critical when the seam is inclined at 90°.

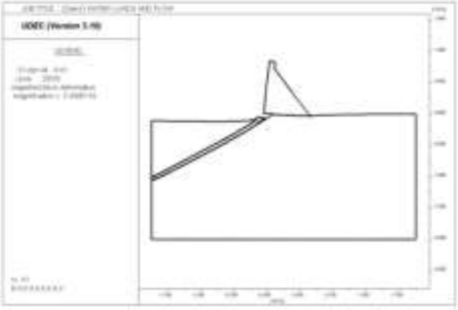

Figure 4 Deformed Shape – Seam 30°

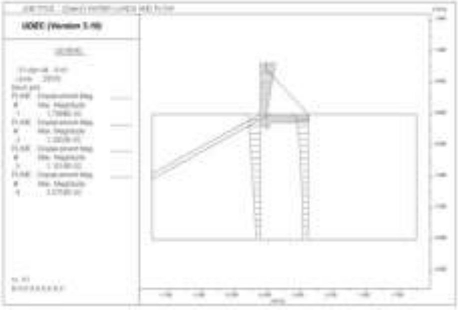

Figure 5 Deformations – Seam 30°

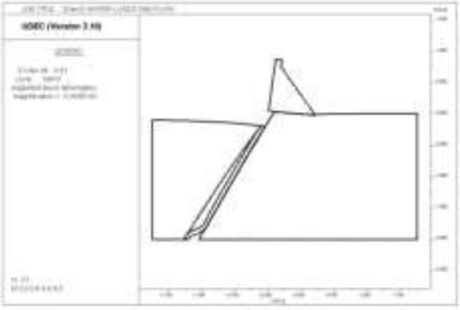

Figure 6 Deformed Shape – Seam 60°

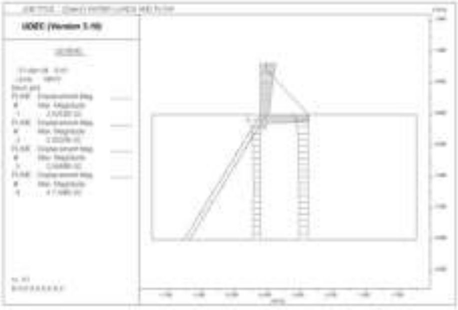

Figure 7 Deformations – Seam 60°

Figure 8 Deformed Shape – Seam 90°

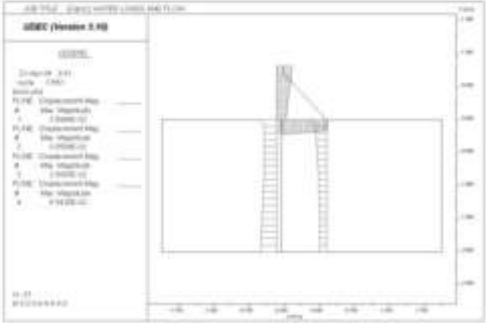

Figure 9 Deformations – Seam 90°

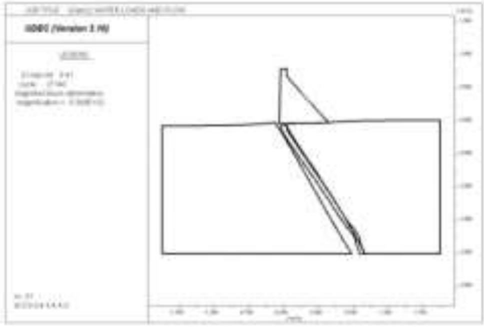

Figure 10 Deformed Shape – Seam 120°

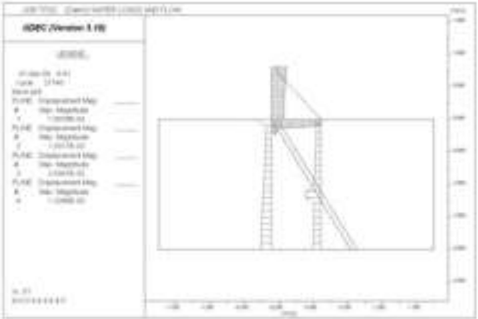

Figure 11 Deformations – Seam 120°

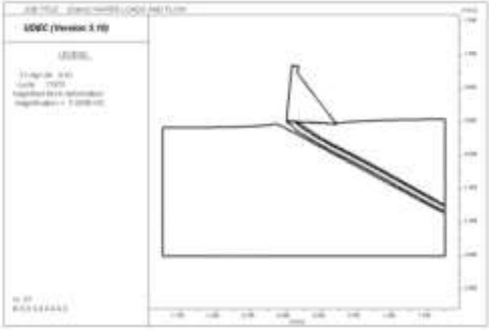

Figure 12 Deformed Shape – Seam 150°

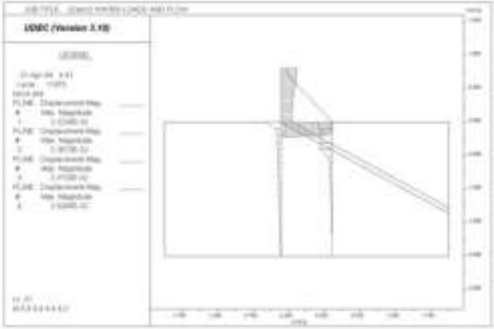

Figure 13 Deformations – Seam 150°

From the major principal stress (σ_1) distributions of the dam-foundation system for all the cases it has been observed that the most stressed zone lies at the toe of the dam. Therefore, in-depth analysis of the dam-foundation system along the depth at the toe has been carried out. Figure 14 presents the σ_1 at toe along the depth for all cases. The presence of seam in the foundation systems increases σ_1 substantially up to a depth of about 40 m after which the effect diminishes for all cases except for the foundation system with 120° inclined seam where σ_1 increases up to a depth of 90–100 m.

The percentage variation of the σ_1 at toe in dam-foundation system with seams with respect to the stresses in intact rock foundation presented in Table 2 also indicates that the zone/depth of influence is maximum for the foundation system with 120° inclined seam, considering a criterion of minimum 10% variation of σ_1. Table 3 presents the depth of influence for different seam inclinations. Though the presence of shear seams of any inclination in the dam-foundation weakens the system, the foundation with the seam inclination of 120° is the most critical one.

Table 1 Deformation at Crest, Heel and Toe

Seam Inclination	Deformation, mm		
	Crest	Heel	Toe
Intact Rock	13.96	4.27	5.80
30°	28.75	12.00	11.02
60°	47.19	25.97	20.47
90°	**65.42**	**38.56**	**28.80**
120°	13.25	10.31	8.57
150°	38.39	23.67	20.73

Table 2 Percentage Variation of σ_1 at Toe

Depth (m)	Percentage variation of σ_1 for different seam inclinations				
	30°	60°	90°	120°	150°
10	**27.14**	**65.04**	**49.39**	**45.56**	**90.95**
20	**9.04**	**31.69**	**20.37**	**31.69**	**57.13**
30	3.85	**15.81**	**8.75**	**26.71**	**46.51**
40	5.52	**8.49**	5.93	**24.87**	**-18.75**
50	3.94	1.45	-0.41	**19.39**	-12.80
60	5.20	-1.43	0.92	**17.23**	-8.11
70	4.54	-2.19	0.45	**13.63**	-4.87
80	2.02	-3.66	-1.61	**12.13**	-5.90
90	3.31	-3.28	-0.10	**10.53**	-2.35
100	3.08	-3.87	-1.30	**7.65**	-1.17
110	4.05	-3.50	-0.23	-11.20	-0.35
120	2.60	-3.80	0.08	-14.19	0.57
130	2.45	-4.35	-1.34	-16.76	-0.23
140	2.98	-3.89	-0.38	-19.41	1.12
150	2.83	-3.35	-1.01	-21.63	1.48
160	2.58	-2.41	-0.42	-23.73	1.20
170	2.52	-2.50	-0.10	-22.88	0.84
180	2.43	-2.92	-1.14	-23.34	1.71
190	2.30	-2.61	-0.42	-22.85	1.63
200	2.24	-2.69	-0.80	-22.60	1.58

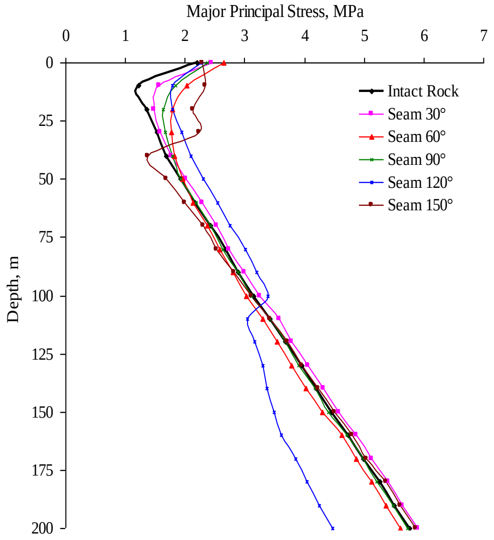

Figure 14 Major Principal Stresses at Toe

Table 3 Depth of Influence at Toe

Seam Inclination	Depth of influence (m)
30°	10 – 20
60°	30 – 40
90°	20 – 30
120°	90 – 100
150°	30 – 40

Dam Foundation with Shear Seam at Toe

In-depth analysis has been carried out considering two major aspects namely the deformations and the major principal stresses at some critical locations viz. a) Along dam foundation interface – 10 cm below the dam base, b) Along the depth at the heel – 20 cm inside from the heel of dam, c) Along the depth at the toe - 20 cm inside from the toe of dam, d) Along the upstream face of the dam – 20 cm inside. The magnified deformed shape (magnified 500 times) and the deformations at selected critical locations for all the cases analyzed are presented in Figures 15 to 26.

The magnified deformed shapes of dam-foundation system show that in all cases the seam is behaving as a discrete boundary and has divided the foundation in two blocks. It can be noted from the figures depicting the deformations along critical locations that generally the deformations are maximum at the crest, heel and the toe of the dam. The deformations, major and minor principal stresses recorded at these locations in respect of various shear seam inclinations are presented in Table 4. From this table it may be noted that the deformation is maximum at the crest irrespective of the inclinations and is critical when the seam is inclined at 90°. It may be noted that due to the presence of seam there is a reduction of major principal stress at the heel for all the cases. However the major principal stresses at the toe are showing an marked increases for the seam inclined at 60°.

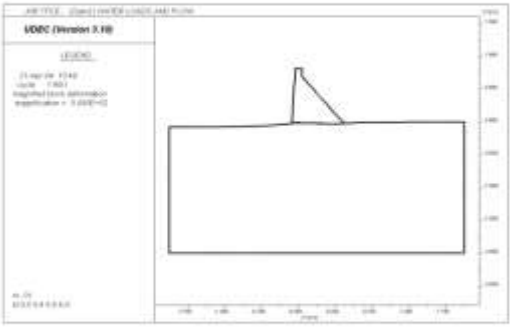

Figure 15 Deformed Shape of Intact Rock

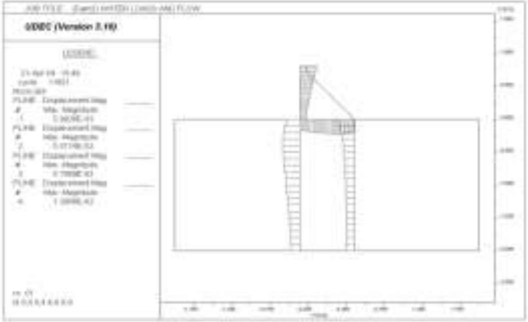

Figure 16 Deformations – Intact Rock

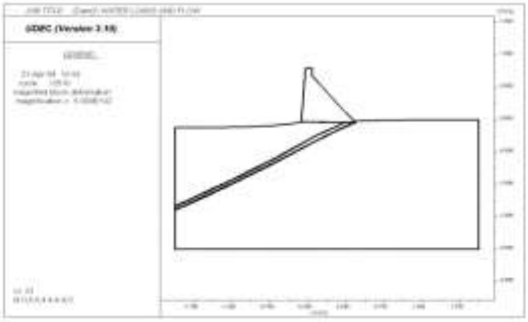

Figure 17 Deformed Shape – Seam 30°

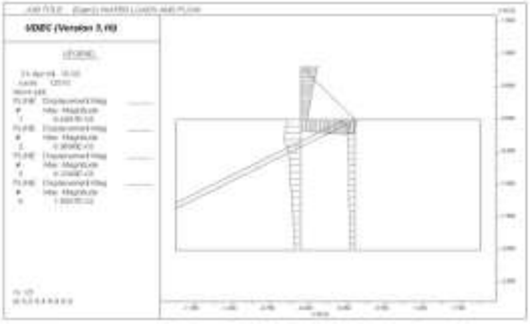

Figure 18 Deformations – Seam 30°

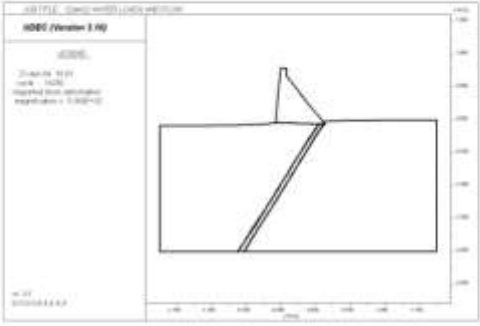

Figure 19 Deformed Shape – Seam 60°

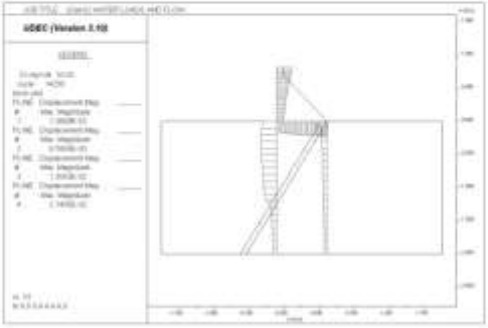

Figure 20 Deformations – Seam 60°

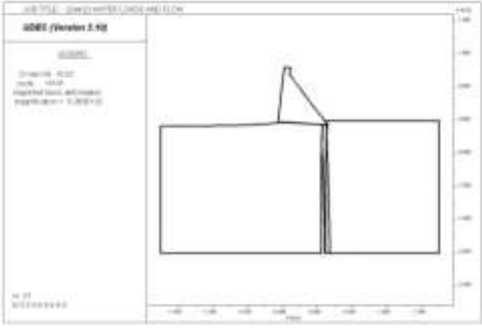

Figure 21 Deformed Shape – Seam 90°

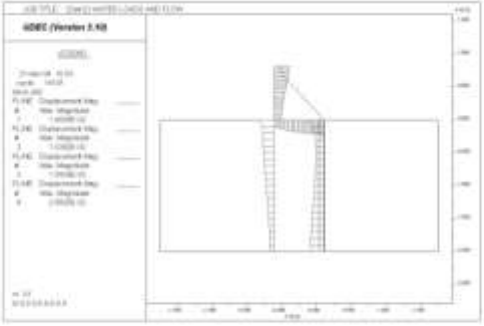

Figure 22 Deformations – Seam 90°

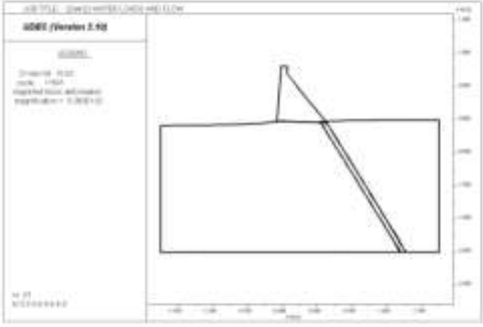

Figure 23 Deformed Shape – Seam 120°

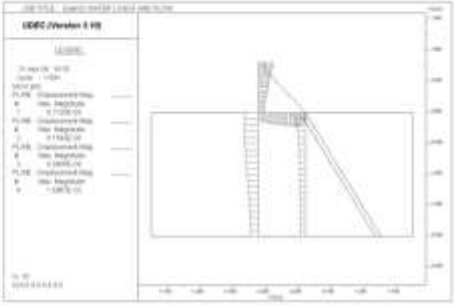

Figure 24 Deformations – Seam 120°

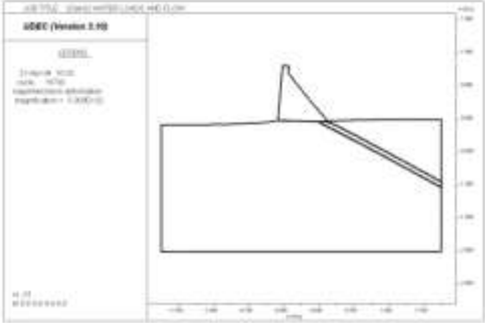

Figure 25 Deformed Shape – Seam 150°

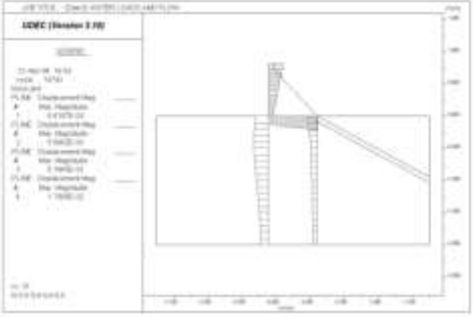

Figure 26 Deformations – Seam 150°

Table 4 Deformation, major and minor principal stresses at the Crest, Heel and Toe

Seam Inclination	Displacement mm			Major Principal Stress MPa	
	Crest	Heel	Toe	Heel	Toe
Intact Rock	13.96	4.27	5.80	1.185	2.205
30°	16.01	6.35	9.24	1.435	1.867
60°	21.40	8.36	13.00	**1.477**	**3.585**
90°	**26.92**	**10.39**	**15.43**	1.099	1.281
120°	18.97	5.87	9.98	1.079	0.206
150°	17.99	5.04	8.75	1.061	0.654

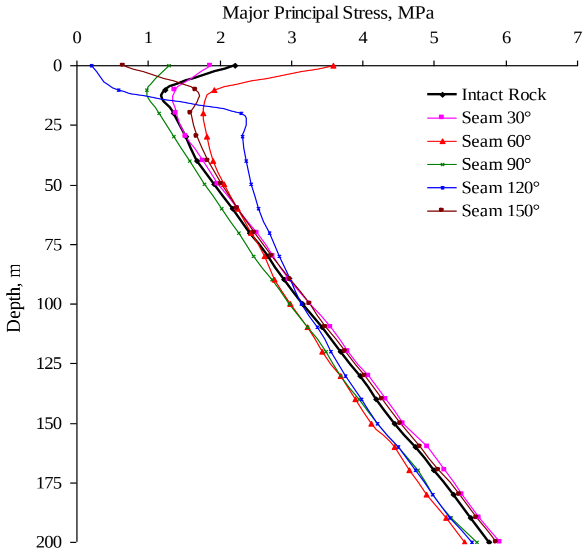

Figure 27 Major Principal Stress at toe

From the major principal stress (σ_1) distributions of the dam-foundation system for all the cases it has been observed that the most stressed zone lies at the toe of the dam. Therefore, in-depth analysis of the dam-foundation system along the depth at the toe has been carried out. Figure 27 presents the σ_1 at toe along the depth for all cases. The presence of seam in the foundation systems increases σ_1 substantially up to a depth of about 40 m after which the effect diminishes for all cases except for the foundation system with 120° inclined seam where σ_1 increases up to a depth of 90–100 m.

The percentage variation of the σ_1 at toe in dam-foundation system with seams with respect to the stresses in intact rock foundation presented in Table 2 also indicates that the zone/depth of influence is maximum for the foundation system with 120° inclined seam, considering a criterion of minimum 10% variation of σ_1. Though the presence of shear seams of any inclination in the dam-foundation weakens the system, the foundation with the seam inclination of 120° is the most critical one.

CONCLUSION

The presence of seam in the dam-foundation system has considerable effect on the foundation behavior. The present study indicates that:

- The stresses and deformations in the dam-foundation system with shear seams increase considerably up to a certain depth with respect to the intact rock.
- If the deformation of the dam-foundation system is considered as the deciding factor for identifying the most critical case, the dam-foundation system with 90° inclined shear seam will be the most critical one.

- If the major principal stress distribution in the dam-foundation system is considered as the deciding factor for identifying the most critical case, the dam-foundation system with 120° inclined will be the most critical one for the cases of shear seam originated from the heel.
- The major principal stresses at the heel and the toe are different for all the cases of seam originating at toe. Generally, the major principal stresses are highly varying compare to each cases and the variation is remarkably more at the toe up to a depth of 20 m. But after that depth, the variation of the stresses is minimum.
- The in-depth analysis carried out for the dam-foundation system along the depth at toe indicates that the presence of seam in the foundation systems increases σ_1 substantially upto a depth of about 10 m for the seam inclined at 60°.
- Though the presence of shear seams of any inclination in the dam-foundation weakens the system, the foundation with the seam inclination of 60° is the most critical one if the stresses upto 10 m are considered.

The present study on the stress-deformation response of the dam-foundation system with shear seam identifies two different critical cases depending upon the chosen parameter to decide the criticality. This conjuncture poses a question to the Geotechnical Engineers to corner about the deciding factor in any analysis to arrive at the critical cases.

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