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Technical Note

Strains induced around cutoff walls of earth dam under full reservoir and drawdown conditions

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ABSTRACT

This paper presents the study pertaining to the strains that are developed near the cutoff walls employed in the foundation medium of the dam section. A total of sixteen finite element simulations are considered in the study, where the combination and placement of the cutoff walls in the foundation medium are varied. A cutoff wall is made to act as a seepage barrier with assigned linear elastic properties. A hypothetical earth dam of height 35 m is provided with a slope of 1V: 2.5H for both the downstream and the upstream sides. The finite element analyses are carried out using PLAXIS – 3D to obtain the principal strains and their variation with respect to time for two different conditions viz. Full reservoir steady seepage and Drawdown conditions. The variations in strains in the dam section and in the foundation medium are found to be more predominant for the two barriers with increased Young's modulus having a spacing of 15 m, first one being located at 0 m and second at 15 m from the center of the dam. The excessive strains would initiate cracks in the cutoff walls. This fact has to be taken to advantage while finalizing the sections for the cutoff walls.

1. Introduction

Geotechnical and hydraulic design considerations play a major role in the overall performance of earth dams constructed on compressible foundation. The presence of cutoff wall in the foundation medium of an earth dam causes an increase and reduction in hydraulic head at the upstream and downstream sides of the earth dam (Harr, 1962; Lambe and Whitman, 1979). Therefore, the maximum gradient exists in the connecting zone of the cutoff wall and the core (Ahari et al., 2000). An explicit analytical solution for the problem of steady, two-dimensional seepage in the vertical plane through a fully penetrating, semipermeable cutoff wall was developed by (Anderson, 2014). Author concluded that there is a significant difference in the results between the three-dimensional (3D) and two-dimensional (2D) analyses (Ahmed, 2015). Singh et al. (2006) outlined the design procedure of a rigid cutoff wall. In order to assess the potential for barrier cracking, the stresses are compared to the estimated tensile strength of the barrier material (Rice and Duncan, 2010). Further, Li and Desai (1983) concluded that the Drucker-Prager model yields lower factors of safety as compared to those by the hyperbolic law; however, the difference does not appear to be significant. Many researchers have studied the various problems pertaining to seepage under the dam structures with the inclusion of vertical cutoff wall and lead to the development of solutions for the same. Ghazavi et al. (2004) studied the dynamic behavior of plastic concrete

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cutoff walls in earth dams subjected to earthquake loading using finite element method. They found that by increasing the rigidity of the cutoff wall, shear stresses and tensile stresses along the wall increased. This gives an indication that at the ground level, designers should pay attention to the safety of the cutoff wall. Feng and Wu (2006) investigated the flow characteristics of masonry dams with a single sheet pile at the downstream toe and situated over a layered soil system. Though the study regarding seepage barriers in dam structure has been studied, its effect on variation and distribution of strains has attracted limited importance. Hence in the present study the variation in strains has been studied for two conditions viz. full dam under steady seepage and drawdown conditions. The position of placement of cutoff walls along with its configuration (single and double cutoff walls) including its material properties has been varied to understand the development of strains in the foundation medium and the earth dam body under full reservoir and drawdown conditions.

2. Materials and Geometry

The hypothetical earth dam considered for the study is 35 m in height with side slopes of 1 in 2.5 on both the upstream and downstream sides with the subsoil depth of 30 m. The full (high) reservoir level is 30 m above the natural ground level. **Figures 1 and 2** portray the earth dam section and the finite element mesh considered in the study. The cutoff wall of width 1.5 m is modeled as an impervious barrier with linear elastic material properties: Unit weight (γ) = 22 kN/m^3 and 24 kN/m^3 and Young's Modulus (E) = 1000,000 kN/m^2 and 25,000,000 kN/m^2. **Table 1** gives the other relevant soil properties used in the finite element simulations.

3. Numerical Modeling

A series of 3-dimensional finite-element analyses (FEA) were performed on an earth dam section involving a seepage barrier to understand the strain development in the dam section and how the strain varies with the position of cutoff walls. A finite-element program, PLAXIS-3D version - 2013.01 has been used to carry out the numerical analyses. Firstly, by entering into the structures mode the primary surfaces have been modeled. Then the intersection and the reclustering of the various surfaces were carried out before the entire primary section was extruded in lateral y-direction for a length of 50 m. Once the dam structure along with the cutoff wall was created according to the geometry specifications mentioned in the study, suitable surface flow boundary conditions were assigned to the surfaces where the seepage was permitted. The side walls on the right and left side of the foundation and also its bottom are assumed as impervious, where the flow of water was not permitted.

Secondly, before generating the mesh for the section considered, it was noted that this finite element program can automatically generate 15-node triangular plane-strain elements and the same has been utilized in this problem. This enables a fourth-order interpolation for displacements, involving a numerical integration consisting of 12 Gauss points where the stresses are

Table 1. Material properties.

Parameter	Shell	Subsoil	Core
Model	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb
Type	Drained	Drained	Undrained (b)
γ (kN/m^3)	16	17	16
γ_{sat}(kN/m^3)	20	22	18
E (kN/m^2)	50E3	200E3	25E3
μ	0.33	0.25	0.30
c'(kN/m^2)	5	1	-
S'$_u$(kN/m^2)	-	-	10
Φ (degrees)	30	35	-
ψ (degrees)	1	5	-
k (m/day)	0.2	3.45	1E-4

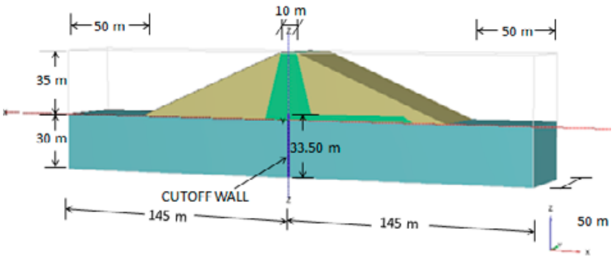

Fig. 1. Earth dam model with single cutoff wall.

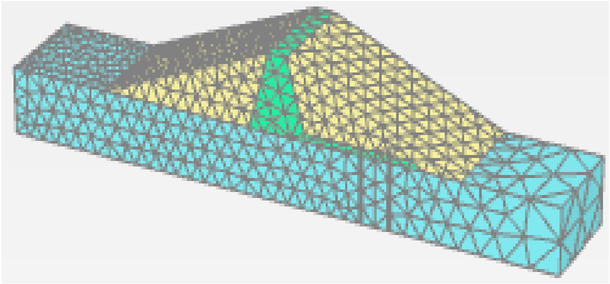

Fig. 2. Finite element mesh with double cutoff walls.

generated. The finite element mesh used in the simulations was checked to satisfy the convergence criteria and then the appropriate mesh was employed in the study. The fine mesh generation option has been adopted in this analysis, in which case the software generates the mesh automatically till the minimized effect of mesh dependency was achieved.

Finally, moving on to the loading criteria, the gravity loading condition was assigned for the case of high reservoir which enables to generate the initial stresses based on the volumetric weight. In order to calculate the pore pressures, steady seepage was allowed. After assigning the high reservoir level to 30 m, the minimum or low water level was assigned to 5 m from the foundation level. These two levels were used as the reference levels in order to perform the drawdown analyses of different durations viz. 5, 10 and 50 days. Proper linear flow functions were assigned for the three drawdown situations with a head fall of 25 m in each of the cases. A fully coupled flow deformation analyses has been performed for drawdown conditions which facilitates to analyze the simultaneous development of deformations and pore water pressures in partially and fully saturated soil mass because of the time dependent hydraulic boundary conditions. This type of analysis accounts for the unsaturated soil behavior as well as suction present above the phreatic level, however this is ignored in the present analyses.

4. Results and Discussions

The stress points are selected in such a way that they are in the proximity of the center (0 m, bottom of the earth dam) and the top (i.e., 3.5 m) of the cutoff wall which is embedded in the core up to a height of 3.5 m above the ground level. The results are obtained at these specific points so that all the intermediate load steps are captured during the actual calculation phase, as these are the key locations subjected to higher stress levels (Ghazavi et al., 2004). A total of 16 finite element simulations were performed with eight models being analyzed for high reservoir steady seepage and eight for drawdown conditions by varying the position of placement of cutoff walls, their configuration (single and double) and the material properties. The cases examined are as follows: four simulations for HR condition with single cutoff wall, two being analyzed for the model incorporating single cutoff wall with lower E value of 1000000 kN/m^2 placed at 0 and 60 m away from the center and other two for the models with similar placement of cutoff walls but with higher E value of 25000000 kN/m^2. The other four simulations were performed on the models with double cutoff wall system placed at [0, 15] m and [45, 60] m away from the center with a center to center spacing of 15 m between them. The similar eight models were then analyzed for drawdown condition. In order to have a realistic understanding of the strain concentrations at various positions, the strain contours are produced and presented in the following sections. In the subsequent sections; the variation and distribution of major and minor principal strains has been studied. These principal strains give an indication of maximum and minimum normal strains developed at considered points (in this study the points are considered at top of foundation level and top of cutoff wall).

Figures 3a-3f depict the variation of major and minor principal strains (ε_1 and ε_3) with respect to time and when the stress points lie near the 0 coordinate of the cutoff wall with respect to its height. The letters D and S represent the combination of cutoff wall placement in the foundation medium for double wall and single wall systems respectively and the numerical values indicate the distance (in meters) from the center of the dam section.

It is noted that, when the cutoff walls are used in double configuration, spaced at 45 and 60 m, the near end cutoff wall which is at 45 m away from the center is subjected to higher strains than the other which is near to the toe of the dam (**Figs. 3a** and **3b**). On contrary, if the cutoff walls are placed at 0 and 15 m, the trend is totally opposite i.e., the barrier at 0 m is subjected to lesser strains than the one placed at 15 m from the center of the dam (**Figs. 3c** and **3d**). In addition to this, there is no much variation in the path traced as well as the final minor principal strain values as depicted in **Fig. 3d**. From these figures it is very clear that the major principal strain recorded at far end cutoff wall placed at 15 m is almost 50% more as compared to the near end cutoff wall placed at the center of a dam. But, for the case of slow drawdown, there is just a difference of 10% - 15%. However, if the single cutoff wall is introduced at a place of location of the far end cutoff wall (i.e., at 45 m and 60 m) in the double wall system; the single barrier is subjected to more or less the same strains as experienced by the near end cutoff wall (**Figs. 3e** and **3f**). By adopting double cutoff wall system in the section, the seepage length increases, thereby reducing the exit gradient. This will enhance the overall dam stability when the two cutoff walls are employed in the section.

Figures 4a-6b show the variation of strains in the foundation medium and dam section. The strains are concentrated mainly in the core portion during the full reservoir condition, whereas the strain contours shift toward the upstream side during drawdown because of

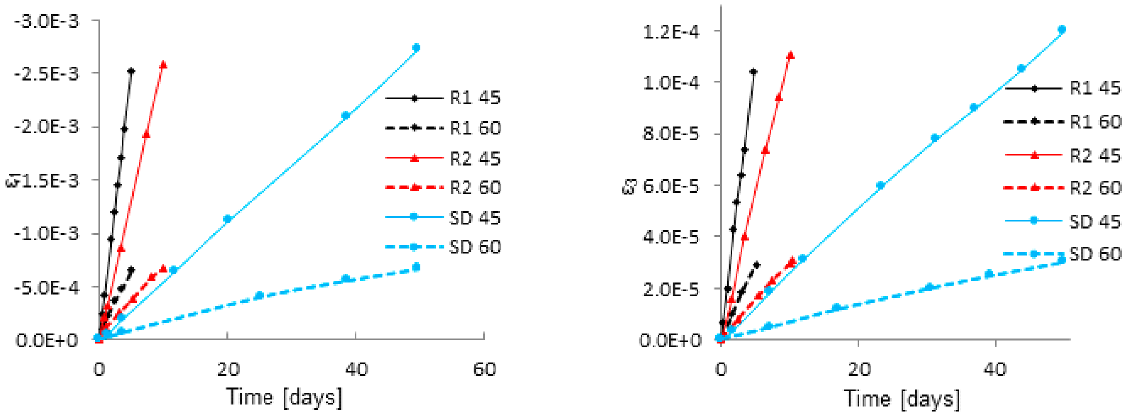

Fig. 3. Variation of **(a)** major principal strain with time for near and far end barriers (left) and **(b)** minor principal strain with time for near and far end barriers (right).

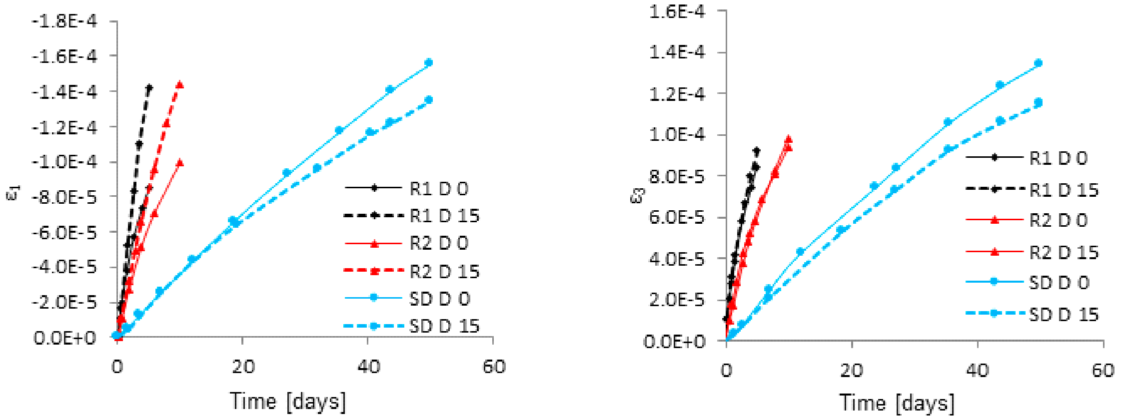

Fig. 3. Variation of **(c)** major principal strain with time for near and far end barriers (left) and **(d)** minor principal strain with time for near and far end barriers (right).

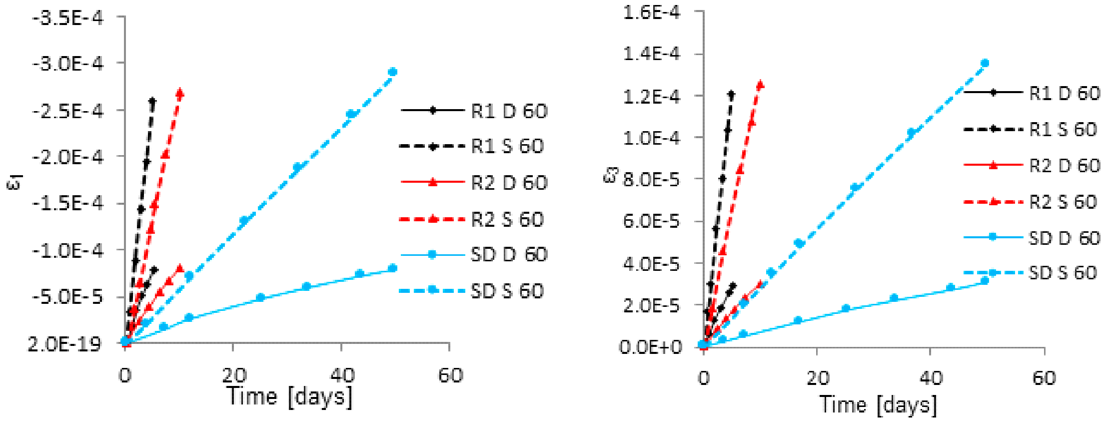

Fig. 3. Variation of **(e)** major principal strain with time for far end and single barriers (left) and **(f)** minor principal strain with time for far end and single barriers.

the pull experienced as a result of the reverse flow of the water. There is dissimilarity in the strain distribution as observed in **Figs. 4a** and **5a**, even though the double cutoff wall system is adopted. In addition to this, these

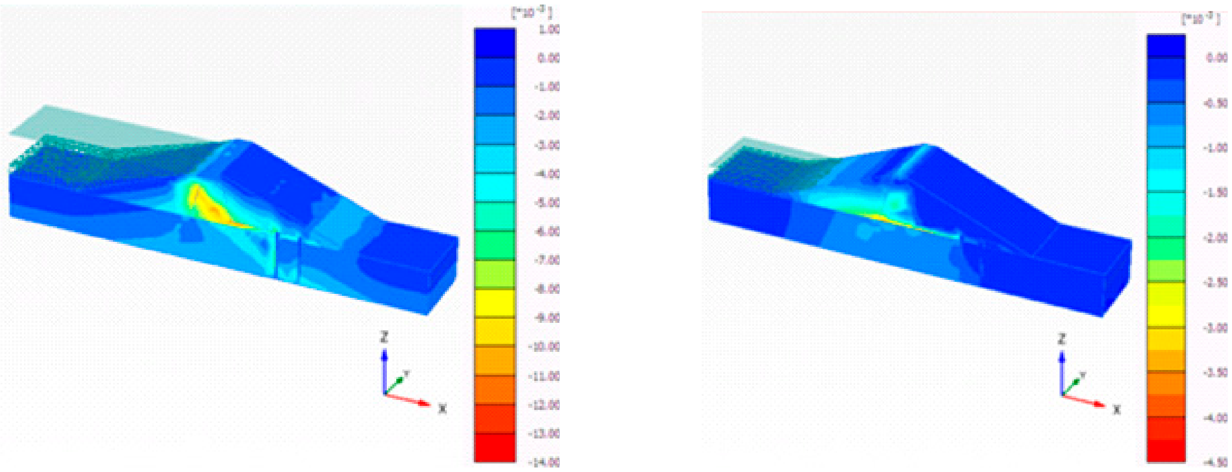

Fig. 4. Major principal strain contours: **(a)** Cutoff walls at 45 m and 60 m with HR condition (left) and **(b)** Cutoff walls at 45 and 60 m with drawdown condition (right).

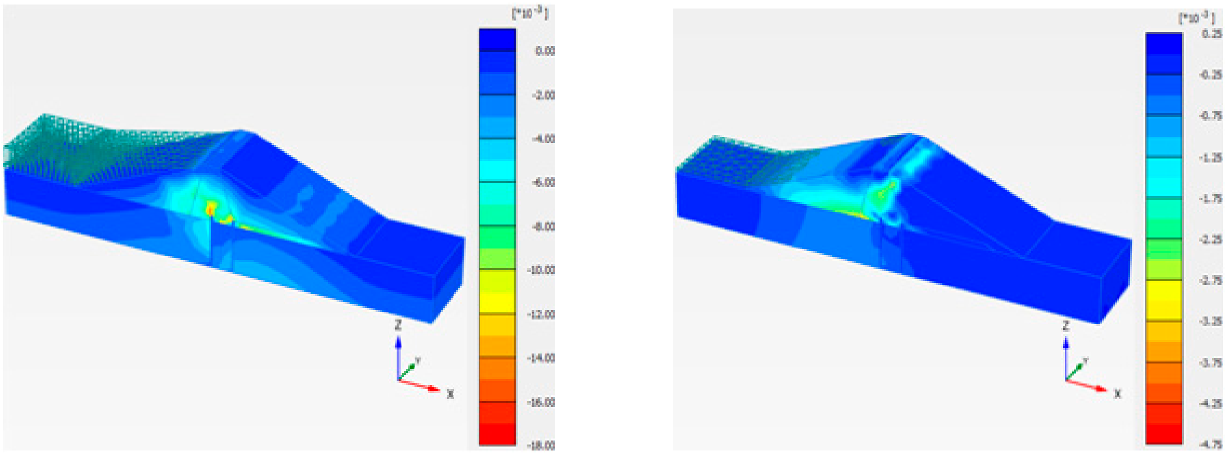

Fig. 5. Major principal strain contours: **(a)** Cutoff walls at 0 and 15 m with HR condition (left) and **(b)** Cutoff walls at 0 and 15 m with drawdown condition (right).

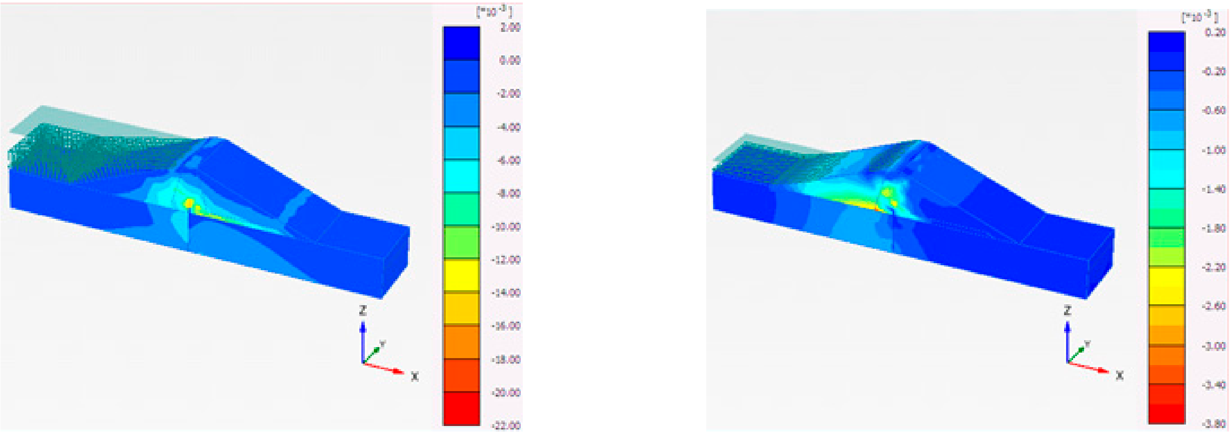

Fig. 6. Major principal strain contours for: **(a)** Cutoff wall at center (0) for HR condition (left) and **(b)** Cutoff wall at center (0) for drawdown condition (right).

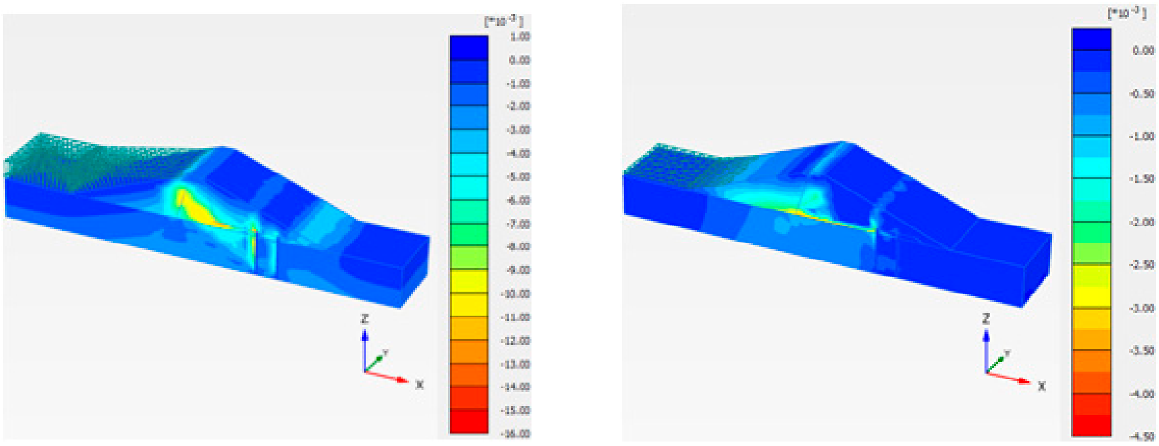

Fig. 7. Major principal strain contours: **(a)** Cutoff walls at 45 and 60 m with HR condition (left) and **(b)** Cutoff walls at 45 and 60 m with drawdown condition (right).

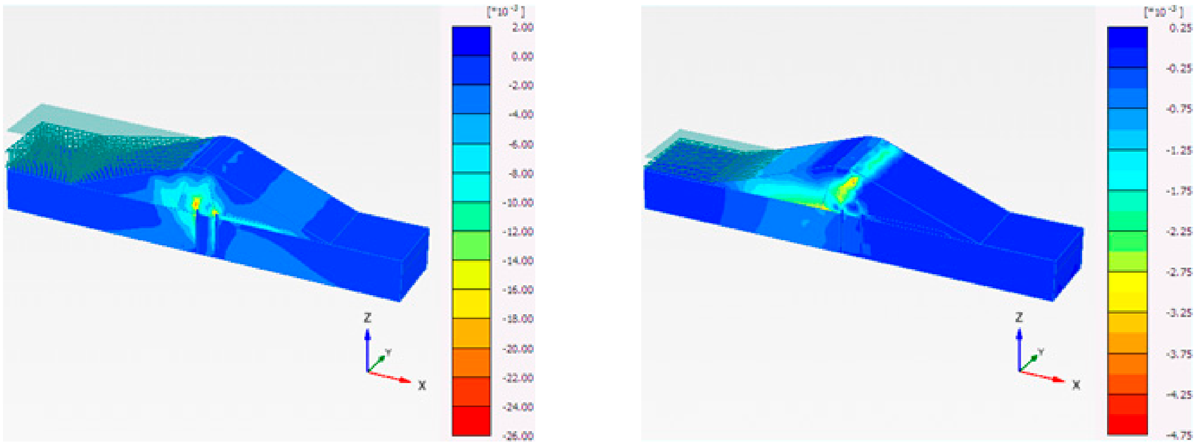

Fig. 8. Major principal strain contours: **(a)** Cutoff walls at 0 and 15 m with HR condition (left) and **(b)** Cutoff walls at 0 and 15 m with drawdown condition (right).

plots also suggest that the periphery of the nearer cutoff walls is subjected to high strains for HR condition.

Figures 5a and 5b show the variation of strains wherein the contours during the high reservoir condition are somewhat distributed throughout the dam section. During the drawdown condition, the strains are generally concentrated on the upstream face of the dam. In addition to this, the downstream top portion is subjected to strains during the drawdown condition. However, for high reservoir condition the lower portion on the downstream side is subjected to higher strains as compared to the strains near the top portion of the dam. This explanation is valid for any combination of cutoff walls considered in the study.

The strain contours are generally of lesser magnitude at the periphery of the cutoff walls when they are placed nearer to the central core portion. However, when the positioning of the cutoff walls are towards the toe end of the dam, the higher accumulation of the strains at the periphery of the barrier can be seen clearly from the contour plots (**Figs. 4a** and **5a**). It is noted that the accumulation of strains is more pronounced as in **Fig. 7a** in comparison with the results in **Fig. 4a**. With the implementation of single cutoff wall, the strains developed in the section as a whole increased by 20% especially for the case of high reservoir as compared to the strains developed in the model with double cutoff walls (**Figs. 5a** and **6a**). However, for the case of drawdown, there is almost no change in the recorded strain values.

The results in **Figs. 7a-8b** are obtained when the stiffness and density of the barrier materials are increased to 24 kN/m^3 and 25000000 kN/m^2 respectively. The developed strain values are increased by almost 45% as compared to the case of full reservoir conditions with negligible change for drawdown conditions. Distinct features (especially on the upstream and downstream slopes) are observed in **Figs. 5b and 8b**, which indicate

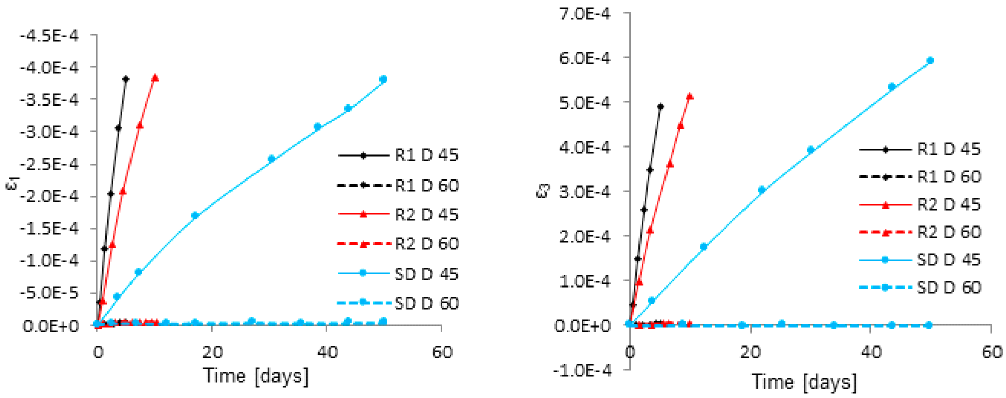

Fig. 9. Variation of **(a)** major principal strain with time for near and far end barriers (left) and **(b)** minor principal strain with time for near and far end barriers (right).

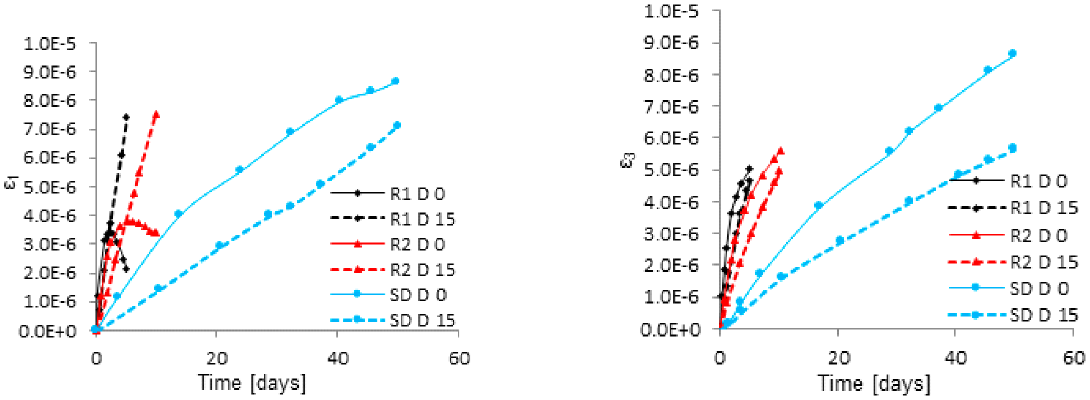

Fig. 10. Variation of **(a)** major principal strain with time for near and far end barriers (left) and **(b)** minor principal strain with time for near and far end barriers (right).

that the strains at the top of the dam increase as the stiffness of the barrier material increases. Furthermore, in **Figs. 7a-8a**, the strain contours are more pronounced as compared to **Figs. 4a-5a**.

For the increased stiffness and density of the cutoff wall material, the strain values escalated drastically. As the stiffness of the material increases, the relative deformation between the surrounding soil and the cutoff wall increases. Hence, it can be averred that the barrier experiences higher strain values as compared to the barrier having lesser Young's modulus. Therefore, a proper selection of materials and their properties is of greater significance in the performance analysis of the earth dams. This activity calls for proper evaluation and interpretation of the results.

Figures 9a-10b depict the variation of strains in the dam section when the stiffer cutoff walls are used. It has been observed that the far end cutoff wall experienced very less strains as compared to those experienced by less stiff cutoff walls. Of late, the research by (Liu et al., 2016) did reveal that, the major principal stress along the cutoff wall increased with the increase in Young's modulus of the cutoff material. As seen from **Figs. 10a, 11a and 11b**, the trend in the strain development varied from rest of the previous observations. The strain values first escalate, reach their maximum value and again show a descending trend when the stress point under consideration is at the top of the cutoff wall (i.e., at 3.5 m).

5. Conclusions

The location and combination of the cutoff walls do influence the variation and distribution of strains in the dam body. The results reveal that, as the duration of the drawdown (5, 10 and 50 days) increases, the strains also increase. It is observed that the connecting region of the cutoff wall and the earth dam is subjected to higher strains for all the reservoir conditions. These strain values in the dam as a whole increased drastically (up to 45%) for the case of stiffer and denser cutoff walls because of the increase in relative deformation between the cutoff wall and the surrounding soil. Even though, the increment in strains is not observed for drawdown cases, there are

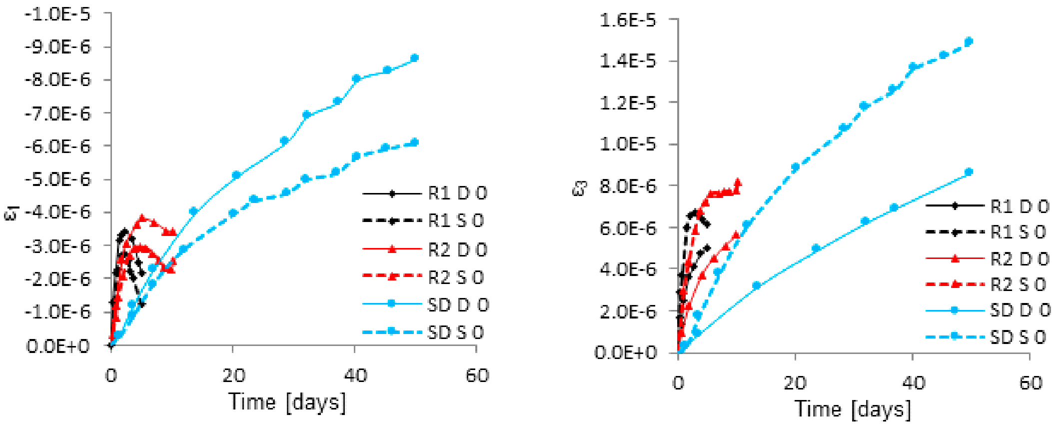

Fig. 11. Variation of **(a)** major principal strain with time for near end and single barriers (left) and **(b)** minor principal strain with time for near end and single barriers (right).

pronounced zones of strain localization at the top of the earth dam just above the location of cutoff wall, when the stiffer cutoff walls are employed in the section. Moreover, if the provision of cutoff wall is planned to be introduced at the center, care should be taken, as the strain values in the dam as a whole are increased and are generally concentrated in the core portion.

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Symbols and abbreviations

HR	High (full) reservoir condition
R1	Rapid drawdown condition for 5 days duration
R2	Rapid drawdown condition for 10 days duration
SD	Slow drawdown condition for 50 days duration
R1 D	Rapid drawdown condition for 5 days duration with double cutoff wall system
R2 D	Rapid drawdown condition for 10 days duration with double cutoff wall system
SD D	Slow drawdown condition for 50 days duration with double cutoff wall system
D	Double wall system
S	Single wall system
γ	Unit weight of soil
γ_{sat}	Saturated Unit weight
E	Young's Modulus
c'	cohesion
S'_u	undrained shear strength
ψ	Dilation angle
ϕ	internal friction angle