Static and Pseudo-static Study of Stress and Displacement of Earth-Fill Dam Using Layered and Single-Layer Models

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Abstract

Earth-fill dams stability in steady state seepage condition is very important, especially during earthquakes. Numerical software analyses require accurate and realistic modeling of construction stages. Since earth-fill dams are constructed in different layers, so these conditions should be considered in software modeling to achieve a reasonable design. In this study, an earth-fill dam is modeled in PLAXIS software and the effects of the number and shape of layers are studied in dry and steady-state conditions. Obtained results in static and pseudo-static analyses show that modeling of earth-fill dams with different layers has significant effects on shear stresses and horizontal displacements. For example, horizontal displacements and shear stresses, increase at least 50% and 17% respectively, in comparison with single layer models. According to the obtained results, it can be mentioned that modeling of an earth-fill dam in the layered model and rather in inclined layers are more reasonable.

Keywords: Earth-Fill dam, Stress distribution, Displacement, Layered model, Pseudo-static analysis

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Introduction

Earth-fill dams are one of the most common types of dams. Their heights are increased to more than 300 m. During high earth-fill dam construction, both stresses and deformations developed in the dam body and its foundation are important in dam safety. (Chen *et al.*, 2014).

Earth dams are designed to allow a limited amount of uniform seepage through their cores and foundations. When seepage exceeds than its allowable amount, internal erosion may occur and increase locally the permeability of preferential flow paths. As the permeability is increased through erosion of finer particles, the hydraulics of seepage zones will also change over time. This can lead to the formation of piping through the dam and the development of subsurface voids, both of which can cause sinkholes on the crest or side-slopes (Fell *et al*., 2003; Bendahmane *et al*., 2008). The occurrence of such localized seepages zones may therefore result in sudden failure of an earth dam (Foster *et al*. 2002; Fell *et al*. 2003).

In a simplified approach consolidation analysis of unsaturated soil is applied to numerical simulation of an earth- rock dam during the process of water-filling. The computational results include stress and displacement fields within the dam and the variations of pore water pressure and phreatic line. The results show that due to the coupling effect between deformation and pore water pressure, the development of pore water pressure in the core-wall of the dam is quicker than that computed from unsaturated seepage analysis without coupling deformation. As soil modulus decreases, the deformation of the dam becomes larger and the coupling effect is stronger, leading to quicker development of pore water pressure and phreatic line. The variations of pore water pressure within the core-wall are related not only to unsaturated seepage induced by variations of water level, but also to the excess pore water pressure induced by deformation. These may explain why there is high water pressure measured shortly after the completion of earth-rock dam. It should be noted that the computations of transient seepage for unsaturated soils are difficult to converge as compared with steady seepage analysis due to iterative calculations related to a variety of factors such as phreatic line, permeability coefficient and soil modulus. The computational parameters should be in line with engineering practice. Extreme values of permeability coefficient and of parameters of constitutive model may aggravate computational convergence and meaningful results are not likely to be achieved (Jie *et al*., 2012).

The finite element method is a powerful tool to analyze and solve problems in constructions of the earth-fill dam as it can calculate the internal deformation of the core and shell so that the stress distribution and load transfer within a dam section can be obtained. Many researchers have used this method to study the deformations and stresses in embankment dams.

A two dimensional plane strain finite element method was used to study the stresses and deformations of an embankment and was proposed to solve the problem of nonlinear material properties (Clough and Woodward, 1967). Based on different testing results, Boughton (1970) gave formulas for the nonlinear elastic modulus and Poisson’s ratio and computed the deformations of a dumped rock-fill dam. Duncan and Chang (1970) proposed a hyperbolic constitutive model for the nonlinear stress-strain relationship of soil, which has often been used for stress and deformation analysis in embankment dams (Kulhawy and Duncan, 1972; Sharma *et al*., 1979; Adikari and Parkin, 1982). Naylor et al. (1981) proposed a nonlinear ‘K-G’ model for finite element analysis in geotechnical engineering and used it to predict the construction performance of the Beliche dam (Naylor *et al.*, 1986). Based on the numerical investigations done by Berhe *et al.*, the performance of earth-fill dams increases with increase in the angle of inclination of the center line of the core from the vertical towards the upstream. Therefore the arrangements of the clay core for dams in seismic areas can be taken as one design criteria during earth-fill dam design (Berhe *et al.*, 2010). The study performed by Derakhshandi *et al.* (2014) has shown that, according to the numerical analysis, the settlement results were consistent with the data recorded by the instruments in terms of both quality and quantity for Vanyar dam located in East Azarbayejan of Iran.

Accurate and exact modeling of earth-fill dam is an important factor to determine stresses and displacements of earth-fill dam correctly and perception of its behavior. Construction of an earth-fill dam is not in one step and relevant to height of earth-fill dam construction operation is step by step. It is expected that number and shape of layers have important effects on stresses and displacements of earth-fill dam.

Clough and Woodward (1967) carried out some stress-strain analyses on a homogeneous embankment over rigid subsoils, the results of which showed that, to correctly simulate the construction process, it is necessary to consider incremental stage construction in comparison to single stage construction. In addition, the vertical stresses obtained from both analyses had nearly the same values, while the difference of settlement was significant.

Authors' previous show that layering of models has influences on dam displacements in static conditions (Amel Sakhi and Ahmadpour, 2015).

In this study an earth-fill dam in both shape, horizontal and inclined layers and in number of 6, 9 and 11 layers is modeled and is analyzed by Finite Element Method (FEM) in dry and steady-state conditions. Then stresses and displacements values of dam body is compared with one layer model.

PLAXIS is a geotechnical software based on the Finite Element Method (FEM). This software simulates seepage in earth-fill dam body using triangular elements. In this research, using very fine elements, values of stresses and displacements of earth-fill dam body are evaluated. In this study, both static analysis and pseudo static analysis (by 0.3g horizontal acceleration) are performed.

Modeling Verification

In order to verify obtained results, a comparison between modeling by Shivakumar *et al*. (2015) and a PLAXIS modeling is performed. Comparison of results shows that results of modeling have good agreement with the results of this research. For example Figure 1 shows normal total stress diagram of dam body in Shivakumar models and Figure 2 illustrates normal total stress diagram of dam body in current research.

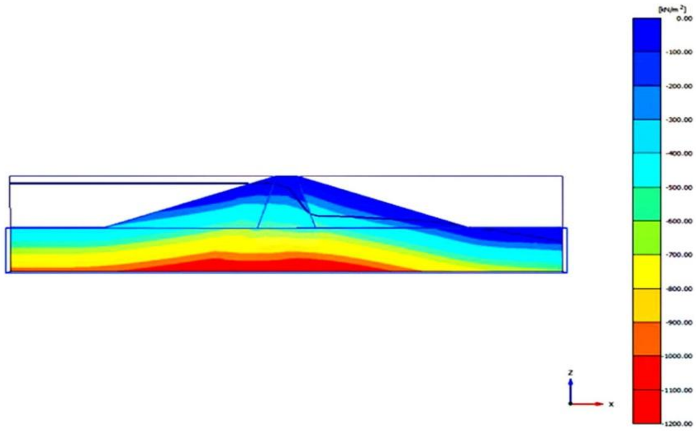

Figure 1. Normal total stress in dam body (Shivakumar *et al.* 2015)

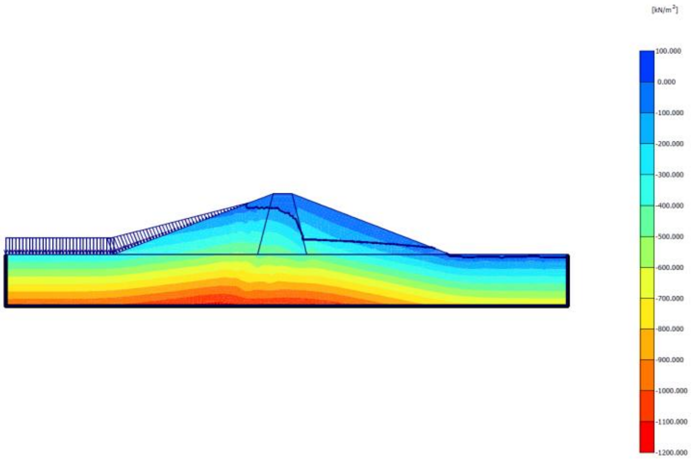

Figure 2. Normal total stress in dam body (Remodeled)

Model Specifications

1. Geometry

Cored dam, considered in this study has 22 m height and 129 m width, respectively. Upstream water level is 80% of dam height. Foundation width and depth are three times of dam's height. Upstream side slope is 1:2.75 (1 vertical - 2.75 horizontal) and downstream side slope is 1:2.5 and core slope is 1:0.5 (Figure 3).

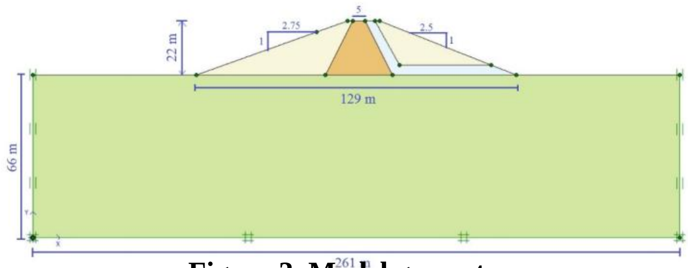

Figure 3. Model geometry

2. Materials Properties

Table 1 presents soil properties used in this research. Mohr-Coulomb constitutive model is used in analysis.

Table 1. Soil Properties

Regions	Material Properties							
	γ (kN/m^3)	γ_{sat} (kN/m^3)	k_x (m/day)	k_y (m/day)	E (kN/m^2)	υ	c (kN/m^2)	ϕ (°)
Crust	16	20	8.64	8.64	2×10^4	0.33	5	31
Core	16	18	8.6×10^{-4}	8.6×10^{-4}	1×10^4	0.35	40	25
Drain	20	22	0.86	0.86	3×10^4	0.35	1	35
Foundation	24	25	4.3×10^{-3}	4.3×10^{-3}	1×10^6	0.25	100	35

3. Dam Modeling

In this study, earth-fill dam is modeled in two different situations, horizontal layered models and inclined layered models. Numbers of layers in different analyses are 6, 9 and 11 (Figures 4, 5, 6, 7, 8 and 9). In finite element mesh 15-node triangular elements has been used. Number of elements are 904, 672 and 505 in single layer, 6 inclined layers and 6 horizontal layers models, respectively. In pseudo-static analyses, 0.3g horizontal acceleration is considered for all models.

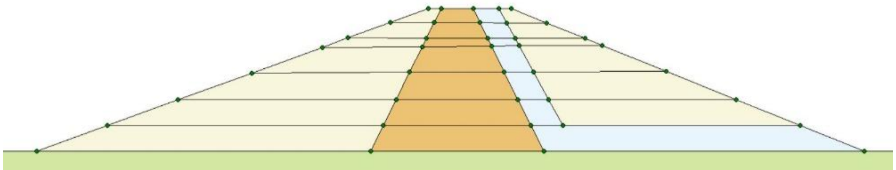

Figure 4. Earth-fill dam model with 6 horizontal layers

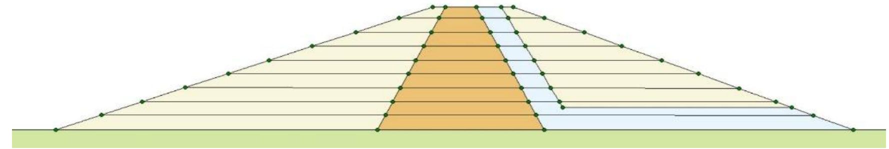

Figure 5. Earth-fill dam model with 9 horizontal layers

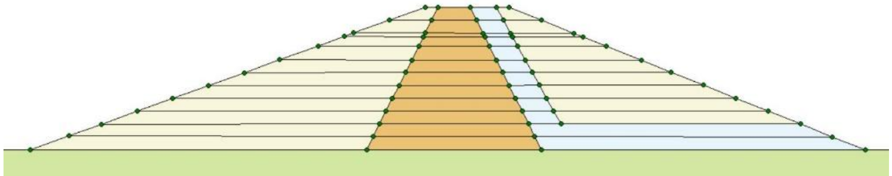

Figure 6. Earth-fill dam model with 11 horizontal layers

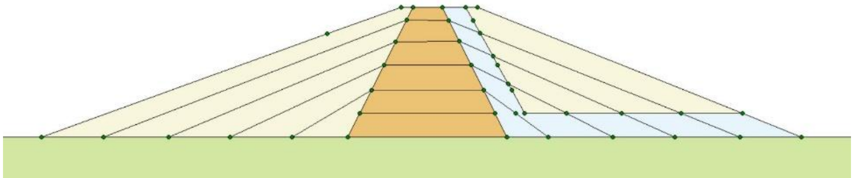

Figure 7. Earth-fill dam model with 6 inclined layers

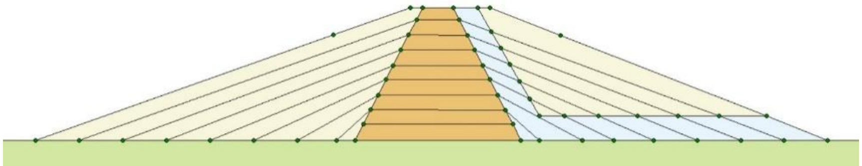

Figure 8. Earth-fill dam model with 9 inclined layers

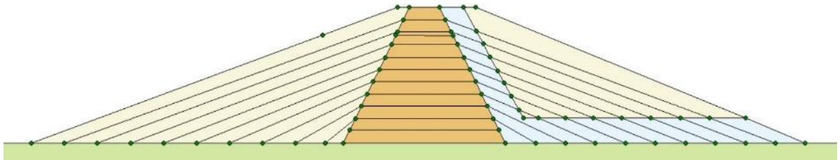

Figure 9. Earth-fill dam model with 11 inclined layers

Results

Obtained results for total stress, total horizontal stress, total vertical stress, shearing stress, effective stress, effective horizontal stress, effective vertical stress, total displacement, horizontal displacement, and vertical displacement are compared for two different models. Using Equation (1), differences are expressed in percent:

$$\text{Diff} = \frac{U_i - U_1}{U_1} \times 100 \quad (1)$$

where U_i is relevant parameter values (stress or displacement) in multi-layered models and U_1 is parameter values in one single-layer model. Earth-fill dam is analyzed in dry and steady-state seepage conditions.

Static and pseudo-static analyses are performed in mentioned conditions, and obtained results are presented in Tables 2 to 11. In these tables, obtained results are presented in percent in comparison with one single layer instead of different horizontal and inclined layers.

Table 2. Total stress results

Seepage condition	Model type	Number of layers	Total stress difference (%)	
			Static	Pseudo-static
Without seepage	Inclined layered models	11	0	0
		9	0	0
		6	0	0
	Horizontal layered models	11	-0.54	-0.56
		9	-1.09	-0.56
		6	-0.54	-0.56
With seepage	Inclined layered models	11	0	0
		9	0.51	0
		6	0	0
	Horizontal layered models	11	-0.51	-0.52
		9	-1.02	0
		6	0	-0.52

Table 3. Total horizontal stress results

Seepage condition	Model type	Number of layers	Total horizontal stress difference (%)	
			Static	Pseudo-static
Without seepage	Inclined layered models	11	-0.03	-0.17
		9	0.17	-0.14
		6	-0.08	-0.14
	Horizontal layered models	11	-0.92	-0.86
		9	-0.66	-0.27
		6	-0.08	-0.08
With seepage	Inclined layered models	11	0	0
		9	0	0
		6	0	0
	Horizontal layered models	11	0	-0.78
		9	0	0
		6	0	0

Table 4. Total vertical stress results

Seepage condition	Model type	Number of layers	Total vertical stress difference (%)	
			Static	Pseudo-static
Without seepage	Inclined layered models	11	0	-0.55
		9	0.54	-0.55
		6	0	-0.55
	Horizontal layered models	11	-1.09	-0.55
		9	0	-0.55
		6	0	-0.55
With seepage	Inclined layered models	11	0	0
		9	0	0
		6	0	0
	Horizontal layered models	11	-1.02	0
		9	-1.02	0
		6	0	0

Table 5. Effective stress results

Seepage condition	Model type	Number of layers	Effective stress difference (%)	
			Static	Pseudo-static
Without seepage	Inclined layered models	11	0	0
		9	0	0
		6	0	0
	Horizontal layered models	11	-0.54	-0.56
		9	-1.09	-0.56
		6	-0.54	-0.56
With seepage	Inclined layered models	11	0.83	0
		9	0.83	0
		6	0	0
	Horizontal layered models	11	0	-0.85
		9	-0.83	-0.85
		6	0	-0.85

Table 6. Effective horizontal stress results

Seepage condition	Model type	Number of layers	Effective horizontal stress difference (%)	
			Static	Pseudo-static
Without seepage	Inclined layered models	11	-0.03	-0.17
		9	0.17	0.14
		6	-0.08	-0.14
	Horizontal layered models	11	-0.92	-0.86
		9	-0.66	-0.27
		6	-0.08	-0.08
With seepage	Inclined layered models	11	-0.01	-0.24
		9	0.28	3.54
		6	-0.12	-0.25
	Horizontal layered models	11	-1.29	-1.18
		9	-0.53	-0.39
		6	-0.08	-0.09

Table 7. Effective vertical stress results

Seepage condition	Model type	Number of layers	Effective vertical stress difference (%)	
			Static	Pseudo-static
Without seepage	Inclined layered models	11	0	-0.55
		9	0.54	-0.55
		6	0	-0.55
	Horizontal layered models	11	-1.09	-0.55
		9	0	-0.55
		6	0	-0.55
With seepage	Inclined layered models	11	0	0
		9	0.83	0
		6	0	0
	Horizontal layered models	11	-0.83	0
		9	0.83	0
		6	0	-0.85

Table 8. Shear stress results

Seepage condition	Model type	Number of layers	Shear stress difference (%)	
			Static	Pseudo-static
Without seepage	Inclined layered models	11	40.98	43.74
		9	41.12	41.69
		6	25.84	29.96
	Horizontal layered models	11	31.57	26.67
		9	30.14	26.82
		6	23.61	23.13
With seepage	Inclined layered models	11	29.63	29.89
		9	35.16	34.86
		6	20.35	23.63
	Horizontal layered models	11	26.56	17.60
		9	21.00	17.44
		6	19.52	18.58

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Table 9. Total displacement results

Seepage condition	Model type	Number of layers	Total displacement difference (%)	
			Static	Pseudo-static
Without seepage	Inclined layered models	11	-31.48	-30.22
		9	-29.87	-28.50
		6	-26.59	-26.58
	Horizontal layered models	11	-34.65	-32.83
		9	-34.68	-33.87
		6	-33.47	-33.63
With seepage	Inclined layered models	11	-35.12	-35.30
		9	-33.00	-33.34
		6	-29.44	-29.76
	Horizontal layered models	11	-39.41	-37.63
		9	-39.50	-38.64
		6	-38.34	-38.61

Table 10. Horizontal displacement results

Seepage condition	Model type	Number of layers	Horizontal displacement difference (%)	
			Static	Pseudo-static
Without seepage	Inclined layered models	11	80.30	76.94
		9	75.42	72.75
		6	55.74	53.34
	Horizontal layered models	11	57.10	53.17
		9	51.01	46.20
		6	31.80	26.59
With seepage	Inclined layered models	11	91.18	102.02
		9	91.96	102.98
		6	78.39	88.04
	Horizontal layered models	11	65.24	75.90
		9	59.34	71.90
		6	45.75	56.15

Table 11. Vertical displacement results

Seepage condition	Model type	Number of layers	Vertical displacement difference (%)	
			Static	Pseudo-static
Without seepage	Inclined layered models	11	-31.41	-30.22
		9	-29.78	-28.50
		6	-26.51	-26.58
	Horizontal layered models	11	-34.62	-32.86
		9	-34.65	-33.86
		6	-33.46	-33.63
With seepage	Inclined layered models	11	-36.32	-36.16
		9	-34.40	-34.36
		6	-30.58	-30.56
	Horizontal layered models	11	-40.55	-38.44
		9	-40.51	-39.50
		6	-39.29	-39.40

Discussion

According to obtained results, differences of total stress, total horizontal stress, total vertical stress, effective stress, effective horizontal stress and effective vertical stress are not so high and they have no significant influences on results, but differences in shear stresses and displacements are more significant.

According to Table 2, changes in total stresses are about 0-1%. Table 3 gives little changes in horizontal total stress in dry situation. In Table 4, horizontal layered models display more changes in total vertical stress in static and pseudo-static analyses.

It can be seen in Table 5 that in static steady-state seepage condition, effective stresses are bigger than effective stresses in static dry condition. Also it can be concluded that pseudo-static analyses have little changes in results. Table 6 indicates that changes in effective horizontal stress are inconsiderable in all models. It is obvious in Table 7 that changes in effective vertical stresses are erratic in static analysis results, but results of pseudo-static analyses in dry conditions have constant negligible values.

Table 8, presents that in both dry and steady-state seepage conditions, inclined layered models have greater shear stresses than single-layer model values, meanwhile increasing of layers increases changes ratios, particularly in static conditions.

It can be seen in Table 9 that, total displacement in both horizontal and vertical layered models decrease with increasing the layers. Also obtained results show that when dam is modeled with different layers, total displacement is less than with one single layer is considered.

Obtained results in Table 10 show that, inclined layered models have greater horizontal displacement, also when steady-state seepage is considered, rate of increases is more than dry condition. It can be mentioned that in inclined layered models with steady-state seepage, horizontal displacements are increased about 2 times in comparison with single layer model. Table 11 shows another view of Table 10. Figures 10-13 show obtained results. (Note: in figures, St= static analysis and PS = pseudo-static analysis)

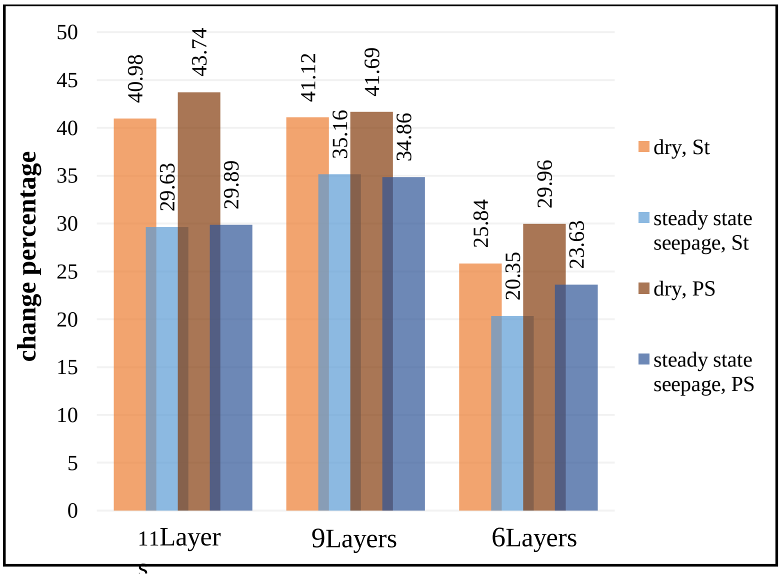

Figure 10. Shear stress variations in inclined layered models

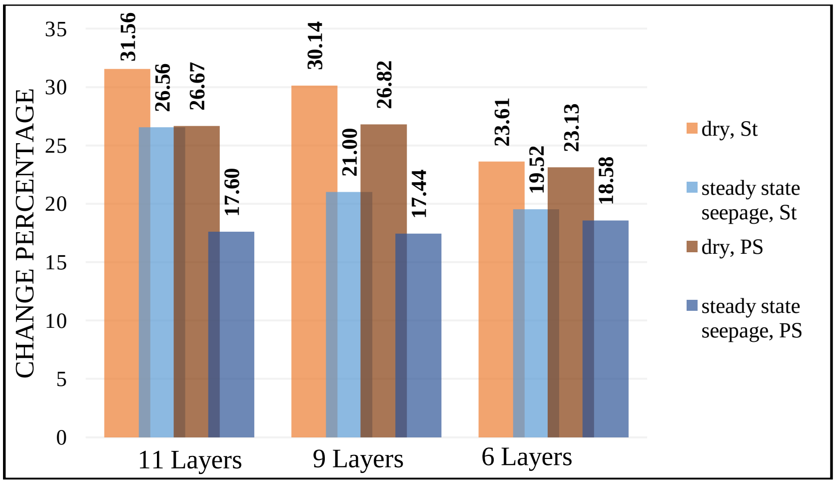

Figure 11. Shear stress variations in horizontal layered models

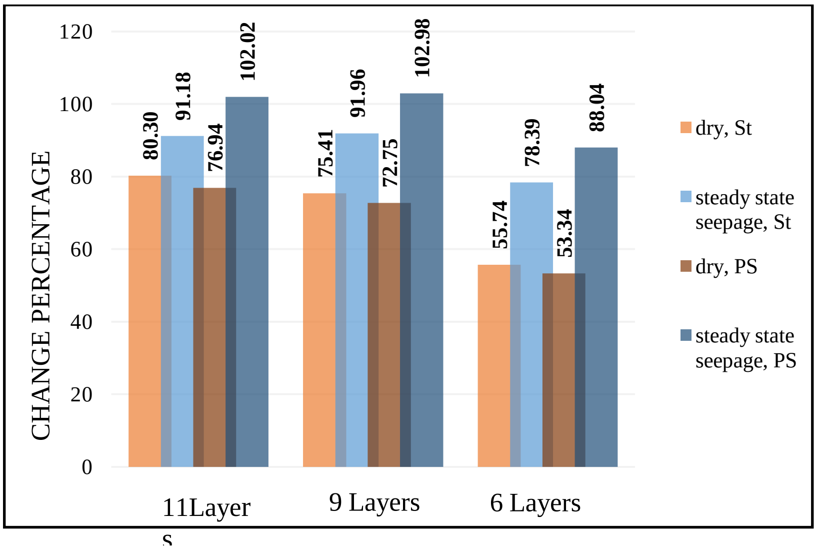

Figure 12. Horizontal displacement variations in inclined layered models

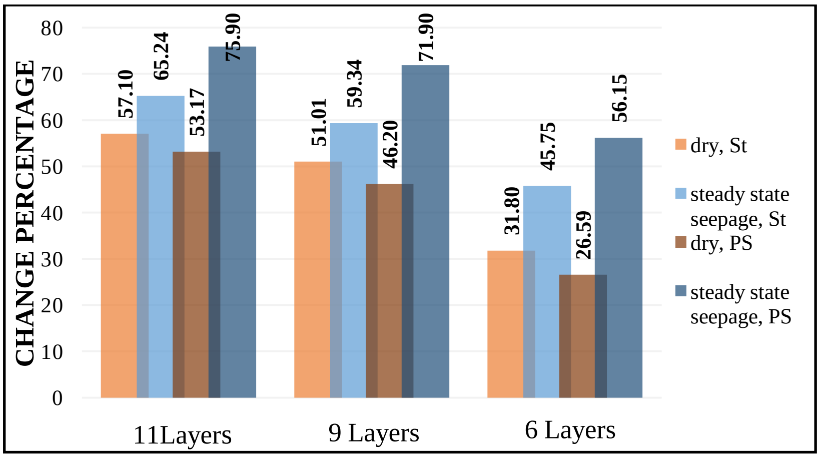

Figure 13. Horizontal displacement variations in horizontal layered models

Conclusion

Construction of earth-fill dams is performed in different layers, so step by step modeling and layered modeling of earth-fill dam seems reasonable for real software modeling. In this study, considering layered software models effects on stresses and displacements values are studied. Based on obtained results it can be deduced that:

1. Changes percentage in total and effective stress also, displacements of horizontal and inclined layered models in comparison with the single-layer model are negligible.
2. Obtained results show that shear stress and horizontal displacement in layered models are increased in comparison with one single-layer model. Shear stress values in layered models are more between 20% - 45% in comparison with the single-layer model. Also, horizontal displacement values are greater between 30% to 100%. Therefore, for more safe and reasonable design, it is better to use layered models instead of single layer model in finite element modeling. It should be mentioned that inclined layered models show more values in horizontal displacement and shear stress than horizontally layered models.
3. Vertical displacements in different layered models are less than vertical displacements in single-layered models.
4. With increasing number of layers, shear stress and horizontal displacement values increase in comparison with single-layer model results.

5. Based on obtained results, shear stress and horizontal displacement of dam body in layered models are more significant in comparison with the single-layer model. Therefore, modeling of a dam in a layered model and rather in inclined layers are more reasonable.

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