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The Effect of Deformation Parameters of Clay-Core on Arching Behaviour of Rockfill Dam

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ABSTRACT

In zoned embankment dams, horizontal and vertical cracks developing in the upstream-downstream direction for various reasons cause internal erosion, resulting in serious consequences such as dam failure. Hydraulic fracturing is one of the mechanisms that cause these cracks to develop in the upstream-downstream direction. Hydraulic fracturing occurs when the stresses at the upstream face of the core are less than or equal to the hydrostatic stresses originating from the reservoir. The arching phenomenon creates the stress environment in which hydraulic fracturing can develop. In transverse arching, one of the arching types, stress transfer occurs from the core to the transition and shell zones. As a result of this stress transfer, the vertical stresses on the upstream surface of the clay core decrease. This study examines the effect on zoned dam transverse arching behavior in combinations where the geomechanical characteristics of the clay core (elasticity modulus and Poisson's ratio) change, provided that the material characteristics in the transition and shell zones are constant. Numerical analyses were carried out using the finite element method using the maximum cross-section of Çınarcık Dam. As a result of numerical analysis, it was seen that the increase in the elasticity modulus and Poisson's ratio values, which are the deformation parameters of the clay core, was effective in reducing the transverse arching potential.

Keywords: Rockfill dam, Soil arching, Elasticity modulus, Poisson's ratio, Hydraulic fracturing

INTRODUCTION

Hydraulic fracturing triggered by arching (silo action) in embankment dams occurs when the hydrostatic stresses arising from the water level in the reservoir are greater than the minor principal stresses occurring in the dam body, causing the dams to collapse with internal erosion developing in the cracks formed in the upstream-downstream direction. Statistical data compiled by ICOLD (1984) and statistical research by Foster et al. (2000) show that approximately 30~50% of embankment dams failed due to internal erosion. Hyttejuvet Dam (Kjaernsli and Torblaa, 1968), Stockton Creek Dam, Wister Dam (Sherard, 1973), and Balderhead Dam (Vaughan et al., 1970) are the most well-known cases in the literature that failed as a result of hydraulic fracturing due to arching.

Topçu (2017) stated that the arching phenomenon occurs in three ways in clay-core embankment dams. The first type is Transverse Arching, which occurs in the adjacent plane between the shell and the core. It is caused by the shell and core having different deformation modules. Since the deformation modulus of the clay core is less than the material used in the shell, it will want to settle more because of the stresses that will develop in the vertical direction. In this case, some vertical stresses will be transferred to the shell. Thus, there will be decreases in vertical stress in the parts of the clay core close to the shell. The second is the Longitudinal Arching between the embankment and the abutment. Especially in embankment dams built in narrow valleys, the stresses in the embankment are transferred to the abutment, and low-stress zones are formed within the embankment. This situation should be noticed by 3D numerical analysis. Another arching type is Local Arching, which occurs especially when the conduit (Tran et al., 2018) and the spillway meet the embankment material. It is generally seen in places where there are materials with different stiffness (such as concrete and soil). In summary, for each type of arching, low-stress zones or tension zones occur in the areas where the event occurs. These stress conditions may cause the formation of tensile cracks because of hydrostatic stresses.

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Factors affecting the transverse arching mechanism are geomechanical and geometric factors. Geometric factors: upstream and downstream embankment slopes, core width and slope, and thickness of transition zones. Geomechanical factors are the stiffness ratio between the core and shell and the foundation compressibility (Talebi et al., 2013). In addition, it is known that factors such as dam height, small-scale irregularities in the foundation profile, abutment profile and slope, and longitudinal profile of the valley are effective factors in the arching phenomenon (Fell et al., 2008).

Possible cracks in the cores of zoned embankment dams are one of the designers' biggest problems. In recent years, great attention has been paid to this problem with numerical analysis studies (Bui et al., 2004; He et al., 2021; He et al., 2022). According to the references mentioned above and observations made in the field, it is determined that the differential settlements that cause stress transfer between adjacent regions lead to the most cracking and that the developing stress conditions create an environment suitable for hydraulic fracturing. The stress results of 2D and 3D numerical analyses performed for zoned dams are also compatible with the data obtained from dam instrument systems (Beiranvand and Komasi, 2021; Soroush and Pourakbar, 2022). Therefore, the most practical method by which the nature of arching behavior can be examined is numerical analysis. If the longitudinal arching behavior of embankment dams is to be investigated, 3D numerical analyses should be performed. Accordingly, within the scope of this study, 2D numerical analyses were carried out to investigate the transverse arching phenomenon using the finite element method for the post-construction situation, using the maximum cross-section of the 125 m high Çınarcık Dam, which was built as a clay-core rockfill type. In the analyses, the effects of the elasticity modulus (E) and Poisson's ratio (ν), which are the geomechanical characteristics of the clay core material, on the transverse arching behavior of the zoned dam are investigated. In this way, the stress conditions that develop with the different settlements of clay core and rockfill materials with different deformation characteristics are presented.

Soil arching phenomenon for zoned dam

Soil arching is defined by Terzaghi (1943) as the stress transfer of a yielding soil mass to an adjacent stationary soil mass in response to relatively different displacements between these two soil masses. Shear stresses developing in the transition plane between moving and stable soil masses eliminate the mobilization of these two masses relative to each other. The shear resistance in this transition plane tries to keep the yielding soil mass in its original state. This reduces the stresses in the yielding soil mass and causes the stresses in the stationary soil mass to increase. This situation is shown schematically in Fig. 1. Shear stresses that develop in the direction opposite to the movement in the transition plane depend on the friction properties of the soils. When a moving soil mass displaces downward, the induced shear stresses force the mass to move upward. This phenomenon is also called "active or positive" soil arching, and it can be generated with only a small movement (Terzaghi, 1936).

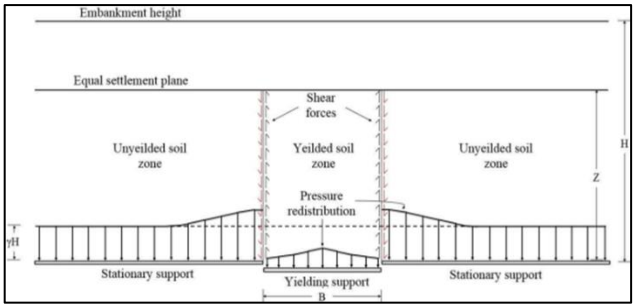

Figure 1. Schematic of soil arching phenomenon (Al-Naddaf, 2017)

Soil arching, which occurs as stress redistribution, is related to the Elasticity modulus and Poisson's ratio, which are deformation parameters that determine the compressibility of stable and moving soil masses. In a zoned dam, the clay core is defined as the moving mass, and the shell is defined as the stable mass. The compressibility of the clay core is greater than the material used in the shell. While the clay core wants to displace more vertically, the shear resistance developed at the clay core and shell interface ensures that the clay core mass remain hanging out. Thus, the stresses developing in the clay core body decrease (Figure 2).

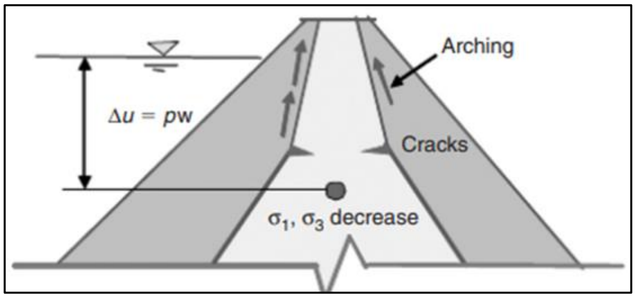

Figure 2. Arch effect in zoned embankment dams (Narita, 2000).

In other words, wall friction transfers a portion of the core’s deadweight into the adjoining shells. This causes low-stress zones to form, especially on the upstream face of the clay core. Normally, the unit weight of clay core material is approximately two times that of reservoir water. In this case, it is impossible for hydrostatic stresses to overcome the stresses in the clay core material for the same levels. However, due to the decreasing stresses resulting from the soil arching phenomenon described above, conditions for failure due to hydraulic fracturing are created. Arching in zoned dams is determined by the coefficient of arching (R_L) using Equation 1. σ_v: Total vertical stress determined from numerical analysis at depth z of the core; γ.z: overburden stress at depth z.

$$R_L = \frac{\sigma_v}{\gamma . z} \tag{1}$$

The coefficient of arching (R_L) takes values between 0 and 1. If it is less than 1, the arching phenomenon has developed. A coefficient of arching close to 0 indicates severe arching. The coefficient of arching in the 26-meter and 34-meter high Holle and Harspranget Dams, which have a thin clay core and where leakage and internal erosion are seen, were determined to be 0.5 (Lofquist, 1951).

MATERIAL AND METHOD

In this study, the maximum cross-section of the Çınarcık Dam was applied to examine the effect of the deformation parameters of the clay core on the transverse arching behavior of the zoned fill dam. Çınarcık Dam is located within the borders of Orhaneli district of Bursa (Figure 3).

Çınarcık Dam, built as a clay-core rock fill type, was built on the Orhaneli Stream flowing in the Susurluk Basin. The volume of the dam is 4771 dam^3. Its height is 125 m from Thalweg. The reservoir volume is 373 hm^3 for normal water level, and the reservoir lake area is 10 km^2. The dam, built to provide drinking and utility water to the industrial city of Bursa located next to it, was also planned as a hydroelectric power plant. It is expected to produce 540 GWh of electricity annually with an installed power of 120 MW.

The maximum cross-section of Çınarcık Dam, which has a crest width of 12 m, is presented in Fig. 4. The upstream and downstream slopes of the rock fill are quite flat. The upstream and downstream slope of the clay core is 1(H):2.5(V). The upstream cofferdam on the upstream slope and the berm arranged at 255 m elevation on the downstream slope were considered stability-enhancing factors. A crack stopper filter was employed in Çınarcık Dam. Thus, with the transition zone consisting of three different zones (sand, gravel, and rock rubble), precautions were taken to prevent the flow in the crack that may occur in the core and the internal erosion that may develop accordingly. The most important point in crack stopper filters is that there is no potential for crack formation within the sand filter. For this reason, the non-plastic (N.P) fine content in sand filters is not desired to be more than 5%. The base foundation of Çınarcık Dam is a peridotite-type magmatic rock.

The Sigma/w module of the Geostudio 2018.R2 program was employed to investigate the effect of the core's deformation parameters on the arching coefficient. In this program, analyses on the maximum cross-section of Çınarcık Dam in plain strain conditions were carried out using the finite element method. The requirements for the finite element method in geotechnical engineering are summarized as equilibrium, compatibility, material constitutive behavior, and boundary conditions (Potts et al., 2001).

Literature research was conducted while selecting deformation parameter values. Values varying depending on the clay material's compaction water content during construction were considered for the Poisson's ratio. The modulus of elasticity of fine-grained soils may vary depending on water content, stress history, and cementation. In numerical analysis, the elasticity modulus (E) of the clay core was selected as 15000, 20000, 25000, 30000, 35000, and 40000 kPa, and the Poisson's ratios (ν) were chosen as 0.35, 0.40, and 0.45. Stress-strain analyses were carried out in eighteen models in which these values were combined. In this study, since the post-construction transverse arching behavior of the zoned embankment dam was examined, analyses were carried out under total stress conditions (undrained). In the analyses for the clay core material, the Mohr-Colulomb material model under total stress conditions and the strength parameters c_u, undrained interception of cohesion, and ϕ_u, undrained angle of internal friction was specified (c_u = 75 kPa; ϕ_u = 10^0). A linear elastic material model modeled the shell, transition zone, and foundation. The relevant parameters were determined from the literature to reflect the general characteristics of these materials (Figure 4). In particular, the elasticity modulus was taken at an exaggerated value so that the bedrock in the foundation showed a fully rigid behavior.

In numerical analysis, the geometric model consists of quads & triangle elements and material zones in Fig. 5. Only vertical displacement is allowed for vertical edges of the geometric model. For horizontal edges, displacement is limited in both directions. In the numerical analysis carried out step by step, the first stage is defining the foundation and establishing the body stresses. In the second stage, the upstream cofferdam is modeled as a whole, and body stresses are created. In twenty-five stages, the main embankment is modeled layer by layer.

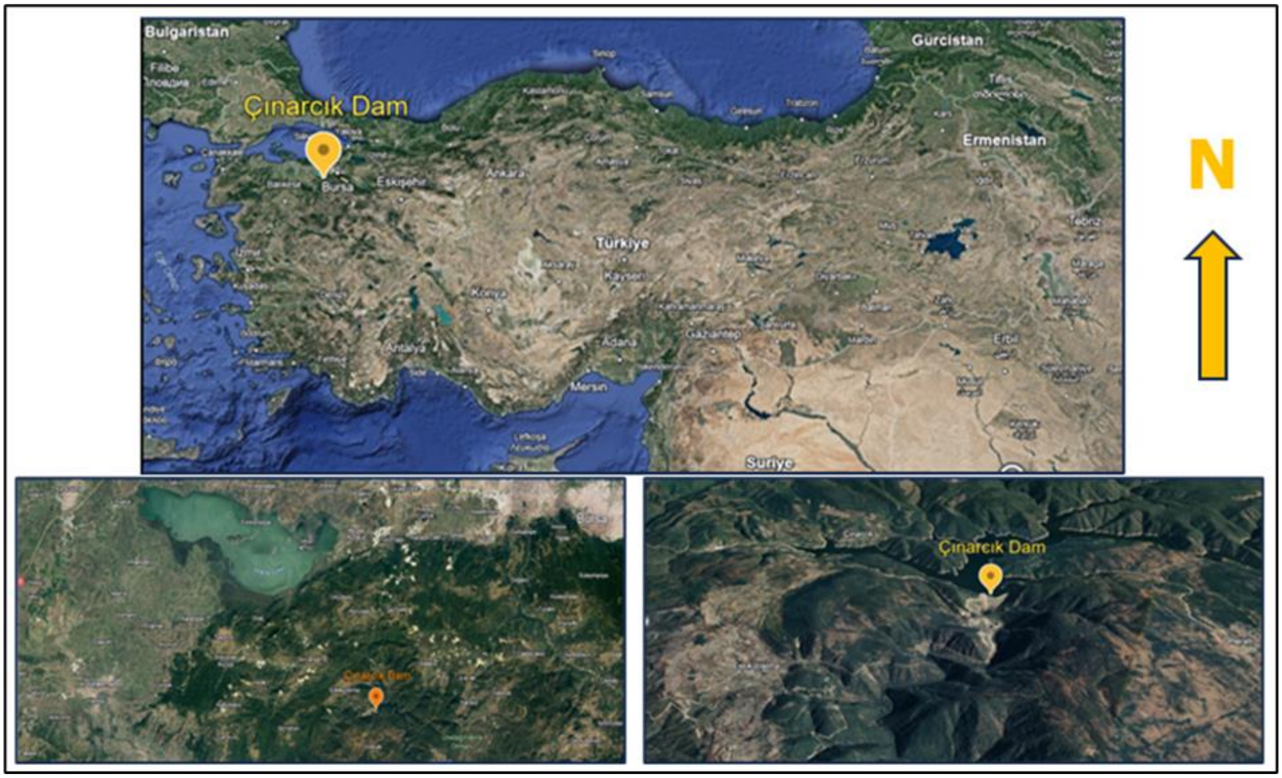

Figure 3. Location of Çınarcık dam

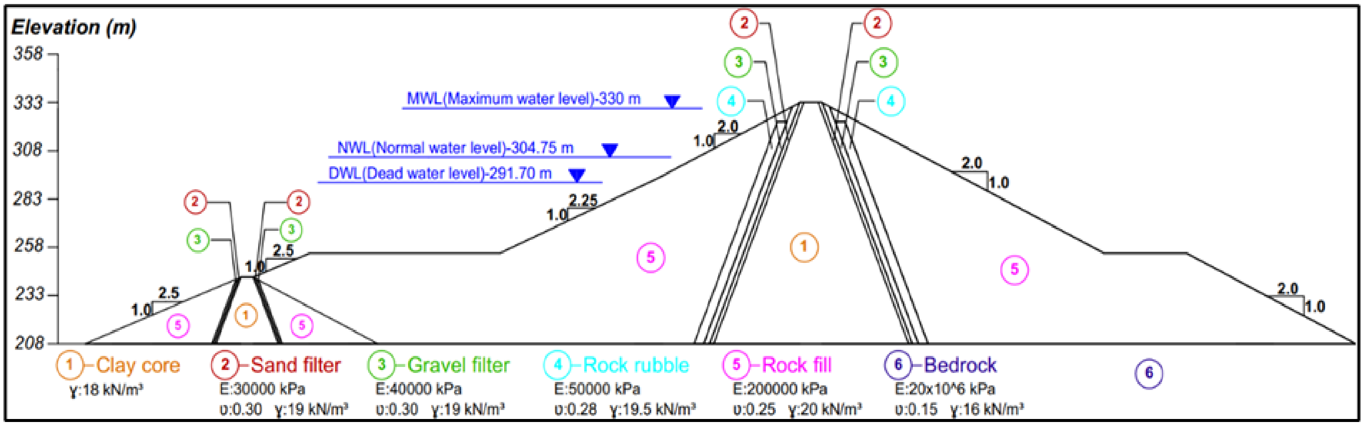

Figure 4. Maximum cross-section of Çınarcık dam and properties of dam material

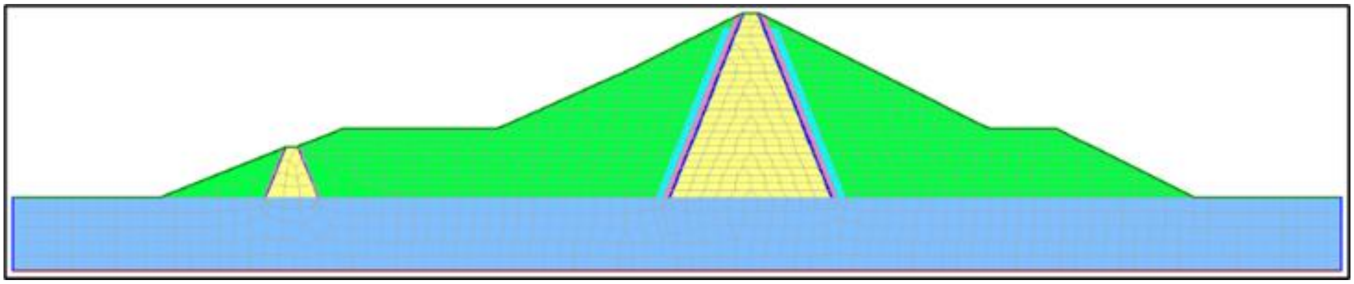

Figure 5. The geometric model consists of quads and triangle elements and material zones

RESULTS AND DISCUSSION

In this study, several analyses to determine the stresses and deformations in the dam body were carried out for 18 different combinations discussed in the previous section. Contours of vertical stress were presented in Figs. 6-7 for Model 1 and Model 18, respectively. These models were selected as extreme cases with the smallest and largest values of clay-core deformation parameters. As seen in these figures, it can be stated that it is expected to occur of transverse arching. This situation is seen more clearly in Fig. 6. Because the selected deformation parameters for the clay core in Model 1 are smaller than the deformation parameters in Model 18, the vertical stress at the base of the clay core in Model 1 is lower than that in Model 18. According to Figures 6 and 7, vertical stresses in the core are smaller than those in the adjacent areas within the shell. However, when the contour of vertical stress is examined, the severity of the transverse arching is higher on the upstream face than in the middle of the clay core.

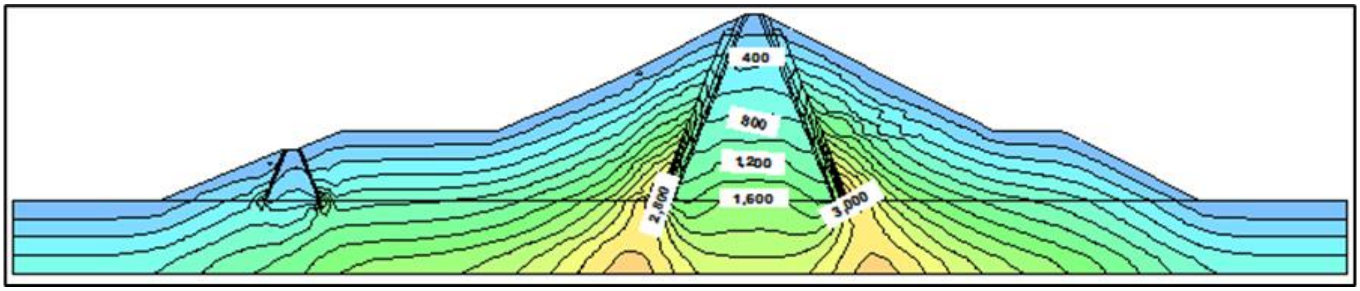

Figure 6. Contour of vertical stress for model 1

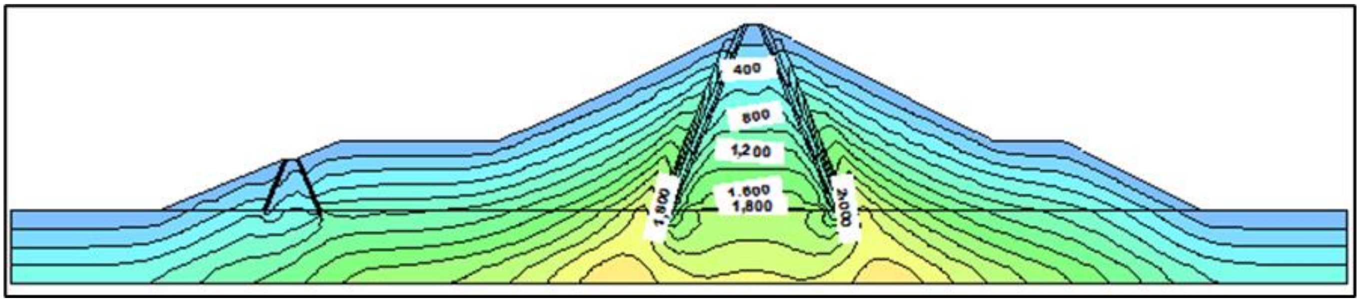

Figure 7. Contour of vertical stress for model 18

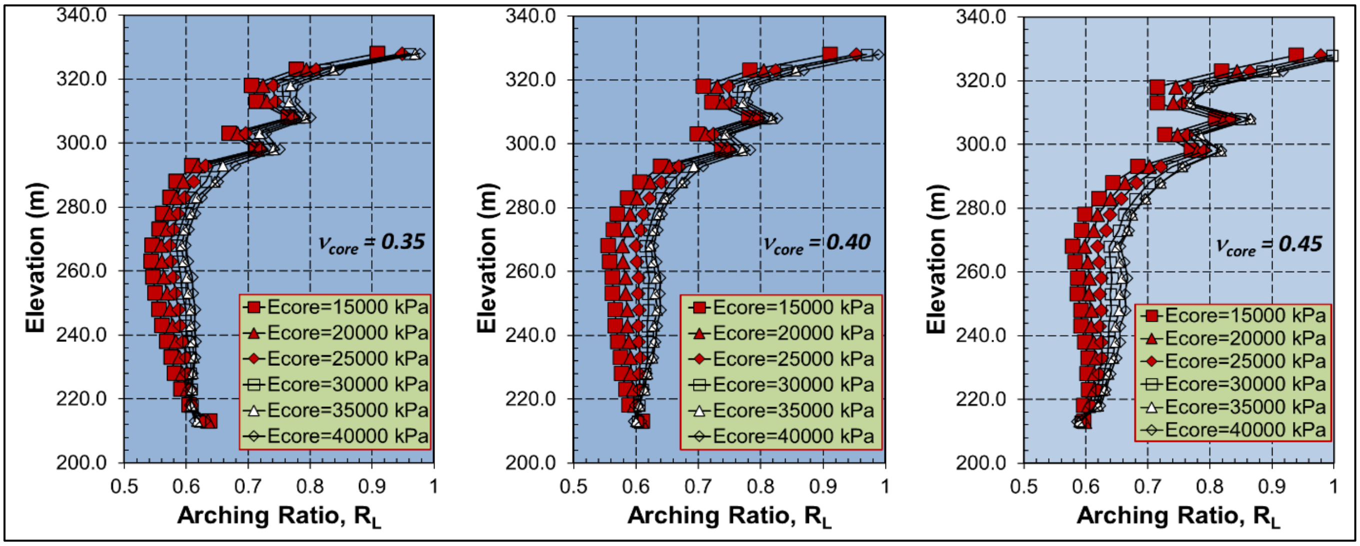

Figure 8. Variation of an arching ratio (R_L) with depth for constant poisson ratio values

The effect of clay-core's Elasticity Modulus (E) and Poisson's ratio (ν) on transverse arching behavior for the upstream face of the clay core was investigated. Transverse arching is more critical for the upstream face of the clay core than for the middle of the clay core. This is because the hydrostatic pressure from the reservoir acts on this surface to cause hydraulic fracturing. Vertical stress values were obtained from finite element analyses to calculate the arching ratio (R_L) on the upstream face of the clay core with Equation 1. Calculated variations of the arching ratio (R_L) values of the Çınarcık dam with depth for the constant Poisson's ratio were illustrated in Fig. 8.

As seen in Figure 8, there is a transverse arching phenomenon for all the 18 combinations discussed in Section 3. According to this figure, increasing the modulus of elasticity causes the arching ratio to increase. It should be stated that this trend was observed for all three Poisson's ratio values. However, this increase is very limited for the case where the Poisson's ratio is 0.35.

Figure 9 was illustrated to comment on the transverse arching behavior more clearly. As seen in Fig. 9, in cases where the elasticity modulus is 30000 kPa, 35000 kPa, and 40000 kPa, increasing the Poisson's ratio from 0.35 to 0.45 effectively increases the arching ratio values. An important point is that the arching value increase is limited for the Elasticity modulus is 15000 kPa, 20000 kPa, and 25000 kPa. So, a dam with a more compact core shows a higher arching coefficient, which, in turn, conveys less stress transmission (Rezaei and Salehi, 2011). In other words, the arching coefficient increases as the modulus of elasticity, which determines the behavior of the clay core under stresses, increases. In addition, as the Poisson's ratio increases in the 2D plane, the arching coefficient increases and stress transfer decreases (Wang, 2014).

The minimum arching ratio (R_L) for 18 combinations varies between 0.544 and 0.602. The minimum arching ratio is 0.544, corresponding to the combination where the modulus of Elasticity Modulus and Poisson's ratio is smallest (E=15000 kPa and ν=0.35). Also, the points corresponding to the minimum arching ratio values are z=0.04H and z=0.48H (H=dam height). The situation where z/H was 0.04 was seen in scenarios where the Poisson's ratio was 0.45.

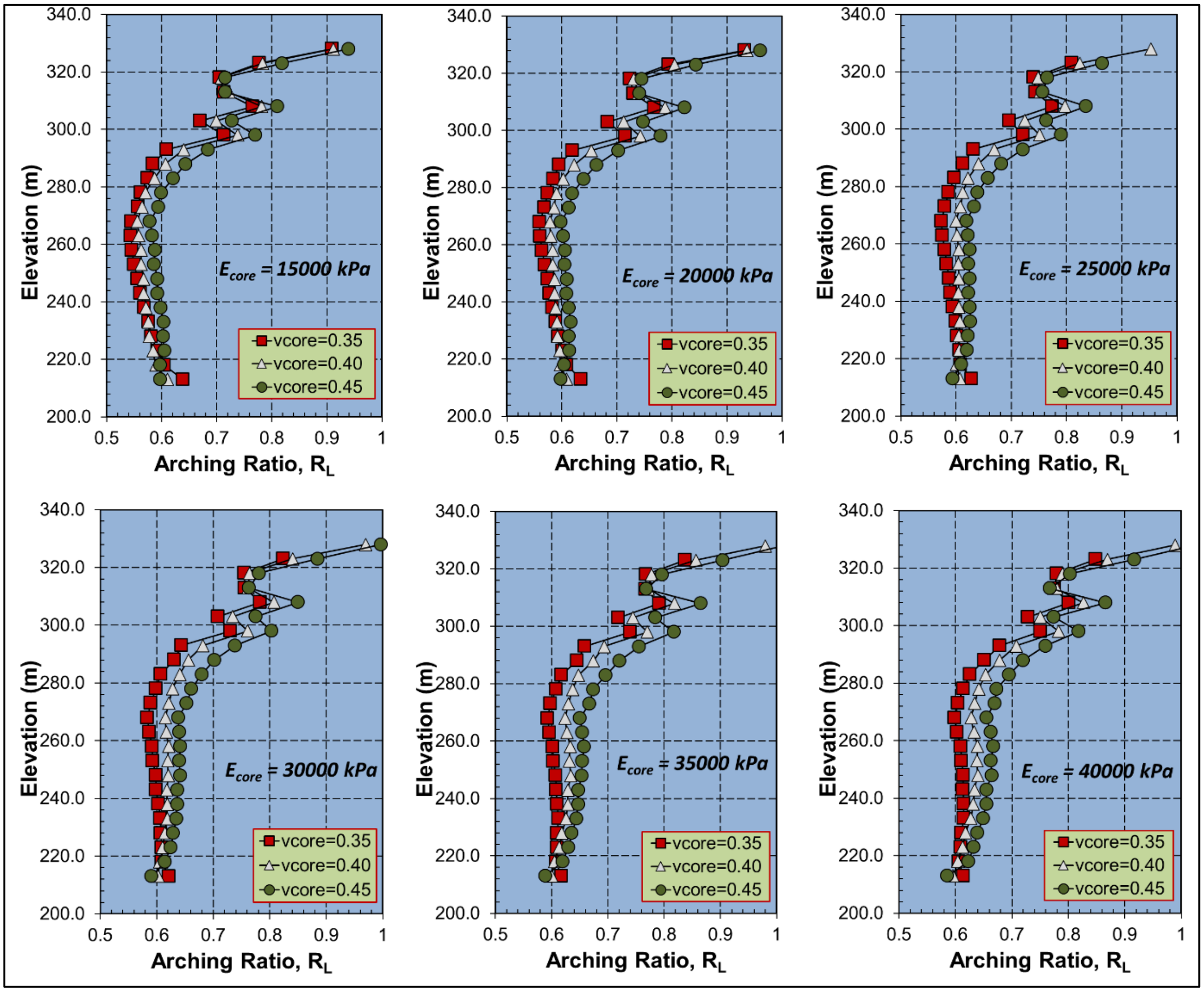

Figure 9. Variation of the arching ratio (R_L) with depth for constant elasticity modulus values

CONCLUSION

Numerical analyses were carried out on a rockfill dam for 18 combinations of 6 different Elasticity modulus and three different Poisson's ratios of clay-core, and the effects on the results were interpreted. The general results are summarized below:

- The smaller the deformation parameters of the clay core, the lower the vertical stress at the base of the clay core, and the transverse arching behavior is more obvious.
- According to numerical analysis results, minimum values of the arching ratio (R_L) for 18 combinations vary between 0.544 and 0.602.
- The situation with a minimum arching ratio value of 0.544 was observed when the elasticity modulus was 15000 kPa, and the Poisson's ratio was 0.35.
- The location of the point corresponding to the minimum arching ratio is determined as z = 0.04H for cases where the Poisson's ratio is 0.45.

The results show that increasing the deformation parameters of the clay core reduces arching. However, it is impossible to state that the arching ratio depends on the deformation parameters alone. The effects of the geometry of the dam and its related zones on the results should also be investigated.

DECLARATIONS

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Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

Authors' contribution

Both authors contributed equally to this work.

Competing interests

The authors declare no competing interests in this research and publication.

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