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Hydraulic Fracturing of Low and High Plasticity Clay in the Thick and Thin Core Sections of Earth Dams

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ABSTRACT
The core of an earth dam plays a crucial role in sealing the dam and mitigating the possibility of hydraulic fracturing. This research aims to investigate the phenomenon of hydraulic fracturing and the effect of the dimensions and cross-sectional shape of the clay core. Hydraulic fracture in the middle of the core and on the upstream side of the core has been investigated for two types of low-plasticity clay (CL) and high-plasticityclay (CH). The end of construction, initial dewatering, and steady-state seepage, as well as the stages of dam construction, have also been considered in the modeling. The results show that CL is the critical soil and CH is the selected soil for the dam's core. Also, the possibility of hydraulic fracture in thicker cores and at the bottom of the core was investigated. The results showed that the criteria of Fukushima and Ghanbari yielded the most optimistic and conservative data, respectively. According to the criteria used in this research, CH soil is safe from hydraulic fracturing, and the possibility of hydraulic fracturing for critical soil (CL) downstream of the dam core was found to be probable.
Keywords: Earth dams, Hydraulic fracturing, Geo-Studio, Seepage, Clay Core.

I. INTRODUCTION

Hydraulic fracturing can occur in the core of an earth dam. This phenomenon often occurs during the first dewatering of the dam when the water pressure suddenly increases. In earth dams, most of the core materials are softer than the shell materials. Since the core must be made of fine aggregate due to the need for very low permeability, its shear resistance is inevitably lower than that of other parts of the dam body(Komasi&Birranvand, 2020). There are several different methods to predict the occurrence of hydraulic fracturing in the dam core, which can be divided into three general groups (Khamesi &Mirghasemi, 2010). The first category is the use of empirical relationships obtained from laboratory or field studies. These relationships provide the water pressure that creates the crack in terms of the stress level in the soil. By comparing this pressure with the water pressure in the upstream elements of the core, it is possible to investigate the occurrence of fracture. From this category, we can mention the relationships described by Ghanbari & Shams Rad (2015), Jaworski et al. (1981), Fukushima (1986), and Mori & Tamura (1987), as well as recent studies by Patel et al. (2017) and Poudel et al. (2017). The second group is the theoretical relationships that have been developed for the models proposed in plastic theory. These relations, like the relations of the first group, provide critical water pressure (Lto, 2007; Sadettin, 2017; Ke et al., 2021; Nathan & Armando, 2022). The modeling of hydraulic fracturing in several dams has been conducted in two dimensions under plane strain conditions (Haeri &Faqhihi, 2008) and has recently been extended (Zalnejad&Emamzadeh, 2023, 2024). The third category involves the use of fracture mechanics as a process for the propagation of an internally pressurized crack (Wrobel et al., 2023), which is not the subject of our discussion in this research.In earth dams, hydraulic fracturing has a destructive role(Solvan& Delatte, 2003), and dam designers are trying to prevent its occurrence (Jian et al., 2022; Young et al., 2022; Gvbert& Andrew, 2021).

The research gap in this field is the existence of numerous relationships for predicting hydraulic fracturing; however, no comparison has been made between the accuracy and precision of these relationships due to numerous uncertainties.

The novelty of the present study lies in the comparison of hydraulic fracturing relationships under conditions before and after the operation and dewatering of earth dams.In this research, various scenarios are employed, unlike the studies of previous researchers who typically use a single criterion to predict hydraulic fracturing in the core of earth dams.

II. HYDRAULIC FRACTURING IN AN EARTH DAM

Hydraulic fracturing in the context of earth dams refers to the process where cracks or fractures form within the dam's body or foundation due to excessive water pressure. This is an unintended and potentially hazardous phenomenon, distinct from the oil and gas industry's use of the term "fracturing".Hydraulic fracturing in earth dams occurs when pore water pressure or uplift pressure becomes high enough to overcome the confining stress of the soil. This can lead to cracking of the dam's core or body, the formation of seepage pathways through the dam, potential internal erosion or piping, and, in worst-case scenarios, dam failure. Several causes of Hydraulic Fracturingwere investigated, such as excessive pore water pressure during rapid reservoir filling; improper compaction of core materials; Low confining stress on vertical planes (especially near the top of the dam or near abutments); Low-plasticity clay cores that are more brittle and poorer core-filter contact, allowing water to concentrate pressure in one area. Several wayswere proposed to prevent it such as use plastic (flexible) clay cores rather than brittle materials; correctly compact soil layers to increase confining stress; Control reservoir filling rates, especially for new or recently repaired dam; Include filter and drainage systems to relieve pore pressure and design core geometry to reduce stress concentration (e.g., use of zoned dams).Signs of Hydraulic Fracturing are Sudden or increased seepage, Unexplained settlement or deformation, Cracking observed on the dam crest or slopes, and Turbid water at seepage exits (indicating internal erosion). In this research, hydraulic fracturing in an earth dam was investigated based on the type of clay core, as shown in the Figs.1-4.

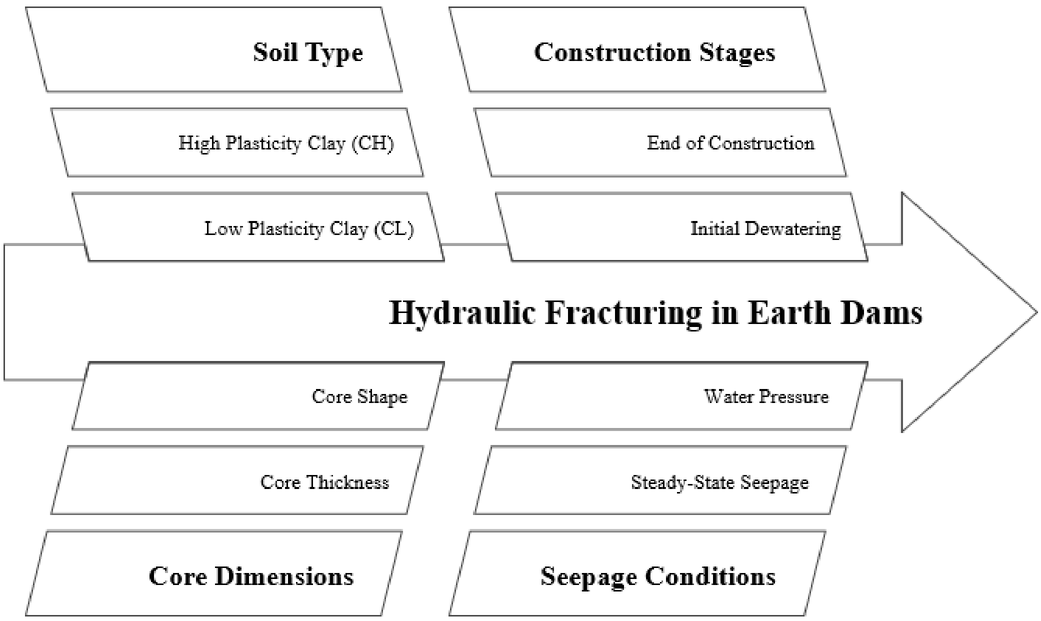

Fig.1. Factors affecting Hydraulic Fracturing in Earth Dams

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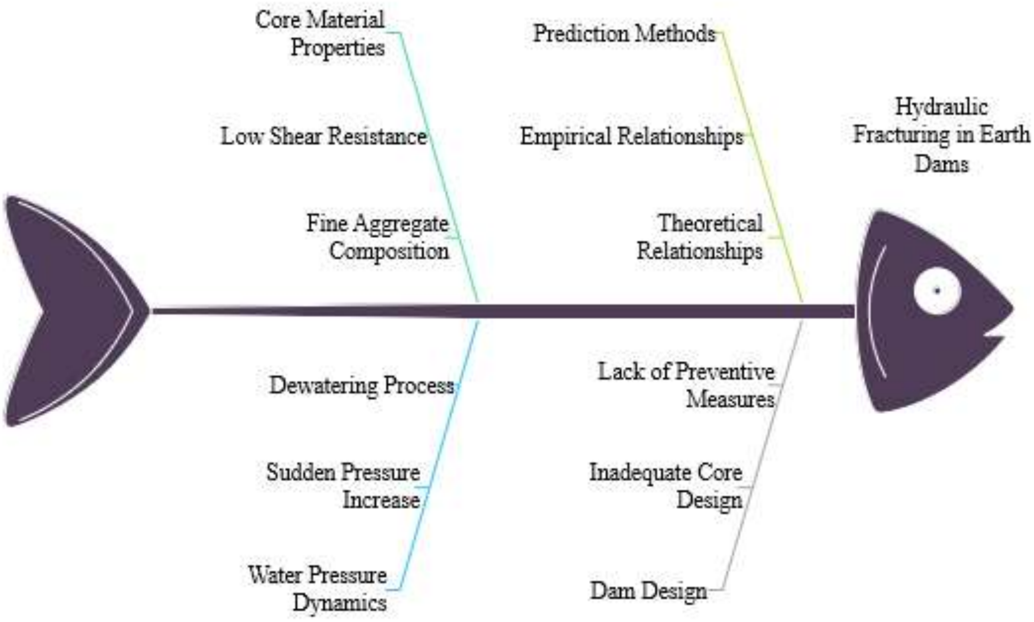

Fig.2. Causes of Hydraulic Fracturing in Earth Dams

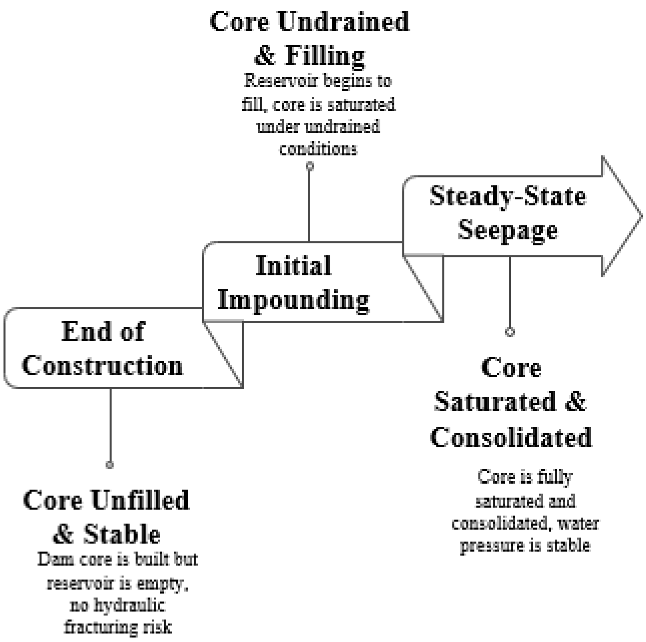

Fig.3. Key Stages in Dam Core Behaviour

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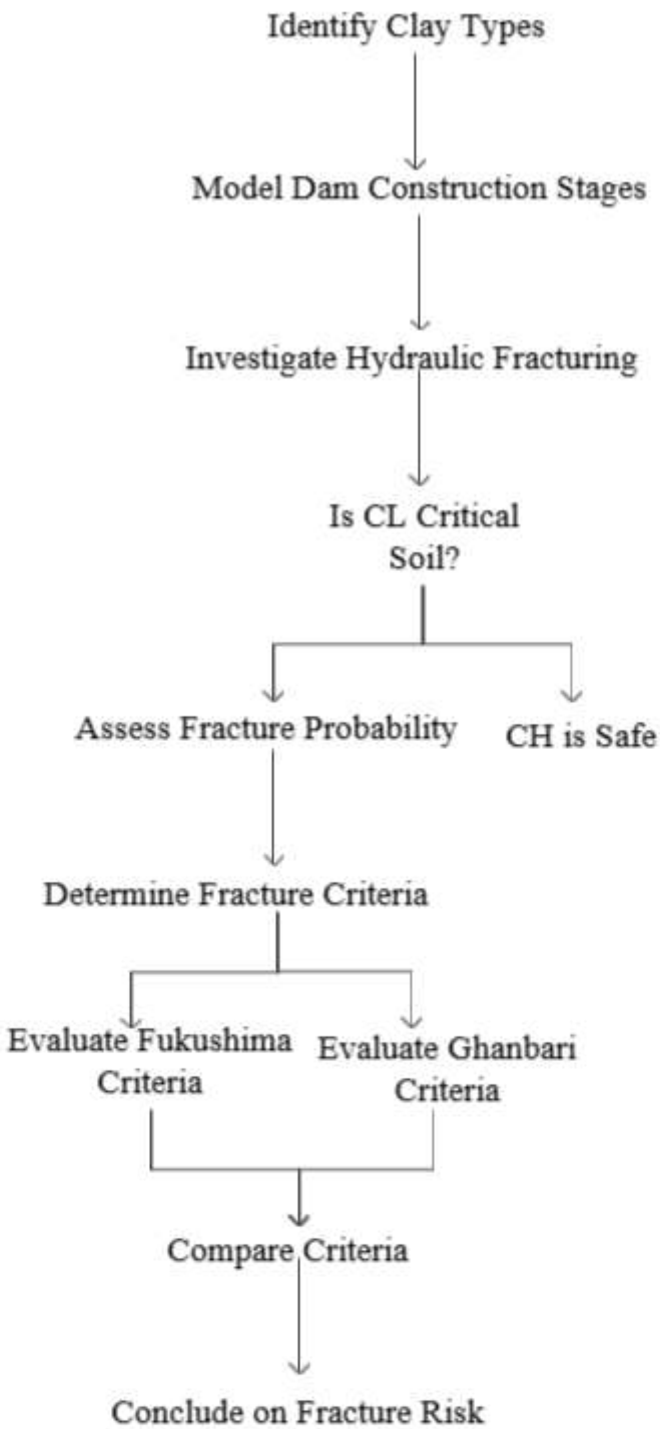

Fig. 4. Hydraulic fracturing evaluation process

III. CASE STUDY

Hajilar is an earth dam with an impermeable clay core located in Iran, built on a river with the same name.Fig. 5 shows the plan and the largest section of this dam (Bandab Consulting Engineers, 2016).

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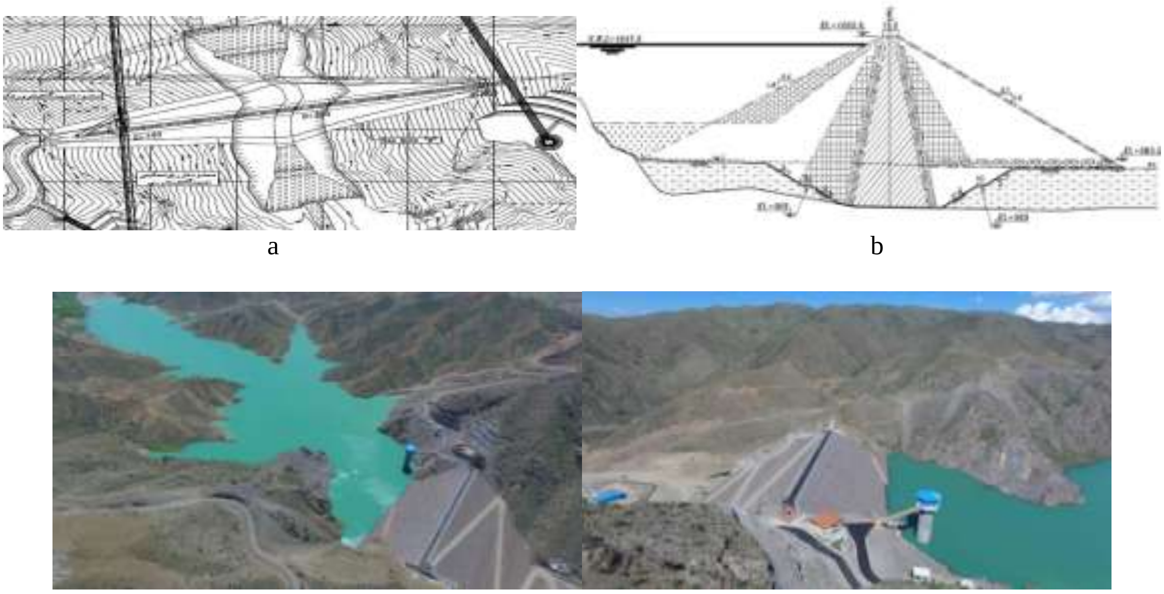

a b

c

Fig.5.a) Plan of dam,b) The largest section of the dam,c) Dam site (Bandab, 2016)

IV. MODELING

The coupling analysis of deformation and pore water pressure has been performed for the Poisson equation resulting from the combination of continuity and Darcy's law. The largest section of the Hajilardam has been used for 2D modeling. The size of the elements is 2 m, andConvergenceis checked with mesh-independent solutions.

The foundation of this dam is also considered non-deformable. The dam shell is modeled elastically, and the clay core of the dam is modeled fully elastoplastic using the Mohr-Coulomb behavior model. The analysis was conducted in three parts: at the end of construction, during primary dewatering, and in steady-state seepage. Due to the high permeability of the shell material, it is assumed that pore water pressure will not be created in the shell during construction (Topchu, 2018). Twenty-one layers have been considered to simulate the staged construction of the dam. Fig.6 shows the step-by-step construction of the dam in the software environment.

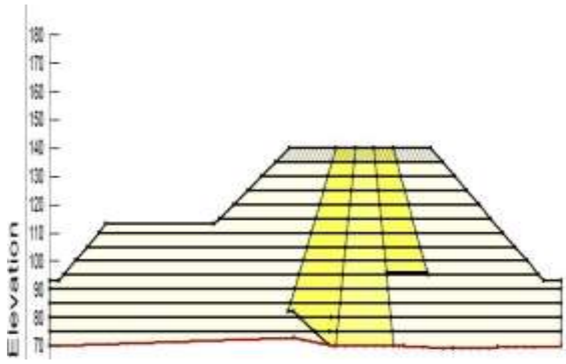

Fig.6. Numerical model after embankment of the 14th layer

The important point at this stage is that the dam body should be modeled with the appropriate number of layers. In the actual construction of earth dams, depending on the type of soil, a large number of layers, typically 20 to 40 cm thick, are used. However, in numerical modeling, it is not feasible to consider the thickness of these layers due to the time-consuming nature of the modeling process. Therefore, numerical modeling is done using thicker layers and in a shorter time. Studies by later researchers have shown that considering 8 to 10 layers is sufficient (Ghanbari& ShamsRad, 2015).If the analysis of the dam body is conducted layer by layer, the maximum vertical displacement of the dam body will occur at the midpoint of the core height. This is while in the one-step analysis, the maximum settlement and vertical displacement are always related to the crest of the dam.

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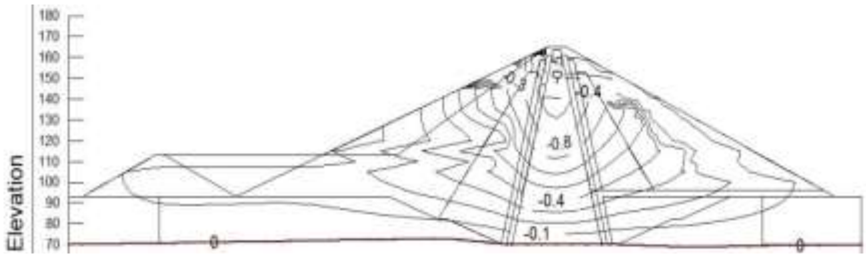

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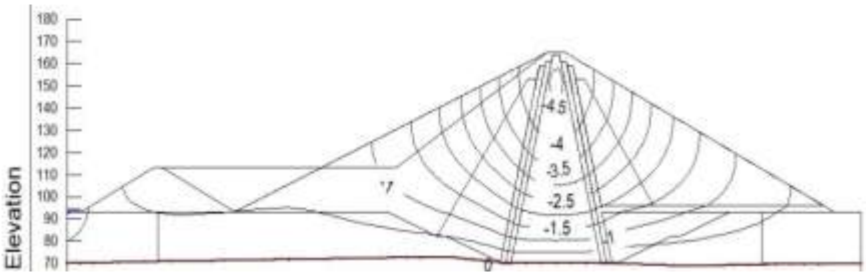


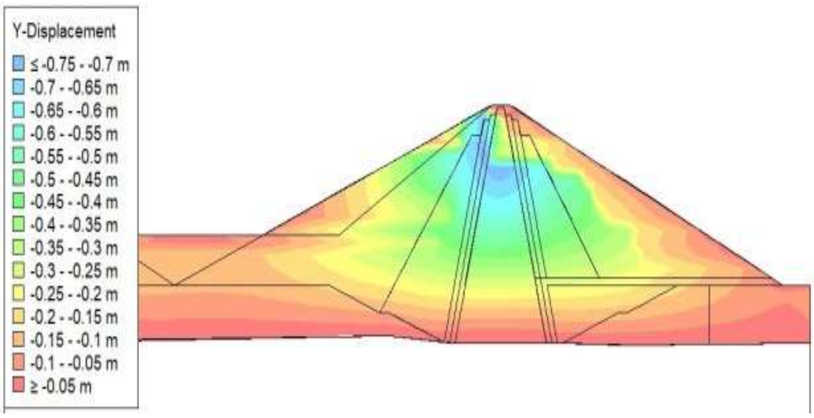
b)

Fig. 7. Vertical displacement (m) a)Step-by-step construction b)Single-step construction

V. RESULTS AND DISCUSSION

Atthe end of the construction stage

At the end of the construction stage, because the reservoir has not yet been filled and there is no water pressure to cause a hydraulic crack, there is no possibility of hydraulic fracturing. Therefore, this stage of analysis was conducted solely to assess the state of stresses and changes in the dam's displacement. On the other hand, according to the step-by-step modeling of the dam construction and embankment simulation layer by layer in the software environment, the maximum change in vertical displacements occurred almost at the center of the core for both CL and CH soil types. Additionally, according to the analysis results and Fig. 8, it was observed that the maximum vertical displacement for CH soil is less than that for CL soil.



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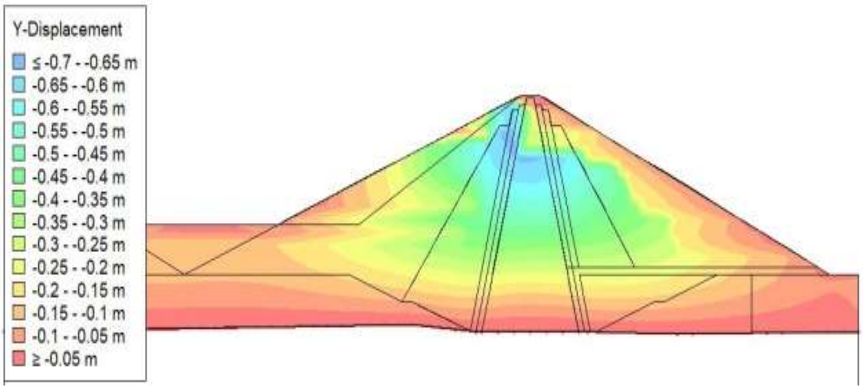

b)

Fig. 8. Vertical displacement at the end of the construction phase: a) CL, b) CH

Initial reservoir impounding

The reservoir impounding often takes place during the rainy season.Therefore, the dam core still lacks sufficient time to be fully consolidated. The impounding rate creates undrained conditions in the core. With these interpretations, in the initial drainage analysis of the core, parameters are considered to be something between UU and CD.

Steady-state seepage

After several years of dewatering, the core is completely saturated, and the free line of water inside it is filled. In such a case, the core is considered to be consolidated, and the incoming loads include the weight of the dam body and the water pressure of the reservoir against which the core acts, drained.

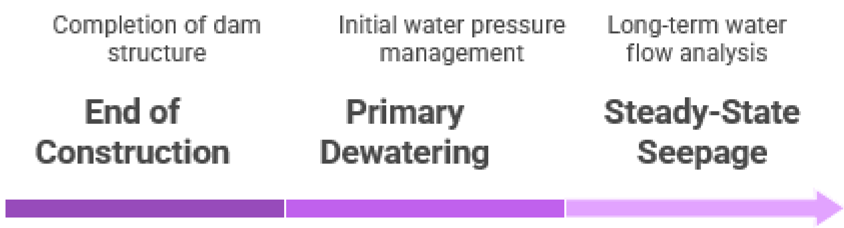

Fig. 9. Modeling the Construction and Behavior of Hajilar Dam

VI. POSSIBILITY OF HYDRAULIC FRACTURING

The occurrence of hydraulic fracturing depends on the state of stress.However, the factors that lead to a reduction in soil stress facilitate the occurrence of fracturing (Cornet et al., 2003). The presence of geometric heterogeneity, loading, and materials is effective in this matter (Paudel, 2017). In this section, simple tensile criteria and Ghanbari shear criteria are used to check the probability of hydraulic fracturing.

Simple tensile criterion

In the simplest mechanism, hydraulic fracture occurs if the pore water pressure (U) exceeds three times the total stress **σ** in an element (U > 3**σ**). These conditions may cause vertical or oblique cracks in the core. This criterion is the most conservative criterion for predicting hydraulic fracturing (Shams Rad, 2018).

Ghanbari and Shams Rad shear criterion (2015)

According to this criterion, the mechanical characteristics of the soil are included in the calculation of the hydraulic fracture pressure, and the value of the fracture pressure is more accurate than the simple tensile criterion. Ghanbari (2015) has presented the hydraulic fracture pressure value, P_f, that is determined by an experimental formula (1).

$$P_f = m\sigma_h + n \quad (1)$$

That parameter m varies between 1 and 2.1, and parameter n, in terms of kg/cm², varies between 0.2 and 0.4 depending on the type of soil, which is the horizontal stress (in the total stress

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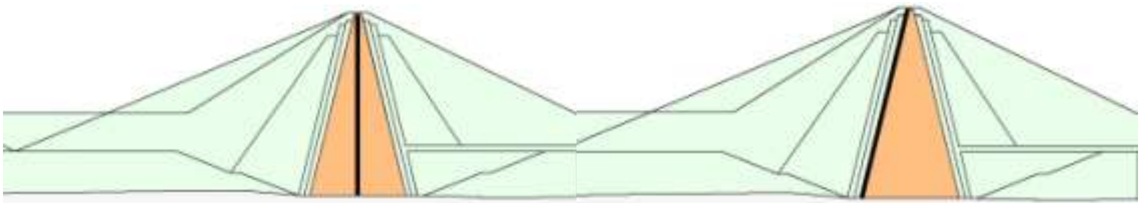
state). The value of this parameter for all types of soils is listed in Table 1.

Table 1.The parameters of the experimental relationship of hydraulic fracture pressure

Soil type	**m**	**n**(kg/cm^2)
Coarse-grained mixed soils with good granularity, containing fine clay grains	1.2	0.4
Sandy soils containing fine grains of silt and clay	1.05	0.25
Sandy soils with good granularity, containing clay and silt	1.05	0.25
Sandy soils with poor granularity, containing clay and silt	1	0.2
Fine-grained soils with high plasticity (CH)	1	0.4
Fine-grained soils with low plasticity (CL)	1.05	0.3

If compaction is done by the ASTM-D698 method,the values of m and n can be reduced by 0.05.If the sample is tested after saturation, the value of n can be reduced by 0.1 to 0.2. Based on this criterion, if the pore water pressure in an element is greater than the hydraulic fracture pressure P_f, the hydraulic fracture is likely to occur (Ghanbari & Shams Rad, 2015).

For the stages of initial dewatering and steady state for both types of materials, the possibility of hydraulic fracturing occurring in two sections within the core and along the oblique line adjacent to the core, as schematically shown in Fig. 10, is considered.

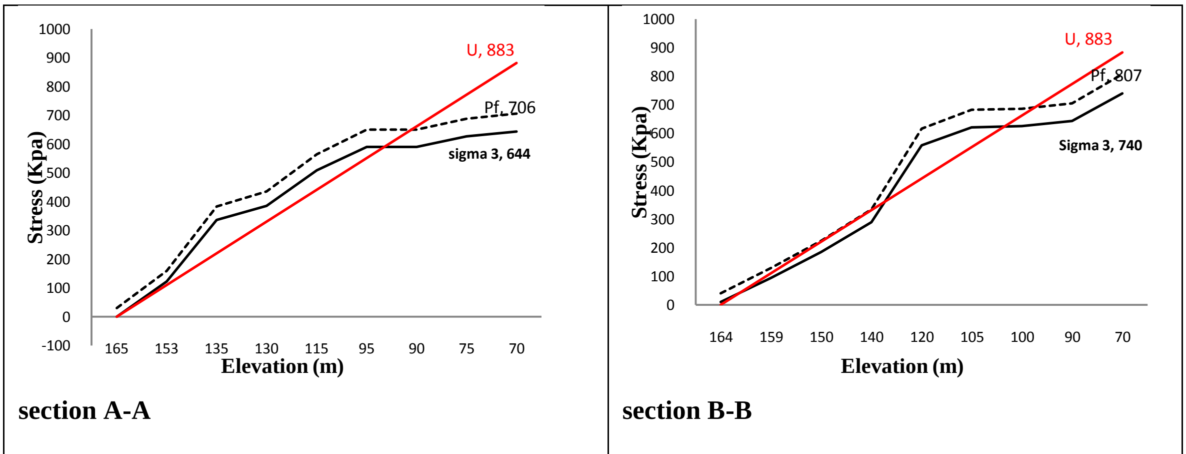


a) b)

Fig. 10.Core Sections for hydraulic fracturing analysis: a) Middle section (A-A), b) Oblique Section (B-B)

Hydraulic fracture in CL soil

In this section, using the simple tensile criteria and the shear criteria, the possibility of hydraulic fracturing at different sections of the Hajilar dam for CL soil is investigated and compared with the pore water pressure. P_f, is the hydraulic fracture pressure, σ_3 , is the minimum total stress, and U represents the pore water pressure, as shown in Fig.11.



a)

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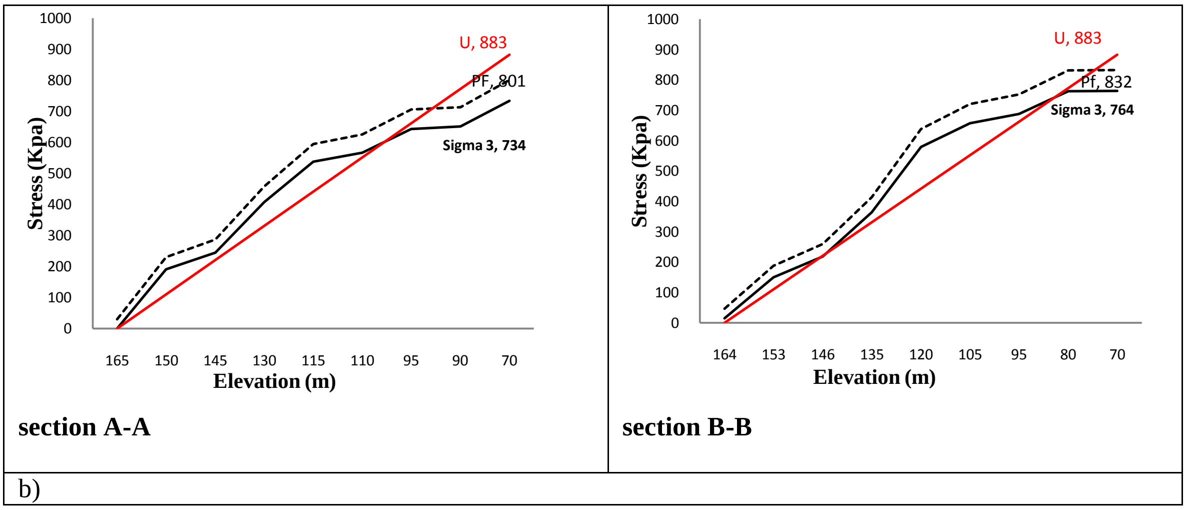


Fig. 11. Stress diagram for CL soil: a) initial impounding, b) steady state stage

Hydraulic fracture in CH soil

In Fig. 12, the graphs drawn compare the changes in hydraulic fracture pressure, minimum principal stress, and pore water pressure at the dam's height, providing a possible indication of potential hydraulic fracture points. Additionally, a diagram of stress changes in confined areas has been drawn for various stages and sections of the core.

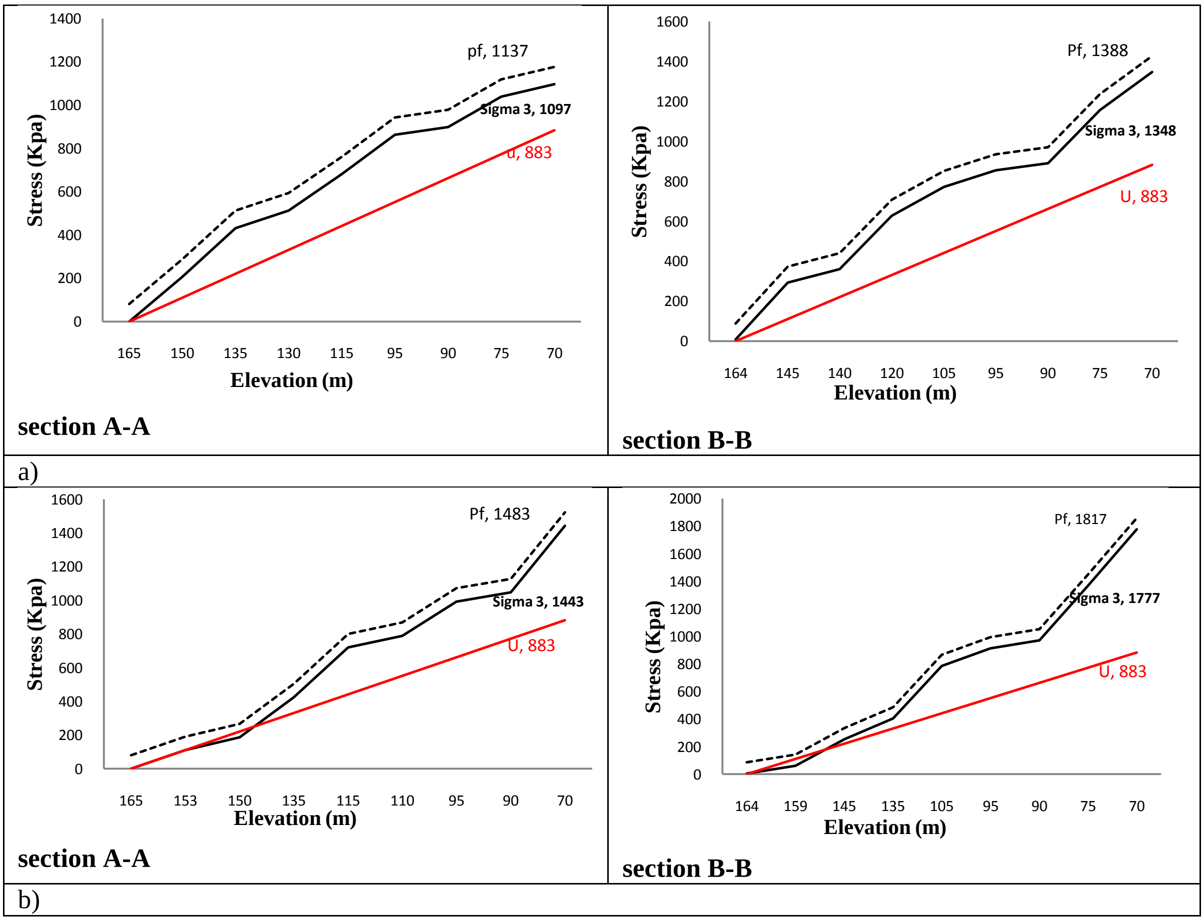
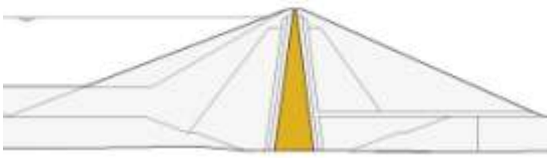


Fig. 12. Stress diagram for CH soil: a) initial impounding, b) steady state stage

Effect of core geometry on hydraulic fracture pressure

In this section, analyses were performed for cores with thicker and thinner sections than the original core for CH soil by modifying the core geometry. By comparing the analysis results, the effect of core geometry on the possibility of hydraulic fracture is investigated. In Fig. 13, the geometry of the Hajilar Dam core is illustrated in a cross-sectional view, showing both thinner and thicker sections.



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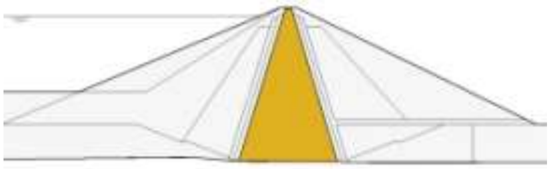
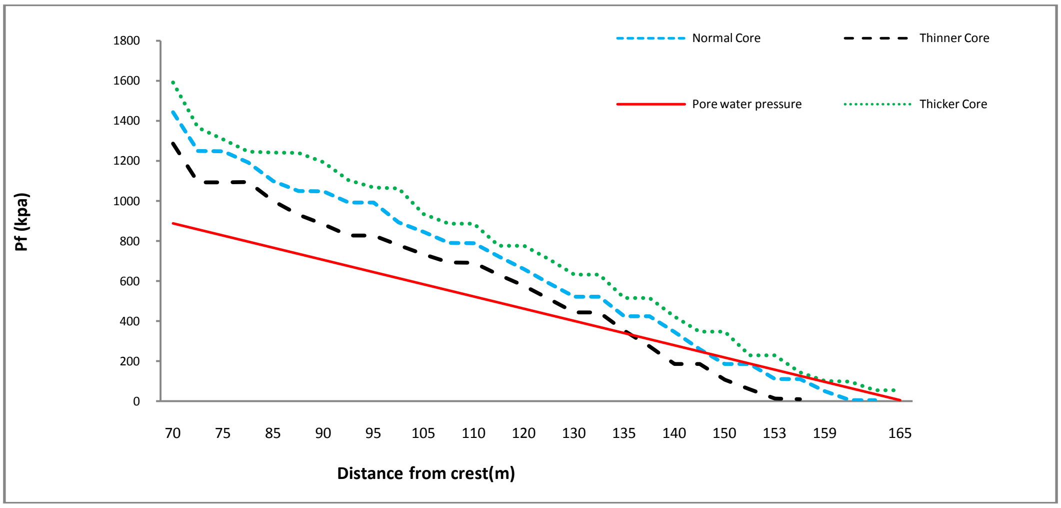


b)

Fig. 13. Geometry of dam core:a) thinner section,b) thicker section

In Fig. 14, the hydraulic fracture pressure is presented for CH soil, based on the simple tensile criterion and the shear criterion of Ghanbari (2015), considering the normal, thinner, and thicker geometries for the dam core.



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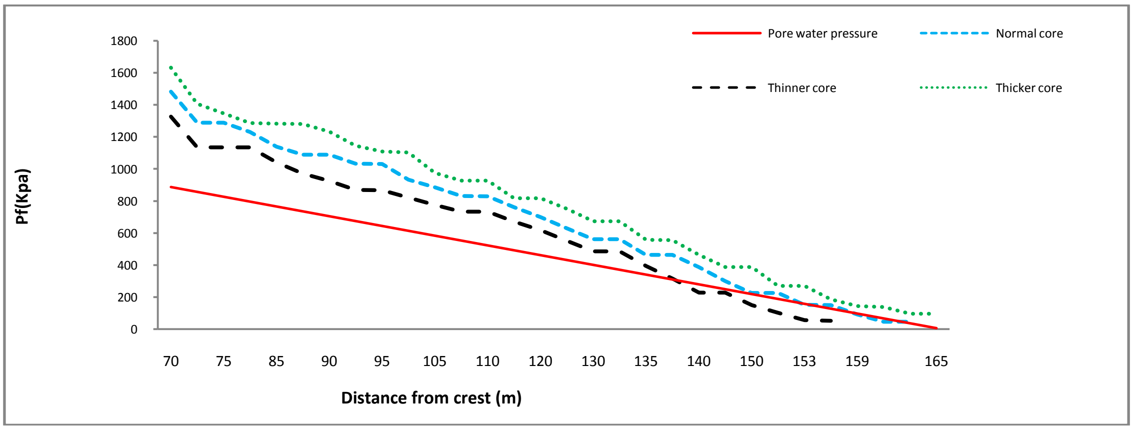

b)

Fig. 14. Comparison of fracture pressure (kPa) considering thinner and thicker cores: a)Simple tensile criteria (CH), b)Ghanbari shear criteria (CH)

According to Fig. 14, it can be concluded that by thinning the core, hydraulic fracture pressure will decrease, and therefore the probability of hydraulic fracture will also increase. Comparison of the above graphs shows that there is a similar trend for changes in hydraulic fracture pressure as the core becomes thinner and thicker. With an increase in core thickness, the hydraulic fracture pressure also increases, resulting in a decrease in the probability of hydraulic fracture. Therefore, the thicker core can be suggested as a solution to prevent the occurrence of hydraulic fracture in earth dams.

Comparing and summarizing the results of hydraulic fracturing

According to the analyses and graphs, it can be seen that in all stages of initial dewatering and steady state, and for all sections, the probability of hydraulic fracture is higher for CL than for CH. On the other hand, for CL soil, compared to CH soil, we observe the phenomenon of hydraulic fracture in more locations at the bottom of the core. This designates CL soil as the critical soil and CH soil as the soil for the construction and implementation of the core.

To ensure the correctness of the selected options as critical and selected borrows (pit), the results obtained from the simple tensile and shear criteria of Ghanbari and Shams Rad (2015) for these two borrows, with the results of other researchers, including Fukushima (1986) and Yamaguchi (2009), are compared.In this comparison, the hydraulic fracture pressure in the initial dewatering stage and the steady-state stage for the middle section of the core are calculated and compared based on the suggested relationships for both CL and CH soil types, as in Fig. 15.

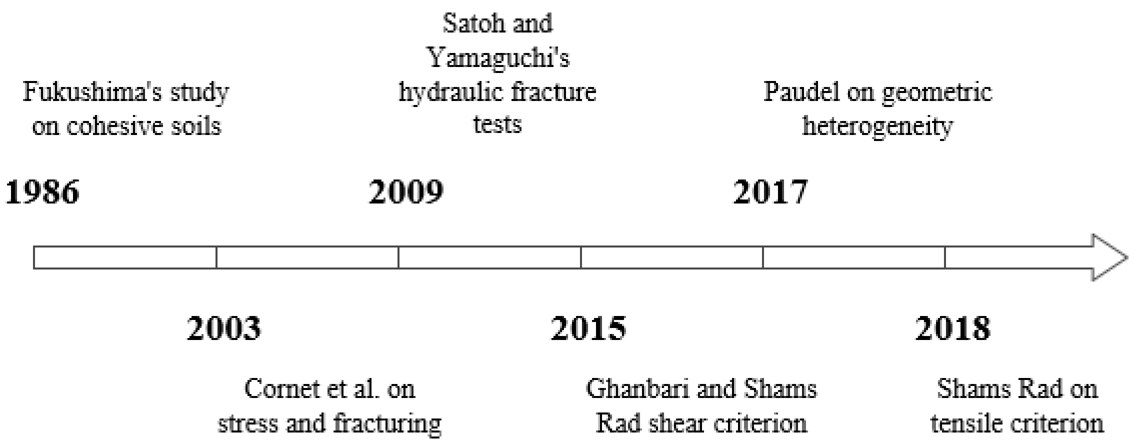

Fig. 15. Understanding Hydraulic Fracturing in Soil

Fukushima studies (1986)

After conducting a series of tests on dense cohesive soils, Fukushima (1986) concluded that the tensile strength of these soils can be neglected in calculatingeffective stresses. The used samples had the shape of a hollow cylinder, and, as mentioned in the conclusion, it was assumed that the distribution of stresses in the radial direction is linear. Also, using the Mohr-Coulomb criterion, he expressed the relationship of hydraulic fracture pressure as follows:

$$P_f = m\sigma_c \quad (2)$$

Where σ_c, is the confined stress, and the coefficient m changes between 1.3 and 1.6.In this research, the value of m is equal to 1.3 for critical soil (CL) and 1.6 for selected soil (CH).

Satoh and Yamaguchi'sstudies (2009)

These researchers utilized materials from a dam under construction to conduct hydraulic fracture tests. The obtained results showed that the hydraulic fracture pressure has a linear relationship with the bypass pressure. Consequently, these researchers proposed the following relationship to calculate the hydraulic fracture pressure.

$$P_f = m\sigma_3 + n \quad (3)$$

In this relationship, m and n are constants whose values are different for different conditions.

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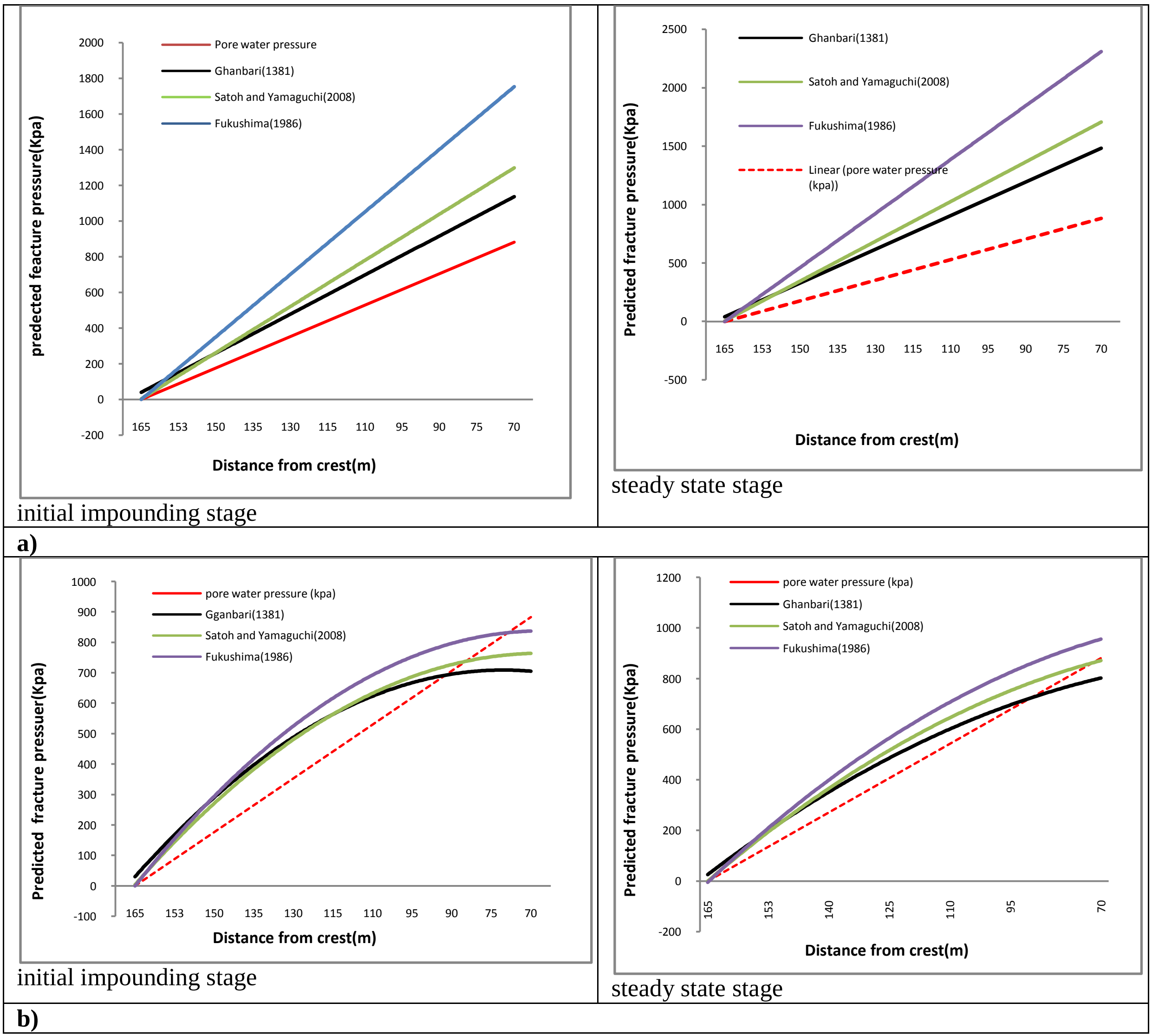
Table 2 shows a summary of the results obtained in this research.

Table 2: m and n coefficients for different soils

n (KN/m^2)	m	Soil type
-14	1.72	Large scale with a maximum size of 2 mm
34	1.29	Large scale with a maximum size of 19 mm
-0.8	1.17	Medium scale with a maximum size of 19 mm
4.6	1.18	Medium scale with a maximum size of 4.75 mm

In this research, according to the size of soil grains, for both selected and critical soil, m and n are considered equal to 1.18 and 4.6, respectively.

In Fig. 16, the hydraulic fracture pressure has been calculated based on the relationships provided by different researchers for both CH and CL soil types (Satoh & Yamaguchi, 2009).



initial impounding stage

steady state stage

a)

initial impounding stage

steady state stage

b)

Fig. 16. Comparison of hydraulic fracture pressure in section A-A: a) CHb) CL

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As can be seen in the above graphs, for CL soil, both in the initial dewatering stage and in the steady-state stage, points downstream of the core are prone to hydraulic failure. Similarly, according to the criteria of other researchers, CH soil is also prone to hydraulic failure. It does not have many hydraulic failures. Therefore, considering the criteria of other researchers, CL soil is recognized as critical soil and prone to hydraulic failure; therefore, its use in the dam core is not recommended.Also, the obtained results show that the Fukushima criterion (1986) is the most optimistic criterion presented for estimating hydraulic fracture pressure. The criteria of Ghanbari & Shams Rad (2015) and Sato & Yamaguchi (2009) also yield nearly identical values for the failure pressure. It is noteworthy that the criterion of Sato & Yamaguchi (2009) does not yield correct results for low stresses, as the coefficient n is negative for fine-grained soils. In the case of low stresses, the hydraulic fracture pressure is also negative, which is incorrect.

In this section, for further comparison, the reliability coefficient of hydraulic failure occurrence is calculated based on the Ghanbari shear criterion for each of the soils at the initial dewatering stage and steady state. Its average values are presented in Table 3 and Fig. 26. This safety factor is the ratio of fracture pressure to pore water pressure. Itvaries depending on the type of soil, stage, and criteria. The calculation of this safety factor is used to compare the results obtained from studies by different researchers and to assess the possibility of hydraulic failure.

Table 3. Mean safety coefficient values for hydraulic fracturing according to Ghanbari (2015)

Soil type	Initial dewatering		Steady-state	
			Section	
	A-A	B-B	A-A	B-B
CL	1.39	2.47	2.02	2.63
CH	1.75	2.66	2.08	2.78

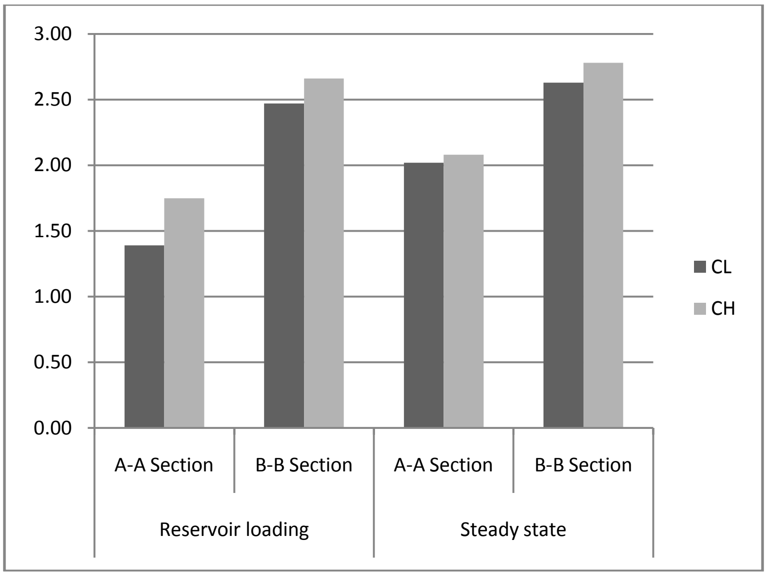

Fig. 17. Schematic comparison of hydraulic failure reliability coefficient values based on Ghanbari and Shams Rad criteria (2015)

According to Table 3and Fig.17, it can be observed that the safety coefficients in the initial dewatering stage are lower than those in the steady-state stage, resulting in a higher probability of hydraulic failure. Therefore, dewatering of the dam reservoir is the most likely time for hydraulic fracturing to occur.Also, the values of the reliability coefficients for the studied dam show that the probability of hydraulic fracturing in the middle section of the core (A-A) is higher than in the side section of the core (B-B).

VII. CONCLUSION

The comparison showed that in CL soil, there was the highest possibility of failure, and also the initial dewatering stage is more critical than the steady state. The probability of hydraulic fracture rupture in the A-A section (middle of the core) is higher than in the B-B section (oblique line next to the core) for both CL and CH soils in the stage of initial dewatering and steady state. To ensure the correctness of the modeling work, the results obtained for critical soil (CL) and selected soil (CH) were compared using other criteria such as Fukushima (1986) and Yamaguchi (2009), and the results of this comparison also showed that the probability of hydraulic fracture in critical soil is more than in selected soil. The comparison of the criteria used in predicting the hydraulic fracture pressure revealed that, in most cases, the Fukushima criterion yields the most optimistic results. In contrast, the Ghanbari criterion yields the most conservative results. It is noteworthy that the criterion of Sato and Yamaguchi (2009) does not yield correct results for low stresses because the coefficient n is negative for fine-grained soils. In the case of low stresses, the hydraulic fracture pressure is also negative, which is incorrect. Additionally, the results indicated that as the core narrows, the hydraulic fracture pressure decreases, and consequently, the probability of hydraulic fracture also increases.

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