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MECHANISM OF HYDRAULIC FRACTURING IN COHESIVE ZONE OF EMBANKMENT DAM CORES - A REVIEW

Poudel, S., Abbey, S.J. and Ngambi, S.
School of Energy, Construction and Environment,
Coventry University, United Kingdom

ABSTRACT

Estimation of critical water pressure is important for inducing hydraulic fracturing in fill dam experimental studies. To review the mechanism of hydraulic fracturing, model tests, numerical simulations and field tests are crucial methodologies. Since hydraulic fracturing is major problem in dam engineering, it has been given much consideration in the past few decades. However, no particular theory can be trusted and is fixed for addressing the mechanism of hydraulic fracturing in cohesive zone of embankment dam due to the complexity of the problem. Therefore, this paper focuses on the different views and methodologies of different studies in hydraulic fracturing in cohesive zone of embankment dam and how these studies differ from one to another.

Key words: embankment dam, hydraulic, hydraulic fracturing, cohesive zone

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1. INTRODUCTION

The failure and cracks in earth dams have many causes including the effect of loading due to overtopping flood, earthquake or explosion, human activities, deterioration and terrorist attacks in dam. Earth dams fail when the magnitude of these imposed actions surpasses the resistance against deformation, slope stability, internal erosion or piping. Hydraulic fracturing has been described by (Jaworski, Duncan and Seed, 1981) as the weak link phenomenon in which fracturing occurs in the least resistant soil under increased water pressure. Crack in dams is due to hydraulic fracturing, differential settlement and dryness. These cracks could be longitudinal or perpendicular and the magnitude will depend on the type of dam. In fill dams, longitudinal cracks are less problematic than the perpendicular cracks due to the orientation of the earth-rock fill dam. It is often considered that the hydraulic fracture in earth rock fill dam causes cracks in dam leading to complete or partial failure of the dam due to internal erosion. It has been clear that the initiation of cracks in earth dam is the cause of hydraulic fracturing and the cracks can propagate completely through the dam resulting in obstruction on its functions. These cracks are the main path for internal erosion. According to Zhu and Wang 2004, the main cause of arching in dam is as a result of differential settlement and settlement of engineering materials depends on strength, (Abbey, et al 2015, 2016 and 2017.) Conditions such as differential settlement and arching can result to low lateral stresses and this is the main cause of hydraulic fracturing in earth rock fill dam. Hydraulic fracturing occurs in soils when water induced pressure acting on a soil element exceeds the lateral effective stress acting on it. Wang, (2014) has it that the effect of low lateral effective stress on soil is more on earth rock fill dam than the effect of eater pressure in terms of hydraulic fracturing. Hydraulic fracturing may occur if 'water wedging' action induced by water entering the crack located at the upstream surface of the core is intensive enough. This is because the water wedging action changes the normal stress intensity at the tip of the crack (Wang et al 2005). This paper considered the mechanisms of hydraulic fracturing in cohesive zone of embankment dam cores.

2. HYDRAULIC FRACTURING

Hydraulic fracturing is a physical phenomenon in which the crack in the soil or rock is induced or expended by water pressure due to the rise in water level elevation. This technology was introduced in 1949 to petroleum industry in a published paper by J.B. Clark of the Stanolind and Gas Company. By 1956, the technique was widely employed in oil and gas exploration by the petroleum industry. Although hydraulic fracturing mechanics has much more usefulness in extracting oil and gas, it is a complex problem in dam engineering especially in embankment dams.

Hydraulic fracturing can occur in theoretical homogeneous embankment, but the probability of its occurrence is higher if the material is not homogeneous with respect to deformability and permeability (Sherard, 1973). According to BertilLofquist(1992), hydraulic fracturing is an effect that may occur in different connection. He means that when liquid pressure is lower than the counter pressure in the surrounding soil, rocks or materials, it experiences a fracturing effects.In case of embankment dam engineering, due to complexity of problem, it has been questioned whether concentrated leaks traversing a dam or dam core can develop as a result of hydro facture. The difficulty with hydraulic fracturing is that the cracks of fractures are hidden from direct observations as it happens inside the dams. Although the fact is unknown, some great experiments and observations demonstrated by Sherard (1973, 1986) and Penman (1982, 1986, and 1991) support the possibility that the hydraulic fracturing is often an active mechanism in the development of concentrated leakage.The occurrence of loose and wet layers, wet joints, in earth cores provide the evidences but the matter is still a controversial. According to Lofquist 1992, hydraulic fracturing occur in dam with existence of special condition.One condition is that the risk of hydraulic fracturing can only takes place if the reservoir pressure in the dam is higher than the total horizontal or vertical pressure at same level. But there should be another condition for hydraulic fracturing to occur.The two criteria which are necessary to generate the hydro fracturing are:

Stress condition: total vertical or horizontal earth pressure on the core of earth dam along the dam is lower than the reservoir pressure at same level.

Structure condition: creating a crack in dam layer or making more permeable layers is necessary for hydraulic fracturing to occur. According to Narita (2000), when water flows passing through soil in an embankment and foundation, seepage forces act on soil particles due to its viscosity. If seepage forces acting in the soil are large enough as compared to the resisting forces based on the effective earth pressure, erosion by quick sand takes place by washing soil particles away from the surface and piping successively develops as erosion gradually progresses. Excessive pressure from water, air drilling fluid, or grout can fracture embankment and foundation materials. Hydraulic fracturing problems have occurred while drilling in embankment as evidenced by reports of loss of fluidcirculation, blowouts, into nearby borings, seepage of drilling fluids on the face of embankment and other similar situation. Hydraulic fracture can occur in both cohesive materials and cohesion less materials and bedrock.it has been found that in soils, hydraulic fracturing can occur when the borehole pressure exceeds the lowest total confining stress (minimum principal stress plus some additional strength, (US Army Corps of engineer, 2014). According to Khanna et al (2016) hydraulic fracturing is an independent phenomenon in which the crack is induced or expanded by water pressure. Different theories in hydraulic fracturing have been reviewed and considered under the following category.

2.1. Analysis of Hydraulic Fracturing – Methods

Analysis of hydraulic fracturing in dam core and the process of its occurrence is a complex phenomenon and the problem is still given a highest priority in dam engineering. Despite of a lot of research by researchers such as Sherard(1972), Duncan (1981), and Ngambi et al (1998), the problem is still unsolved. However, according to the experiment done by Chinese researcher Yin (2006) and English Researcher Ngambi(1998) there are two different methods to analyse the occurrence of hydraulic fracturing process. Two suggested method for analysing hydraulic fracturing are Total stress analysis and effective stress analysis. In these two methods of analysis, their criteria and the outcomes are different from each other's. According to Wang (2004), the condition for existence of hydraulic fracturing in case of total stress analysing method is that the local total stress on a point of dam core wall should be less than or equal to the water pressure of the out of dam core wall at the point of same elevation. This method of analysing was used by Potts, Dounias (1996) to evaluate the hydraulic fracturing in Dyke Dam in UK. Where as in case of effective stress analysing method the local effective stress at the point of wall in dam core should be less than or equal to zero. The effective stress analysis method is used to analysis the hydraulic fracturing by comparing the local stress and the water pressure at the same point of the wall of dam core.

During the starting stage of filling in the reservoir, the permeability of the dam core is low since the materials in the core are unsaturated state. During this phase, the water pressure does not have any effect in the inner part of the core because the water pressure that is created by filling activities has not travel to its inner part. Only change in water pressure occurs in upstream face of the dam core and this change is negligible. So the effective stress analysing method does not work here to analyse hydraulic fracturing. However, total stress analysis method can be used to analyse the hydraulic fracturing. To analyse hydraulic fracturing by adopting total stress analysing method, the parameters of model of core soil have to be obtained from the undrained shear tests on the unsaturated core soil. But usually the parameters of model of core soil are often obtained from drained shear test of the saturated soil which is just opposite of what required and not in standard to analyse using total stress analysing method. So in order to solve the problem (Yin 2006) purposed a method to analyse hydraulic fracturing. In his method, pore water pressure and local effective stress of soil are calculated by using the theory of effective stress analysis. Here according to soil mechanics principle, summation of local effective stress and pore water pressure gives local total stress.

2.2 Studies on Hydraulic Fracturing - Experimental

The mechanism of hydraulic fracture in soils has been studied in the laboratory by some researchers Nobari et al, (1973), Jaworski et al, (1981) and Panahet al (1994). Recent investigation on the possibility of hydraulic fracturing in embankment dam during earthquake using seepage fracture tests were carried out in various condition of pore water pressure, overburden confining pressure and dynamic shear stress induced by earthquake. These studies have shown that water pressure can induce hydraulic fracturing in soils, however, important factors influencing hydraulic fracture in the clay core of embankment dams such as water contents, degree of saturation, degree of compaction, fine contents, clay mineral, as well as initial stress state receive little consideration. The study and ideas of hydraulic fracturing these days are the outcomes of the study based on laboratory experiments. In order to do laboratory experiments, researches had used two geometrical shape samples in which one sample was in rectangular with a cavity while the other one was cylindrical with cracks.

2.2.1. Rectangular Sample

With the failure of Teton Dam in 1976, there was increasing interest of the researcher to find out the reason behind its failure. So there were some authority to investigate the problem such as Chadwick 1977, Duncan et al (1981) and some agencies. In order to investigate the problems, Seed et al (1979) used laboratory experimental study on hydraulic fracturing. In the experiments the soil core of Teton Dam was investigated by them and the dimension of a cubic specimen was 20.30 in side length was used. They suggested an empirical formula $p_f = m\sigma_h + \sigma_{ta}$ which was based on theoretical and experimental analysis in order to calculate critical water pressure.Similarly Saeed Asadi in 2013 followed the same technique to establish experimental study on hydraulic fracturing in the Bakhtyari Dam. His team conducted tests on very small sample or mini core of the dam which were 30mm in diameter and 60mm high and the sample contain the hole of 3mm in diameter for axial injection. The sample were loaded triaxially with the constant confining pressure between 2 to 17MPa and a constant axial stress which was about 10 percent greater than the confining pressure. So from this test, his team concluded that the propagation and initiation of the crack is dependable in specimen’s size and size of axial borehole.

In Duncan et al(1977), experiment, numerous hydraulic fractures were made by the help of dyed glycerine in order to identify propagation of crack and detail of hydraulic fracture morphology. Then the specimens were injected into silty clay rectangular box confined within the rectangular chamber (dimension of 10cm, 10cm and 39cm) tri axial loading cell. The chamber was movable in one side in order to use as loading plate. Since the loading plate was made transparent and clear to inspect while performing the experiments. As shown in fig below 1, the remaining five sides of the chambers were lined with neoprene bladders which were inflatable. The function of that inflatable bladder was to control the three principle stresses acting on the sample freely by adjusting air pressure. Soil was passing inside the chamber with the help of the hole in loading plate.

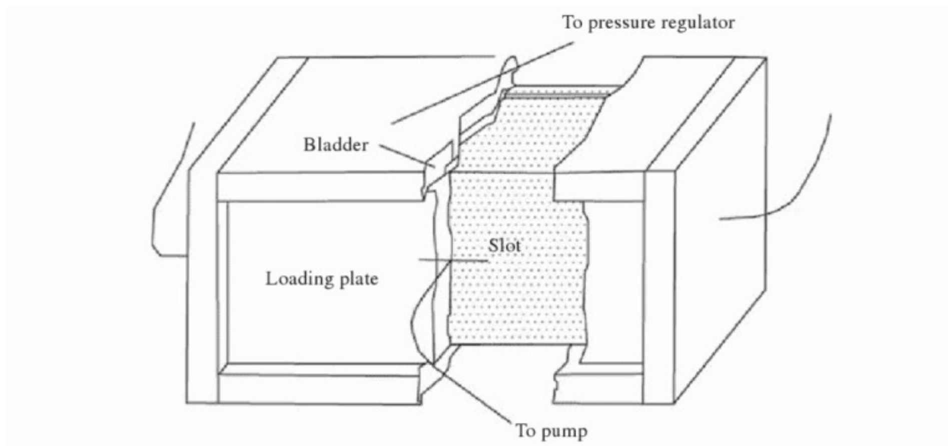

Figure 1 Hydraulic fracturing cell (Wang 2014)

By using the triangle blade a narrow about 0.04mm rectangular hole was cut through the middle of sample in each sample with the long axis of the rectangle spanning the sample width. The triangular blade was attached to the end of the rod which was 30cm long and 3mm in diameter.

Similarly, Panah (1994) used a hollow square soil sample to investigate the hydraulic fracturing under true triaxial stress state. The researcher drew conclusion from the test that the critical water pressure which is responsible for inducing hydraulic fracturing had something to do with minor and major principal stresses and the shear strength of the dam soil core under undrained unconsolidated condition of sample soil. This conclude that with the increasing in major principle stress there will be reduction in critical water pressure inducing the hydraulic fracturing.

2.2.2. Cylindrical Sample

The first person to investigate the laboratory experiments using cylindrical sample to investigate the hydraulic fracturing was Bjerrum et al (1972). And he later on jointly perform test with Anderson in (1972) again in compacted silty clay. In their experiments, the cylindrical sample had dimension of 13cm high and 8cm in diameter was used with triaxial apparatus. Before performing the actual test, a 0.30cm in diameter and 4cm long piezometer was inserted from the bottom in the sample. With the end of the test, there was a vertical fracture plane was induced under the water pressure. Here the pressure in horizontal direction was equal to the pressure inducing the close of the cracks. The other researcher called Venkatachalam et al, 1991 suggested that the stress and strain characteristics of soil core should be considered while investigation hydraulic fracturing in cylindrical soil sample in 1991. Similarly, another study in hydraulic fracturing investigated by Mhach et al (1994) concluded that initiation and propagation of the hydraulic fracturing in the lab is very unlike as that occur in embankment dam. The reason behind this variation was the difference in mode of applying water pressure.

In the history of hydraulic fracturing study, Duncan et al (1973) had great name as they jointly investigated the condition required to induce hydraulic fracturing in the lab. In their work, they concluded that the hydraulic fracturing is the result of critical tensile stress based on different tests under various loading condition. Others researchers such as Sun (1985), Huang (1989) Mori et al (1987) had used conventional triaxial apparatus and circular cylindrical sample.

3. MODEL TESTING ON HYDRAULIC FRACTURING

According to Bjerrum et.al. (1972) before confirming field testing procedure in Dead Sea, there were series of laboratory tests were done. In the laboratory testing, a small scale piezometer was placed in the soft silty clay container, a tank. The container contained porous stone on both end and those were directly connected with the reservoir as following fig 5 during this experiments, overall permeability was calculated by differentiating the level of reservoir from one side to another and waiting till the inflow rate is equal to outflow rate. After that two piezometers were installed named A and B. During observation it was found that in piezometer B, the ground water level had reduced to ground surface. Under this condition, piezometer A had been applied with an excess head. The applied head was maintained for a measured time interval. In this duration, readings on time against inflow rate were taken. For second experiments the head was raised by 20cm of water but the time period or intervals was constant as in the previous step. The process of increasing applied head by 10cm of water was done continuously till the measured flow rate showed a significant or fundamental change. If the excess applied head was maintained then the failure surface in the form of crack could be seen from the transparent side of the tank. The cracks could be observed about 10cm above from the tip of piezometer. If the researcher had allowed inflow continue further at same allowed head then there would be increase in magnitude of cracks in first instant but it would be partially closed later on. Another case was if the applied excess head was made equivalent to zero after fracturing, and then increase furthermore then cracks would have been seen from the transparent side of the tank to close and to reopen. In this experiment the crack was in horizontal direction not in vertical that means the danger of failure was not intense.

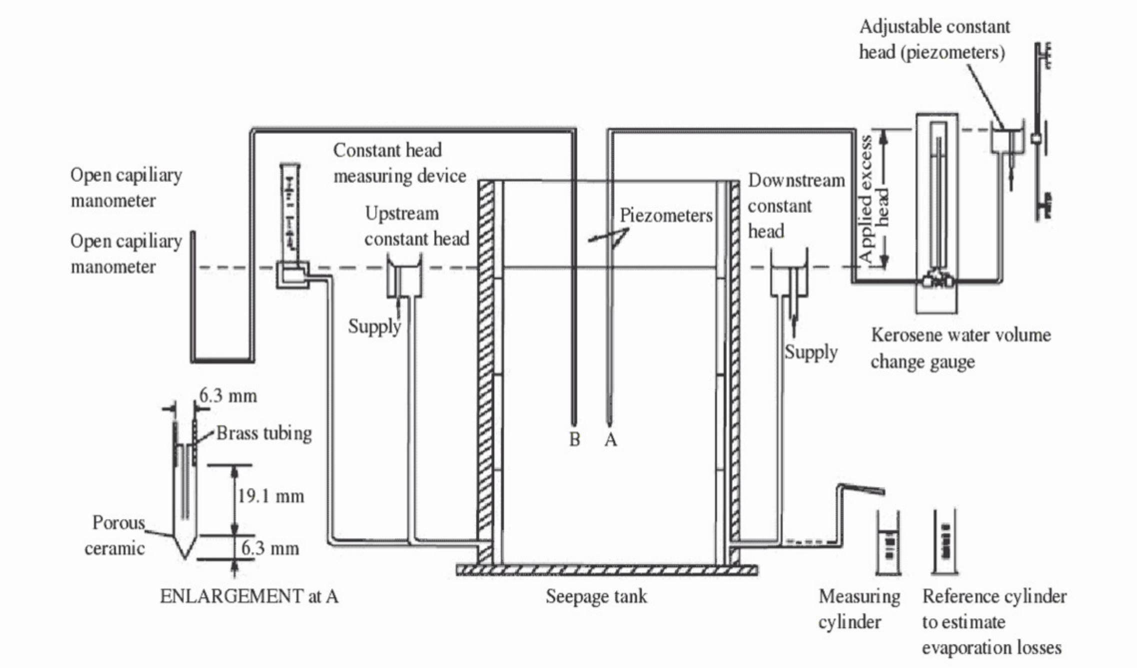

Figure 2 Model test tank (Wang 2014)

This experiment of model test proved that the hydraulic fracturing can occur in situ outflow permeability test at smaller pressure based on this experiment, Bjerrum et.al. (1972) had developed the concept to clarify the process of hydraulic fracturing and he had derived a theory. His analysis gave the new idea of factor involved, which includes the initial stresses in the ground and the final stresses after the installation of piezometer.

Soon after Bjerrum (1972) theory, another researcher named Hammer in 1989 did model test experiment. This model testing on hydraulic fracturing was done in small embankment dam in Canyon. In order to stimulate hydraulic fracturing in earth fill dam, he set up glass box model with dimension of 5m long, 0.60m wide and 1.30m high. After completing the experiments, he concluded that the vertical stresses of the dam can be reduced by arching the bottom or the lower part of the dam. Similarly, Shen et al (1994) had developed centrifuge model test which are widely used in civil engineering even for hydraulic fracturing in embankment dam.

4. HYDRAULIC FRACTURING BY FIELD TESTING

The studies in bore holes are always conducted in order to study hydraulic fracturing during field testing studies. While looking the research area, in case of dam engineering, the series of permeability field tests were done in dead see in Israel and in Oslo Norway. The testing was carried out by Bjerrum in 1972. In 1966, permeability test was carried out in the rain proof core of dyke dam. The core of the dam was made up of natural clay dumped into slurry trench constructed in the centre of the dyke. This test was done in order to evaluate the quality of the core soil. For this purpose, a porous bronze piezometer was pushed into the soil core by Bjerrum 1961 and the rate was measured at which water bolted from it when a surplus head was applied. This test was carried out in order not to disturb soil around the piezometer at constant head outflow tests. While performing more than 1000 tests in the dyke dam, it indicated that the core permeability to be of the order of $10^{-4}cms^{-3}$. This test indicated that permeability of soil core which are determined at higher pressure where fracturing had occurred was an error by 1000 times which gave conclusion that the pronounced increase in soil and water contact area and there was probability of emerging an easy drainage path alongside shoulders of the Dyke Dam. In history, several fields' tests were performed in order to investigate hydraulic fracturing in clay core by Penma (1976) in the Llyn Dam. In his tests he concluded that the hydraulic fracturing can easily initiate and propagate along the weak horizontal plane which was formed during construction period. In this test, the closing pressure of the sample lied between major and minor principle stresses. The test performed by allocated authority of Independent Panelto review the cause of Teton Dam failure indicate the opposite of what Penma (1976) concluded. In later case, showed that not horizontal plane but vertical plane which was normal to dam axis was more prone to propagate and initiate hydraulic fracturing. These two cases are just opposite with each other. There are many evidences which show that the different field test done by different researchers have different results. The field test done by Perkin and Yu (1989) Sam (2004), Murdoch (1995) and Ashadi (2013) had very different results.

5. NUMERICAL SIMULATION OF HYDRAULIC FRACTURING

In order to solve complex problem especially in dam engineering, numerically simulation are widely used method as an effective method to investigate the hydraulic fracturing. Potts et al, (1996) had analysed three sections by using nonlinear finite element methods. The method was discussed by Naylor after two years in 1998. The analysis was based on experiment done on puddle core embankment. According to Binnie (1978), the reason behind the failure of Dyke dam after first filling, was hydraulic fracturing. So the researchers performed analysis on the construction and initial impounding on the small puddle clay core dam. In order to recreate failure mode, in this test, the Imperial College Finite Element Programme was in charge throughout the study period.In this experiment, in order to incorporate with a Mohr-Coulomb yield criteria the sample soil was modelled as a nonlinear elastic strain softening plastic material. In order to solve finite element method, Binnie 1978 used Newton Raphson method. By using iterative sub stepping method, he integrated the elasto- plastic equation. He had used reduced integrated 8 node isoperimetric plane strain element. In his numeral simulation analysis, he had stimulated construction by using switching on gravity to successive layers of sample. So all elements which were not used in construction were less stiff and weight free. Soon after the elements were constructed, he initiated the calculation of stresses and displacement. In this mechanism the weight of each layer was switched on over 5-10 increment.

For this test, embankment dam with 30m high and 15m deep cut off trench was chosen which is shown in fig below 3.

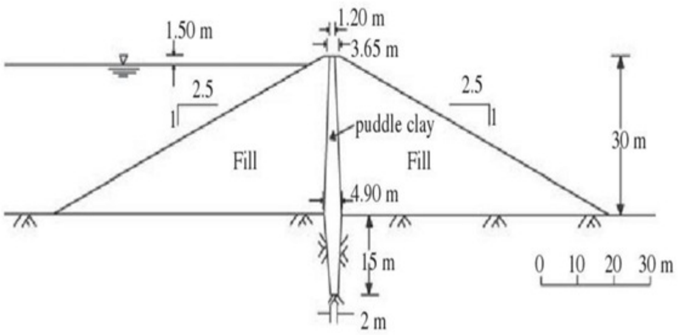

Figure 3 Finite element mesh and boundary condition (assumed section of Dale Dyke dam)(Faghihi 2008)

The mesh size and boundary condition for Finite Element Analysis (FEM) is illustrated in fig 4. Another fig 5 represents the potential hydraulic fracture at the end of impounding. Here in fig 5, the minimum total stresses are plotted at the upstream core boundary and at a small distance in the boundary. The results showed that in the trench, the reservoir water pressure exceeds the minimum total stress when a comparison between reservoir water pressure and minimum stresses was done. There was a higher minimum stress than the reservoir pressure in the core of the dam at the upstream boundary but the reservoir pressure was equal to the medium stress which was acting inside the boundary. In this case it was assumed that the impounding in very slow but in constant rate which is far away from the real dam. In real dam filling process, the reservoir filling is speedy and relatively fast.

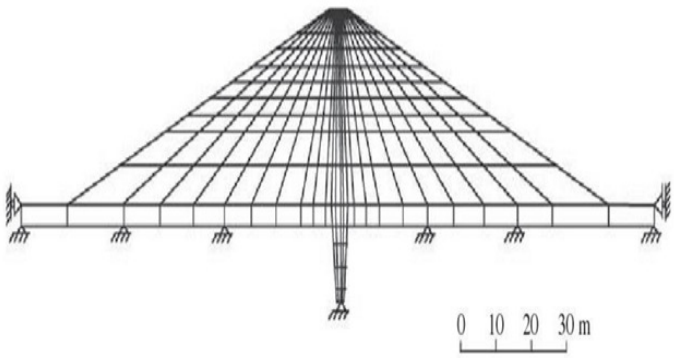

Figure 4 Finite element mesh and boundary condition (assumed section of Dale Dyke dam) (Faghihi 2008)

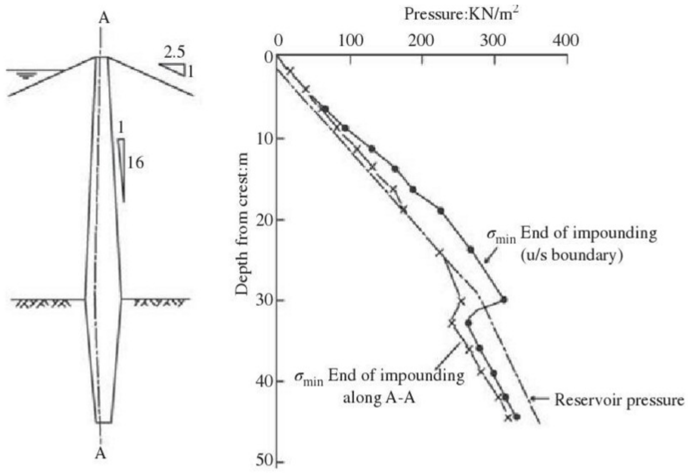

Figure 5 Minimum total stress of the core after drained impounding of Dale Dyke dam near upstream boundary (Faghani 2008).

FEM of this analysis is shown in fig 6. According to FEM results, reservoir pressure is equal to the minimum stresses at the core at upstream boundary at a depth between 7m and 12m. Here in inside boundary, the minimum stresses are lower than the reservoir pressure for the depth which is lower than 8m. So this two analysis indicate the hydraulic fracturing occur in trench. In first case the reservoir was filled in slow rate where local perturbations in stress over length greater than 0.5m and the depth 10-20m below the crest level induce and rise hydraulic fracturing. In later case when the reservoir was filled rapidly in last 7.5m the hydraulic fracturing occurred around the depth of 10m below the crest.

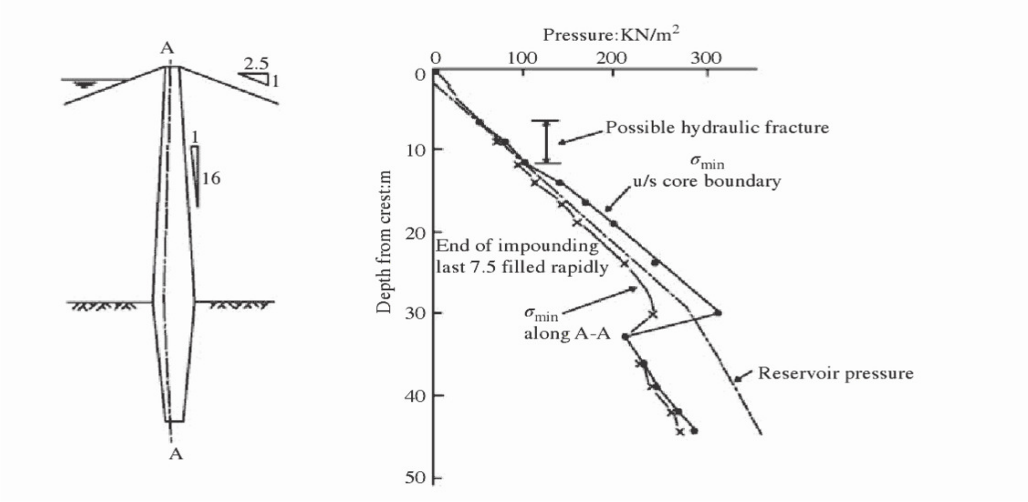

Figure 6 Minimum total stress of the core due to undrained impounding near the upstream boundary of Dale Dyke dam, (Faghihi 2008).

In order to investigate the hydraulic fracturing in The Dyle Dyke dam, the last 7.5m was filled relatively fast. It was assumed that the dam core behave like in undrained condition.

6. CONCLUSIONS

In conclusion, it can be said that despite of performing numerous lab experiments, numerical modelling, there is no particular theory that can adequately explains hydraulic fracturing and cracking investigated in lab test or field test. In many of the tests water pressures were applies at slow rate or some did not specify the rate, so soil can be assumed at partly drained. In some of the lab tests the boundary conditions on the samples were not accurately defined and no sufficient water was available to extend and maintain a newly formed crack. Similarly, in numerical modelling too, some of the analysis were done in 2D and some were in 3D so many of the proposed theories are based on major assumptions and some of it even don’t clarify drained and undrained soil parameters.

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