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Hydraulic Fracturing in Core of Earth and Rockfill Dams

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Abstract **– Hydraulic fracturing has become one of the major problems in rock fill dams, since it plays a significant role in the initiation and extension of cracks in the clay core. There have been a number of well-studied cases in which dams have failed or been damaged by concentrated leaks for no apparent cause. In some of experiences, investigators concluded that differential settlement cracks were the probable causes, even though no cracks were seen on the surface. Hydraulic fracturing is generally considered as a key cause which may induce the leakage of the dam during first filling. The likelihood of the occurrence of hydraulic fracturing increases with increasing the water level or the crack depth. The lower part of the dam core is the zone in which the phenomenon of hydraulic fracturing may be induced easily. Hence it is necessary that every precaution be taken against leakage to ensure safety of the dam. The investigations of results indicate that hydraulic fracturing in earth and rockfill dams can be controlled and is helpful to reduce the likelihood of the occurrence of hydraulic fracturing by increasing any of Young's Modulus, increasing the Poisson's Ratio and increasing the density of core soil**

Keywords **– Dams, Hydraulic Fracturing, Cracking, Pore Water Pressure.**

I. Introduction

Hydraulic fracturing has become one of the major problems in rock fill dam, since it plays a significant role in the initiation and extension of cracks in the clay core. Hydraulic fracturing may occur in the upstream face of clay core of a rock fill dam in the case the vertical effective stress in the core is reduced to levels that are small enough to allow tension fracture to occur. This situation may arise if the total stress in the core is reduced by an arching effect where the core settles relatively to the rock fill. Pore water pressure in the core will also increase during impounding, and this will further reduce the effective stress in the core. Wedging due to water pressure may crack the upstream face of clay core. Loftquist indicated that arching in the clay core of a rock fill dam may result in leakage and internal erosion based on his observation on thin impervious cores of the 26m high Holle dam and 34m high Harspranget dam as being as low as half of the normal overburden pressures. The incident in Hyttejuvet dam in Norway that caused unexpected leakage occurred during the first filling of the reservoir, Kjaernsli and Torblaa. Similar incidents for the unusual leakage occurred just before the reservoir became full during the initial filling of Balderhead dam in England reported by Vaughan et al. The failure of Stockton and Wister dams in USA were suspected as being due to hydraulic fracturing, Sherard. An investigation to the leakage that occurred at Viddalsvatn dam in Norway indicated that hydraulic fracturing might be the cause, (Vestad). The failure of Teton dam in USA during the first reservoir filling also identified hydraulic fracturing as a possible cause, (Independent Panel). To enhance the understanding of the hydraulic fracturing mechanism in the upstream face of the clay core of a rockfill dam in general, the effects of construction time and impounding rates of the dams experiencing hydraulic fracturing were then studied. The rates of embankment and impoundment did not affect the hydraulic fracturing on the clay core of the rockfill dam. Lo and Kaniaru studied and compared the embankment and impoundment rates of five dams; Balderhead, Hyttejuvet, Viddalstavn, Teton and Yard's Creek dams which experienced hydraulic fracturing.

There have been a number of well-studied cases in which dams have failed or been damaged by concentrated leaks for no apparent cause. In some of these experiences, investigators concluded that differential settlement cracks were the probable causes, even though no cracks were seen on the surface. In these examples, it was not determined whether the crack was open before the reservoir filled or whether it might have opened afterward. In several unsolved problems on the safety of the earth-rock fill dam, the problem of hydraulic fracture in the soil core of the earth-rock fill dam is one that is widely paid attention by designers and researchers. Hydraulic fracturing is generally considered as a key cause which may induce the leakage of the dam during first filling. The likelihood of the occurrence of hydraulic fracturing increases with increasing the water level or the crack depth. The lower part of the dam core is the zone in which the phenomenon of hydraulic fracturing may be induced easily.

There should be no possibility of free water to flow from upstream to downstream face. Free flow implies flow of water under pressure through continuous crack or passage and no seepage flow through soil pores. Once a concreted leakage starts, it rapidly enlarges and is almost impossible to stop. Hence it necessary that every precaution be taken against leakage to ensure safety of the dam. In well-constructed dams there should not be loose pocket left to provide free passage and adequate care must be taken to obtain a tight contact joint between the dam and foundation. Current practice is not to provide conduits in the body of dam as these may cause leakage or water pressure escaping from them may cause erosion and leakage. The potential of leakage mainly arises from the possibility through cracks, which may results from differential settlement, tensile stresses or hydraulic fracturing, the last is caused by water pressure in excess of compressive stress on any plane.

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With finite element analysis it is possible to identify the zones susceptible to tensile strains or hydraulic fracturing and it incorporate the remedial measures in the design. Hence leak control measures with respect to core, filter, and downstream drainage still remain important.

Although cracks in earth and rockfill dams have caused trouble since earlier days of dams building, little published information on the subject was disseminated before 1950. This situation has changed rapidly during the last few years and today it is well known that the cracks have developed in the impervious section of many dams and that unusually large settlements are not always ‘villain’.

Cracks may occurs in the longitudinal direction (along the dam axis) as well as transverse direction (across the dam axis). Open cracks may occur on the crest and slopes. Concentrated leakage may develop through suspected but unseeable cracks below the water line in the transverse direction, more likely to be horizontal but also possible in the vertical plane. Loss of drilling fluid in the borehole would be an indication of possible cracks.

II. Objectives

The primary objectives of this research review are the following:

1. To study the criterion for hydraulic fracturing.
2. To study the phenomenon hydraulic fracturing in earth and rockfill dams.
3. To study the literature review on cause of hydraulic fracturing and how to control hydraulic fracturing in earth and rockfill dams.

III. Criterion for Hydraulic Fracturing

Previous studies have suggested different methods for determining the water pressure required to induce hydraulic fracturing. These methods may be classified into three groups (Wang and Zhu 2006). The first are theoretical methods such as the cylindrical or spherical cavity expansion theories in elastic or elastic-plastic mechanics (as in Yanagisawa and Panah (1994)). The second are empirical methods based on field or laboratory tests (such as those of Mori and Tamura (1987)). The last are conceptual models based on laboratory tests and theories in fracture mechanics (FM) (as in Murdoch (1993c)). A crack in the core, which allows water to enter the core, is a prerequisite for hydraulic fracturing (Wang and Zhu 2007). Thus, hydraulic fracturing is actually the propagation of the crack under water pressure. FM can be used to investigate the problem. The finite element method (FEM) has been widely used in simulating stresses and strains on earth-rockfill dams during construction and impounding. This should be considered while establishing the criterion for hydraulic fracturing. The earth-rockfill dam is usually simplified as a plane strain problem in the FEM analysis. Thus, the criterion for hydraulic fracturing. Under the plane strain condition, the crack propagation may be in mode I, mode II, or a mixed mode I-II. Because the stress state in the core is very complex and the spreading of the crack can be induced by the combination of normal stress perpendicular to the crack face and shear stress parallel to the crack face (Vallejo 1993), the criterion for hydraulic fracturing should be investigated according to the mixed mode I-II. Based on experimental study of the fracture behavior of a silty clay that is the core Jun-jie WANG et al. Water Science and Engineering, Dec. 2009, Vol. 2, No. 4, 95-102 97 material of the Nuozhadu Earth-Rockfill Dam in Western China (Wang et al. 2007), a criterion for hydraulic fracturing was formulated:

$$\{K_I^2 + K_{II}^2\}^{0.5} = K_{IC} \qquad (1)$$

where K_{IC} is the mode I fracture toughness of the core soil, and K_I and K_{II} are the stress intensity factors of mode I and mode II cracks, respectively. The J integral proposed by Rice (1968) is a parameter indicating the intensity of nominal stress, and it is a constant for different integral routes. The relationship between the J integral and stress intensity factor for a mixed mode I-II crack under plane strain conditions can be described as (Anderson 1991).

$$J = \frac{1-\nu^2}{E}\{K_I^2 + K_{II}^2\} \qquad (2)$$

where E and ν are the Young’s modulus and the Poisson’s ratio of the material, respectively. The value of J can be obtained with the FEM (Hellen 1975; Delorenzi 1985; Hamoush and Salami 1993). The value of $\{K_I^2 + K_{II}^2\}^{0.5}$ in Eq. (1) can be obtained from Eq. (2).

3.1 *Critical Water Pressure*

Water pressure at the beginning of hydraulic fracturing phenomenon is called critical water pressure. Based on lab and field investigations various theories to calculate critical water pressure have been suggested. Wang and Zhu (20006) have suggested five such theories and they are:

1. The theory of hydraulic fracturing based on the theory of experimental study in the circular cavity, and combined with the theorical formulas from circular formula expansion theory in elastic-plastic mechanism.
2. The theory of hydraulic fracturing based on the theory of experimental study in the spherical cavity and combined with the theoretical formulas from spherical formula expansion theory in elastic-plastic mechanism.
3. Theories based on true triaxial stress state analysis.
4. Empirical formula based on field and lab formula.
5. The theory of hydraulic fracturing based on tests conducted in “envelope” shaped cracks in cubic specimens, and combined with the theories from fracture mechanism.

Crack or Hydraulic Fracture Through Core

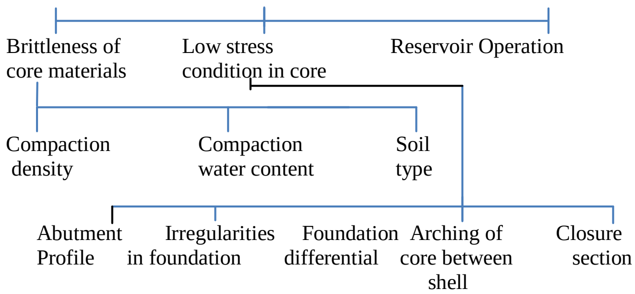

Fig. 1. Fault tree diagram for the formation of a crack or hydraulic fracture through the core (Foster, 1999)

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Influence of likelihood of cracking or collapse			
Factor	More likely	Neutral	Less likely
Compaction density[1]	Poorly compacted, < 95% standard compaction density ratio[2]	95-98% standard compaction density ratio	Well compacted, > 98% standard compaction density ratio
Compaction water content	Dry of standard optimum water content (approx.. OWC 3%)	Approx. OWC 1% to OWC 2%	Optimum or wet of standard optimum water content
Soil type[3]	Low plasticity clay fines	Medium plasticity clay fines	High plasticity clay fines Cohensioless silty fines

Note:

1 For cracking, compaction density ratio is not a major factor. It is more important for wetting induced collapse

2 < 93% standard compaction. Dry of OWC, much more likely

3 Soil type is not as important as compaction density and water content

3.2 *Phenomenon of Hydraulic Fracturing in Earth and Rockfill Dams*

If there is no transfer or distribution of stress, the vertical stress on a horizontal plane in the center of core should be γ z, where γ is the compacted unit weight of the core material, and z is the height of soil column above the plane. Neglected free board, the water pressure will be $\gamma_{w\,z.}$ Since γ is about twice γ_w, the possibility of potential fractures would arise only with considerable stress distribution or transfer. F.E.M analysis has indicated that in homogeneous embankments there is a transfer of stress from center to slopes. In zoned embankments, if the core is more compressible than the shells, compressive stress will be transferred from the core to the shell through interfacial shear. However, even without transfer, the stress on the two vertical planes, one longitudinal along the dam axis, and the other transverse to it, will normally less than the vertical stress by the factor K_o and will be equal to $K_O\ \gamma$ z. If K_O is equal to 0.5 or less, vertical hydraulic fracturing may take place parallel or normal to the dam axis, the latter resulting in possible leakage. Vaughan (1970) has illustrated by an instructive diagram (Figure 2), the various stages of development of hydraulic fracture in a dam core.Above table indicate that cracking or hydraulic fracture of the core is more likely if the soil is brittle and there is low stress condition present and the factors which initiate it. These are based on the literature, including Lambe (1958), Leonards and Narain (1963), Sherard et al. (1963), Sherard et al. (1972a and b), Sherard (1973, 1985), Truscott (1977), Jaworski et al. (1981), Gillon and Newton(1988), Lo and Kanairu (1990), Lawton et al. (1992), Charles (1997), Høeg et al. (1998) and a review of case studies Foster (1999), Foster and Fell (1999), Foster et al. (1998).

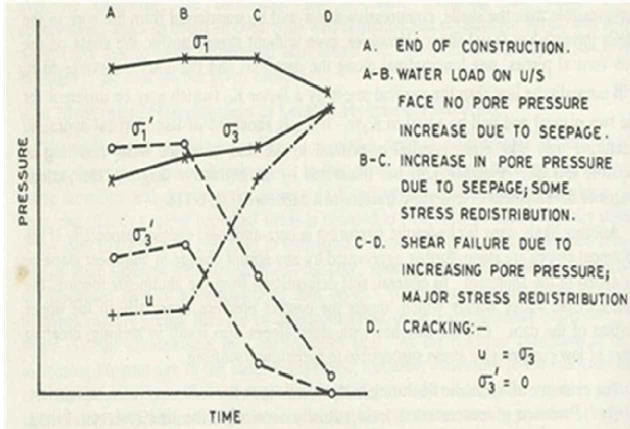

Fig. 2. Various stages of development of hydraulic fracture in a dam core

The evidence of hydraulic fracturing in dams falls into the following main categories:

1. Evidence of concreted leaks, soon after the first filling, which may or may not cause failure.
2. Records of well designed and constructed central core dams in which nearly full reservoir pressure was measured in piezometers at the downstream face of the core.
3. Discovery of ‘wet seam’ inside impervious dam sections, with water content higher than could be nearly accounted for by ant mechanism other than the entry of water into an open crack.
4. F. E. M. studies indicating the occurrence of zones susceptible to hydraulic fracturing.

3.3 *Piping in the Embankment*

Piping in dam embankments initiates by one of three processes: backward erosion, concentrated leak and suffusion. *Backward erosion* piping refers to the process in which erosion initiates at the exit point of seepage and progressive backward erosion results in the formation of a continuous passage or pipe. *Concentrated leak* piping involves the formation of a crack or concentrated leak directly from the source of water to an exit point and erosion initiates along the walls of the concentrated leak. Figure 3 shows conceptual models or the development of failure for backward erosion piping and concentrated leak piping. The sequence of events leading to failure by the two models is essentially the same, however the mechanisms involved in the initiation and progression stages are different. *Suffusion* involves the washing out of fines from internally unstable soils. Soils which are gap-graded, or which have only a small quantity of fine soil in a mainly coarse sand or gravel are susceptible to suffusion.

Potential Breach Mechanisms are:

– Gross enlargement of the pipe hole;
– Unravelling of the toe;
– Crest settlement, or sinkhole on the crest leading to overtopping;
– Instability of the downstream slope.

Figure 4 shows a failure path diagram illustrating the possible sequence of events leading to dam breaching. Only marginal increases in the permeability of the core

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may be required to increase pore pressures in a low permeability downstream zone sufficiently to initiate downstream sliding, so it is assumed that the progression of piping to form a hole is not necessarily required for this failure mechanism. It is assumed that failure by gross enlargement of the pipe or unravelling of the toe requires continuing flow and therefore this is only possible if the pipe remains open.

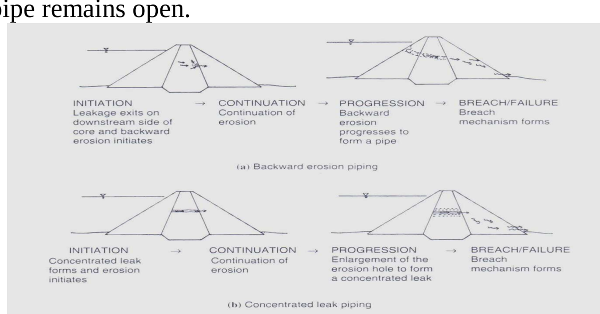

Fig. 3. Model for development of failure by piping in the embankment (a)backward erosion (b) concentrated leak (Foster, 1999)

Piping Through the Foundation

Piping in the foundation initiates by one of four processes: concentrated leak, backward erosion, suffusion, or blowout/heave followed by backward erosion. As for piping through the embankment, it is possible to develop a single failure path diagram for the assessment of concentrated leak piping and backward erosion piping. Figure 4 to Figure 6 show the failure path diagram for piping through embankment and the foundation.

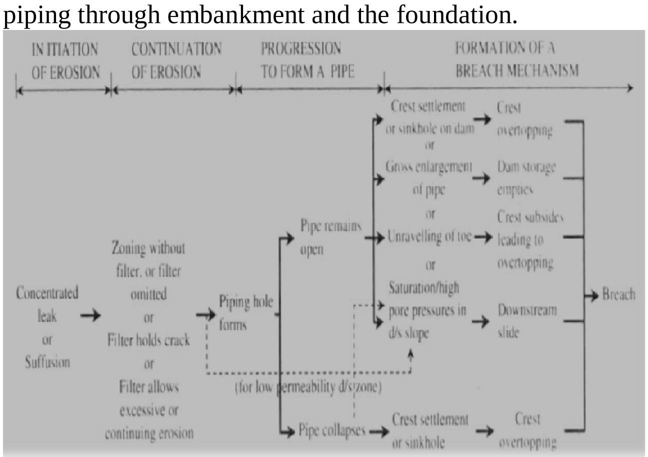

Fig. 4. Failure path diagram by piping through the embankment (Foster, 1999)

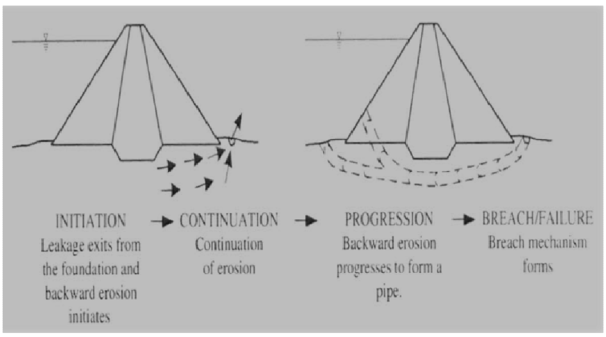

Fig. 5. Model for development of failure by piping in the foundation (Foster, 1999)

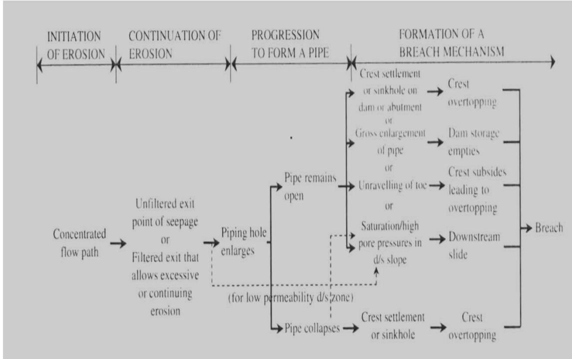

Fig. 6. Failure path diagram by piping through the foundation – concentrated leak and backward erosion piping (Foster, 1999)

Failure can occur even if the pipe collapses, by either by crest settlement (sinkhole) leading to overtopping, or slope instability. Also it is assumed failure is possible by crest settlement, even if the pipe remains open due to the potential for settlements associated with crack filling action in the foundation.

IV Literature Review

4.1 *Hydraulic Fracturing*

Hydraulic fracturing is an independent phenomenon in which the crack is induced or expanded by water pressure. Now the question is why is crack induced or expanded by water pressure? There are two different viewpoints, one is expansion of crack is result of critical tensile stress acting on the crack plane. The other is expansion is the result of critical shear stress acting along the crack plane.

Hydraulic fracturing can occur in a soil mass when water pressure acting on soil element exceeds the lateral effective stress acting on it. Low lateral stresses are caused by several conditions, most often differential settlement and arching. Arching occurs when soil settles differentially (Zhu and Wang, 2004).

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 (Independent panel to review the cause of Teton Dam Failure, 1976).

Hydraulic fracturing is also defined as the weak link phenomenon in which fracturing will occur in the least resistant soil subjected to increased water pressure (Jaworski, Duncan and Seed, 1981). 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). 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 may change the normal stress intensity at the tip of the crack (Wang, Zhu, Zang, 2005).

Under the plane strain condition, the crack propagation may be in mode I, mode II, or a mixed mode I-II. Because the stress state in the core is very complex and the

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spreading of the crack can be induced by the combination of normal stress perpendicular to the crack face and shear stress parallel to the crack face (Vallejo 1993), the criterion for hydraulic fracturing should be investigated according to the mixed mode I-II. Based on experimental study of the fracture behavior of a silty clay that is the corematerial of the Nuozhadu Earth-Rockfill Dam in Western China (Wang et al. 2007), a criterion for hydraulic fracturing was formulated.

Grouting of dam foundations of both soil and rock using pressures high enough to cause hydraulic fracturing enabling the grout to flow out of grout hole in concentrated stream, has been understood and applied practically since before 1960. Since about 1970, it has been known that hydraulic fracturing has often occurred inadvertently when boring are drilled in completed dam cores and pressure in the drilling fluid at the bottom of the hole exceeds the adjacent embankment earth pressure.

There is a difference between hydraulic fracturing at the bottom of bore holes by pressurized drilling fluid, however and hydraulic fracturing by reservoir water acting on the upstream face of the dam core causing concentrated leaks of water to enter into the core. Since about 1975, with wide acceptance that hydraulic fracturing causes leaks through dams under certain conditions there has been a corresponding increase in published literature on the subject (Jaworski., et. al. (1981)., Kuthway and Gurtowsky, 1976., Seed and Duncan, (1981)., Widjaja., et. al. (1982)). However still there is no general agreement among specialists about the different aspects of the phenomenon. When a concentrated leak occurs through dam core, the source of leak is under water and it is not possible to pinpoint the cause of leakage by direct evidence. In subsequent investigations, the cause has to be established by a process of elimination, which always leaves room for doubt. In spite of such uncertainty, competent specialist believe that there is now firm evidence available supporting the conclusion that hydraulic fracturing may cause small concentered leak occur in otherwise well designed and constructed dams, and even there is no large differential settlement (Sherard, 1973).

The differential settlement of the compacted embankment creates strains which change the internal stress distribution. In this action, the internal pressure increases in some location and decreases in others. In localized but fairly large zones within the dams, the effective minor principal stress is reduced to nearly zero or even to tensile stress if the dam has sufficient cohesion to withstand tension.

When the reservoir rises above of these surfaces with low stress in the core, water can enter from the surface from the upstream face in a concentrated thin layer. When the reservoir pressure becomes slightly greater than the embankment stress, there is no resistance to the entry of water into the embankment in a concentrated leak. As the reservoir is continuously to rise, increasing the water pressure in the water filled crack, the stress condition in the crack are changed, the impervious embankment material is deformed and the crack is open wider. Experience has further shown that no significant 'excess pressure' is needed to initiate the fracturing action. Hassani., et. al. (1983, 1985) carried out comprenhsive theoretical and experimental studies of the mechanism of hydraulic fracturing in thick wall hollow soil cylinders subjected to differential pressures. These authors found good correspondence between their theoretical predications experiential results. Some of their findings, in qualitative terms were:

1. A linear relationship exists between fracturing pressure u_f and confining pressure P_o. The slope of the line is close to 45° but $u_f > P_o$ by a small intercept. This intercept decrease with increasing initial moisture content and increases with the tensile strength of the soil.
2. As the duration for which the inside fracturing pressure is maintained is increased u_f goes down.
3. u_f decrease with an increase in the ratio of vertical to lateral pressure.

4.2 *Settlement Allowance in Earth and Rockfill Dams*

As per IS: 8826 (1978) and reprint in 1983, at the end of construction, the crest of the dam should be suitably raised above the designed top level of the dam to allow for post-construction vertical deformation resulting from compression and/or settlement of the embankment and foundation so that there may be no reduction in the designed freeboard above the maximum reservoir level This extra height of the dam is provided in the form of a longitudinal camber over the designed top level, varying from zero at the abutments to a maximum value at the centre of gorge where the dam will be the highest and the settlement of the embankment will be the most. The extra height to be so provided to compensate for compression in the fill material should generally be between 0.2 percent and 0.4 percent of the embankment height, depending on the soil type, in respects of earth embankments and roekfill dams where the rnaterial is placed in layers and compacted with the addition of water. The deformation on account of compression in the embankment would be greater in the case of dumped rocklill. Generally, a provision of 1 to 2 percent of the embankment height above the designed top level may be provided to account for both embankment compression and foundanon settlement in respect of earth and rockfill dams.

Table 1. Examples of central core earth and rockfill dams with measured settlement

Dam zone		Settlements inside the dam until end of construction	Total settlements inside the dam	Total settlements at the crest	Years after end of construction
Srinagarind (H = 140 m)					
Core	(m)			0.8 (H_{140})[1]	2.5
	(% of H)			0.57	
Shell d/s	(m)			0.8 (H_{100})	2.5
	(% of H)			0.8	
Kinda	(H = 76 m)				
Core	(m)	0.95 (H_{35})	1.42 (H_{35})	0.54 (H_{76})	3.3
	(% of H)	1.25	1.87	0.71	
Shell d/s	(m)	0.58 (H_{26})	0.65 (H_{26})		3.3
	(% of H)	0.76	0.86		
Monasavu	(H = 85 m)				
Core	(m)	1.68 (H_{35})	1.80 (H_{35})	0.33 (H_{85})	1.5
	(% of H)	1.98	2.1	0.39	
Shell d/s	(m)	0.32 (H_{35})	0.45 (H_{35})		1.5
	(% of H)	0.38	0.53		

[1](H_{index}) = Height of the measuring instrument above foundation (m)

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I. Above table indicates that settlement is in meter and is greater in core as a percentage height of dam than in shell.
II. Settlement in the dam from the end-of-construction to the end of measuring time increase, by around 50% in the core and about 12% in the less deformable shell.

Table 2. Influence of post construction settlement at crest on cracking (after J. Justo)

Crest settlement (mm)	Kind of cracking
Less than 50	No cracking of dam
Equal to or greater than 50	Transverse cracking of dams compacted dry may appear
Greater than 100	Reinforced concrete facing without perimetral joint may crack
Equal to or greater than 130	Longitudinal cracking between core and shell may appear
Greater than 160	Longitudinal cracking of core compacted may appear
Greater than 180	Hydraulic fracturing may appear
Equal to or greater than 220	Transverse cracking of core ompacted wet may appear. Longitudinal cracking between core compacted wet and shell may appear
Equal to or greater than 350	Asphaltic concrete facing may crack
Greater than 400	Longitudinal cracking of core compacted wet may appear. Reinforced, concrete facing with perimetral joint will crack
Greater than 1000	No uncracked dam in those studied
Greater than 1200	All dams exhibits transverse cracking
Equal to or greater than 1400	Serious cracking of asphaltic concrete facing
Equal to or greater than 3800	Cracking needs substitution of reinforced, concrete facing

4.3 *How to Control Hydraulic Fracturing in Earth and Rockfill Dams*

The investigating results indicate that Hydraulic fracturing in earth and rockfill dams can be controlled and is helpful to reduce the likelihood of the occurrence of hydraulic fracturing by:

1. Increasing any of Young's Modulus
2. Increasing the Poisson's Ratio
3. Increasing the density of core soil

The factors affecting the self-healing of the crack in the soil core of earth and rockfill dam has also been investigated by the laboratory experiments. The factors include the depth of crack, grain size of base soils, the grain size of filter soil. In order to investigate the influence of factors the earth and rockfill dams have been simplified to a five layered structure and a cylindrical specimen with a five layered structure is suggested. Experiments indicate that self-healing of the crack is induced under a water pressure of 300 kPa. The maximum of the flow rate through the sample before the occurrence of self-healing of the crack (critical flow rate) is different in different experiments. The critical flow rate increases with increase in crack depth and the value of $D_{15}/d_{85.}$ The clogging of inflow part of outflow filter due to accumulation of transported particles may be the main reason why a reduced percolation rate is observed in these experiments.

V. Conclusions

Hydraulic fracturing in core of earth and rockfill dam depends upon the following factors:

1. Properties of core materials, greater the cohesion lesser the chances of hydraulic fracturing
2. Density of core materials and compacting effort used for compaction in construction of core in earth and rockfill dams i.e. more the compacting effort lessen the chances of hydraulic fracturing
3. Stress conditions of core materials during first filling of earth and rockfill dam
4. Increasing any of Young's Modulus to control of hydraulic fracturing
5. Control of placement water content in core

References

[1] Djarwadi, D., Suryolelono, K.B., Suhendro, B., and Hardiyatmo, H.C. 2009: Failure Criterion of Soils during Hydraulic Fracturing Test. Proceedings 1st International Conference on Sustainable Infrastructure and Build Environment in Developing Country. Bandung 2 -3 November 2009. pp: G.30-G.35
[2] Fenton G. A., Griffiths D. V. (1997). Extreme hydraulic gradient statistics in stochastic earth dam. Journal of Geotechnical and Geoenvironmental Engineering, 123(11): 995–1000
[3] Hassani, A. Wahed, Bharat Singh, S S Saini and M C Goel. 1985. "Laboratory simulation of hydraulic fracturing." 9th ICSMFE, Los Angles.
[4] Justo, J. L.973. "The cracking of earth and rockfill dams." 11th ICOLD Congress, Madrid, v Independent Panel to Review Cause of the Teton Dam Failure. 1976: Report to US
[5] Jaworski G. W., Duncan J. M. and Seed H. B (1981). Laboratory study of Hydraulic Fracturing, J. Geotech. Engrg. Div., ASCE, Vol.107, No.GT6, June, PP713–732
[6] Department of the Interior and the State of Idaho on Failure of Teton Dam. US Government Printing Office. Washington DC. Lo, K. Y., and Kaniaru, K. 1990: Hydraulic Fracture in earth and rockfill dams. Canadian Geotechnical Journal. Vol 27. No 4. pp 496-506. vol. IV.
[7] Independent panel to review cause of Teton dam failure (1976). Report to U.S. Department of the Interior and the State of Idaho on Failure of Teton dam, U.S. Bureau of Reclamation, Denver, Colo., Dec.
[8] Huang Wenxi (1982). Several views on research of embankment dams. Water Resources and Hydropower Engineering, 4: 23–27
[9] Hydraulic fracture in earth and rock-fill dams, 1990, K. Y. Lo, Kiny Kaniaru, *Canadian Geotechnical Journal*, 27(4): 496-506
[10] Jaworski, G. W,. J. M. Duncan and H. B. Seed. 1981. "Laboratory study of hydraulic fracturing." Journal. Geotech. Divn. ASCE. June.
[11] Jaworski, G. W., Duncan, J. M. and Seed, H. B.: Laboratory study of hydraulic fracturing, Proc. ASCE, 107 (GT6), 713-732, 1981 [in Japanese]
[12] Kuthway, F. M. and T. M. Gurtowsky. 1976. "Load transfer and hydraulic fracturing in zoned dams." Journal. Geotech. Divn. ASCE. September.
[13] Li Jinhui, Wang Yuan, Hu Qiang (2006). Probability analysis of seepage failure of embankments based on stochastic finite element method[J]. Rock and Soil Mechanics, 27(10): 1847–1850
[14] Lo K.Y., Kaniaru K (1990). Hydraulic fracture in earth and rock-fill dams, Can. Geotech. J., Vol.27, No.4, pp496–506
[15] Mori, A. and Tamura, M.: Hydrofracturing pressure of cohesive soils, Journal of the Soils and Foundations, 27 (1), 14-22, 1987

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[16] Ohne, Y.: Failure causes of Embankment Dams, Proceeding of the 9th Asian Regional Conference on Soil Mech. and Found. Engineering, Bangkok, 1991

[17] Phoon K.-K., Kulhawy F. H (1999). Characterization of geotechnical variability. Canada Geotechnical Journal, 36: 612–624

[18] Seed, H. B. and J. M.Duncan 1981. "The Tendon dam failure – A retrospective review". 10th ICSMFE. Stockholm, Sweden, vol. 4.

[19] Teton Dam Failure Interior Review Group: First interim report on the Teton Dam Failure, 1976

[20] Vaughan, P. R.: The use of hydraulic fracturing tests to detect crack formation in embankment dam cores-Initial report, Department of Civil Engineering, Imperial College, London, 1971

[21] Leonards, G. A. and Narian, J.: Flexibility of clay and cracking of earth dams, J. Soil Mech. Found. Div., ASCE, 89 (SM2), 47-98, 1963

[22] Vaughan, P. R., Kuth, D. J., Leonard, M. W. and Pradoura, H. H. M.: Cracking and erosion of the rolled clay core of Balderhead Dam and the remedial works and adopted for its repair. 10th ICOLD, Montorial, 73-93, 1970

[23] Neuman, S. P.: Saturated unsaturated seepage by finite elements, Proc. ASCE, HY, 99 (12), 2233-2250, 1973

[24] Nobari, E. S. and Duncan, J. M.: Effect of reservoir filling on stress and movements earth and rockfill dams, Geotecnical Engineering Report, No. TE-72-1, Univ. of California, Berkeley, 1-198, 1972

[25] U. S. Department of the Interior Teton Dam Failure Review Group: Failure of Teton Dam, 1977

[26] U. S. Department of the Interior Teton Dam Failure Review Group: Failure of Teton Dam, 1977

[27] Hydraulic fracturing in earth and rockfill dam, 2014, Jun Jie Wang, John Wiley and Sons, Singapore.

[28] Loftquis, B. 1951: Earth pressure in a thin impervious core. Transaction 4th International Congress on Large Dams. New Delhi. Vol 1. Pp 99- 109.

[29] Kjaernsli, B., and Toorblaa, I. 1968: Leakege through horizontal cracks in the core of Hyttejuvet dam. Norwegian Geotechnical Institute. Publication no. 80. pp 39-47.

[30] Sherard, J. L. 1973: Embankment Dam Cracking. In Embankment Dam Engineering-The Casagrande Volume. New York. John Wiley & Sons.

[31] Sherard, J. L., and Dunnigan, L. P. 1989: Critical Filter for Impervious Soils. Journal of Geotechnical Engineering Division. ASCE. Vol 115. No GT7. pp 927-947.

[32] Vestad, H. 1976: Viddalsvatn dam, a history of leakages and investigations. Transactions of 12th International Congress on Large Dams. Mexico. Vol 2. pp 369-390.

[33] Vaughan, P. R., Kluth, D. J., Leonard, M. W., and Pradoura, H. M. M. 1970: Cracking and erosion of the rolled clay core of Balderhead dam and the remedial works adopted for its repair. Transaction of 10th International Congress on Large Dams. Montreal. Vol 3. pp 73-93.

[34] Wu Qingxi, Lu Tairen, Wu Shiwei (1987). Computation of the structural reliability index with correlated random variables. Applied mathematics journal of Chinese universities, 2(3): 323–329

[35] Wu Qingxi, Lu Tairen, Wu Shiwei (1987). Computation of the structural reliability index with correlated random variables. Applied mathematics journal of Chinese universities, 2(3): 323–329

[36] Widjaja, H., Duncan, J. M., and Seed, H. B. 1984: Scale and Time effects in hydraulic fracturing. Miscellaneous Paper GL-84-10. US Army Engineers Waterways Experiment Station. Vicksburg, MS.

[37] Zeng Kaihua (2000). Study on the mechanism and influencing factors of hydraulic fracturing in earth core rockfill dam. Ph.D. thesis, Hohai university, Nanjing, China

[38] Zhang Wohua, Fang Zhongjiang, Ren Tinghong (2005). Reliability analysis for seepage burst of Jiujiang dike on Changjiang river. Journal of Zhejiang University (Engineering Science), 39(7):976–982

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