Risk of Embankment Dam Failure from Viewpoint of Hydraulic Fracturing: Statistics, Mechanism, and Measures

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ABSTRACT

Dams and reservoirs are artificial structures built to actively and effectively manage and exploit water resources. However, dam failures may induce catastrophes that often threaten human life and all socio-economic activities. Among the causes of dam failures, hydraulic fracturing is considered to be one of the most probable as it brings about concentrated leakage that results in the failures or incidents of fill dams, especially at the first reservoir filling. This paper focuses on reviewing studies on the mechanism of hydraulic fracturing in embankment dams. The statistics for many dam failures and incidents related to hydraulic fracturing are provided. Some measures for preventing hydraulic fracturing are also reviewed. Based on the review, a summary of incidents and failures related to hydraulic fracturing in embankment dams is given and possible future studies are discussed.

Keywords

dam failure, dam incident, embankment dam, hydraulic fracturing

1. Introduction

Dams and their reservoirs are artificial structures that are constructed to exploit and manage water resources (Stematiu, 2006). They have significant meaning in terms of the socio-economic development of each country and region because they not only protect the downstream lands against the ravages of floods, but they also supply water for multi-purposes such as irrigation, drinking water, and hydropower. Nowadays, the risks of floods and droughts are becoming global problems due to the effects of climate change and the unsustainable exploitation or management of water resources (Lehner *et al.*, 2006; Van Aalst, 2006; Zhang *et al.*, 2009; Piao *et al.*, 2010; Urama and Ozor, 2010). Hence, dams and their reservoirs are becoming more important and are thought to be active and effective solutions for managing water resources.

In cases of failures, however, dams and reservoirs can lead to catastrophes that even threaten human life and all socio-economic activities (Independent Panel to Review Cause of Teton Dam Failure, 1976; Charles, 2011; Fu *et al.*, 2018). Among the causes of dam failures, hydraulic fracturing is considered to be one of the most possible as it brings about concentrated leakage that results in the incidents or even failures of embankment dams, especially at the first reservoir filling (Sherard, 1986; Ngambi *et al.*, 1997; Nishimura *et al.*, 1998; Ng and Small, 1999; Haeri and Faghihi, 2008; Ghanbari and Rad, 2015; Khanna and Chitra, 2016; Salari *et al.*, 2018). Nevertheless, a perfect

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agreement has not yet to be made on the hydraulic fracturing phenomenon and knowledge related to it. For example, the exact mechanism for crack initiation and propagation by hydraulic fracturing in embankment dams is still not sufficiently understood. As a result, the measures for preventing hydraulic fracturing from occurring in embankment dams are still controversial. This paper aims to review the investigations of hydraulic fracturing in soil and embankment dams from theoretical studies, the results of experiments on hydraulic fracturing, and statistical data on dam failures or dam incidents related to hydraulic fracturing, and to review the studies on possible measures against hydraulic fracturing in embankment dams. Some potential studies for the future are then recommended.

2. Hydraulic fracturing in embankment dams

2.1 Mechanism of hydraulic fracturing in embankment dams

Hydraulic fracturing is generally described as the process under which cracks are induced in soils or rocks and then propagated by water pressure (Jaworski *et al.*, 1981; Mhach, 1991). This process is commonly applied by the oil industry to enhance the permeability of the near-well region of oil and gas reservoirs (Murdoch, 1993a, 1993b, 1993c; Poudel *et al.*, 2017). It is also encountered in engineering applications such as drilling into foundations and grouting for foundation improvements (Xu *et al.*, 2015). Recently, after the failures of many embankment dams, in which hydraulic fracturing is considered to have been the most probable cause, much more attention has been paid by researchers in both engineering and academia to gain insight into the mechanism of hydraulic fracturing.

In a study of the possible causes of many embankment dam incidents, Sherard (1986) briefly elucidated the basic mechanism by which hydraulic fracturing creates concentrated leakage in embankment dams. The study revealed that, due to some situations of differential settlements, arching action, or desiccation, cracks (both visible and invisible) are formed in the dam body. At the same time, such phenomena (i.e., differential settlement, arching action, and desiccation) also lead to the redistribution of internal stress in some local zones in embankment dams. In such zones, the minor principal stress is reduced to nearly zero or even tensile stress. These zones are called low-stress zones or loose zones.

When filling a reservoir, the water level of the reservoir rises up, and subsequently, the water pressure in the embankment dam increases. In low-stress zones, the water pressure becomes higher than the minor principal stress. Under this condition, the seepage in the dam enter into the existing cracks (even invisible cracks) that formed previously, and then induce stress concentration at the crack tips. The stress conditions in the embankment are then changed, and the cracks open or expand to wider ones. Ngambi *et al.* (1998) also explained a similar mechanism for the propagation of pre-existing cracks in embankment dams by water pressure. The explanation states that as the tensile strength of soil is very small, cracks easily propagate through embankments, resulting in the failure of many dams.

To predict or evaluate the risk of hydraulic fracturing in an embankment dam, a simple criterion of comparing total minor principle stress (σ_3) at a certain point with the water pressure (W) at such a point can be applied. The hydraulic fracturing phenomenon is considered to occur when it meets the equation as follows (Jaworski *et al.*, 1981; Sherard, 1986; Ngambi *et al.*, 1997; Nishimura *et al.*, 1998; Ng and Small, 1999; Nayebzadeh and Mohammadi, 2011; Tran *et al.*, 2018a, 2018b):

$$\sigma_3 < W \quad (1)$$

where total minor principle stress (σ_3) in the embankment dam could be determined by in-situ monitoring or by numerical simulations; and water pressure (W) at a certain point in the embankment dam is calculated by the equation as follows:

$$W = \gamma_w \cdot h_w \quad (2)$$

in which γ_w is the unit weight of water and h_w is the vertical deep from the phreatic line of the embankment dam to such a certain point.

2.2 Controversial aspects of the theory of hydraulic fracturing in embankment dams

Even though much understanding of the hydraulic fracturing phenomenon of soil has been achieved, the exact mechanism of this phenomenon is still controversial. For example, while one viewpoint supposes that cracks expand under a shear mode (Vaughan, 1971; Mori and Tamura, 1987; Panah and Yanagisawa, 1989; Yanagisawa and Panah, 1994), many investigations suggest that the propagation of the initial cracks occurs under a tensile mode (Torblaa and Kjoernsli, 1968; Bjerrum *et al.*, 1972; Nobari *et al.*, 1973; Jaworski *et al.*, 1981; Savvidou, 1981; Ngambi *et al.*, 1998; Nishimura and Shimizu, 2004; Nishimura, 2005). On the other hand, other studies (Wang *et al.*, 2007, 2009; Wang and Liu, 2010) suggest that the cracks propagated by hydraulic fracturing sometimes occur under a mixture of both shear and tensile modes.

Another controversy is related to the role of pre-existing cracks in embankment dam incidents resulting from hydraulic fracturing. Torblaa and Kjoernsli (1968) supposed that there are no open cracks in embankment dams before the occurrence of hydraulic fracturing during the impounding of their reservoirs. In a study by Mori and Tamura (1987) using laboratory tests, the investigators concluded that the effect of pre-existent cracks on hydraulic fracturing pressure was negligible. On the other hand, many investigations have pointed out the vital role of existing discontinuities, such as cracks and zones of loose soil, in the initiation of hydraulic fracturing in soil samples and embankment dams. Sherard (1973) pointed out the substantial evidence of the existence of cracks that may sometimes be very narrow and invisible in embankment dams even when the dams have been constructed well by experienced engineers and based on excellent designs. This evidence has led to the conclusion that hydraulic fracturing in fill dams is, in fact, due to the propagation of existing cracks. Jaworski *et al.* (1981) suggested that hydraulic fracturing occurs only if there are some discontinuities. The important role of the initial cracks in the initiation of hydraulic fracturing has also been confirmed in many subsequent studies by Ngambi *et al.* (1998) and Nishimura and Shimizu (2004).

Even though there have been some controversies on the role of the initial cracks, in terms of the occurrence of hydraulic fracturing in embankment dams, many studies have concluded the importance of pre-existing cracks (Torblaa and Kjoernsli, 1968; Bjerrum *et al.*, 1972; Nobari *et al.*, 1973; Jaworski *et al.*, 1981; Savvidou, 1981; Ngambi *et al.*, 1998; Nishimura and Shimizu, 2004; Nishimura, 2005; Wang *et al.*, 2007, 2009; Wang and Liu, 2010). It can be said that, therefore, two vital conditions are governing the initiation of hydraulic fracturing in embankment dams. The first one is the condition under which the stress in some local zones of embankment dams is reduced, facilitating the development of hydraulic fracturing. The second is the existence of cracks in dams that play a role as the initial cracks of hydraulic fracturing.

3. Differential settlement and arching action in embankment dams

3.1 Relationship between hydraulic fracturing and phenomena of differential settlement and arching action

Hydraulic fracturing is thought to be closely related to the phenomena of differential settlement and arching action (Zhu *et al.*, 2015). In embankment dams, the phenomenon of differential settlement often occurs in the zones between the fill soil and the dam abutments, the fill soil and the concrete structures, such as culverts and spillways,

the impervious cores and their shoulders, and the cut-off seepage trenches and the abutting foundations (Ngambi *et al.*, 1997; Tran *et al.*, 2018a, 2018b). In these zones, as the materials have different elastic moduli, the materials will settle differentially and the stress at the zones may decrease to zero or even to tension. The reduction of stress due to differential settlement in some local zones in embankment dams is called the arching action phenomenon. Under this condition, the criterion in equation (1) is met. At the same time, because of the decrease in stress in such zones by arching action, some discontinuities such as cracks can form. It can be said that the decrease in stress along with the formation of cracks create the conditions that facilitate the initiation of hydraulic fracturing when a dam's reservoir is filled even at the first impounding.

3.2 Differential settlement and arching action near dam abutments

Figure 1 shows the condition under which cracks occur near a steep abutment of a rigid rock foundation due to the phenomena of differential settlement and arching action. One of the earliest investigations that considers the effects of the slope of dam abutments as well as the foundation deformation on the formation of zones of low stress and tensile cracks in embankment dams was conducted by Casagrande (1951) using finite element analyses. Subsequent studies by Covarrubias (1969), Kulhaway *et al.* (1969), Casagrande and Covarrubias (1970), Hoeg *et al.* (1995), Bui *et al.* (2004) and He *et al.* (2014) also revealed conclusions similar to those of the early study by Casagrande (1951), namely, that the existence of a steep rigid rock abutment or abrupt irregularities can be important factors leading to the occurrence of zones of low stress or even tensile stress. As a result, tensile cracks are formed in these zones. The failures of Upper Clear Boggy Site 50 dam (USA), Stockton Creek dam (USA) (as reported by Sherard (1973)), and Teton dam (USA) in the study of Seed (1981) are thought to be related to the arching action and hydraulic fracturing near the dam's abutments.

Figure 1: Dam longitudinal section - Formation of zones of low stress and cracks near a culvert and steep abutment in an embankment dam

3.3 Differential settlement and arching action near dam culvert

In another case, illustrated in Figure 1, the zones of low stress and cracks are formed near a boxed-concrete culvert due to the effects of the phenomena of differential settlement and arching action. This occurrence has been confirmed in many past investigations using both theoretical methods and analyses of laboratory or in-situ tests (Casagrande and Covarrubias, 1970; Sherard, 1973; Ngambi *et al.*, 1997; Kobayashi *et al.*, 2012). The phenomena thereby facilitate the occurrence of hydraulic fracturing along the buried conduits in embankment dams. Concentrated leakage occurring along the conduits due to hydraulic fracturing, leading to the failures of many dams, has been recorded. In such dam failures, both Ngambi *et al.* (1997) and Sherard (1972) considered hydraulic

fracturing to be the most probable cause that might have resulted from decreasing the normal stress on the sides of the buried embankment dams' culverts by arching action.

In addition, Sherard (1973) also supposed that it is very difficult to compact the fill soil perfectly so that there are no gaps or discontinuities on the interface between the embankment fill soil and the materials of the culverts or the dam abutments, for example, when the culvert is in an unsuitable shape (such as pipe or box shape) or the abutments are very steep. Therefore, some gaps or discontinuities may exist that play the role of the initial cracks for the occurrence of hydraulic fracturing. Consequently, the risk of hydraulic fracturing becomes higher than that in the cases of embankment dams having suitable culvert shapes. Furthermore, a combination of both factors — an unsuitable culvert shape and steep dam abutments — increases the severity of arching action and the potential for hydraulic fracturing adjacent to culverts (Tran *et al.*, 2018a).

Figure 2: Dam cross-section —Formation of zones of low stress and cracks in the dam's impervious core and cut-off seepage trench

3.4 Differential settlement and arching action in dam's impervious core and cut-off seepage trench

Figure 2 displays the mechanism of the formation of cracks in the impervious cores and core trenches due to the occurrence of differential settlement and arching action between the cores, trenches, and their shoulders. It is common that the compressibility of the impervious cores and core trenches is often much higher than that of the core shoulders, especially at rock-fill dams with impervious cores of clay erected on rock foundations (Nayebzadeh and Mohammadi, 2011; Zhu *et al.*, 2015; Ghafari *et al.*, 2016). Due to the effects of differential settlement and arching action, the cracks readily form and propagate due to the hydraulic fracturing through the cores and trenches. This mechanism is thought to be related to the incidents of many earth rock-fill dams, especially historical dams designed with very narrow impervious cores and narrow cut-off seepage trenches, built to decrease the pore-water pressure during construction, such as the cases of Dale Dyke dam (England), Hyttejuvet dam (Norway), Balderhead dam (England), and Yard's Creek Upper Reservoir dam (USA), as discussed in the studies of (Binnie, 1978; Sherard, 1986; Ng and Small, 1999; Haeri and Faghihi, 2008; Khanna and Chitra, 2016).

3.5 Differential settlement and arching action due to other causes

Some zones of low stress and cracks also occur in embankment dams by differential settlement resulting from the existence of a highly compressible layer in the dam foundation, as shown in Figure 3 (Narita, 2000). However, the risk of the formation of these kinds of cracks can be diminished considerably by conducting thorough geological investigations before construction. Moreover, embankment shrinkage, insufficient compaction, and earthquakes can be other factors related to crack initiation anywhere in the embankments. It is also possible that more than one of these factors may be combined with the mechanisms of differential settlement cracking presented previously to make tension and cracking zones more severe and to facilitate the occurrence of hydraulic fracturing.

Figure 3: Dam longitudinal section —Formation of zones of low stress and cracks due to the existence of a highly compressible layer in the dam foundation

4. Dam failures and dam incidents under hydraulic fracturing mechanism

Based on statistical data, the investigations of (Babb and Mermel, 1968; Jansen, 1983; Foster *et al.*, 2000; Stematiu, 2009; Charles, 2011) have suggested that internal erosion caused by seepage or concentrated leakage is one of two dominant causes leading to embankment dam failures or incidents along with overtopping. Among the mechanisms inducing internal erosion, hydraulic fracturing has been considered as the most probable one (Sherard, 1986; Lo and Kaniaru, 1990; Murdoch, 1993a, 1993b, 1993c). This section provides the statistical databases for 36 dam failures or dam incidents in the world (as shown in Table 1) in which the causes of such failures or incidents are thought to be associated with hydraulic fracturing. Table 1 may not be able to summarize all dam incidents because of the fact that many other dam failures or incidents occurred, but could not be recorded. In many cases mentioned in Table 1, the causes of the dam incidents or failures were concluded to be related to hydraulic fracturing. In some cases, however, the exact causes are still controversial. Nevertheless, the current author infers that hydraulic fracturing might be a possible cause due to the fact that, in such cases, the locations of the incidents or failures were in the zones that are susceptible to cracking and hydraulic fracturing, as discussed in the previous sections.

Notably, most of the dam failures and incidents occurred at the first filling of their reservoirs (in 28 of the 36 cases), as shown in Figure 4 and Table 1. To explain this trend in dam failures and incidents, (Ngambi *et al.*, 1998) relied on the theory of fracture mechanics and the results of laboratory tests to suggest that the resistance of disturbed soil specimens to hydraulic fracturing (corresponding to the resistance of embankment dams to hydraulic fracturing soon after the completion of their construction) was very low and much smaller than that of undisturbed soil specimens. Therefore, it is seen that dams at the early stages after construction are more susceptible to hydraulic fracturing than dams that have been in operation for a long time.

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Figure 4: Distribution of dam incidents according to the time of the incidents

Table 1: Statistics for dam incidents or failures related to hydraulic fracturing

Dam name - Country	Year of completion	Year of incident or failure	Location of incident	Reference
Blackbrook - UK	1797	1799	Near narrow cut-off seepage trench	Kennard, 1972; Binnie, 1987; Skempton, 1989
Redmires Lower - UK	1849	1850	Near culvert	Binnie, 1981; Claydon and Reilly, 1996; Swales, 1932
Bilberry* - UK	1845	1841;1843;1852	Near narrow cut-off seepage trench and culvert	Binnie, 1981
Rhodeswood - UK	1852	1858	Near narrow impervious core	Binnie, 1981; Skempton, 1989
Doe Park - UK	1861	1863	Near narrow cut-off trench and culvert	Binnie, 1981; Skempton, 1989
Dale Dyke - UK	1863	1864	Near narrow impervious core and cut-off seepage trench	Skempton, 1989
Grizedale - UK	1866	1867	Near narrow cut-off seepage trench	Skempton, 1989
Walshaw Dean Lower - UK	1907	1907	Narrow cut-off seepage trench	Barnes, 1927; Charles, 1990; Skempton, 1989; Tedd <i>et al.</i> , 2002
Walshaw Dean Middle - UK	1907	1907	Near narrow cut-off seepage trench, narrow impervious core, and culvert	Barnes, 1927; Robertshaw <i>et al.</i> , 1998; Wood, 1946
Coulter - UK	1908	1912	Near narrow impervious core	Charles, 1990; Gallacher, 1988
Balderhead - UK	1964	1967	Near narrow impervious core	Vaughan, 1971
Winscar - UK	1975	1976-1980	Near dam's abutment and culvert	Routh, 1988
Horndoyne - UK	1990	1990	Near culvert	Charles, 2005

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Table 1: Statistics for dam incidents or failures related to hydraulic fracturing (continued)

Dam name - Country	Year of completion	Year of incident or failure	Location of incident	Reference
Roddlesworth Upper - UK	1865	1904	Near narrow cut-off seepage trench	Binnie, 1981; Skempton, 1989
Warmwithens - UK	1870	1970	Near culvert	Wickham, 1992
Greenbooth - UK	1962	1983	Near dam's abutment	Flemming and Rossington, 1985
Carno Lower - UK	1911	2005	Near culvert	Rowland and Powell, 2006
Upper Clear Boggy Creek Site 50 - USA	1970	1970	Near the abrupt change in the dam's foundation	Sherard, 1972
Leader Middle Clear Boggy Creek Site 33 - USA	1963	1969	-	Sherard, 1972
Leader Middle Clear Boggy Creek Site 15 - USA	1965	1966; 1968	Near cut-off seepage trench	Sherard, 1972
Upper Red Rock Creek Site 42 - USA	1966	1967	Near culvert	Sherard, 1972
Caney Coon Creek Site 2 - USA	1964	1964	Near culvert	Sherard, 1972
Upper Red Rock Creek Site 48 - USA	1964	1964	Near culvert	Sherard, 1972
Upper Clear Boggy Creek Site 53 - USA	1963	1964	Near culvert	Sherard, 1972
Cherokee Sandy Creek Site 8A - USA	1963	1964	In cracking-loose zone formed by desiccation	Sherard, 1972
Little Wewoka Creek Site 17 - USA	1960	1960	Near culvert	Sherard, 1972
Owl Creek Site 13 - USA	1957	1957	Near culvert	Sherard, 1972
Owl Creek Site 7 - USA	1957	1957	Near culvert	Sherard, 1972
Wister - USA	1948	1949	At closure section and irregular foundation surface	Sherard, 1972
Leader Middle Clear Boggy Creek Site 29 - USA	1962	1970	Near culvert	Sherard, 1972
Hyttejuvet - Norway	1965	1966	Near narrow impervious core	Torblaa and Kjoernsli, 1968
Teton - USA	1975	1976	Near narrow cut-off seepage trench and steep dam's abutment	Independent Panel to Review Cause of Teton Dam Failure, 1976
Stockton Creek - USA	1850	1850	Near steep dam's abutment	Sherard, 1973
Viddalsvatn - Norway	1972	1973	Near impervious core	Vestad, 1976
Yard's Creek Upper Reservoir - USA	1965	1965	Near narrow impervious core and Irregularities in the dam's foundation	Sherard, 1973
KE 2/20 REC - Vietnam	2008	2009	Near culvert and steep dam's abutment	Nguyen and Ho, 2009; Tran <i>et al.</i> , 2018a

Note: * In the case of Bilberry dam, even though the cause of the dam failure in 1852 was concluded to be overtopping, hydraulic fracturing was also thought to be a possible cause of the internal erosion that led to the dam settlement in advance of the dam failure.

** Keywords: dam incidents, dam failure, hydraulic fracturing, internal erosion

5. Measures to reduce the risks of hydraulic fracturing

It is clear that the occurrence of hydraulic fracturing in an embankment dam is serious and may even threaten the safety of the dam. As a result, consideration of measures to prevent or to provide a precaution against the risks of dam incidents due to hydraulic fracturing is truly necessary. Towards that purpose, Sherard (1992) suggested that a well-designed filter is of primary importance and that other measures to reduce differential settlement cracks are of secondary importance. A suitable filter (as shown in Figure 5) is one that is able to safely control concentrated leaks due to not only the classical-mechanical erosion mechanism but also the hydraulic fracturing mechanism. A study of Ngambi *et al.* (1998), based on the results of laboratory tests, also verified the importance of the filter in preventing hydraulic fracturing because of its function as a stopper of crack propagation. A recent publication by Wang (2014) also confirmed this advantage of filter zones. Nowadays, a suitable filter is considered a requirement among the standards of design and construction of embankment dams in many countries.

For the sake of decreasing the potential for differential settlement cracks in embankment dams, and reducing the risk of hydraulic fracturing, the study of Sherard (1992) recommended some measures. Firstly, for hydraulic fracturing occurring near the abutments of embankment dams, Sherard suggested excavating the abutments to make flatter slopes and to eliminate abrupt changes or irregularities in the dam abutments or dam foundations (as shown in Figure 6). The purpose of this measure is to reduce the risk of arching action near the dam abutments that result in cracks and tensile zones in the embankments. Subsequent studies by Hoeg *et al.* (1995) and He *et al.* (2014) also verified the efficiency of this measure.

Secondly, to prevent hydraulic fracturing from occurring adjacent to the dams' culverts, Sherard advised that other culvert shapes be applied in practice. The recommended culvert shapes should have slightly slanted outer surfaces. In particular, Sherard (1992) and Ngambi *et al.* (1997) suggested culverts with slanted outer slopes in the ratio of one in the horizontal direction to eight or ten in the vertical direction (i.e., the gradient of the outer slanted walls of 0.1 to 0.125). Nowadays, among the many standards for the design and construction of buried culverts in embankment dams being used in developed countries (Japan and USA), it is also recommended that buried culverts have outer slanted walls with a gradient of 0.1 to 0.3 (as illustrated in Figure 7) (Japan Highway Corporation, 1992; FEMA, 2005). Recent studies by Tran *et al.* (2018a, 2018b) have suggested a critical gradient of the slanted walls of at least 0.4. Many investigations have concluded that changing the culvert shape is a generally accepted and effective measure for preventing the risk of hydraulic fracturing from occurring near the culverts of embankment dams (Ngambi *et al.*, 1997; Sherard, 1992; Tran *et al.*, 2018a, 2018b) because changing the shape not only brings efficiency in reducing arching action but also helps facilitate the compaction of fill soil against the exterior surfaces of the culverts. However, there have been controversies regarding the final conclusions for the critical gradient of the outer slanted walls of buried culverts. Also, the previous investigations were often conducted for certain case studies (Tran *et al.*, 2018a, 2018b) or for cases which did not consider the effects of the combination of more than one factor that lead to arching action and the potential for hydraulic fracturing near the culverts to be more severe, such as the arching action resulting from the combination of both an unfavorable culvert shape and a steep dam abutment (Ngambi *et al.*, 1997; Sherard, 1992). Therefore, more studies must be conducted on this measure to perfectly prevent hydraulic fracturing adjacent to the culverts of embankment dams, such as analysing the risk of hydraulic fracturing in the embankment dam under combined effects of many factors or evaluating the risk of hydraulic fracturing on the viewpoint of safety factor (FS).

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Figure 5: Dam cross-section —Current trend of embankment dam design with a wide thickness of impervious core and filter

Thirdly, to reduce the arching action and to control the hydraulic fracturing occurring in the impervious cores and the cut-off seepage trenches, (Sherard, 1973) also suggested changing their shapes by using more slanted slopes. It was common that the impervious cores and cut-off seepage trenches of embankment dams in the 18th and 19th centuries in England were often designed and constructed with very narrow thicknesses (Charles, 2011). Therefore, the dams were very susceptible to arching action and hydraulic fracturing. As a result, many dams experienced incidents or even failures, as shown in Table 1. In the current trend, the dams with impervious cores and trenches often have wider thicknesses (as shown in Figure 5). Recent studies by Nayebyzadeh and Mohammadi (2011), Ghafari *et al.* (2016), and Djarwadi *et al.* (2017) have also verified the advantages of this measure to control hydraulic fracturing occurring in the impervious cores and trenches of embankment dams.

For measures against hydraulic fracturing, many achievements have been made based on earlier studies. However, the outcomes of such studies are still far from perfect. Therefore, more comprehensive studies on measures against hydraulic fracturing in embankment dams are still important tasks to accomplish.

Figure 6: A part of dam longitudinal section —Measure to reduce risk of hydraulic fracturing occurring near unfavorable dams' abutments

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Figure 7: Current common culvert shape in an embankment dam in Japan with outer slanted walls with gradient of 0.1

6. Conclusions

The aim of this paper was to review the previous studies on hydraulic fracturing that is thought to be the cause of many embankment dam incidents or failures. Based on this review, the following conclusions are drawn:

(1) According to the statistics on the dam failures and dam incidents that were thought to be related to the hydraulic fracturing phenomenon, it has become obvious that embankment dams truly have the potential for incidents due to hydraulic fracturing especially at the first filling of the reservoirs in the cases of the dams with unfavorable conditions, such as unsuitable culvert shapes, steep dam abutments, irregularities on the dam abutments or foundations, very narrow impervious cores or impervious trenches. Consequently, considerations must be given to effective measures for reducing the risks of dam incidents due to hydraulic fracturing from the design and construction stages; this will play an important role in dam safety.

(2) Even though many studies have been focused on measures for safely controlling the risk of dam incidents due to hydraulic fracturing and many measures have been recommended, the effectiveness of some of the measures has been poorly proved or has not obtained perfect agreement. Therefore, it is necessary to study the measures more closely to improve dam safety against hydraulic fracturing.

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