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EFFECTS OF CULVERT SHAPES ON POTENTIAL RISK OF HYDRAULIC FRACTURING ADJACENT TO CULVERTS IN EMBANKMENT DAMS

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ABSTRACT: Hydraulic fracturing is generally considered as one of the most probable causes of dam failures and concentrated leakage occurring adjacent to the outlet conduits in embankment dams. It is thought that hydraulic fracturing will occur in a fill dam when the stress in the dam is reduced to levels that are lower than the water pressure, causing the subsequent propagation of cracks in the dam body. This phenomenon might be closely related to the arching action which occurs around the culverts due to the effects of the culvert configurations. The aim of this study is to investigate the effects of culvert shapes on the potential for hydraulic fracturing close to culverts in fill dams using the finite element method. Many numerical analyses are taken here to determine the stress distributions around culverts with various shapes. The possibility of hydraulic fracturing is then predicted by comparing the values of normal stress and water pressure. The results reveal that there is a probable risk of hydraulic fracturing occurring adjacent to box-shaped culverts in embankments. In addition, box-shaped culverts with inclining chamfers or arc-chamfers on the culvert top also have a similar potential for hydraulic fracturing because the chamfers have a negligible effect on the stress on the sides of the culverts. However, in culverts with slanted walls, that have a gradient for the slanted walls equal to 0.4 or greater, the risk of hydraulic fracturing might be reduced.

Keywords: Hydraulic fracturing, Arching action, Culvert Shape, Dam failure, Finite Element Method (FEM).

1. INTRODUCTION

Hydraulic fracturing is defined as a physical phenomenon in which the cracks in soils or rocks are propagated or expanded by water pressure. This phenomenon is generally considered as one of the most probable causes leading to the concentrated leakage and incidents of many fill dams soon after the completion of the dam's construction [1-2,4-5,7-9,13-14]. In general, to predict the occurrence of hydraulic fracturing at any point in a fill dam, the normal stress of the point is compared with the water pressure at that point [8,14]. If the water pressure is higher than the normal stress, it is thought that hydraulic fracturing has occurred. Previous studies revealed that the risk of hydraulic fracturing increases in cases where the arching action is present [1,4-5,7-9,14]. Due to this arching action, the stress in fill dams can be reduced to a level lower than the water pressure.

Arching action often occurs among different materials that have different elastic moduli, such as between impervious cores and shoulders, culverts and fill soil or fill soil and foundations. This phenomenon is also thought to be related to the incidents at Teton Dam (USA), Dyke Dale Dam (England), Balderhead Dam (England) and Hyttejuvet Dam (Norway) [1-2,4-5]. In these dams, due to significant differences in elastic moduli between the impervious core and the upstream, downstream gravel zones in the shoulders led to arching action and the formation of horizontal cracks in narrow width parts of the central earth core. During the filling of the above reservoirs, the water levels rose and the cracks were opened by water pressure on the upstream face of the cores. Water pressure induced the concentration of stress at the tips of the cracks. As the tensile strength of soil is very low, the cracks could have been propagated from the upstream face to the downstream face of the cores, resulting in the dam incidents.

On the other hand, it is generally identified that arching action and hydraulic fracturing also occur around the culverts of fill dams where there is a considerable difference in elastic moduli between the culvert materials and the fill soils. According to the results of in-situ observations combined with numerical analyses, a past investigation concluded that hydraulic fracturing is the most likely cause of the concentrated leakage and failure of many low dams along the outlet conduit especially after a heavy rain [8]. A recent study also considered hydraulic fracturing and arching action as causes of the failure at the KE 2/20 REC dam – an agricultural dam in Central Vietnam that broke just under one year after it was put into operation [14]. Furthermore, the dam failures recorded at seven low dams in Oklahoma and three low dams in Mississippi are thought to be related to the occurrence of arching action and hydraulic fracturing close to the conduits of the dams [13].

It is clear that such above-mentioned examples demonstrate the high risk of dam failure due to hydraulic fracturing adjacent to culverts. Hence, proposing countermeasures for reducing the risk of hydraulic fracturing is truly necessary. Culverts utilized in practice generally have a pipe shape, a box shape or a horseshoe shape. Past researches have revealed, however, that using culverts with these shapes brings about the potential risk for inducing arching action and hydraulic fracturing [8,14]. Changing the culvert shape to reduce the risk of hydraulic fracturing close to culverts was discussed in previous studies [8,12,14]. Nevertheless, the effects of the culvert shape on the possibility of hydraulic fracturing have not been clearly or logically addressed. The purpose of this study is to find the relationship between culvert configurations and arching action as well as the risk of hydraulic fracturing adjacent to culverts by using finite element analyses. The results of the simulations suggest some good culvert shapes prevent hydraulic fracturing around the culverts of fill dams, especially those employed in agricultural dams with low to medium heights.

2. DESCRIPTION OF MATERIALS

To investigate the effects of the different culvert shapes on the risk of hydraulic fracturing in fill dams, some background information on a dam failure was utilized here as a case study. The case study dam is called KE 2/20 REC dam; it is located in Central Vietnam and was built for the purpose of creating a storage reservoir for irrigation. Construction of the dam was started in October 2006 and was completed and put into operation in July 2008. The related structures consisted of the main dam (maximum height of 12.5 m), a saddle dam, a spillway (11.2 m width) and a pipe culvert (design flow of 0.037 m^3/s). However, in June 2009 – just under one year after it was put into operation - the dam broke at the location of the pipe culvert [10]. A real image of the dam soon after the failure is shown in Fig. 1.

A recent study has suggested that the cause of the dam failure is associated with the hydraulic fracturing and arching action occurring adjacent to the pipe culvert due to the combined effects of the culvert shape and a steep excavation slope of the dam's foundation [14]. The cross section of the pipe culvert of the dam is given in Fig. 2. By using the finite element method, the previous study revealed that a pipe-culvert shape enables arching action to occur easily. Based on this finding, two countermeasures for reducing the risk of hydraulic fracturing, by changing the culvert shape, were also proposed. Nevertheless, the risk of hydraulic fracturing of box-shaped culverts as well as the effects of both box culverts with slanted walls and the gradient of the slanted walls on hydraulic fracturing have not yet been considered. In this study, the effects of other culvert configurations on the potential risk of hydraulic fracturing in dams are investigated. In this paper, the physicomechanical properties of the fill soil material, the culvert concrete, and the foundation are taken from the previous investigation and are summarized in Table 1.

Fig. 1 KE 2/20 REC dam failure [14]

Table 1 Material properties [14]

a. Fill soil	
Total density (ρ):	2.018 Mg/m^3
Dry density (ρ_d):	1.673 Mg/m^3
Soil cohesion (c):	23.0 kN/m^2
The angle of internal friction	16°47'
The coefficient of permeability	6.247×10^{-5} m/s
Elastic modulus (E):	16800 kN/m^2
Poisson's ratio (v):	0.3
b. Reinforced concrete	
Total density (ρ):	2.45 Mg/m^3
Elastic modulus (E):	2.4×10^7 kN/m^2
Poisson's ratio (v):	0.2
c. Foundation	
Elastic modulus (E):	1.0×10^7 kN/m^2
Poisson's ratio (v):	0.25

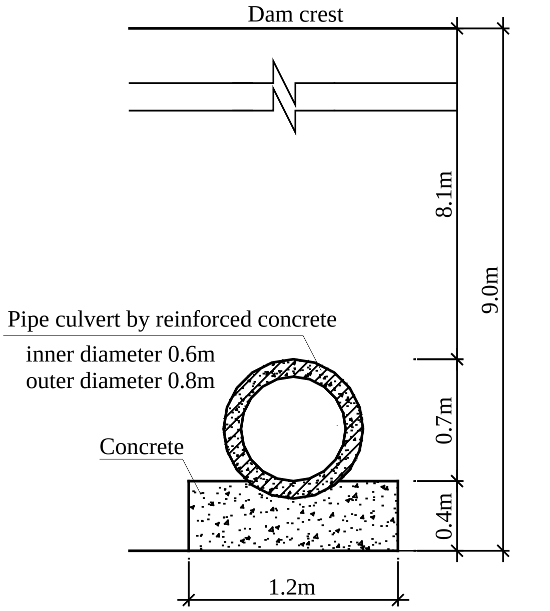

Fig. 2 Cross section of pipe culvert of KE 2/20 REC dam [14]

Figure 3 shows the culvert shapes considered in this study. The dimensions of these culverts, including the height of 1.1 m and the width of 1.2 m, are kept to be similar to those of the pipe culverts (in Fig. 2) in the case study dam. In Fig. 3a, a box-shaped culvert is displayed. In the case of Fig. 3b, the box-shaped culvert (Fig. 3a) is changed by inclining the chamfers (*IG*=1.0) in variations of 0.1 m in the vertical direction and 0.1 m in the horizontal direction. In Fig. 3c, the culvert shape is modified by a combination of inclining chamfers (*IG*=1.0) and slanted walls with a gradient (*G*). The final culvert shape (in Fig. 3d) is a modification of the culvert shape seen in Fig. 3c with the replacement of the inclining chamfers (*IG*=1.0) by the arc-chamfers with the radius of the arc (*r*). In the case of Fig. 3d, the arc-chamfers are adjusted so that they are tangents of the top lines and the slanted walls of the culverts in order to make continuous transitions on the culvert boundary.

3. NUMERICAL ANALYSIS

3.1 Purpose of numerical analysis

The finite element method (FEM) is often utilized in studies of the stress-strain distribution in dams and the earth pressure on buried pipes [6] as well as in investigations of hydraulic fracturing in fill dams [5,7-8,14]. Based on finite element analyses, the stress distribution around a culvert can be determined, after which the possibility of hydraulic fracturing can also be predicted by comparing the stress with the water pressure at corresponding locations. In this paper, therefore, FEM was applied to evaluate the likelihood of hydraulic fracturing around culverts with different configurations (illustrated in Fig. 3). Thereby, the effectiveness of different culvert shapes for preventing hydraulic fracturing was checked, and the shapes that would be effective for reducing the potential of hydraulic fracturing adjacent to the conduits were then suggested for application to the design and construction.

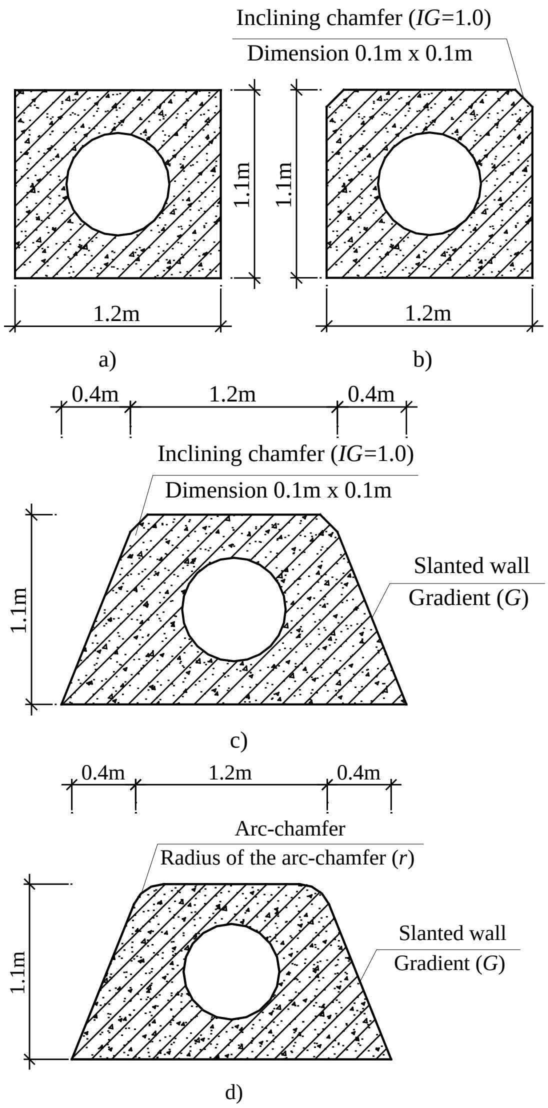

Fig. 3 Culvert shapes calculated in this study

3.2 Model description

The finite element analyses in this study were based on the fundamental theories of linear elastic and plane stress problems. In general, there are two types of two-dimensional problems that are plane stress and plane strain. In this research, it seems that the plane stress problem is more suitable to simulate stress condition around the culverts in the dam. As a result, the essential material properties for the simulations consisted of only the total density (ρ), the elastic modulus (E) and Poisson's ratio (v). In addition, to model the loading process in the construction, the dam body was simulated by six successive layers of fill material and the maximum height of each layer was about 1.5 meters (as displayed in Fig. 4). Past research revealed that the number of simulation layers often has little effect on stress [3]. Therefore, even though simulating the dam with only six layers was not similar to the actual deformation conditions of construction, this number of layers of fill soil was acceptable for determining the stress in the dam. In addition, as the main focus of the analyses was to determine the stress distribution around the culverts and since decreasing the number of simulation layers would help save time, this number of layers of fill soil was deemed acceptable. The simulation algorithm was almost the same as that in a previous study [14].

Figure 4 shows the finite element mesh for a representative case of the culvert shape (Fig. 3d) containing arc-chamfers with a radius of r=0.1 m and slanted walls with a gradient of G=0.4. The other finite element meshes are nearly similar. In these models, because the culvert configurations are symmetrical, only half-culvert sections are included. As seen in Table 1, the elastic moduli of the concrete and the foundation of the culvert are much higher than the elastic modulus of the fill soil. For the sake of simplicity, the deformations of the culvert and the foundation are not calculated for the models here.

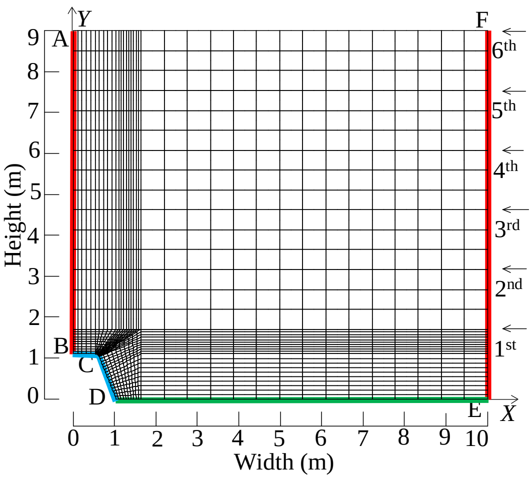

Fig. 4 Finite element mesh in case of r=0.1m and G=0.4 (as in Fig. 3d)

As shown in Fig. 4, the dimensions of the simulated body consist of a height of 9 meters and a width of 10 meters. The model contains 3,836 nodal points and 1,225 elements. The elements close to the culvert are divided into smaller dimensions to increase the accuracy and the details of the normal stress distributions around the culverts. All the elements are eight-node quadratic quadrilateral elements. The nodal points along the periphery of the culvert (B-C-D boundary – the blue line and the blue arc in Fig. 4) are assumed to be fixed absolutely. All nodal points on the contact surface between the embankment and the foundation (DE boundary – the green line in Fig. 4) are constrained to move only in the Y-direction, while the movements of the nodal points on the AB an EF boundaries (the red lines in Fig. 4) are fixed to be zero in the X-direction and are hypothesized to be free in the Y-direction.

4. RESULTS AND DISCUSSION

4.1 Potential for hydraulic fracturing adjacent to box-shaped culverts

Past investigations using experimental observations and numerical analyses revealed a high risk for hydraulic fracturing along outlet conduits in the case of box-shaped and horseshoe-shaped culverts [8]. A recent study also used FEM to show that hydraulic fracturing can occur easily adjacent to pipe culverts [14]. In this section, FEM is used to recheck the decline in normal stress at the sides of a box-shaped culvert (illustrated in Fig. 3a) as well as a box-shaped culvert with inclining chamfers (illustrated in Fig. 3b) resulting from arching action. Simultaneously, the potential for the occurrence of hydraulic fracturing close to the culverts is also verified. The distribution of normal stress minus water pressure (σ_n-W) for such culvert configurations are shown in Fig. 5. Specifically, the values of (σ_n-W) on edges of the elements that were contacted directly between fill soil and the concrete culverts was calculated and was displayed in this figure as well as Figs. 6 to 8. Based on this graphs, the effect of arching action, as well as the risk of hydraulic fracturing around the culverts, might be predicted.

Furthermore, in this study, the water pressure is determined for the case of the water table level being at the dam crest (Fig. 2). This case corresponds to one of the most adverse situations in which there has been heavy rain for many days leading to the complete saturation of the dam body. Under this situation, the risk of hydraulic fracturing might become higher because of the increase in water pressure. This assumption is generally consistent with conditions of the dam failures occurred adjacent to the culverts that were recorded in previous investigations [8,13].

As seen in Fig. 5, the (σ_n-W) distribution is demonstrated in the relationship graphs versus the distance along the culvert periphery (L). This distance is calculated from the origin at the midpoint of the culvert top (similar to point B in Fig. 4). In both cases of culvert shapes, shown in Figs. 3a and 3b, the normal stress on the sides of the culverts are significantly reduced to be really lower than the water pressure due to the effect of the arching action. The maximum value of (σ_n-W) at the sides of the culverts is about -6 kN/m^2. Therefore, it can be concluded that there are actual risks of hydraulic fracturing adjacent to the box-shaped culvert as well as the box-shaped culvert with the inclining chamfers. These results seem to be consistent with the conclusions of past studies [8].

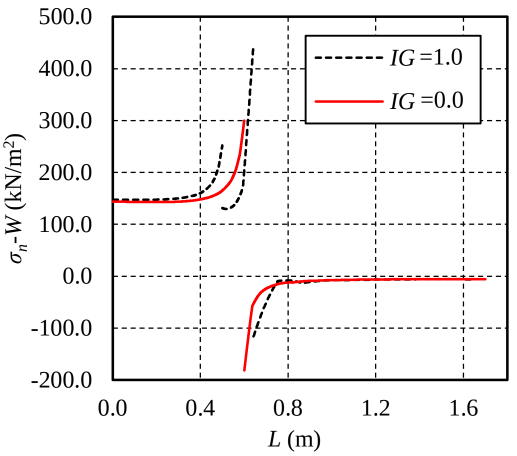

Fig. 5 Distribution of normal stress (σ_n) minus water pressure (W) around box-shaped culvert (Fig. 3a – IG=0.0) and box-shaped culvert with inclining chamfers (Fig. 3b – IG=1.0)

In addition, the results of the numerical analyses reveal that the use of the inclining chamfers led to significant changes in the stress distribution within and close to the scope of the chamfers (L=0.4m ~ 0.8m). The inclining chamfers, however, had a negligible effect on the stress on the vertical walls of the culverts. As indicated in Fig. 5, the stress distributions on the sides of both culvert configurations are nearly similar. On the other hand, the graphs in Fig. 5 also show some points for which the values for (σ_n-W) have abruptly decreased at the intersecting points between the top and the walls of the box-shaped culvert (Fig. 3a) as well as at the intersecting points of the inclining chamfers with the top and the side of the culvert (Fig. 3b). Nevertheless, the sudden changes in (σ_n-W) at the intersecting points are just singularities because the normal stress (σ_n) of these points cannot be defined perfectly.

4.2 Effect of the gradient of slanted walls on the risk of hydraulic fracturing adjacent to culverts with inclining chamfers

To reduce the potential risk of hydraulic fracturing adjacent to culverts with a box shape, many investigations have suggested that the culvert configurations should be changed [8,12]. Such studies proposed a culvert shape with a gradient of 0.1 for the slanted walls of the culverts. In this section, the effectiveness of culverts with different slopes of slanted walls against hydraulic fracturing is analyzed using numerical models. The simulated culvert configurations are the culvert shape in Fig. 3c, including the inclining chamfers (IG=1.0), and the slanted walls with gradients varying from 0.1 to 0.5.

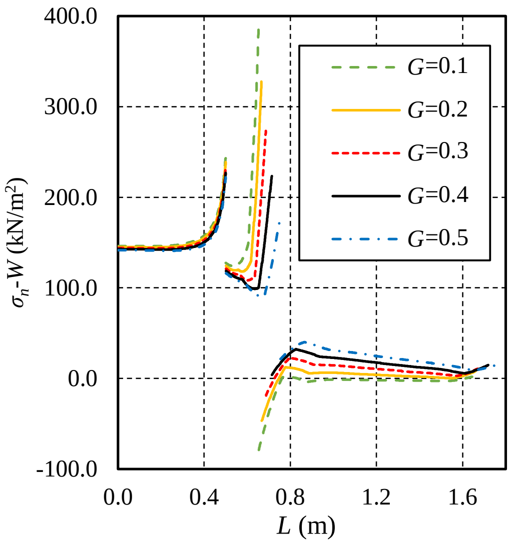

Fig. 6 Distribution of normal stress minus water pressure (σ_n-W) around culverts with inclining chamfers (IG=1.0) and slanted walls (Fig. 3c)

Figure 6 shows the distribution of (σ_n-W) around the culverts. It can be seen that the minimum value for (σ_n-W) increases when the gradient of the slanted walls is changed from 0.1 to 0.5. It seems to suggest that the effect of arching action might be lowered in cases of higher gradients of the slanted walls. Particularly, in cases where the gradient is under 0.3, the normal stress (σ_n) is lower than the water pressure (W) in the areas close to the intersecting points between the inclining chamfers and the slanted walls. This means that there is a high possibility of hydraulic fracturing adjacent to the culverts in such cases. The results in Fig. 6 also reveal that when the gradients are equal to or higher than 0.4, it might be possible to control the risk of hydraulic fracturing along the outlet conduits. The critical gradient of 0.4, pointed out in this study, is greater than that in the conclusions of past researches [8,12]. The findings, however, seem to be consistent with the proposals of a recent investigation [14].

4.3 Effect of arc-chamfers on the risk of hydraulic fracturing adjacent to culverts

In this section, FEM is used to evaluate the potential for hydraulic fracturing around the culvert seen in Fig. 3d in which the inclining chamfers (IG=1.0) in Fig. 3c was replaced by arc-chamfers with the radius of the arc (r) changed from 0.1 m to 0.4 m. Figure 7 indicates the distribution of (σ_n-W) around the culvert when the radius of the arc-chamfers is kept the same, 0.1 m, and the gradients of the slanted walls are increased from 0.2 to 0.5. Slightly different results are obtained compared with those drawn in the previous section, even though the minimum value for (σ_n-W) still increases when the gradient of the slanted walls is increased. However, in cases where the arc-chamfer's radius is equal to 0.1 m, the normal stress could be greater than the water pressure all around the culverts when the gradient of the slanted walls has values of just 0.3 or higher. These results seem to suggest that the arc-chamfers created a better stress transfer in scopes adjacent to the chamfers compared with the cases of the inclining chamfers. Nevertheless, the current authors recommend that a higher value for the gradient of the slanted walls (such as 0.4 or greater gradients) should be selected in practice in order to increase the safety factor and as a precaution against under-calculated conditions.

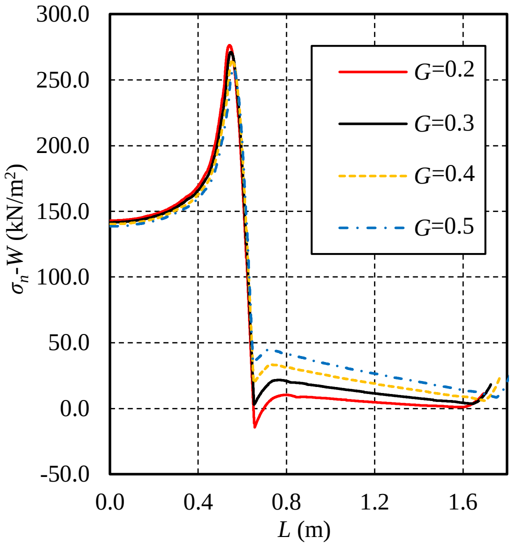

Fig. 7 Distribution of normal stress minus water pressure (σ_n-W) around culverts with arc-chamfers (r=0.1m) and slanted walls (Fig. 3d)

Figure 8 shows the distribution of (σ_n-W) around the culverts in cases where the radius of the arc-chamfers is changed from 0.1 m to 0.4 m and a gradient of 0.4 is selected for the slanted walls. The case of the culvert configuration with the inclining chamfers (IG=1.0) and the slanted walls (G=0.4) is also shown in Fig. 8 to compare the results with those in the cases of the arc-chamfers. The results indicate that there are remarkable differences in the stress distribution within the scope of the chamfers (arc-chamfers or inclining chamfers). As for the slanted walls, however, the values for (σ_n-W) are almost similar. This finding seems to be comparable to the aforementioned inferences made in the preceding section on the box-shaped culverts.

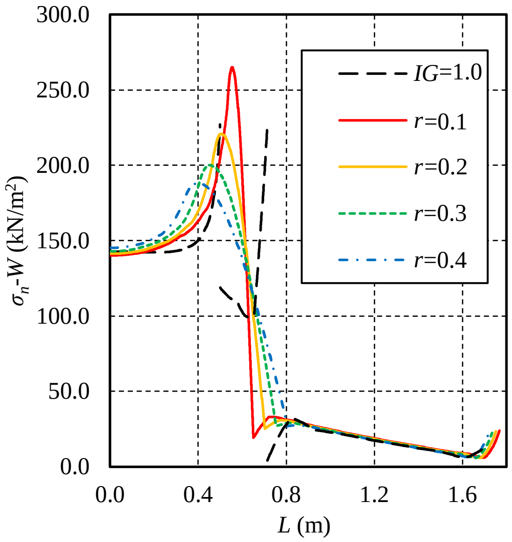

Fig. 8 Effect of arc-chamfer radiuses (r=0.1m-0.4m) and inclining chamfers (IG=1.0) on the distribution of normal stress minus water pressure (σ_n-W) around culverts (G=0.4)

5. CONCLUSION

As mentioned earlier, the aim of this paper was to research the risk of hydraulic fracturing adjacent to culverts with different configurations using numerical analyses. Based on the results discussed in the previous section, the following conclusions are drawn:

(1) There is a potential for hydraulic fracturing close to box-shaped culverts and box-shaped culverts with inclining chamfers because the normal stress on the sides of the culverts is reduced by arching action to point of being lower than the water pressure. For the case calculated in this paper, all of the normal stress minus the water pressure (σ_n-W) on the sides of two box-shaped culverts is lower than 0.0 kN/m^2. The maximum value for (σ_n-W) on the culvert's walls of either culvert shape is just about -6 kN/m^2.

(2) Culverts with slanted walls can reduce the risk of hydraulic fracturing compared with culverts with vertical walls. In the Japanese standard, the slanted walls with gradient's values from 0.1 to 0.3 are suggested for applying to construction. Based on the simulated results in previous sections, however, we recommend that the gradient of 0.4 or higher values should be applied to practice to control the potential for hydraulic fracturing around the culverts.

(3) The chamfers on the culvert top (in the inclining-form or the arc-form) can have significant effects on the stress within the scope of the chamfers, but little effect on the stress on the culvert walls. Therefore, the chamfers have little meaning in reducing the risk of hydraulic fracturing on the sides of culverts. In practice, the selection of the chamfer type or the dimensions of the chamfers should be considered and determined based on necessity as well as on the construction conditions so that the culverts can be manufactured more easily.

Dams and reservoirs are generally identified as active and effective solutions to the exploitation and management of water resources. Nevertheless, incidents induced by hydraulic fracturing along outlet conduits may lead to severe damage in the downstream areas. To ensure safe working conditions around the culverts of dams, the selection of the culvert configuration should be considered from the planning, design and construction stages in order to reduce the risk of hydraulic fracturing. Moreover, the solution whereby the culvert shape is changed should be combined with other countermeasures to provide higher safety factors against hydraulic fracturing. The focus of future work will be to research other countermeasures for preventing hydraulic fracturing as well as to examine the effects of other factors, such as excavation slope, the configuration, and settlement of the dam foundation, and the dam abutment in terms of how they are related to the potential for hydraulic fracturing in fill dams.

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7. REFERENCES

[1] Binnie G. M., The collapse of the Dale Dyke dam in retrospect, Quarterly Journal of Engineering Geology, Vol. 11, Issue 4, 1978, pp.305-324.

[2] Independent Panel to Review Cause of Teton Dam Failure, Report to U.S. Department of the Interior and the State of Idaho on Failure of Teton Dam. U.S. Bureau of Reclamation, 1976.

[3] Jafari F., and Salmasi F., Effect of embankment soil layers on stress-strain characteristics, Iranica Journal of Energy & Environment, Vol. 5, Issue 4, 2014, pp.369-375.

[4] Khanna R., and Chitra R., Hydraulic fracturing in the core of earth and rockfill dams, International Journal of Engineering Innovation & Research, Vol. 5, Issue 1, 2016, pp.136-142.

[5] Mohsen S., and Faghihi D., Predicting Hydraulic Fracturing in Hyttejuvet Dam, International Conference on Case Histories in Geotechnical Engineering, August. 2008, Paper 40.

[6] Mosadegh A., and Nikraz H., Buried pipe response subjected to traffic load experimental and numerical investigations, International Journal of GEOMATE, Vol. 13, Issue 39, 2017, pp. 01-08.

[7] Ng K. L., and Small J. C., A case study of hydraulic fracturing using finite element methods, Can. Geotech. J. 36, 1999, pp. 861-875.

[8] Ngambi S., Nakano R., Shimizu H., and Nishimura S., Cause of leakage along the outlet conduit underneath a low fill dam with special reference to hydraulic fracturing, Rural and Environment Engineering, Issue 35, 1998, pp. 35-46.

[9] Ngambi S., Shimizu H., Nishimura S., and Nakano R., A fracture mechanics approach to the mechanism of hydraulic fracturing in fill dams, Transactions of the JSIDRE 195, 1998, pp. 47–58.

[10] Nguyen C., and Ho S. T., Analysis causes of dam break of KE 2/20 REC dam - Ha Tinh province, Journal of Water Resources & Environmental Engineering, Special Issue, 2009, pp. 86-91 (In Vietnamese).

[11] Nishimura S., and Shimizu H., A study of the measurement of fracture toughness in the cohesive soil – the relationship between the size of initial crack and diameter of the specimen, Paddy and Water Environment, Vol. 2, Issue 1, 2004, pp. 27–32.

[12] Sherard J. L., Trends and debatable aspects in embankment dam engineering, Geotechnical Special Publication No. 32, Embankment Dams, 1992, pp.416-422.

[13] Sherard J. L., Decker R. S., and Et-ryker N. L., Hydraulic fracturing in low dams of dispersive clay, Proceedings of ASCE Specialty Conference on the performance of earth and earth supported structures, 1972, pp.653-689.

[14] Tran D. Q., Nishimura S., Senge M., and Nishiyama T., Research on the cause of dam failure from viewpoint of hydraulic fracturing – a Case study of a dam failure in Vietnam, International Journal of GEOMATE, Vol. 14, Issue 41, 2018, pp.86-94.