International Journal of GEOMATE, Jan., 2018 Vol.14, Issue 41, pp.86-94
Geotec., Const. Mat. & Env., DOI: https://doi.org/10.21660/2018.41.57454
ISSN: 2186-2982 (Print), 2186-2990 (Online), Japan

RESEARCH ON CAUSE OF DAM FAILURE FROM VIEWPOINT OF HYDRAULIC FRACTURING – CASE STUDY OF A DAM FAILURE IN VIETNAM

*Duy Quan Tran[1], Shinichi Nishimura[2], Masateru Senge[2] and Tatsuro Nishiyama[2]

[1]The United Graduate School of Agricultural Sciences, Gifu University, Japan; [2]Faculty of Applied Biological Sciences, Gifu University, Japan.

*Corresponding Author, Received: 8 Sept. 2017, Revised: 23 Oct. 2017, Accepted: 31 Oct. 2017

ABSTRACT: It is widely believed 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, a condition which allows for crack propagation in the dam body. The risk of hydraulic fracturing may increase when arching action occurs in the dam body. The aim of this study is to explain the cause of a dam failure using the finite element method. A case study, KE 2/20 REC dam, investigates a dam in Vietnam that failed a little under one year after it was put into operation at positions adjacent to the culvert. A build-up model is taken to simulate the stress-strain state in the dam body. Research reveals that the normal stress around the culvert was reduced to levels much lower than the water pressure. This reduction was due to the arching action associated with the effects of the culvert shape and the foundation. The findings suggest that the cause of the dam failure was related to the hydraulic fracturing phenomenon. Based on this conclusion, two countermeasures are proposed. These countermeasures are combinations created by changing the culvert shape and either shifting the position of the excavation slope 5.0 meters away from the former position or replacing the fill soil between the culvert and the excavation slope with a concrete block. The countermeasures are then verified by numerical models. The results show the effectiveness of the countermeasures for reducing the risk of hydraulic fracturing.

Keywords: Hydraulic fracturing, Arching action, Culvert, Dam failure, KE 2/20 REC dam.

1. INTRODUCTION

Hydraulic fracturing is the propagation and development of cracks under the effect of water pressure. Hydraulic fracturing has been identified as one of the possible causes leading to the concentrated leakage and failure of many fill dams especially at the first reservoir filling [2]-[3], [5]-[7], [9]-[10]. It is generally accepted that hydraulic fracturing will occur when the normal stress at any point is exceeded by the water pressure [6]-[7]. Previous studies revealed that hydraulic fracturing is closely related to the occurrence of arching action in the dam body. Arching action often occurs among different materials, such as between impervious cores and shoulders, culverts and fill soil or fill soil and foundations [2]-[3], [5]-[6], [10]. Under loading, materials with different elastic moduli can lead to differential displacements and then induce arching action. Due to this action, the stress in fill dams can be reduced. Past researches indicated that an incident at the Hyttejuvet Dam during the initial filling of the reservoir was related to the hydraulic fracturing phenomenon [3], [5]. The arching effects in the clay core of this dam caused a reduction in stress to levels that were much lower than the water pressure. In such a situation, under water pressure, seepage can penetrate through the existing cracks in the dam and induce stress concentration at the crack tips. As the tensile strength of soil is very small, the cracks can easily propagate through the embankment, resulting in the failure of the dam. Similar incidents, also identified as coming from the hydraulic fracturing mechanism, occurred at Balderhead (England), Stockton (USA), Wister (USA), Viddalsvatn (Norway), and Teton (USA) Dams during the first reservoir filling [2].

In addition, arching action also occurs easily around culverts. Due to arching, the normal stress on both sides of a culvert can be reduced to values that are much lower than the water pressure. According to field observations, past research concluded that hydraulic fracturing is the most probable cause of leakage along outlet conduits [6]. However, little attention has been paid to arching that was brought about by the effects of slopes excavated for the construction of culverts.

It is clear that hydraulic fracturing is a serious issue as it can lead to dam failures. Therefore, much research in recent years has focused on predicting the potential risk of hydraulic fracturing in earth or rockfill dams. These studies can be divided into three groups [3], [10]. The first relies on cylindrical or spherical cavity expansion theories in elastic or elastic-plastic mechanics. The second is based on field or laboratory tests. The last uses theories of fracture mechanics combined with laboratory tests.

In past researches, numerical analyses using the finite element method (FEM) were often performed to predict hydraulic fracturing in fill dams or foundations. The computed results of these analyses were then compared with the results of in-situ or laboratory tests. In the study by Ng and Small (1999), FEM was used to explain the cause of the incident at Hyttejuvet Dam due to hydraulic fracturing [5]. Ngambi et al. (1997) investigated the potential risk of hydraulic fracturing adjacent to the conduits buried in fill dams using a FEM analysis combined with in-situ observations [6]. In addition, the results of FEM models were utilized for a comparison with the results of laboratory experiments in a study on the response of buried pipes subjected to traffic loads [4]. The comparisons showed a good agreement. As the case study in this paper, therefore, a finite element procedure is applied to find the cause of a real dam failure.

A case study of a dam failure in Vietnam, called KE2/20 REC dam, was used for this study. The dam is located in Ha Tinh Province in Central Vietnam. The dam's initial purpose was to create a reservoir to supply irrigation water for farmland (about 30 hectares). Construction of the dam and reservoir was started in October 2006. After 2 years, the dam was completed and was 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 (width of 11.2 m), and a culvert (design flow of 0.037 m^3/s). After being in operation for just under one year, the dam failed in June 2009 [1], [8].

Past research concluded that the dam failed due to the piping mechanism [8]. Even though the research somewhat explained the cause of the failure, it did not point out what happened before the seepage had formed. The current authors believe that the dam failure may be related to the hydraulic fracturing phenomenon. The focus of this study, therefore, is to explain the cause of the dam failure under the hydraulic fracturing mechanism using a numerical analysis. Some countermeasures against the risk of hydraulic fracturing are also proposed, and numerical analyses are performed to verify the effectiveness of the countermeasures.

2. DESCRIPTION OF DAM FAILURE

Much research in recent years has focused on explaining dam failures due to concentrated leakage. Hydraulic fracturing is considered to be one potential cause of concentrated leakage especially at the first filling soon after the dam completion. The risk of hydraulic fracturing may become higher when the normal stress in the dam is reduced by the arching effect and the level of the water in the reservoir rises. Past researches pointed out that dam failures were caused by hydraulic fracturing at Hyttejuvet, Balderhead, Stockton, Wister, and Teton Dams during the first impounding [2].

This paper introduces a dam failure that will be used as a case study called KE2/20 REC dam. The dam is situated in Central Vietnam. It failed at the location of the culvert just under one year after it was put into operation under completely normal conditions, namely, without the incidence of an earthquake or rain, and with an approximately normal water level in the reservoir of +30.5 m [8].

Fig. 1 KE 2/20 REC dam failure

Fig. 2 Erosion after broken culvert segment

Observations after the failure showed that a segment of the culvert had broken in the middle and that the water flow had then caused deep erosion in the foundation, approximately 8.5 m in length in the water flow direction and 3.5 m in depth. There was also no sign of seepage from the shoulder of the dam. At the same time, the broken segment and a part of the dam body close to the culvert were swept toward the downstream [1]. Real images of the dam failure are given in Figs. 1

and 2. The results of in-situ surveys after the dam failure showed that the slope of the excavation on the left side of the culvert (looking from upstream to downstream) was rather steep. In reality, the observed slope was just 1:0.5 (vertical and horizontal directions, respectively), even less than seen in Figs. 1 and 2, even though the required design value was 1:1. Figure 3 shows a longitudinal section of the dam that was idealized from the design section and in-situ observations.

Additionally, after the dam failure, researchers conducted in-situ and laboratory experiments to determine the physico-mechanical properties of the fill soil and the foundation. Nine undisturbed samples of fill soil were gathered. The samples consisted of seven samples from the dam body, close to the location of the dam breach, and two undisturbed samples from locations adjacent to the first segment of the culvert which had not yet been swept toward the downstream. The results of the experiments given in the geological description in the previous research showed that the culvert and the dam were erected on a firm foundation of cracked and weathered rock – a kind of argillaceous slate. The elastic modulus of the foundation was much higher than the value of the fill soil. The experiments also pointed out that the fill soil used here has a high percentage of clay. In this paper, the physico-mechanical properties of the fill soil and the foundation are taken from previous studies on the dam and are listed in Table 1. In addition, the in-situ tests on the fill soil after the dam failure revealed that the embankment had not been compacted carefully. The real relative compaction (90.4%) had not reached the required value (95%) [1].

Cross sections of the dam and the culvert are presented in Figs. 4 and 5, respectively. It can be seen that the culvert is a reinforced concrete circular conduit and was placed on a foundation bed 0.4 m in depth. The physical parameters of the culvert materials are summarized in Table 1.

From the above descriptions, the current authors suspected that the cause of this dam accident might be related to the hydraulic fracturing mechanism. There may have been discontinuities in the fill soil adjacent to the culvert after the construction process. Moreover, due to the effect of the culvert's shape, arching action could have occurred on the left side of the dam. With the excavation of a steep slope and a considerable distinction in the elastic moduli between the embankment and the foundation, arching can become severe. When the water level of the reservoir rose, the water pressure grew higher than the normal stress on both sides of the pipe culvert; the stress was reduced to a small value by the arching action. Under this condition, the discontinuities acted as the initial cracks that were extended and propagated by the water pressure. This process might have led to the dam failure.

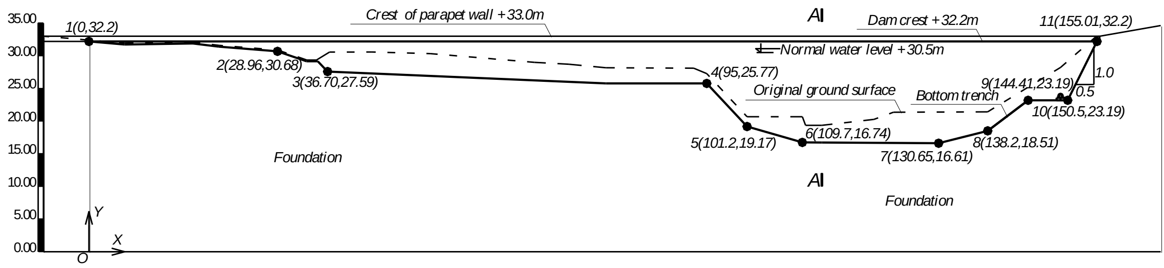

Fig. 3 Longitudinal section and data of nodal points on boundary in numerical model

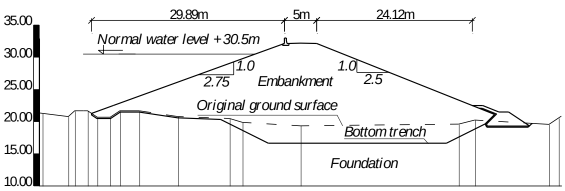

Fig. 4 Cross section of dam (A-A)

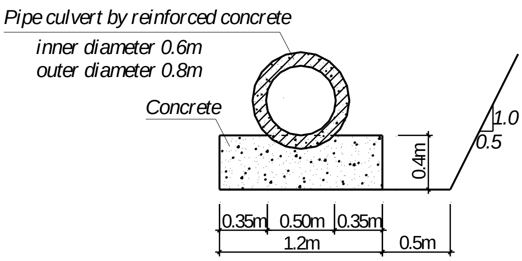

Fig. 5 Cross section of culvert

3. NUMERICAL ANALYSIS

3.1 Purpose of numerical analysis

In recent years, numerical analyses using the finite element method have been widely applied in investigations of the stress-strain distribution in dams. In previous studies on the hydraulic fracturing phenomenon in soil or the earth pressure on buried pipes, the finite element method was often used to yield numerical results [3], [4]. In this research, therefore, the authors set up a plane stress build-up analysis using the finite element method to simulate the stress-strain state in the dam. A simple criterion for predicting the potential risk of hydraulic fracturing at any location in the dam body using the output results of the analysis was utilized by comparing the normal stress with the water pressure at that point. Such a build-up analysis allows for a better simulation of the influences during construction, and the results of the analysis can show the distributions of stress and displacement in the dam, especially at positions adjacent to the conduit, to verify the arching effect. In addition, a numerical analysis was also used to check the effectiveness of the countermeasures proposed to reduce the risk of the occurrence of hydraulic fracturing in embankment dams.

Table 1 Material properties

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 kPa
Angle of internal friction (φ):	16º47’
Coefficient of permeability (k):	6.247×10^{-5} m/s
Elastic modulus (E):	16800 kPa
Poisson’s ratio (v):	0.3
b. Reinforced concrete	
Total density (ρ):	2.45 Mg/m^3
Elastic modulus (E):	2.4×10^7kPa
Poisson’s ratio (v):	0.2
c. Concrete of foundation bed under pipe	
Total density (ρ):	2.4 Mg/m^3
Elastic modulus (E):	2.1×10^7kPa
Poisson’s ratio (v):	0.2
d. Foundation	
Elastic modulus (E):	1.0×10^7kPa
Poisson’s ratio (v):	0.25

3.2 Model description

A build-up analysis by FEM was performed to analyze the deformation and stress in a longitudinal section of the dam which includes the cross section of the culvert as well. In this analysis, the dam body was simulated using 12 successive layers of fill soil. In reality, a fill dam is made up of a large number of layers of fill material. The layers are compacted carefully to reach a certain density. Nevertheless, simulating the dam body with too many layers of fill soil can cause the model to be bulky and can result in the analysis taking a long time to solve due to the numerous elements. In this paper, therefore, the number of soil layers was selected to be 12. This was also to guarantee that the maximum height of each element would be less than 1.5 m. Moreover, to simulate the stress-strain in the dam body, especially adjacent to the culvert, the linear elastic theory was used. Thus, only elastic properties, such as the total density, the elastic modulus, and the Poisson’s ratio of the materials, given in Table 1, were necessary for this model.

In this study, even though the shape of the culvert is symmetrical, the boundary conditions are unsymmetrical due to the effects of the excavation. As a result, this analysis used the whole longitudinal section of the dam. In addition, the elastic modulus of the foundation is much higher than that of the embankment. Thus, for the sake of simplicity, this model just simulates the dam body. The coordinates of the 11 main nodal points on the boundary are shown in Fig. 3. The coordinates of the other nodal points were calculated from the coordinates of these main nodal points.

The finite element mesh, which consists of 641 elements and 2121 nodal points, is shown in Fig. 6. All the elements are eight-node quadratic quadrilateral elements, and the elements adjacent to the culvert have smaller dimensions than the others in order to improve the accuracy and the details of the stress distribution around the culvert. The model is also assumed to be restrained at the foundation. Theoretically, when these nodal points were fixed, the stress at these points was equal to zero. However, this did not simulate the actual stress state on the boundary. Therefore, to improve the accuracy of the model, the nodal points between the 9**th** and the 10**th** main nodal points (in Fig. 3) were set up to be free in the horizontal direction.

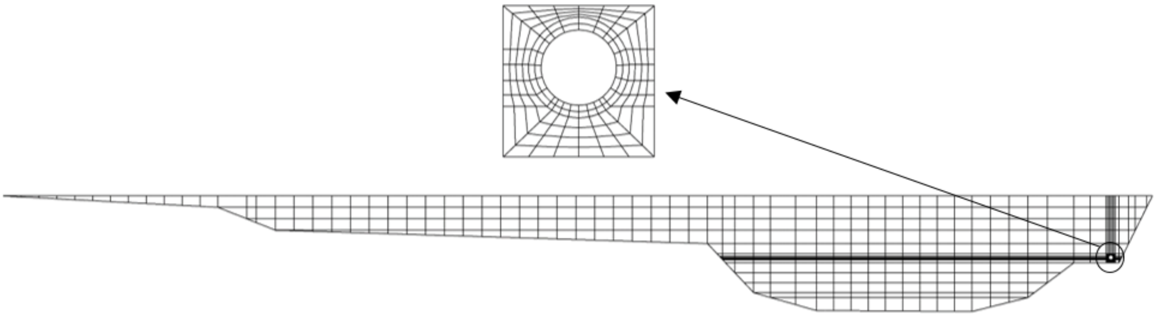

Fig. 6 Finite element mesh model

4. RESULTS OF NUMERICAL ANALYSIS

4.1 Distribution of displacement

The deformation mesh for the dam, magnified 10 times, is shown in Fig. 7. In this figure, the black lines are the initial element mesh and the red lines are the deformation mesh of the model. In other words, under loading, the nodal points of each element will displace and the initial mesh will become the deformation mesh. As shown in this figure, the maximum vertical displacement occurred around the mid-height of the embankment. This corresponds to some past researches using the build-up model [3], [6], [10]. However, it seems dissimilar to the results obtained from research conducted by Nguyen and Ho (2009). That research also used FEM to simulate the stress-strain in a dam body, but the conclusion they drew was that the maximum displacement was at the dam crest [8]. This inconsistency might be due to the difference in simulation algorithms. In Nguyen and Ho's study, the dam body was simulated with only one layer, while the model in this research consisted of 12 layers. The model used here might be more consistent with the real conditions of a dam around one year after its completion, because the stress-strain state in a dam body can be significantly affected by the construction process and the consolidation condition.

The displacement distribution around the pipe culvert is also displayed in Fig. 7. It is seen that the vertical displacement of the fill soil columns on both sides of the pipe is higher than that in the column of the fill soil above the crown of the pipe. This is because the elastic moduli of the culvert material and the foundation were much higher than the elastic modulus of the fill soil. Therefore, differential displacements occurred under loading and induced arching action adjacent to the culvert. This result is verification of the above suspicions.

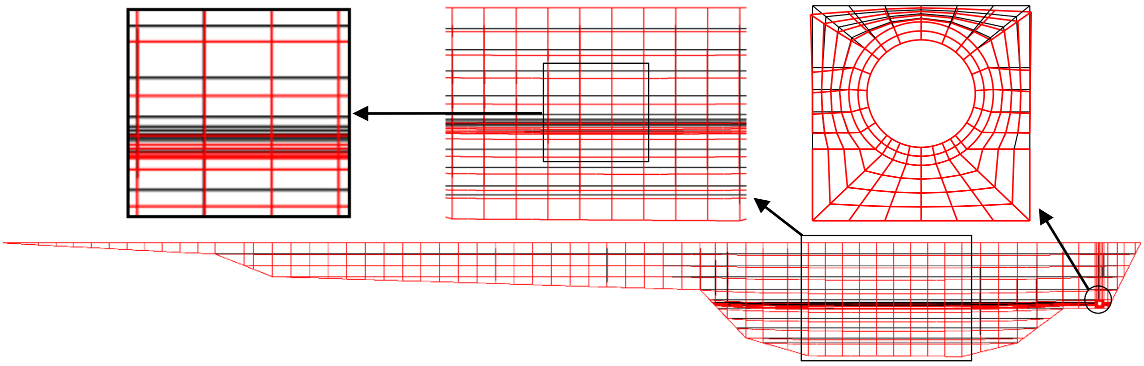

Fig. 7 Deformation mesh of analysis (scale factor = 10)

4.2 Distribution of stress around culvert

As most stress in soil is compressive stress, for convenience, the sign for stress levels in this research are positive for compressive stress and negative for tensile stress. Figure 8 indicates the relationship of the normal stress (σ_θ) and the normal stress minus the water pressure (σ_θ - W) around the pipe culvert versus the theta angle (θ^o) with the sign convention of theta, as seen in Fig. 9. The normal stress on both sides of the culvert, especially at the bottom of the pipe, was clearly reduced and much lower than the stress at the top of the pipe. This might be due to the arching effect. These results are similar to those of a past research that also addressed the cause of leakage along an outlet conduit underneath a low fill dam [6]. Moreover, the results of Fig. 8 show that all the stress was still compressive stress, although the normal stress on both sides of the culvert was significantly reduced by the arching action. This is slightly inconsistent with the results of the previous research [8].

As detailed in Fig. 8, when the theta angle is smaller than 96.0° and higher than 248.7°, the normal stress is really exceeded by the water pressure. The minimum value of the normal stress minus the water pressure (σ_θ - W) is -53.06 kPa when the theta angle is equal to 39.4°. It can be concluded that hydraulic fracturing may have occurred in these regions. This coincides with the inferences of this early research.

Moreover, the results from Fig. 8 also indicate that the normal stress distribution around the pipe culvert is unsymmetrical. The normal stress around the culvert was peak to maximum when the theta angle was equal to 167.3° rather than 180°. This might due to the effect of the excavation shape.

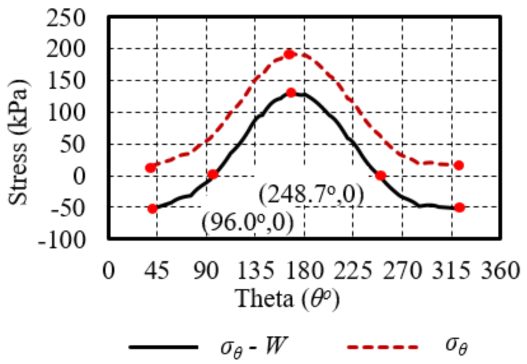

Fig. 8 Graph of stress around pipe culvert versus theta angle (θ^o)

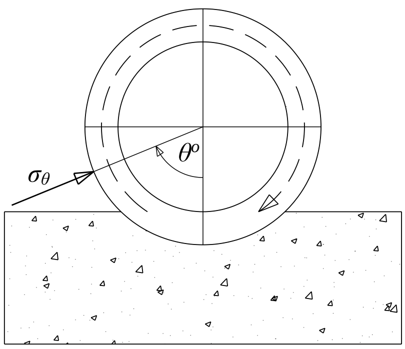

Fig. 9 Convention of theta angle (θ^o)

5. DISCUSSION AND PROPOSALS FOR COUNTERMEASURES

5.1 Discussion

Shortly after the dam failed, research was carried out by Nguyen and Ho (2009) to find the reason for the failure. In their research, it was concluded that the failure was related to the piping mechanism, whereby, when the water level of the reservoir rose, seepage occurred around the culvert where the fill soil had not been carefully compacted. In addition, cracks might have formed at abutting locations between the dam body and the foundation on the left side due to tensile stress. The seepage caused the erosion of the soil grains and created cavities in the dam. When the dimensions of the cavities were large enough, the upper portions of the dam collapsed. These conclusions might somewhat explain the cause of the failure in the KE 2/20 REC dam [8]. The present authors, however, believe that the previous research did not clearly explain what had happened prior to the occurrence of the piping phenomenon. Therefore, this research focuses on establishing a build-up model using FEM to explain the cause of the dam failure under the hydraulic fracturing mechanism that might have occurred prior to the piping mechanism.

The results of this study indicate that the cause of the dam failure may be related to hydraulic fracturing phenomenon around the culvert. They also confirm the high risk of hydraulic fracturing adjacent to a conduit that can result in such a failure. The findings coincide with the conclusions of Ngambi et al. (1998). On the other hand, there are significant differences in the methodology and the results between this study and the research of Nguyen and Ho (2009). Our analysis shows that the normal stress on both sides of the culvert was reduced considerably by the arching effect. However, the stress was still compressive stress (as in Fig. 8). Thus, there may have been no tensile cracks on the left side of the dam; this differs from the conclusions drawn in the previous research on the dam failure. Nevertheless, discontinuities, such as gaps and hairline cracks, represent the initial cracks that existed in the fill soil adjacent to the culvert during the construction process due to the negligent compaction. When the water pressure was higher than the normal stress, water may have penetrated the initial cracks and induced crack propagation in the dam body.

In addition, the results of the analysis seem to suggest that the culvert shape and the excavation slope are important factors related to arching action adjacent to the culvert, the reduction of normal stress on both sides of the culvert, and an increase in the potential risk of hydraulic fracturing close to the culvert. To confirm this suspicion, a test case was performed. In the test case, the culvert shape was changed to another shape, while the other conditions, namely, excavation slope, loading conditions, and boundary conditions, were kept the same. As indicated in Fig. 8, the normal stress around the upper part of the pipe culvert is higher than the water pressure; hence, this part might be safe from hydraulic fracturing. Therefore, to make the new culvert shape in the test case, the upper part of the pipe culvert was maintained. On the other hand, the lower portions of the pipe culvert were changed to slanted walls with a slope of 0.4H:1.0V in the horizontal and vertical directions, respectively. As discussed before, the gradient of the excavation slope was 0.5, which seems to be rather steep. However, the height of the culvert was much lower than the excavation slope; thus, the gradient of the slanted walls in the test case was chosen to be 0.4. The slanted walls were also considered to be tangential lines with the upper part of the pipe culvert making a continuous connection between the two parts of the culvert. A diagram of the test case is given in Fig. 10.

Figure 11 shows the distribution of normal stress minus the water pressure around the culvert with a new shape in the test case. In this graph, the horizontal coordinate axis was selected to be an X-axis that was different from the horizontal coordinate axis in Fig. 8. Due to changing the culvert shape, the X-axis might be more suitable for demonstrating the relationship of the normal stress and the water pressure around the culvert. As can be seen in Fig. 11, the stress state around the culvert experienced a more significant change than that seen in the results of the former analysis. On the right side of the culvert, the normal stress is really higher than the water pressure; hence, it can be concluded that there was no possibility of hydraulic fracturing on this side. Nevertheless, the normal stress is still lower than the water pressure. This may be due to the effects of the excavation.

By comparing the distribution of normal stress minus the water pressure in Figs. 8 and 11, the results seem to confirm that the stress-strain state around the culvert was affected remarkably by the shape of the culvert. In addition, the slope of the excavation also had an effect on the arching action. This research is thought to be the first study that elucidates the KE 2/20 REC dam failure under the viewpoint of hydraulic fracturing. It suggests that hydraulic fracturing may occur easily around the culvert in a dam body. Therefore, it is necessary to consider the risk of hydraulic fracturing in the design and construction processes of culverts underneath fill dams. Simultaneously, countermeasures to prevent the potential risk of hydraulic fracturing should be proposed.

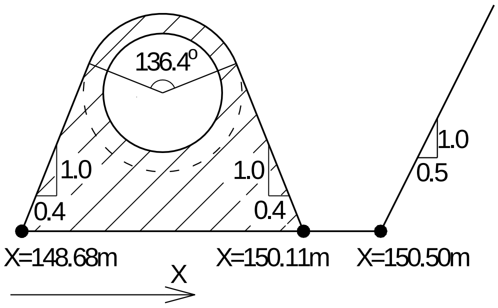

Fig. 10 Test case – changing culvert shape

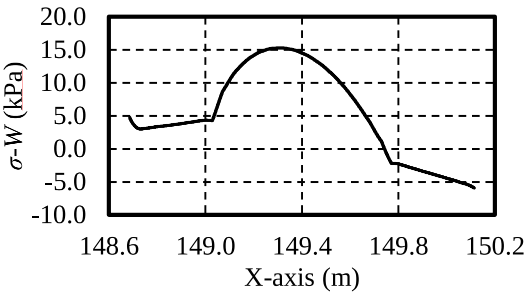

Fig. 11 Distribution of normal stress (σ) minus water pressure (W) versus X coordinate axis around culvert in test case

Besides the positive aspects of this research, the contact behavior between the fill soil and the foundation or the concrete culvert, that have an elastic moduli much higher than that of the embankment, has not been considered for the models employed in this analysis. This could lead to slight errors in the calculation at some local points. Future studies, therefore, will aim at using better models to simulate the stress-strain state of the case study.

5.2 Proposals for countermeasures

As discussed previously, hydraulic fracturing is one of the potential causes of dam failures. Therefore, it is obvious that proposing countermeasures to prevent the risk of hydraulic fracturing is necessary. In practice, when a culvert underneath a fill dam is designed, some measures, such as building cutoff seepage walls, applying soft clay around the culvert or using a filter, are often taken. These measures, however, are thought to be just precautions against internal erosion [6]-[7]. Past research on measures against hydraulic fracturing along culverts have revealed that such measures can also prevent or reduce the risk of hydraulic fracturing. Moreover, using a culvert with slanted walls has also been proven advantageous in reducing the arching action around a culvert [6]. However, these measures do not consider the effects of the excavation slope on the arching action. This research, therefore, focuses on proposing two countermeasures, namely, changing the culvert shape and reducing the effects of the excavation slope, to lower the arching effect, and hence, to prevent hydraulic fracturing. Both of the countermeasures were evaluated for their effectiveness by a FEM that has the same procedure as that mentioned previously. The countermeasures proposed in this study might be notably different from those in other researches.

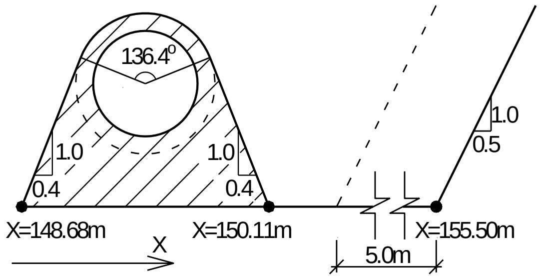

Fig. 12 First countermeasure – changing culvert shape and moving excavation 5.0 m

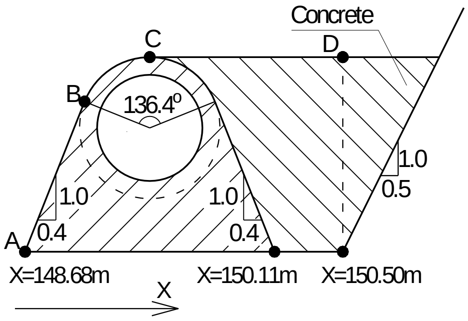

Fig. 13 Second countermeasure – changing culvert shape and placing concrete block between culvert and excavation

The results from the test case indicated that the excavation slope also influences the stress state around the culvert according to the arching action. Hence, only changing the culvert shape is not enough to prevent the risk of hydraulic fracturing in locations between the culvert and the excavation. Therefore, finding ways to reduce the arching effect due to the excavation is an important part of each countermeasure. Figures 12 and 13 show diagrams of the countermeasures in which the culvert shapes are similar to the culvert shape in Fig. 10.

The first countermeasure is a combination of changing the culvert and shifting the position of the excavation 5.0 meters away from the former position, as displayed in Fig. 12. The distribution of the normal stress minus the water pressure (σ - W) around the culvert is illustrated in Fig. 14. It is clear that the normal stress was really higher than the water pressure. Therefore, it can be concluded that, with this countermeasure, there would be no possibility of hydraulic fracturing adjacent to the culvert. Nevertheless, if the excavation is moved too far away, the excavation volume might be increased, thus leading to a little difficulty in the construction.

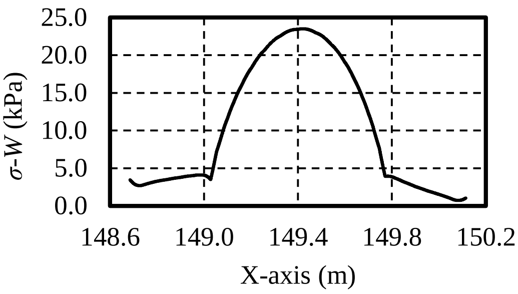

Fig. 14 Distribution of normal stress (σ) minus water pressure (W) versus X coordinate axis around the culvert of first countermeasure

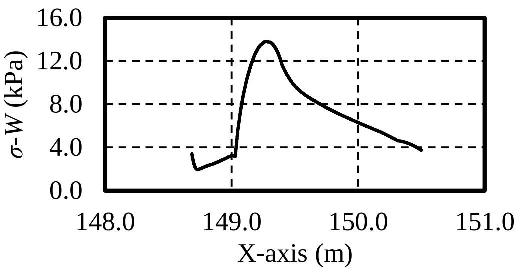

Fig. 15 Distribution of normal stress (σ) minus water pressure (W) versus X coordinate axis along ABCD edge (as in Fig. 13)

In some situations, an excavation that is too far from the culvert can be impossible. The second countermeasure is shown in Fig. 13. In this countermeasure, besides changing the culvert shape, the fill soil between the culvert and the excavation is replaced by a concrete block. The distribution of the normal stress minus the water pressure (σ - W) on the ABCD edge (in Fig. 13) is demonstrated in Fig. 15. The results confirm that the second countermeasure might also be significantly efficient for reducing the risk of hydraulic fracturing along culverts.

6. CONCLUSION

Based on the above study, the following conclusions can be made:

(1) Hydraulic fracturing can occur easily when the normal stress on both sides of a culvert is reduced by the arching effect to be lower than the water pressure. In the case study used here, the minimum value of the normal stress minus the water pressure (σ_θ - W) is -53.06 kPa on the right side of the pipe culvert. The arching action may have been related to the KE 2/20 REC dam failure brought about by the hydraulic fracturing mechanism. The regions where theta angle θ (as in Figs. 8 and 9) is lower than 96.0° and higher than 248.7° have a high risk of hydraulic fracturing.

(2) The culvert shape has a significant effect on initiating arching action. Moreover, an excavation

with a high slope will contribute to even more serious arching.

(3) In the case study addressed here, changing the culvert shape from the pipe culvert to another shape with a gradient of the slanted walls equal to 0.4, along with shifting the position of the excavation slope 5.0 meters away from the former position or replacing the fill soil between the culvert and the excavation with a concrete block, was seen to reduce the risk of hydraulic fracturing adjacent to the culvert.

Dam failures due to hydraulic fracturing can lead to severe damage to the downstream areas. Therefore, measures against hydraulic fracturing are extremely important in terms of ensuring the safe working conditions of dams. The focus of future work will be to research other countermeasures for preventing hydraulic fracturing and the effects of an excavation slope on arching action.

7. ACKNOWLEDGEMENTS

The authors would like to gratefully acknowledge Prof. Dr. Chien Nguyen, Dr. Sy Tam Ho, and Ha Tinh of the Hydraulics Construction Consultant Joint Stock Company - Vietnam for providing valuable input data for this research.

8. REFERENCES

[1] Institute of Civil Engineering, Report of analyzing causes of KE 2/20 REC dam failure - Ha Tinh province, 2009 (In Vietnamese).
[2] Khanna, R and Chitra, R., Hydraulic fracturing in core of earth and rockfill dams, International Journal of Engineering Innovation & Research, Volume 5, Issue 1, 2016, pp. 136-142.
[3] Mohsen, S. and Faghihi, D., Predicting Hydraulic Fracturing in Hyttejuvet Dam, International Conference on Case Histories in Geotechnical Engineering, August. 2008, Paper 40.
[4] Mosadegh, A. and Nikraz, H., Buried pipe response subjected to traffic load experimental and numerical investigations, International Journal of GEOMATE, Vol. 13, Issue 39, November. 2017, pp. 01-08.
[5] 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.
[6] 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, JSIDRE, No. 188, 1997, pp. 93-102.
[7] 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.
[8] 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, November. 2009, pp. 86-91 (In Vietnamese).
[9] Nishimura, S. and Shimizu, H., A study of the measurement of fracture toughness in cohesive soil – relationship between the size of initial crack and diameter of specimen, Paddy Water Environ (2004) 2, 2004, pp. 27–32.
[10] Wang, J. J., Zhang, H. P., Zhao, M. J. and Lin, X., Mechanisms of hydraulic fracturing in cohesive soil, Water Science and Engineering, Volume 2, Issue 4, 2009, pp. 95-102.