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Sensitivity analysis of leakage of rockfill dam caused by composite geomembrane defect

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Abstract. To study the influence of different geomembrane defects on the seepage field of a typical concrete inclined wall rockfill dam with a dam height of 85m, the saturated-unsaturated seepage finite element theory is applied to construct a three-dimensional numerical calculation model, and the seepage field of the dam under different geomembrane defects is numerically simulated and analysed. The calculation conditions of geomembrane defect size, head height, defect position, defect number and spacing are worked out respectively, and then the influence law of composite geomembrane breakage on dam seepage under pressure head is analysed. The results of the calculation model show that when the composite geomembrane has a single size defect and different position defect. The leakage caused by defects is relatively small, which has little effect on the overall seepage of the dam; When there are many defects in composite geomembrane, there is a linear relationship between the number of defects and the seepage of the dam body. When the defects are more concentrated, the phenomenon of concentrated seepage may occur, and the seepage of the dam body changes obviously.

1. Introduction

Geomembrane is a kind of polymer chemical flexible material with small specific gravity, strong extensibility, high deformation adaptability, corrosion resistance, low temperature resistance and good frost resistance. It is mainly used in reservoir projects such as rockfill dams, dikes, concrete dams (rehabilitation), cofferdams and reservoirs, and other anti-seepage projects such as reservoirs, canals and landfills⁰. At present, the built water reservoir. The number of earth-rock dams accounts for more than 92%, and geomembrane seepage control has obvious advantages in design and cost, so it has been paid more and more attention by water conservancy workers. According to the incomplete statistics of international commission on large dams (ICOLD) in 2010, 167 large earth-rock dams in the world have adopted geomembrane to prevent seepage. Geomembrane can be used as seepage prevention body of newly built dam and leakage repair^[2] of old dam. In 1966, geomembrane was first used for anti-seepage of concrete dams in China. At present, there are some high-rise new rockfill dams in China, such as Tangfangmiao rockfill dam^[3] with a height of 53m in Yunnan Province, Tiancun rockfill dam^[4] with a height of 48m in Guangxi Province and Renzhonghai rockfill dam^[5] with a height of 56m in Sichuan Province, all of which use composite geomembrane for anti-seepage and have been running well up to now. As to the leakage of old dam. Many earth-rock dams in China have been successfully repaired with geomembrane, among which the biggest seepage head of geomembrane is Shibianyu directional blasting rockfill dam^[6] with a height of 85m in Shaanxi Province. Foreign countries have tested the quality of



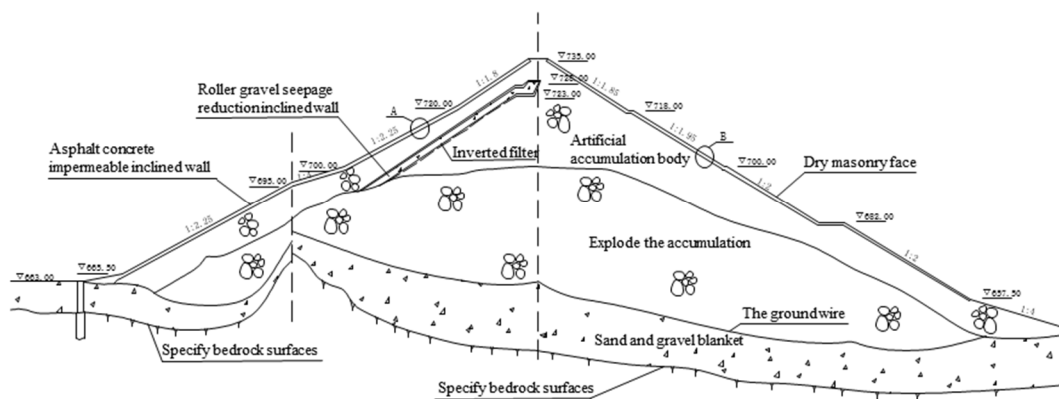
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28 geomembranes of 200,000 m² in a project. The results show that there are 26 water leakage holes in every 10,000 m², of which 15% are hole defects[7]. Nosko et al.[8] found that the defects with the size of 0.5 ~ 10 cm² accounted for 85.8% of the total defects through the quality inspection of more than 300 geomembranes with the size of about 3.25 million m², and the bursting and piercing caused by the underlying stones accounted for 71.17% of the total defects. Therefore, it is known that geomembrane is prone to produce defects during operation after construction, which have a direct impact on dam seepage control. In this paper, three-dimensional saturated-unsaturated seepage finite element method is used to build a three-dimensional model, and the seepage field of the dam under different defects of geomembrane is numerically simulated and analyzed, and the influence of defect leakage of geomembrane on seepage characteristics of rockfill dam is studied.

2. Composite geomembrane defect simulation schemes

2.1 General situation of geomembrane impervious rockfill dam

The maximum dam height, crest elevation, crest length and crest width of a reservoir dam are 85.00m, 735.00m, 265.00m and 7.50m respectively. Upstream dam slope ratio is 1:1.73, and downstream dam slope ratio is 1:1.43. The riverbed dam foundation adopts inverted well type artificial vertical excavation earth-rock cutoff wall, with the maximum depth of 21.8m, and grouting curtain is used for seepage control around it. See figure. 1 for typical cross-sectional view of geomembrane impervious rockfill dam.



B-4		0.5	25m above the dam slope	1	—
B-5		0.5	30m above the dam slope	1	—
C-1		0.5	20m from the dam foot	1	—
C-2	Defect location	0.5	50m from the dam foot	1	—
C-3		0.5	80m from the dam foot	1	—
C-4		0.5	100m from the dam foot	1	—
D-1		0.5	50m from the dam foot	1	—
D-2	Number of defects	0.5	50m from the dam foot	3	10
D-3		0.5	50m from the dam foot	5	10
D-4		0.5	50m from the dam foot	7	10
D-5		0.5	50m from the dam foot	9	10
E-1	Defect spacing	0.5	50m from the dam foot	5	0
E-2		0.5	50m from the dam foot	5	5
E-3		0.5	50m from the dam foot	5	10
E-4		0.5	50m from the dam foot	5	20

2.3 Three-dimensional model construction

2.3.1 Boundary conditions. The typical rock-fill dam section is analyzed and calculated, and the typical cross-section of dam body is selected to establish a three-dimensional finite element model. Setting of boundary conditions: the four side boundaries and bottom boundaries of the dam foundation are approximately fixed impervious boundaries, and the upstream and downstream slopes on the upper surface of the dam foundation are water head boundaries. The upper surface of the composite geomembrane is the water inlet surface. The dam body, dam crest and slope above the upstream and downstream waterline are seepage boundaries. The grid contains 476969 domain elements, 52240 boundary elements and 2879 edge elements.

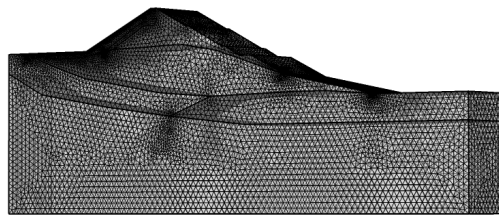


Figure 2. Computational model meta-grid partition diagram

2.3.2 Permeability coefficient of dam body and dam foundation

Because the original defect on geomembrane is small, which affects the calculation accuracy, the equivalent permeability coefficient method is used to analyze the proposed project, and the geomembrane can be equivalent to the soil with relative thickness by setting the velocity per unit area and the head difference between the two sides as constant values. The equivalent formula is as follows:

$$\frac{k_1}{k_2} = \frac{\delta_1}{\delta_2} \quad (1)$$

The geomembrane is 1mm thick and the permeability coefficient is 1×10^{-11} cm/s. When constructing the model, the thickness of geomembrane is equivalent to 1m by adjusting the permeability coefficient, that is, the permeability coefficient of geomembrane equivalent soil is equivalent to 1×10^{-8} cm/s. See table 2 for details:

Table 2. Permeability coefficient of each soil layer of dam body and dam foundation.

Soil layer name	Parameter	Permeability coefficient k(cm/s)
Geomembrane equivalent soil		1.00×10^{-8}
Asphalt earth-rock inclined wall		1.00×10^{-5}
Earth-rock cut-off wall		1.00×10^{-6}
Anti-seepage inclined wall		1.00×10^{-3}

Sandy pebble	1.00×10^{-2}
Blasting rockfill	1.50×10^{-2}
Artificial rockfill	1.00×10^{-2}
slope deposit	1.00×10^{-2}
bedrock	2.48×10^{-5}

3. Analysis of calculation results

The seepage quantity under working condition I geomembrane without defects is analyzed and calculated, and the seepage quantity is 41.81m/d/100m. This seepage quantity is taken as the basic seepage quantity, and compared with the seepage quantity under other working conditions, and the difference is regarded as the defective seepage quantity. Figure 3 is the velocity streamline diagram of composite geomembrane without defects.

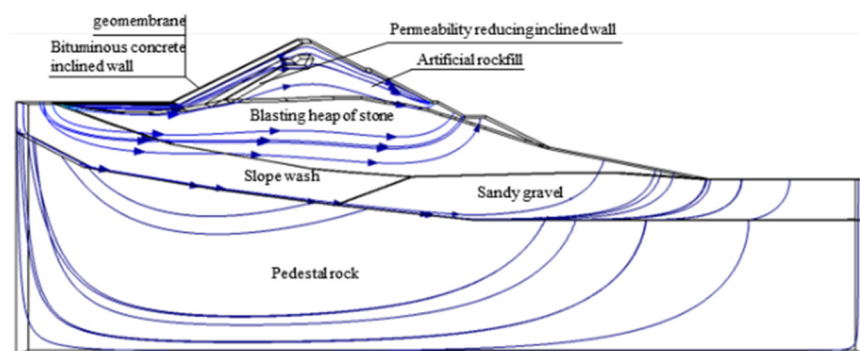


Figure 3. Velocity streamline diagram of composite geomembrane without defects.

3.1 the influence of defect size

According to the model constructed in the second section, the defect side lengths of 0.1m, 0.2m, 0.5m and 1.0m are simulated and calculated, and the defect positions are all taken 50m away from the dam foot, and the seepage flow of the dam body under four working conditions is obtained. Figure 4 is the velocity streamline diagram of the composite geomembrane defect size of 0.7m.

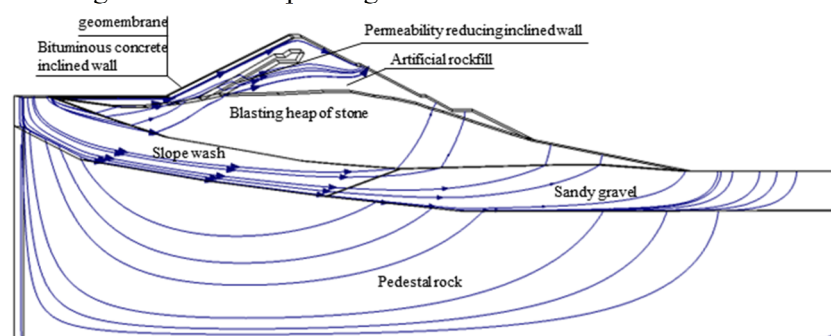


Figure 4. Velocity streamline diagram of composite geomembrane with defect size of 0.7m.

See Table 3 for the calculation results of stable seepage quantity of dams with different defect sizes. From the calculation results of seepage quantity, it can be concluded that the larger the defect size of composite geomembrane, the greater the leakage quantity of dam body. Compared with the leakage of 41.81m/d/100m under the defect-free condition, the leakage under the four working conditions increased by 1.74m/d/100m, 2.64m/d/100m, 3.88m/d/100m and 5.85m/d/100m respectively. The increasing rates were 3.9%, 6.3%, 9.3% and 12.3% respectively. The difference of increase rate increases with the increase of defect size. Therefore, it is concluded that when the composite geomembrane has a single size defect, the leakage caused by the defect is relatively small, which has little effect on the overall seepage of the dam; With the increase of defect size, the rate of leakage increases, and the rate of seepage flow increases, but there is no linear relationship.

Table 3. Stable seepage amount of different defect size.

Calculated working condition	Defect size (m)	Leakage (m/d/100m)	Increase rate of leakage (%)	Increase rate difference (%)
A-1	0.1m	43.55	4.2	-
A-2	0.2m	44.45	6.3	2.1
A-3	0.5m	45.69	9.3	3.0
A-4	0.7m	47.66	14.0	7.1

3.2 the influence of water head height

According to the model construction, the defects with side length of 0.5m are set at different heights of the dam slope, and the head heights of composite geomembrane defects are 10m, 20m and 30m, so as to obtain the seepage flow of the dam body under three working conditions. Figure 5 is the velocity streamline diagram of geomembrane defects on the dam slope under the head height of 30m.

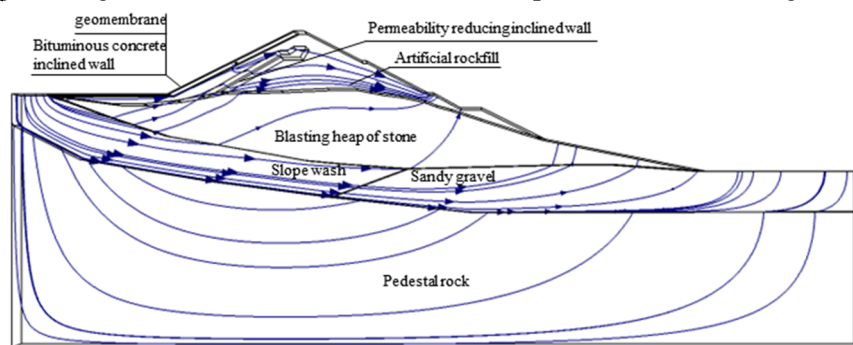


Figure 5. Velocity streamline diagram under 30m head height of geomembrane defect on dam slope.

See Table 4 for the calculation results of seepage flow of dams with different head height defects. From the calculation results, it can be concluded that the greater the head height at the geomembrane defect, the greater the seepage flow of dam body. Compared with the leakage of 41.81m/d/100m under the defect-free condition, the leakage under the five working conditions increased by 4.05m/d/100m, 4.24m/d/100m, 4.37m/d/100m, 4.5m/d/100m and 4.59m/d/100m respectively 5%, 10.8%, 11.0%, and the difference of increase rate decreases with the increase of head height. Therefore, it is concluded that the defective head height has a great influence on the seepage flow of the dam body, but with the increase of the head height, the growth rate of seepage flow slows down, and the influence of the head height on the seepage flow of the dam body is limited.

Table 4. Stable seepage quantity of defects with different head heights.

Calculated working condition	Head height (m)	Leakage (m/d/100m)	Increase rate of leakage (%)	Increase rate difference (%)
B-1	10m	45.86	9.7	-
B-2	15m	46.05	10.1	0.4
B-3	20m	46.18	10.5	0.4
B-4	25m	46.31	10.8	0.3
B-5	30m	46.40	11.0	0.2

3.3 the influence of defect location

According to the model construction, it is proposed that defects with side length of 0.5m are located at 20m, 50m, 80m and 100m away from the dam foot, and the seepage flow of dam body under four working conditions is obtained. Figure 6 is the velocity streamline diagram of geomembrane defect at 100m away from the dam foot.

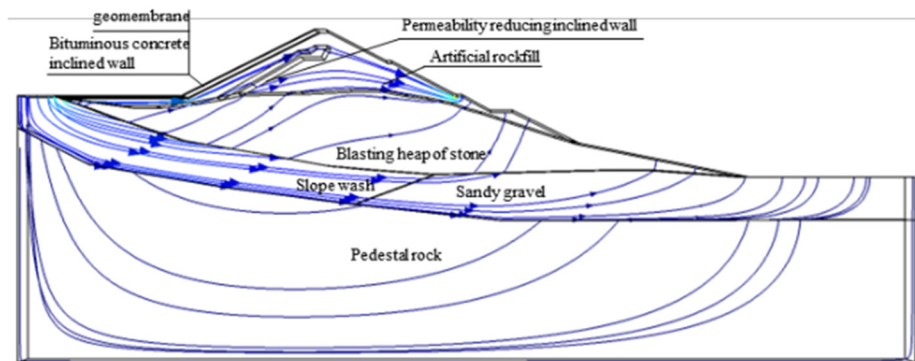


Figure 6. velocity streamline diagram under geomembrane defect 100m away from dam foot.

See Table 5 for calculation results of seepage flow of dam body with defects at different distances from dam foot. From calculation results of seepage flow, it can be concluded that the smaller the distance between defects and dam foot, the greater the leakage of dam body. Compared with the leakage amount of 41.81m³/d/100m under the defect-free working condition, the four working conditions increased by 2.98m³/d/100m, 2.87m³/d/100m, 2.84m³/d/100m and 2.78m³/d/100m, with the increase rates of 7.1% and 6.9 respectively. Therefore, it is concluded that the closer the defect is to the dam foot, the greater the seepage quantity of the dam body, but the change of seepage increase rate is not obvious, and the difference of seepage increase rate decreases slowly. It is concluded that the defect position has little influence on the change of seepage quantity.

Table 5. Stable seepage quantity of defects at different distances from dam foot.

Calculated working condition	Distance from dam foot (m)	leakage (m ³ /d/100m)	Increase rate of leakage (%)	Increase rate difference (%)
C-1	20m	44.79	7.1	-
C-2	50m	44.68	6.9	-0.2
C-3	80m	44.65	6.8	-0.1
C-4	100m	44.59	6.6	-0.2

3.4 the influence of the number of defects

According to the model construction, the geomembrane defects with a side length of 0.5m are proposed, with a distance of 50m from the dam foot and a defect spacing of 10m. The seepage flow of the dam body under four working conditions is obtained by setting 1~4 defect apertures respectively. Figure 7 is a velocity streamline diagram with 9 geomembrane defect apertures.

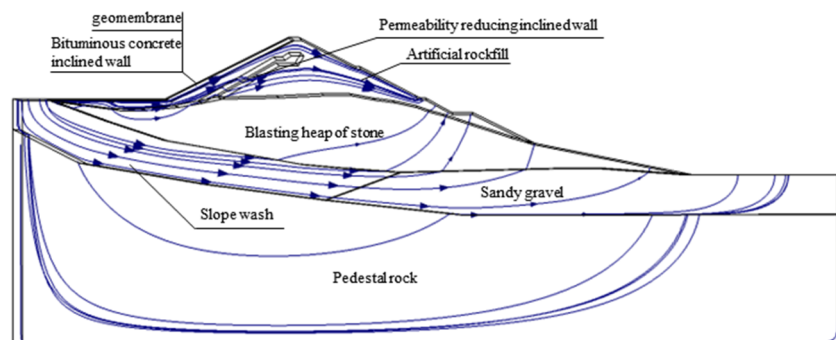


Figure 7. Velocity streamline diagram of 9 defect apertures of geomembrane on dam slope.

See Table 6 for calculation results of seepage flow of dams with different number of defects of geomembrane. From calculation results of seepage flow, it can be concluded that the more defects of composite geomembrane, the greater the leakage of dam body. Compared with the leakage of

41.81m/d/100m under the defect-free working condition, the leakage under the four working conditions increased by 2.87m/d/100m, 3.38m/d/100m, 3.85m/d/100m, 4.35m/d/100m and 4.87m/d/100m. With the proportional increase of the number of defects, the leakage increase rate also increases proportionally, and the difference of the increase rate is basically stable. There is a linear relationship between the increase of the number of defects and the seepage flow of the dam body. Because the seepage flow of the dam body is regarded as laminar flow, and there is no cross influence among the streamlines, the number of defects has a major impact on the seepage flow of the dam body.

Table 6. Stable seepage amount of geotextile with different defect numbers.

Calculated working condition	Number of defects	Leakage (m/d/100m)	Increase rate of leakage (%)	Increase rate difference (%)
D-1	1	44.68	6.9	-
D-2	3	45.19	8.1	1.2
D-3	5	45.66	9.2	1.1
D-4	7	46.16	10.4	1.2
D-5	9	46.68	11.6	1.2

3.5 the influence of defect spacing

According to the model construction, geomembrane defects with a side length of 0.5m are proposed at a distance of 50m from the dam foot, the number of defects is set to 5, and four working conditions of 0m, 5m, 10m and 20m are proposed in turn, so as to obtain the seepage quantity of the dam body under four working conditions. Figure 8 is the velocity streamline diagram with a distance of 20m between geomembrane defects.

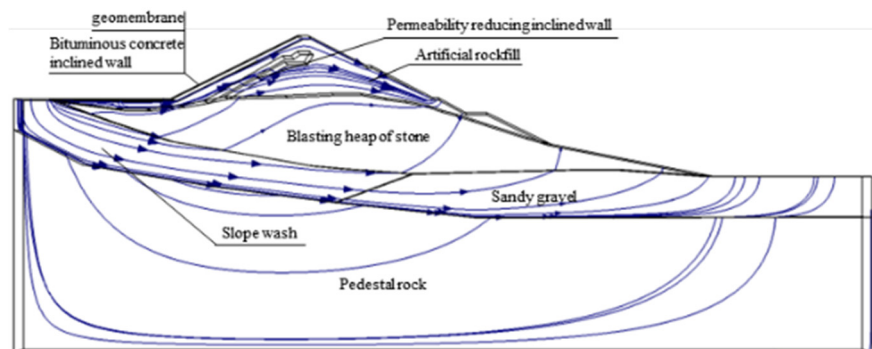


Figure 8. Velocity streamline diagram of geomembrane defect spacing of 20m on dam slope.

See table 7 for the calculation results of seepage flow of dams with different defect spacing of geomembrane. it can be concluded from the calculation results that compared with the seepage flow of 41.81m/d/100m under the non-defect working condition, the seepage flow under the four working conditions has increased by 3.97m/d/100m, 3.55m/d/100m, 3.25m/d/100m and 3.22. The larger the leakage of the dam body. When the defect location is more concentrated, the phenomenon of concentrated seepage may occur, so the seepage quantity of dam body changes obviously.

Table 7. Stable seepage number of geotechnical models with different defect spacing

Calculated working condition	Defect spacing (m)	Leakage (m/d/100m)	Increase rate of leakage (%)	Increase rate difference (%)
E-1	0	45.78	9.5	-
E-2	5	45.36	8.5	1.0
E-3	10	45.06	7.8	0.7
E-4	20	45.03	7.7	0.1

4. Conclusion

In this paper, taking a rockfill dam as an example, the geomembrane defects with different influencing factors are numerically simulated by COMSOL software, and the different variation laws of dam

seepage under the influence of various defect factors are obtained, and the following conclusions are drawn:

1) The single size defect of composite geomembrane has little influence on the leakage of dam body, but with the increase of defect size, the leakage of dam body also increases, and the growth rate of leakage is also increasing.

2) Defective head height has a great influence on seepage flow of dam body, but with the increase of head height, the growth rate of seepage flow slows down, and the influence of head height on seepage flow of dam body is limited.

3) The closer the defect is to the dam foot, the greater the seepage flow of the dam body, but the change of seepage increase rate is not obvious, the difference of seepage increase rate decreases slowly, and the defect position has little effect on the change of seepage flow.

4) The more defects of composite geomembrane, the greater the leakage of dam body. As the number of defects increases proportionally, the rate of leakage increases proportionally, and the number of defects is basically proportional to the leakage of dam body.

5) When there are many defects in the composite geomembrane, the distance between the defects has a certain influence on the leakage of the dam body, but the influence degree is small, and the smaller the gap between the defects, the greater the leakage of the dam body. When the defect location is more concentrated, concentrated seepage may occur.

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