STUDY ON BEHAVIOR OF AFRD DURING EARTHQUAKE AND THE CONDUCTED REINFORCEMENT

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ABSTRACT

The Yashio dam, a 90.5 m high asphalt faced rockfill dam (AFRD), holds an upper reservoir of the Shiobara Pumped Storage Power Plant (PSPP). The 2011 off the Pacific coast of Tohoku Earthquake (The 2011 Tohoku Earthquake) hit the dam and the surrounding area. The maximum acceleration values were about 50 x 10^{-2} m/s^2 (50 gal) at the bedrock and 250 gal at the dam crest respectively. Two major cracks occurred at the asphalt facing along the left and the right abutments, while the recorded accelerations were smaller than the acceleration considered at the design stage. Several studies were conducted to pursue the crack mechanism. This paper indicates that cracks may occur at the asphalt facing of AFRD if the dam structure allows strains to be concentrated at some specific facing part in the event of a strong excitation. For the Yashio dam case, we estimated that the cracks occurred in the asphalt facing due to the concentrated strains around the dam crest. The repair works of the asphalt facing were conducted with the consideration of resuming the power plant operation early, durability of the repair work and prevention of cracks by the concentrated strain around the dam crest.

INTRODUCTION

The Yashio dam is located at a 300 km distance from the epicenter of the 2011 Tohoku Earthquake. Recorded acceleration and the location of the seismometers are as shown in Table 1 and Figure 2. respectively. Two major cracks occurred in the asphalt facing due to the earthquake. This paper reports studies on behavior of the Yashio dam (AFRD) during the earthquake, estimated crack mechanism and conducted repair works.

Table 1. Maximum acceleration by the 2011 Tohoku Earthquake (unit: gal).

Location	Unit	Stream direction	Dam axis direction	Vertical direction
Bedrock	EA-2	43	53	45
Dam crest	EA-10	174	157	105
	EA-11	253	185	175
	EA-12	252	104	156
	EA-13	66	66	43

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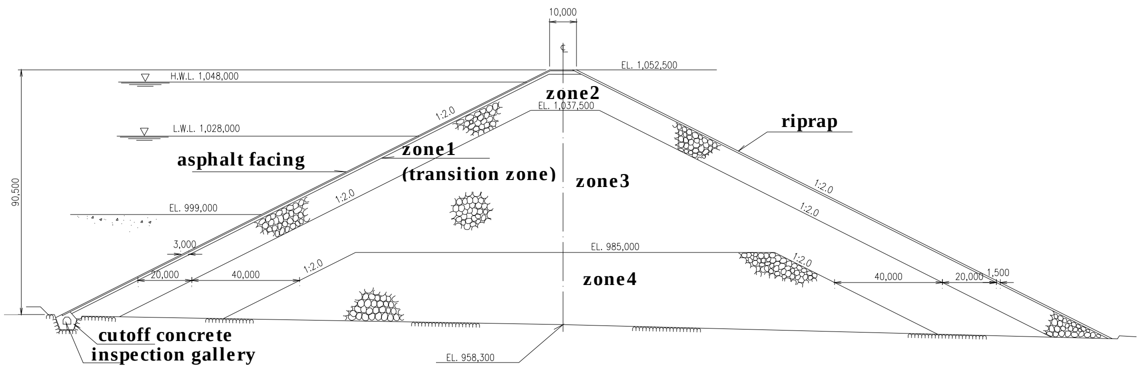
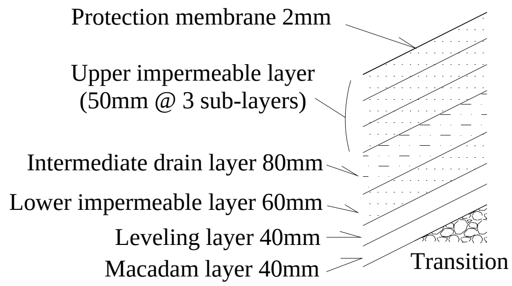
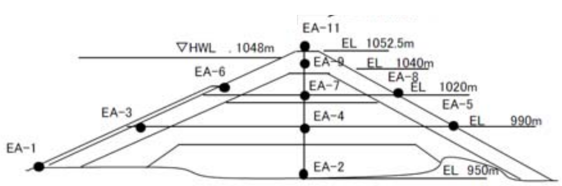


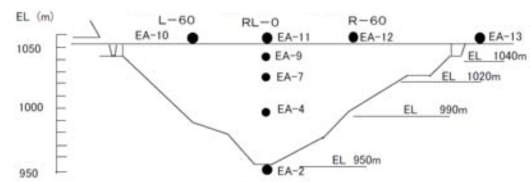


Detail of the asphalt facing

Figure 1. Cross section of the Yashio dam.



(Cross section)



(Front view)

Figure 2. Location of the seismometers.

FACING DAMAGES BY THE EARTHQUAKE

The facing of the Yashio dam consists of an upper impermeable layer, an intermediate drainage layer, a lower impermeable layer, a leveling layer and a macadam layer as shown in Figure 1. The intermediate drainage layer is set to detect water leakage in the cases of facing damages.

The water leakage occurred after the 2011 Tohoku Earthquake, which indicated some damages in the asphalt facing. A visual inspection was conducted immediately after the earthquake, and two major cracks were found. Then, the cracks below the water level were investigated by divers and underwater cameras. The cracks were about 70 to 80 m-long. These were parallel to the left and the right abutments. The cracks were carefully investigated during the temporary repair work by a visual inspection and using a concrete cutter to take sample pieces from the facing where the crack was too narrow for the visual inspection. The depths of the cracks were checked by a core drill survey near the dam crest. The cracks were deeper at the higher elevation. The cracks penetrated the asphalt facing near the dam crest and reached the macadam layer (Tsukada et al. 2012). Considering the situation, we estimated that the cracks occurred near the dam crest at first and propagated downward.

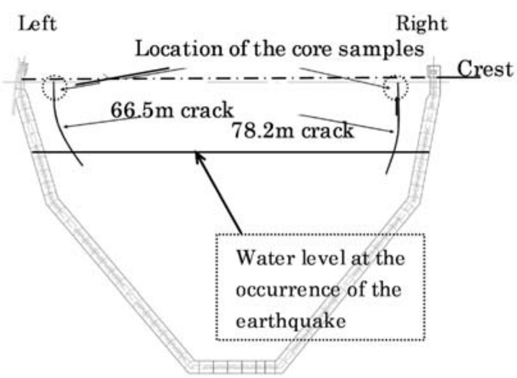


Figure 3. Location of the cracks.

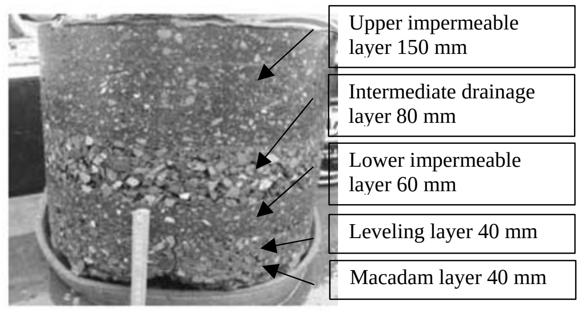


Figure 4. Core sample of the facing.
(Dia. 500 mm, Left side crack)

REVIEW OF SEISMIC DESIGN OF THE ASPHALT FACING

Mechanical characteristics of the asphalt facing

The fine grained asphalt concrete was applied to the impermeable layer of the facing. The composition of the asphalt concrete was designed as shown in Table 2 in consideration with its flexibility and stability. The fine grained asphalt concrete has a smaller yield tensile strain when its temperature is low or loading strain rate is high, as shown in Figure 5. Therefore, seismic force during winter season would be a critical condition for the asphalt facing. The test results are tabulated in Table 3, including bending, shear and compression tests (Ishii et al. 1988).

20 years after the dam construction, the flexibility of the asphalt facing was checked by bending tests under -15 ℃ temperature and strain rate of $1x10^{-2}$ /sec. The test specimens were taken from the upper impermeable layer near the dam crest, which consists of 3 sub-layers. The yield tensile strains by the tests were $2.1\text{-}2.5x10^{-3}$ at the surface, $2.0\text{-}2.5x10^{-3}$ at the second sub-layer, and $2.3\text{-}2.4x10^{-3}$ at the third sub-layer respectively. The test results were averaged at $2.3\ x10^{-3}$. There was not clear difference among the results, and distinct deterioration by ultra violet rays was not found in the surface although the test results were slightly smaller than the yield strain value of $2.9x10^{-3}$ at the design stage.

Table 2. Composition of the fine grained asphalt concrete.

Max. aggregate size (mm)	Compostion (kg/ton)						
	Aspahlt	Aggregate		Crushed sand	Fine sand	filler	
						Stone powder	Additive
		13-5mm	5-2.5mm	2.5-0mm	2.5-0mm		
13	85	166	267	276	83	115	8

Table 3. Yield strain of the fine grained asphalt concrete.

Test temperature	Item	i) Earthquake		ii) Imppounding	
		Yeild strain (x 10^{-3})	Strain rate (1/sec)	Yeild strain (x 10^{-3})	Starain rate (1/sec)
5℃	Compressive	21.0	8.0 x 10^{-3}	70.0	8.0 x 10^{-3}
	Tensile	10.0	1.0 x 10^{-2}	50.0	1.0 x 10^{-2}
	Shear	8.8	2.0 x 10^{-2}	130.0	2.0 x 10^{-2}
−15℃	Compressive	12.0	8.0 x 10^{-3}		
	Tensile	2.3	1.0 x 10^{-2}		
	Shear	28.0	2.0 x 10^{-2}		

Assumed condition:

i) Earthquake: Water temperature is 5 or -15℃, strain rate is approx. 10^{-2} 1/sec

ii) Inpounding: Water temperature is 5℃, and the lowest strain rate of the test machine

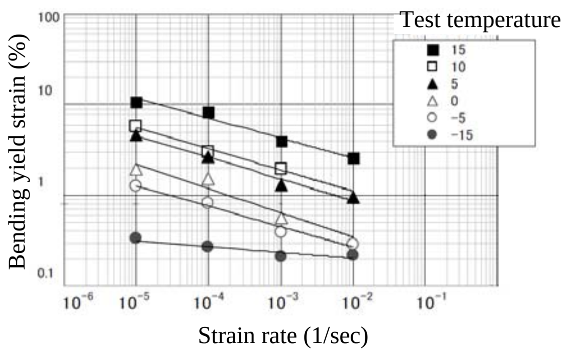


Figure 5. Relation between bending yield strain and strain rate.

Shaking test in the design stage

Earthquake resistance of the asphalt facing was checked in the design stage by shaking tests with a 3D model as shown in Figure 6. The results of the shaking tests are summarized as follows.

a. The distribution of the surface cracks are shown in Figure 7.
b. Horizontal cracks occurred when the shaking direction is the stream. The first crack is located around 1/5-1/4 of the slope length below the dam crest.
c. Several cracks occurred parallel with the left abutment when shaking was in the dam axis direction. The first crack is located at 1/8 of the crest length away from the left abutment.
d. In the case of shaking by the stream direction, acceleration value causing a first crack was smaller than the one when shaking was in the dam axis direction.

The actual cracks in the facing by the 2011 Tohoku Earthquake showed similar crack propagation of the test results when shaking direction is the dam axis. However, exceeding acceleration was not dam axis direction for the actual dam behavior according to the seismometer records.

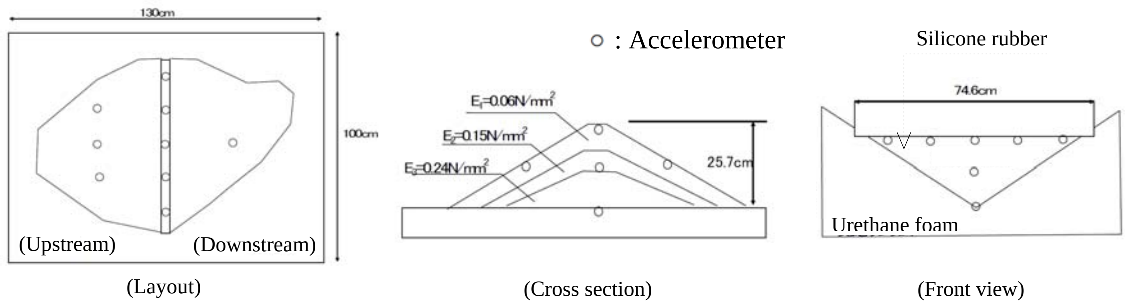


Figure 6. Three dimensional shaking test model.

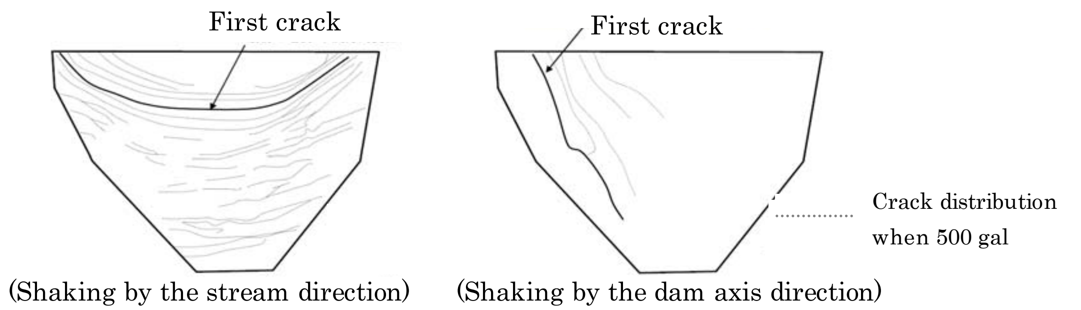


Figure 7. Distribution of cracks by the shaking test.

STUDY ON AFRD BEHAVOIR DURING THE EARTHQUAKE

Numerical dynamic analysis

The Yashio dam behavior during the earthquake was studied by a 3D numerical analysis, applying an equivalent linearization analysis method. The seismic wave record by EA-2 unit in the bedrock was used for the analysis. The analysis model includes the dam and its surrounding terrain as shown in Figure 8. The asphalt concrete facing was not modeled individually, assuming the facing would show same response with the dam body. Maximum acceleration and strain by the analysis are shown in Figure 9. The results of the analysis were judged as reasonable, since the calculated accelerations almost match the recorded ones although the analysis results were a little larger.

Maximum strain by the analysis was around 1/5 of the slope length below the dam crest center. Maximum values are 1.78×10^{-4} of tensile strain, 1.81×10^{-4} of compressive strain, and 2.97×10^{-4} of shear strain respectively. The calculated strains are small in comparison with the yield strain of the fine grained asphalt concrete of the facing, while the major cracks occurred by the 2011 Tohoku Earthquake. Further assessment was, therefore, needed to pursue the crack mechanism.

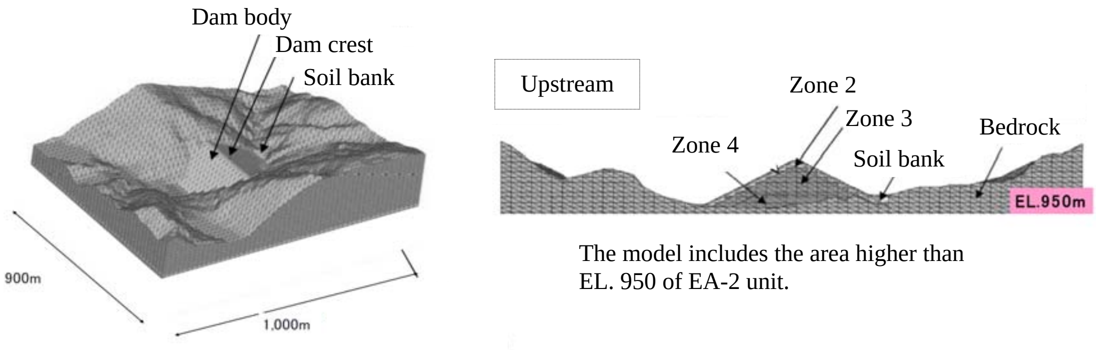


Figure 8. Three dimensional numerical analysis model.

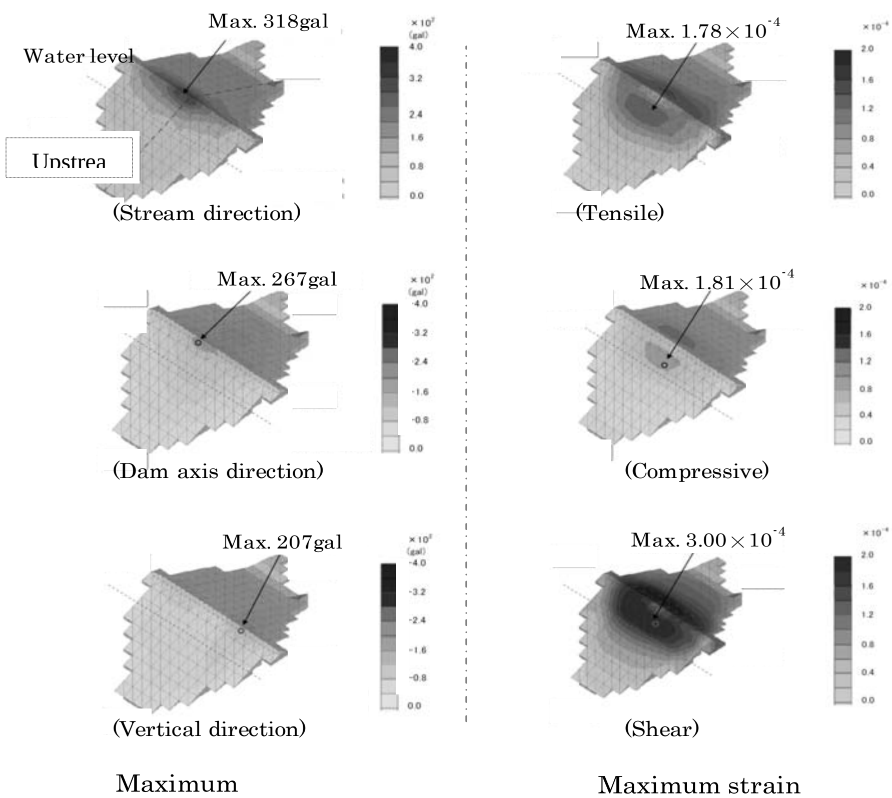


Figure 9. Maximum acceleration and strain at the surface by the analysis.

Analysis of the seismometer record at the dam crest

The asphalt facing structure at the top is shown in Figure 10. The sand mastic connects the asphalt facing and the concrete block. The cracks in the asphalt facing were investigated carefully for further assessment. The cracks in the facing reached the sand mastic and the joints of the concrete block. We measured the openings of the concrete block joints, and confirmed the joint openings where the cracks reached were larger than others. The joint openings during the earthquake were estimated based on the following assumptions.

a. The openings of the concrete block joints before the earthquake were set at 12 mm equally.
b. Relative displacements along the dam crest would widen or close the openings accordingly during the earthquake. The relative displacements were estimated by integration of the acceleration time histories. The acceleration record obtained at EA-10, 11, 12 and 13 were used for the estimation.
c. The joint openings would be equal in each section, i.e. from EA-10 to 11, EA-11 to 12 or EA-12 to 13.

The results are shown in Table 4. The joint displacements are all greater than the yield tensile strain of the sand mastic. The yield tensile strain of the sand mastic is 2.5×10^{-2} under -5 °C temperature and strain rate of 1×10^{-2} /sec, which is more flexible than the asphalt concrete. This estimation indicates the strain level may exceed the yield strain if the structures allow the strains to be concentrated at some specific location.

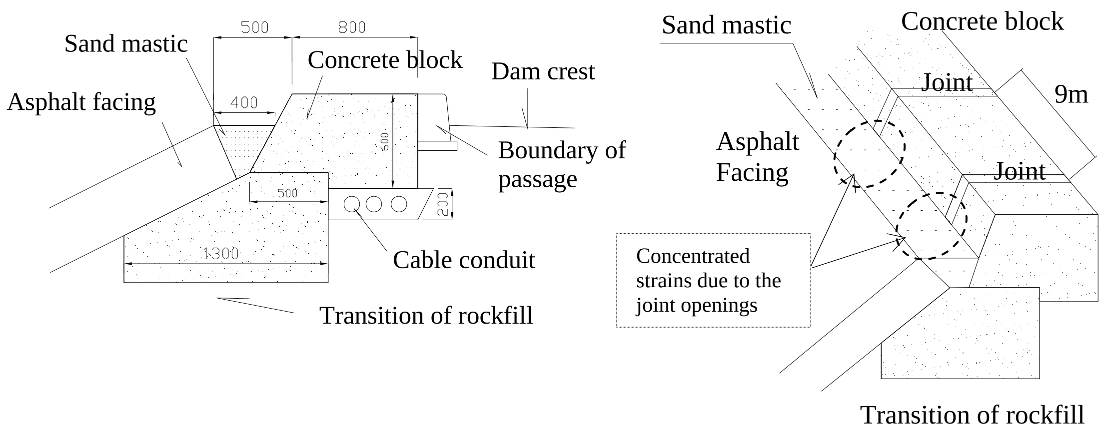


Figure 10. Facing structure at the dam crest.

Table 4. Estimated joint openings by integrating the actual acceleration.

Sectioon	Max. displacement	Number of joints	Joint openings		Note
			Displacement	Strain	
EA-10 to 11	3.9mm	6	0.7mm	0.054	Yeild strain of the sand mastic is 0.025
EA-11 to 12	4.4mm	9	0.5mm	0.041	
EA-12 to 13	5.7mm	6	1.0mm	0.079	

Estimated crack mechanism by the numerical dynamic analysis

The strains in the facing during the earthquake were evaluated from the results of the 3D numerical analysis for further assessment. The strain time histories at the dam crest were modified to be concentrated at each concrete block joint. The original joint openings before the earthquake were set to 12 mm for the evaluation.

The concentrated strain exceeds the tensile yield strain of the sand mastic ($=2.5 \times 10^{-2}$) at the left side at first. The first exceeding strain at the left side was calculated at the No.3 joint where the actual crack occurred. The strain values also exceed the yield level at other joints of the left side in the next moments. Following this, the strain values at the right side exceed the yield level. The first exceeding strain at the right side was calculated at the No.23 joint, while the actual crack occurred at the next joint. The result shows a reasonable match. The estimated tensile strains at other joints also exceed the yield level in the time history, while there was no remarkable damage in the area. We estimated the first cracks released the stress and the strain.

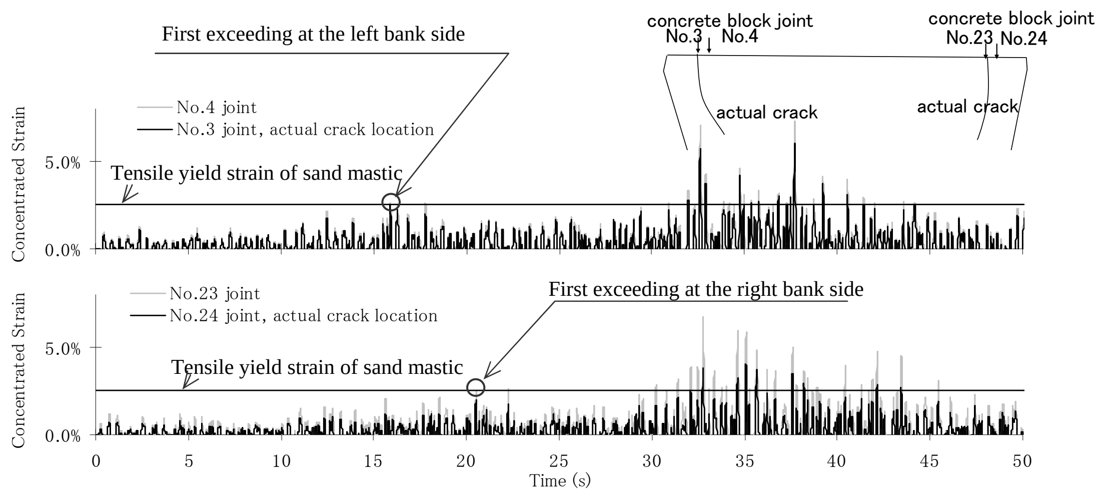


Figure 11. Concentrated strain by estimates at the actual crack location.

It should be noted from the studies that cracks may occur in the asphalt facing where structures allow strains to be concentrated at some specific part of the facing in the event of a strong excitation. In the Yashio dam case, we estimated that the strains were concentrated at the concrete block joints of the dam crest. The cracks would occur near the dam crest, and propagate downward (Tsukada et al. 2013).

CONDUCTED REINFORCEMENT

The cracks in the asphalt facing had to be repaired in order to secure the dam reservoir capacity for the power operation, which should be completed before the summer season when electricity demand would increase. The asphalt facing was temporally repaired from the surface. Repair material was carefully selected since fall of ambient temperature at night would widen the openings of the cracks. Low elastic asphalt mastic was used to close the cracks, which would have higher flexibility and allow fluctuation of the crack openings. The repaired areas were covered with asphaltic non woven sheets in order to shut water intrusion as shown in Figure 12. The cracks in the submerged area were closed with conventional epoxy material since fluctuation of crack openings and water temperature would be small. This repair method enabled early completion, and the Shiobara power plant resumed its operation 2 months after the 2011 Tohoku Earthquake.

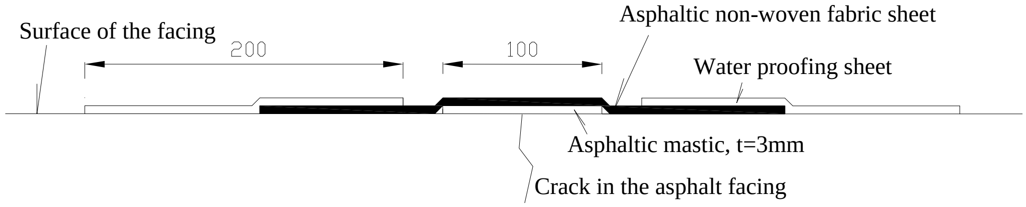


Figure 12. Temporary repair.

A durable measure was conducted after the summer season. The cracked asphalt facing was repaired as shown in Figure 13. We conducted a tensile bending test using a full-scale model, and confirmed that the tensile yield strain is greater in comparison with the original structure. The lower part of the upper impermeable layer was cut 10cm in width, and was filled with the low elastic asphalt mastic. Considering workability, the asphalt mastic was mixed with organic fibers which restrained the mastic flow from the filled area. The filled asphalt mastic was covered with asphaltic non-woven fabric sheets. The upper and middle parts of the layer were re-paved. Re-pavement works were arranged so that the pavement joint should keep 50cm away from each joint, which follows the original design of the facing.

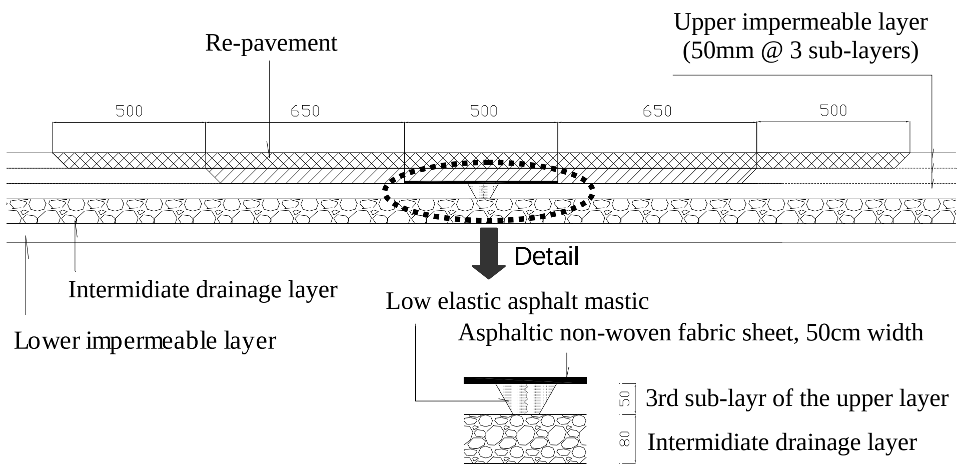


Figure 13. Cross section of the repair work for the upper impermeable layer.

Following the durable measure, the facing structure near the concrete block joint was reinforced as shown in Figure 14. We designed the reinforcement work using material which has an excellent elongation so that the strain would not be transferred from the joint opening to the asphalt facing. The asphalt mastic was used 10cm in width for overall facing thickness. The property of the asphalt mastic was confirmed by bending tests. The yield tensile strain of the asphalt mastic is more than 50%, while the one of the sand mastic is 2.5% under the assumed earthquake condition in Table 3. We conducted a FEM analysis, and confirmed the tensile strain of the asphalt facing due to the assumed joint opening is small in comparison with the yield strain. A copper plate was set beneath the asphalt mastic to not transfer the stress and the strain from the concrete block joint. Furthermore, the facing in the surrounding areas were re-paved with the asphalt concrete which composition was modified to have larger elasticity.

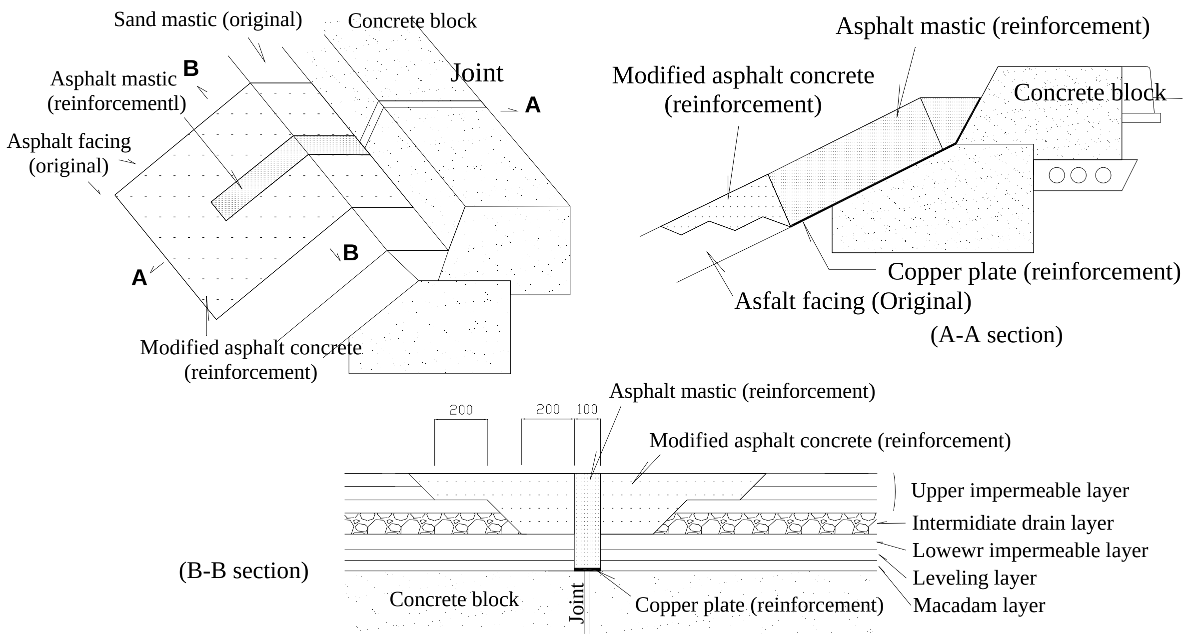


Figure 14. Reinforcement at the dam crest area.

CONCLUSION

This paper reports the crack mechanism of the asphalt facing of the Yashio dam. We estimated the cracks in the facing occurred due to the concentrated strains at the concrete block joints of the dam crest. The repair works were conducted in consideration of resuming the power plant operation early, durability of the repair work and prevention of cracks by the concentrated strain around the dam crest. The AFRD's structural feature allowed inspections and repair works from the surface, and the repair works were completed in a short period of time.

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