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INSPECTION AND EVALUATION OF DAM AFTER SERIAL EARTHQUAKE

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Abstract

Serial earthquake, especially with magnitudes of 5.0 MW or bigger can cause damages in anything including dams. In accordance with the provisions of the International Commission on Large Dams (ICOLD), there is an obligation for dam owners to inspect dams after an earthquake of magnitude greater than Mw 5, 0. In this paper, the inspection consisted of three following elements: 1) Review of past data 2) Visual inspection (field examination) 3) Report preparation. The analysis included settlement analysis. The data used in settlement analysis was the distance between the dam and the epicenter, the peak ground acceleration, and the intensity of the earthquake felt at the location of the dam. The analysis The results showed that due to the propagation of the earthquake in the bedrock received at the BMKG station at Lombok Airport (Praya), acceleration in the bedrock or peak ground acceleration in the earthquake sequence from July 29 to August 19 was very low, ranging from 20 to 110 gal or around 0, 02 to 0.11 g. In Lombok cases, rockfill dams were more resistant to earthquakes than homogeneous earthfill dams.

Keywords: Serial Earthquakes, Rockfill & Earthfill.

INTRODUCTION

Earthquake is a natural phenomenon of the Earth to release energy. Earthquake can be grouped into two types: volcanic and tectonic earthquakes. Volcanic earthquakes are one of the main signs that a volcano is restless. Tectonic earthquakes are caused by the movement of plates when energy accumulated within plate boundary zones is released. Tectonic earthquakes are usually larger than volcanic earthquakes (USGS, 2019). The tectonic process is very complex. Many countries, such as Indonesia, Philippines, Japan, New Zealand, Caribbean, Middle East and Arabian Peninsula are located around the tectonic plate interactions. In this situation, seismic activity is a common thing. Some events may occur with small magnitudes, but it is getting dangerous when earthquakes happen with larger magnitudes.

Dams are water structure constructions that must be designed to be resistant to earthquakes with a certain magnitude. Since a dam holds a large volume of water, a dam collapse can cause huge losses including properties and lives in the downstream area. For this reason, it is necessary to do a safe design with regard to seismic conditions.

The impacts of earthquakes to dams include:

a. shockings on the body of the dam and its complementary that can cause damages,
b. The active fault is very dangerous to the dam foundation. The shift of the dam foundation can cause the dam collapses,
c. Rockfall that can damage complementary buildings underneath,
d. Landslides that can damage embankments, large volumes of landslides can also cause large waves or even tsunamis in reservoirs,
e. RTE = reservoir triggered earthquake, which is an earthquake caused by changes in loading in the fault located in the

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reservoir. This earthquake can cause water waves that can overflow above the peak of the dam.

ICOLD (1988, 2016b) gave guidance for assessing earthquake hazard and evaluating parameters for dynamic analysis of dams as well as supplementary buildings such as power houses, tunnels, building pickings, hydromechanical work, and other constructions that support the operation of a dam. The stages to carry out dynamic analysis that take earthquake loads into account are as follows:

a. Conduct an earthquake hazard assessment, by investigating the source of an earthquake within a radius of 100 km or up to 300 km depending on the location of the seismic conditions of the dam. The product of earthquake hazard assessment is a seismotectonic map that describes active conditions, subduction earthquakes and other seismic information needed to analyze earthquake hazards,
b. Conduct earthquake hazard analysis, based on seismotectonic maps produced from earthquake hazard assessments. In the earthquake hazard analysis, earthquake magnitude and distance will be calculated for the purpose of OBE (Operating Base Earthquake) and SEE (Safety Evaluation Earthquake) using probabilistic (Probabilistic Seismic Hazard Analysis = PSHA) and deterministic (Deterministic Seismic Hazard Analysis = DSHA) methods. From the two analyzes, based on the provisions in ICOLD [2], one of the two that is suitable for seismic conditions will be chosen in the dam designs and evaluations. The final results of earthquake hazard analysis are input parameters for dynamic analysis with earthquake loads in the form of historical acceleration time for earthquakes from subduction zones, active faults and Benioff zones respectively for OBE and SEE earthquakes,
c. Perform dynamic analysis with earthquake loads on the dam with parameters of historical acceleration time. This approach is to get a settlement at the top of the earth fill dam, or to find out whether the tensile stress that occurs in a concrete dam caused by the earthquake load can be held back by the quality of the concrete.

At present, the use of pseudo static methods in dynamic analysis by applying earthquake loads is no longer permitted, because the loading mechanism in this analysis is not in accordance with the mechanism of earthquake operations at the dam. The result of pseudo static analysis is the safety factor of the slope of the embankment during an earthquake. Currently dynamic analysis with seismic loads is generally carried out using the finite element method both two-dimensional (2D) and three-dimensional (3D). So far, 3D analysis is more realistic than 2D analysis.

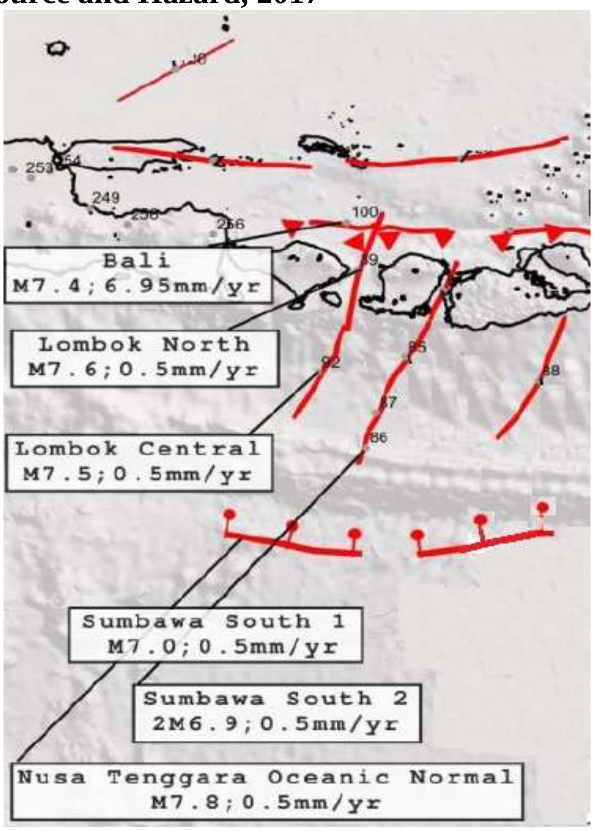
ICOLD (2016), dams are allowed to damage but do not collapse, the completion of the upper part of the dam should not be more than half of the freeboard reservoir, there should be no uncontrolled release from the reservoir, and the thickness of the filter pile zone should not reduce more than half the initial thickness. The dam and its complementary buildings must be carefully and accurately designed to meet the above requirements. ICOLD (2016), suggests that these requirements can be fulfilled by

a. Dams must be planned to be resistant to SEE earthquakes,
b. Complementary construction related to the release from reservoirs such as "bottom outlet", "spillway gate", "hydro mechanical" equipment, electrical resources must be able to be operated after an earthquake occurs,
c. The design of power house, internal tower and other buildings have to follow the earthquake regulations in the country, or be designed based on an earthquake with a return period of 475 years if calculated by the PSHA method (probabilistic seismic hazard analysis).

2. Case of Serial Earthquake in Lombok Island

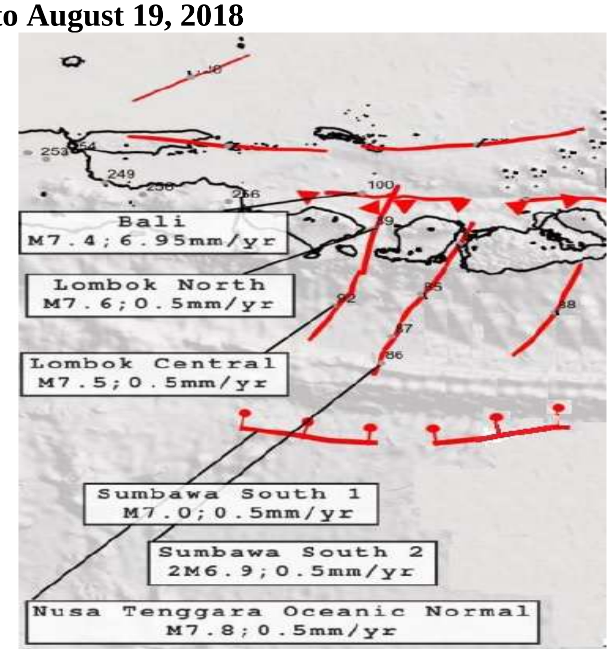
The island of Lombok is located in an active tectonic region, according to the book "National Earthquakes: Sources and Hazard" (2017), Lombok Island is surrounded by several earthquake sources, including the Thrust Arc Back Zone in the north, the megathrust in the south, also faults system in the West and East, as shown in Figure 1

Figure 1 Active tectonics in the Lombok region based on the Map of National Earthquake Source and Hazard, 2017



The recent Lombok earthquake was a series of large earthquakes starting at the magnitude of 6.4 on July 29 2018 followed by magnitude of 7.0 on August 5, 2018, then magnitude of 6.2 on August 9, 2018, finalized by magnitudes of 6.3 and 6.9 on the same day (August 19, 2018). The epicenters of the 4 large earthquakes on the island of Lombok are shown in Figure 2. From the result of geographical analysis based on distribution and focal mechanism of earthquakes, it is known that the series of Lombok Earthquakes was related to the movement of faults on the back arc of Lombok Island. The overlay result between background seismicity models and aftershock distribution patterns indicates that the distribution of aftershocks was consistent with the background of seismicity patterns which indicates a cluster pattern of west and east. Thus, a series of earthquakes was related to the first and second major shocks. The earthquakes were predicted generated by two adjacent segments that pushed each other. Referring to the results of observations of the main earthquake parameters from July 29 to August 19 2018, the initial evaluation of the deformation model, uplift gradient and displacement were carried out in relation to the seismic background pattern. Uplifting generally occurs on the north coast of Lombok in the order of tens of centimeters. From the simulation study, it was found that the sequence of large earthquake was triggered by train loads / displacement stresses. As a result of the earthquake on August 19, there was a tendency that the strain loading pattern towards the east.

Figure 2 The epicenters of large earthquakes that rocked the island of Lombok from July 29 to August 19, 2018



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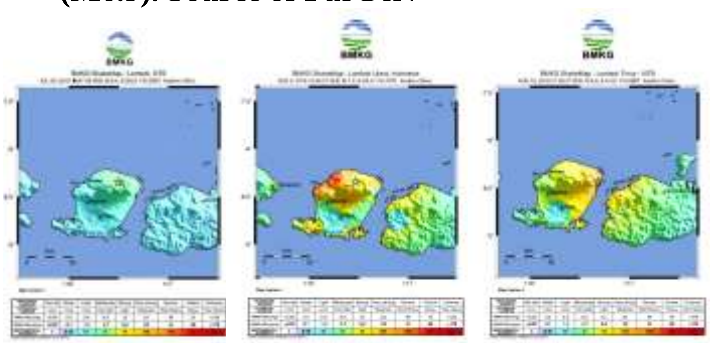
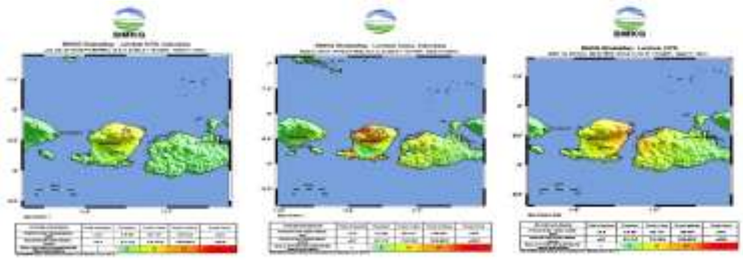
This research is further to detail the source of this earthquake and its implications for the adjacent area. Back arc fault line of this case is often referred to as the Flores fault because it is associated with the 1992 earthquake-tsunami on Flores which resulted in victims of up to around 2000 people. But as this fault line stretches from Alor-Wetar Island, Flores, Sumbawa, Lombok, to Bali; therefore it was proposed to be named as the Nusa Tenggara Rear Arc Fault Zone which consists of many segments, including the Lombok segment which was the source of the recent Lombok earthquake. The intensity map issued by the BMKG shows that a series of preliminary earthquakes and large earthquakes have a range of intensities from MMI IV to VIII or from II to IV on the BMKG (SIG-BMKG) Earthquake Intensity Scale. Figure 3 shows the Intensity Range Map. BMKG concluded that the impact of the earthquake that occurred on August 5 and August 19 2018 reached the maximum intensity of MMI VIII-IX in West Lombok, East Lombok and North Lombok. This means that only buildings that have been designed based on the principles of earthquake resistant buildings will be fine. Buildings that are not designed based on the principles of earthquake resistant buildings will suffer significant damage.

Figure 3 Maps of Lombok Earthquake Intensity on the MMI (above) and SIG-BMKG (bottom) scales on 29 July 2018 (M6.4), 5 August 2018 (M7.0), and 19 August 2018 (M6.9). Source of PusGeN





Based on the series of major Lombok earthquakes that occurred from 29 July to 19 August 2018, it was found that there were anomalies in the magnitude of peak ground acceleration at the Praya International Airport station (south of the epicenter). The anomaly was the peak ground acceleration (PGA) recorded at the station was very small, compared to the PGA value recorded at Taliwang station (southeast of the epicenter). The PGA values recorded at both BMKG stations are presented in Table 1 (Rudiyanto, 2018).

Table 1. PGA value recorded at 2 BMKG stations (Rudiyanto, 2018)

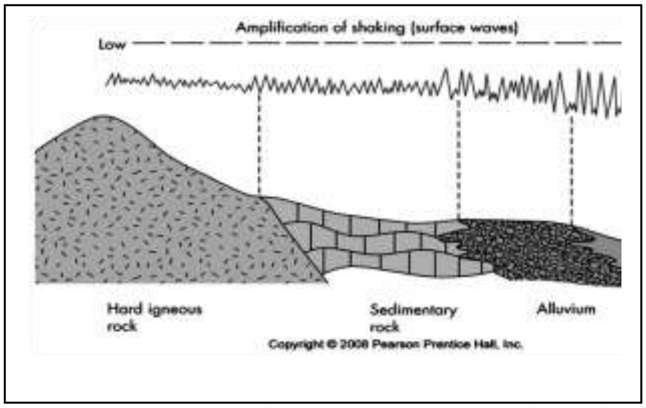
No	Station	Code	Lat	Long	D (km)	PGA (Z)	PGA (N)	PGA (E)	SC
1	Earthquake 29 July 2018, Mw 6.4								
	Lombok International Airport	MASE	- 8.766	116.28	47,90	3,03	6,22	5,66	B
	Taliwang	TWSI	-8.74	116.88	55,90	15,79	30,70	41,31	B
2	Earthquake 5 August 2018, Mw 7.0								
	Lombok International Airport	MASE	-8.77	116.28	48,00	17,88	43,44	29,87	B
	Taliwang	TWSI	-8.74	116.88	58,48	11,10	14,40	18,89	B
3	Earthquake 9 August 2018, Mw 5.9								
	Lombok International Airport	MASE	-8.77	116.28	36,97	13,35	28,71	33,50	B
	Taliwang	TWSI	-8.74	116.88	80,84	6,37	9,01	13,68	B
4	Erathquake 19 August 2018, Mw 6.9								
	Lombok International Airport	MASE	-8.77	116.28	48,90	4,960	10,03	12,06	B
	Taliwang	TWSI	-8.74	116.88	34,70	172,875	252,60	293,20	B

D : Distance
SC : Site Class

METHODOLOGY

Peak Ground Acceleration

Peak ground acceleration is the acceleration value on the bedrock. This acceleration will decrease as long as its movement away from the epicenter. It eventually decays at a certain distance. Peak ground acceleration is increased by a weaker medium. Figure 4 shows the acceleration of earthquake acceleration in various media.



Estimating Embankment Earthquake-Triggered Deformations

Dam inspection must be conducted immediately after an earthquake. A complete dam inspection procedure has been submitted by ICOLD (1988. 2016a). In the bulletin the examination will be carried out in 2 stages, namely:

a. immediate (initial) inspection after the earthquake by the dam authority
b. Advanced inspection by professional engineers

Emergency response after an earthquake is divided into 3 activities, namely:

a. Earthquake data collection (magnitude, epicenter, distance to the dam, and other information needed in connection with the earthquake)
b. Earthquake data process and immediately report to superiors to provide information whether or not evacuation is needed in the downstream area of the dam,
c. Conduct initial inspections to identify conditions and the level of danger.

Dam that must be inspected after an earthquake is determined based on the distance of the dam to the epicenter and the earthquake magnitude. ICOLD (2016a) provides a guidance that cover earthquake magnitude and the distance of the dam to the epicenter, as stated in Table 2 below. Moreover, Table 3 shows the relationship between earthquake intensity and inspection response.

For this reason, earthquake information is very necessary. BMKG provides earthquake information including magnitude, earthquake location and depth of the earthquake source. It is informed to the community within 3 minutes after an earthquake in the territory of Indonesia.

Table 2. The relationship between earthquake magnitude and the distance of the epicenter to the dam that must be examined (ICOLD, 2016a)

Magnitude	Distance (km)
> 4.0	25
> 5.0	50
> 6.0	80
> 7.0	125
> 8.0	200

Table 3 Relationship relationship between earthquake intensity and response of inspections

Respon Level	Earthquake Intensity (MMI)	Inspection Response
A	MMI < 4	No need special inspection
B	MMI 4 – 5	Inspection within 18 hours
C	MMI 5 – 6	Inspection within 6 hours
D	MMI 6 – 7	Inspection prompt after shocks
E	MMI > 7	Inspection prompt after shocks

Inspection of dam after being shaken by the earthquake at an early stage is carried out visually. It is to determine the type and level of damage that can be seen from visual conditions such as cracks, settlements, landslides, and seepage or leakage in the downstream of the dam. This inspection can determine the need for dam rehabilitation, the need for emergency action to save the dam and its downstream area, or the need for reducing the water level of the reservoir, so that the hazard of flush flood in the downstream if the dam collapses can be reduced or even avoided.

It is difficult to know internal damages of the dam. Therefore, dams have to be equipped with instrumentation for various measurements of technical parameters such as pore water stress,

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total stress, and deformation of dam. Almost all Internal changing after receiving earthquake loads can be known using dam instrumentations.

Inspection also must be conducted on dam instrumentations and all energy sources for driving the instrumentations and hydro mechanical equipments. Damage and malfunction of hydro mechanical equipments can endanger the dam.

Physical examination of the dam at this early stage is a step to find out the condition of the dam and the safety of downstream area. The first action in rescuing a dam is reducing the reservoir water, so that the hydraulic load can be reduced. Therefore, it is necessary to consider the construction of a bottom outlet with hydro mechanical equipment. The hydro mechanical equipment has to be earthquake resistant to a certain magnitude according to seismotectonic conditions of dam.

Procedures in ICOLD (2016 a) for a visual inspection of a dam after the earthquake was shaken are as follow

a. Immediately conduct visual inspections to the dam and its complementary buildings such as spillway, intake and others,
b. If it is known that the dam will collapse, immediately inform the government to evacuate the downstream area of the dam,
c. If it is known that reservoir inflow is smaller than usually, immediately check whether the river has been blocked by landslides. Stream blocking by landslide can easily produce flush flood,
d. A more detailed inspection must be carried out immediately even though damages seem not to cause the collapse of the dam,
e. Perform detailed inspections according to the procedure, and if the results show that the dam is unlikely to collapse, then the next step is as follows;
   - Check damages on the top of dam,
   - Check cracks, subsidence, shifts, seepage, new springs, rock fall etc. on embankments,
   - Check toe drain, and identify whether there is uncontrolled seepage, and check the discharge at the V-notch gauge,
   - Check the diversions and its hydro mechanical equipments whether there is a shift, or other damages,
   - Check the intake and its hydro mechanical equipments and valves,
   - Check the power plant facilities, penstock, control buildings and its hydro mechanical equipments,
   - Check the emergency of power plant and electrical systems,
   - Check whether there is an avalanche on the slope of the reservoir,
   - Check if there is rock fall around the dam and its complementary buildings,
   - Check dam instrumentation in detail and its interpretation thoroughly to find out the condition of the dam,
   - Check all complementary buildings.
f. Conduct an overall evaluation based on the results of detailed inspections of the dam after the earthquake was rocked, whether the dam still has a risk to collapse in the future, including Settlement Analysis, using the Swaisgood graph as presented in Figure 12. The magnitude of the settlement of dam after being shaken by a series of large earthquakes is calculated using
   $S = S_1 + S_2 + S_3 + S_4$
   With
   S : settlement of dam
   S_1, S_2, S_3, S_4 : settlements of dam after first,second, third, and fourth shocks
g. Make complete and detailed reports including rehabilitation plans, implementation times and rehabilitation costs.

According to data from the River Basin Organization, Nusa Tenggara 1, there are 33 dams in Lombok Island as shown in Table 1. Heights of the Dams are at least 15.00 meters, according to the ICOLD criteria, the dams are categorized as large dams.

A map of the locations of dams in Lombok Island and the epicenter of the first earthquake on 29

July 2018 with a magnitude of Mw 6.4 is shown in Figure 4. Distances between the dams and the epicenter of the earthquake are presented in Table 4.

Figure 4 A Map of the Locations of Dams in Lombok Island and the Epicenter of the First Earthquake on 29 July 2018

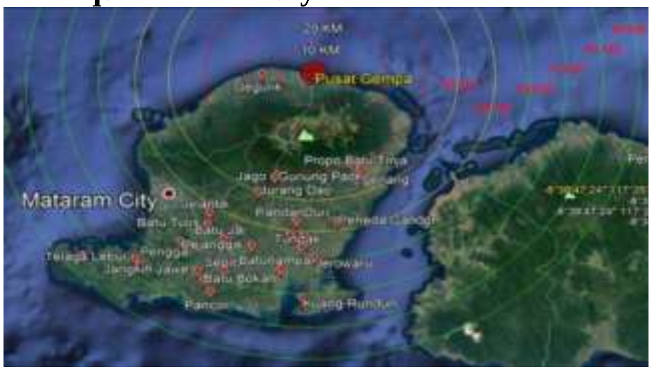

Table 4 Distances between the dams and the epicenter of the earthquake

Distances	No	Dams
0 – 10 km		----
10 – 20 km	1	Gegurik Dam
	2	Bayan Dam
	3	Lokok Tawah Dam
20 – 30 km		-------
30 – 40 km	4	Gunung Paok Dam
	5	Jago Dam
	6	Kembar II Dam
	7	Propok Batu Tinja Dam
	8	Senang Dam
40 – 50 km	9	Jurang Dao Dam
	10	Pandanduri Dam
	11	Penede Gandor Dam
50 – 60 km	12	Jelantik Dam
	13	Batu Tulis Dam
	14	Surabaya Dam
	15	Inen Raja Dam
	16	Kali Ujung Dam
	17	Lingkok Lamun Dam
	18	Tundak Dam
	19	Breinge Dam
60 – 70 km	20	Batujai Dam
	21	Mapasam Dam
	22	Pengga Dam
	23	Pejanggik Dam
	24	Pare Dam
	25	Batu Nampar Dam
	26	Jerowaru Dam
70 – 80 km	27	Kengkang Dam
	28	Jangkih Jawe Dam
	29	Sepit Dam
	30	Batu Bongkah Dam
	31	Pancor Dam
	32	Kuang Rundun Dam
80 – 90 km	33	Telaga Lebur Dam

RESULTS AND DISCUSSIONS

Inspection of Gegurik Dam

The Gegurik Dam is located 10-20 km from the epicenter of the first strong earthquake on 29 July 2018 with a magnitude of Mw 6.4. During the earthquake, the Gegurik dam was empty. Because water collected during the previous rainy season has been used for irrigation supply. After being rocked by 3 consecutive strong earthquakes on July 29, August 5 and August 9 with the magnitudes of Mw 6.4, Mw 7.0, and Mw 6.2; longitudinal cracks and transverse were found on the top of the Gegurik Dam with widths ranges from 3 to 5 mm, the parapet was stretched around 3 mm, and the rip-rap was torn. Figure 5 shows the Gegurik dam after the earthquake.

Inspection of Jago Dam

Jago Dam is located 30-40 km from the epicenter of the first strong earthquake on July 29, 2018. During the earthquake, the Jago dam is full of water. The results of inspections carried out on August 16, 2018 showed that there were some cracks on the top of the dam with widths range from 10 to 170 mm. Uncontrolled seepage occurred on the downstream of embankment. Figure 6 shows photographs of the Jago dam after the earthquake.

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Figure 5 the Gegurik dam after the earthquake

Inspection of Pandanduri Dam

Pandanduri Dam is located 40-50 km from the epicenter of the first strong earthquake. During the earthquake, the Pandanduri dam is filled of water at a low water level. The results of inspections conducted on August 16, 2018 indicate that there was a longitudinal crack on the access road. The road is on the saddle dam of the Pandanduri dam. Figure 7 shows the Pandanduri dam after being shaken by the earthquake. Figure 8 shows the inspection on hydromechanics of Pandanduri Dam. Figure 9 shows pore water pressure in the core zone of Pandan Duri dam at station 650. Figure 10 shows settlements in the Pandanduri core zone at each layer's elevation at station 660 and reservoir water level. Figure 11 show the seepage discharge read in the V-notch gauge.

Figure 6 the Jago dam after the earthquake

Figure 7 the Pandanduri dam after the earthquake

Figure 8 the inspection on hydromechanics of Pandanduri Dam

Figure 9 the pore water pressure in the core zone of Pandan Duri dam at station 650

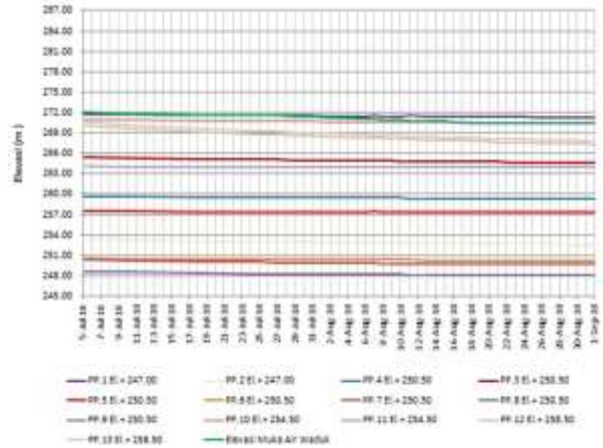


Figure 10 settlements in the core zone of Pandanduri Dam at each layer's elevation at station 660 and reservoir water level

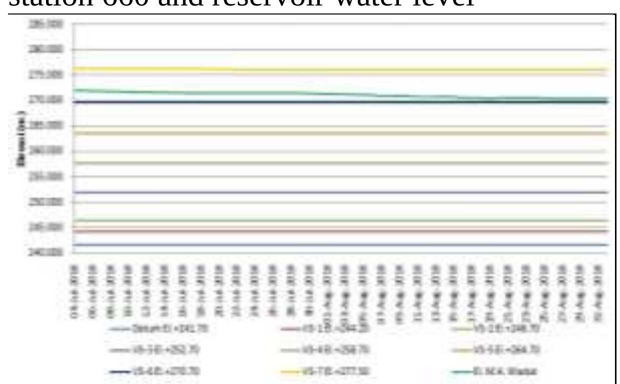
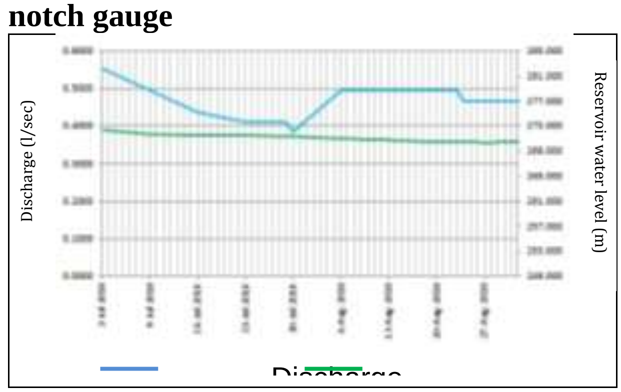


Figure 11 seepage discharge read in the V-notch gauge



Discussions

The two dams under study: Jago Dam and Pandanduri Dam were rocked by 4 major earthquakes from 29 July to 19 August 2018,

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recalculation analysis will be carried out at the dam;

a. Jago Dam with a height of 15 meters is located in the range of 30-40 km from the epicenter. This dam experienced a crack of 17 cm until the third earthquake on August 5, 2018, this crack enlarged to 20 cm due to a large earthquake on August 19, 2018.
b. Pandanduri Dam, 42 meters high, is located at a distance of 40-50 km from the epicenter. This dam did not experience a crack at the top of the dam, but it has not been measured whether there was a decrease in the dam's peak during the inspection.

Since there is no dam on Lombok that has an accelerometer, the peak ground acceleration (pga) that occurs at the dam site was estimated based on the pga recorded at the Meteorology Climatology and Geophysics (BMKG) station at Praya International Airport. The pga values recorded at the station shown in Table 1 are in the range of 37 to 49 km, so that they can represent the PGA values at the dam to be analyzed.

The results of the settlement analysis at the peak of the dam affected by the earthquake were calculated as a cumulative settlement after being rocked by a series of large earthquakes from 29 July to 19 August 2018 and is shown as

a. First Earthquake : Mw = 6,4 and PGA (N) = 0,006 g
b. Second Earthquake: Mw = 7,0 and PGA (N) = 0,043 g
c. Third Eathquake : Mw = 6,2 and PGA (N) = 0,028 g
d. Fourth Earthquake : Mw = 6,9 and PGA (N) = 0,010 g

Figure 12 the Swaisgood graph

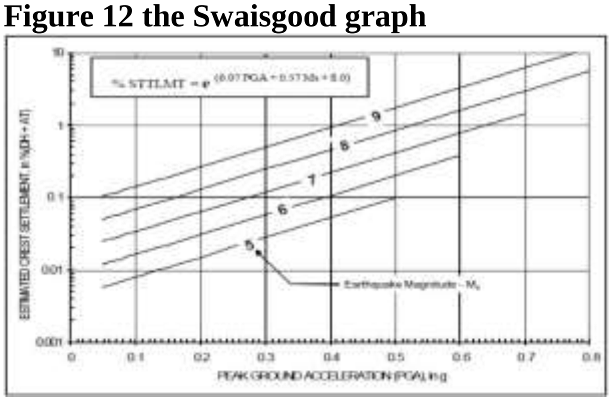

Figure 12 shows the graph of the relationship between the estimated amount of settlement at the peak of the dam with the PGA value at the dam that was rocked by the earthquake. Based on the graph, the estimation of settlements is shown below

Settlement of Jago Dam = (0.015 + 0.025 + 0.017 + 0.021)% x the height of the Dam
= 0.078 % x the height of Jago Dam
= 0.078 % x 1,500 cm
= 1.170 cm

Settlement of Pandanduri Dam = (0.015 + 0.025 + 0.017 + 0.021)% x the height of the Dam
= 0.078 % x the height of the Dam
= 0.078 % x 4,200 cm
= 3.276 cm

CONCLUSION

This research has discussed the effect of the earthquake on the dam, Inspection of the dam after the earthquake and some examples of dam inspection after the Lombok earthquake. Some conclusions that can be conveyed from this paper are

a. Earthquakes are natural phenomena that must be considered in the design of a dam, so that the dam can withstand and not collapse if a maximum earthquake occurs in accordance with the seismotectonic conditions in which the dam was built,
b. It is necessary to inspect and evaluate the condition of the dam after being rocked by an earthquake to determine the rehabilitation phase,
c. How to inspect the dam after being hit by a large earthquake must be done immediately.
d. Earthquake analysis of large dams in areas with high seismic activity must be carried out in a credible manner, as stated in ICOLD,
e. Settlement of Jago Dam and Pandanduri Dam after the serial earthquake was 1.170 cm and 3.276 cm,

f. The height of dam has to be refixed.

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