Risk-assessment of hydropower plant susceptible to seismic hazard by 3D spectrum analysis

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Abstract. Recently, new fault zones are identified in central Borneo due to the ongoing geomorphological anomalies along the Rajang-Crocker Belt. The Kapit-Belaga region along the Rajang River system are located in between active trending strike-slip faults. By 2025, this region will have 3 operational large hydropower dams namely, Bakun, Murum and Baleh which are approximately 120 km apart in radius. Even though central Borneo is known to be a stable area, the assessment of seismic risk for existing dams is vital. The seismic failure of Konya Dam, India in 1967 proved that occurrences of catastrophic earthquake in low seismicity region is possible. Furthermore, earthquake frequency model shows that it is plausible for the Crocker fault system to produce seismic ruptures of magnitudes ≥7.0. The research of risk-assessment for hydropower in this work is motivated by the possibility of larger seismic hazard within the Crocker fault system. Hypothetical seismic loadings from Tosya and Aydin earthquakes’ records are adopted as inputs to replicate long-distance waves for the Response Spectrum Analysis (RSA) by ANSYS® ACADEMIC. Results show that tensile zone develops at the reservoir bed, extending to the dam foundation. When the seismic load is at 0.625 g Peak Ground Acceleration (PGA) – which is equivalent to magnitude 6.0 earthquake, the mechanical responses of the dam body excitation and hydrodynamic pressure from the impact of the reservoir due to seismic excitation triggers structure failure at the mid crest and bottom of the dam.

1. Introduction

Borneo is a continental region which elastic thickness of the lithosphere is thin, with high heat flow and low velocities of sediment yielding at shallow depths in the mantle [1]. Due to the ongoing geomorphological anomalies along the Rajang-Crocker Belt [2], new dextral strike-slips which deflected streams and sinistral faults appears, surrounding central Borneo [3]. The Kapit-Belaga region along the Rajang river system are located in between these major strike-slip faults. By year 2025, Sarawak will have 3 operating large dams in 120 km radius of the Kapit-Belaga region, namely Bakun Murum and Baleh. Bakun and Murum are built on fault lines underlying the Rajang River System. Although Borneo is relatively stable, strong seismic motion were recorded by the Malaysia Meteorological Department’s seismological station (Station KASM) near the region of responsible [4]. The Konya, India earthquake in 1967 is an example that earthquakes with surface-wave magnitude of 6.5 can occur in a region considered stable with no apparent seismicity [5]. Thus, the risks of large
earthquake occurrences in the Kapit-Belaga region cannot be dismissed. Furthermore, earthquake frequency model suggests the reoccurrences of large earthquake caused by the Crocker fault system after the 2015 Ranau earthquake in Sabah, Malaysia is plausible [6]. On top of that, the peak ground acceleration (PGA) for 500 years return period in Malaysia has doubled from 0.5 g PGA to 1.0 g PGA after the Aceh earthquake in 2004 [7]. Due to the characteristics of the tectonic settings in Borneo[1-3], the low rates of average fault slips mean that earthquake disasters with return period measured in thousands of years can occur unexpectedly because they are difficult to estimate [8]. Since earthquake with destructive characteristic in the Asia region is caused by the long period vibration [7] and long-wave propagated from various epicentres [9], there are risks for Bakun dam or Murum dam to endure seismic excitation caused by strike-slip rupture around the region.

Therefore, to mitigate seismic hazard of operating dams, it is crucial to assess the seismic risks. Our previous studies analysed the hypothetical risk assessment of Murum dam when introduced to long long-wave propagation [10]. The results showed that Murum dam can withstand up to 0.1 g PGA shaking and the critical cracking occurs at the base of the dam. However, the scope of study excluded the reservoir body which is crucial because dams are built at the end of the valley, directly above the fault line to prevent river erosion of the valley when there is a tectonic lift due to seismic excitation. In this work, hypothetical seismic time-histories are adopted to replicate potential seismic excitation propagating from ruptured fault lines belonging to the Crocker fault system. ANSYS® ACADEMIC is utilized to simulate the Response Spectrum Analysis (RSA) via finite element method.

2. Modelling of Murum dam
Murum dam in figure 1. (a), is a large concrete gravity dam located at Murum river in Belaga, Sarawak, Malaysia. It is designed to withstand Operating Basis Earthquake (OBE) which is equivalent to 0.1 g PGA shaking or earthquake which has about 50% probability of occurrence during the service life of 100 years, with a return period of 145 years. The design is based on the ICOLD (2010) [11]. However, to understand the performance of RSA, 5% damping is excluded from the simulation. The parameters of the dam are as in figure 1. (b). The height is 141 m, the length along the crest section of the dam is 473 m and the width transverse to the riverbed is 75 m. The reservoir capacity is 12,000 hm³ and the depth is 135 m. The numerical modelling and meshing with tetrahedral element are constructed using ANSYS® ACADEMIC. The dam and the reservoir are fixed at the bottom as shown in figure 1. (c) and the dam structure is defined to be a target for contact simulation to recreate the reservoir impact on the dam during seismic excitation. In figure 1. (d) the dam structure and the reservoir are at equilibrium. To instruct recognition of ground acceleration input, the definition of pressure direction for every working pressure, \( P_i \) at the bottom of the numerical model for is expressed by equation (1):

\[
\bar{P}_i = \frac{(P_j X + P_k Y + P_l Z)}{(P_j^2 + P_k^2 + P_l^2)^{1/2}}
\]  

Where, X, Y, Z are the components of unit vectors normal to centre of element; \( P_j, P_k, \) and \( P_l \) are the working pressures at X,Y and Z directions, and the values \( i, j, k \) and \( l \) represent surface nodes. The dam structure is defined as concrete with Young’s Modulus of 31.2 GPa and Poisson’s Ratio of 0.18. The density of the reservoir water is 0.998 gcm³.

3. Static, Modal and Respond Spectrum Analysis
This work employs RSA to visualize the possible seismic damage when Murum dam is loaded beyond 0.1 g PGA [10,12], simulating a magnitude 6.0 earthquake. The initial conditions of the Murum dam is calculated via 3-dimensional static analyses followed by modal analysis. RSA combines the modal analysis with the hypothetical seismic spectrum to generate displacement and stress data. Figure 2 shows the time-histories employed for the RSA which are adopted from Aydin and Tosya earthquakes. Only single-point response spectrum is considered for this simulation.
Figure 1. The numerical modelling of Murum dam by ANSYS© ACADEMIC. (a) Aerial photo of Murum dam reservoir at Murum river. (b) The dimension of Murum dam and part of the reservoir. (c) Meshed numerical model with definition of load and fixtures. (d) Cross-section contour of the static reservoir pressure on the dam structure shows that it is at an equilibrium.

Figure 2. The seismic response spectra of Tosya and Aydin earthquake adopted as time-history input for spectrum analysis.

3.1. Static Analysis
The static analysis is similar to the pseudo-static analysis, whereby the magnitude vector of the load is broken down into components. However, the earthquake load is not defined by the factor value of the dam’s dead weight. In this work, the magnitude of the earthquake load is defined as the PGA load itself. Therefore, the discussed results are direct feedback of the seismic excitation. The conditions of the static analysis are featured in figure 1. (c). At the loading node, indicated by the upright arrow,
acceleration loadings in g PGA term, where 1g PGA = 9.81 ms\(^{-2}\) is defined. Murum dam is in a region of 0.03 g PGA where the probability of exceedance (PE) is lower than 10% in 50 years [13]. In 1994, magnitude 4.7 and 5.3 earthquakes occurred in Kapit – approximately 120 km radius from the dam [14]. These events fit the simulated recurrence frequency within the Crocker Fault system with magnitude ≥5 with return period about 20 years [6]. Therefore, the suitable loadings for RSA are: 0.08 g, 0.1 g, 0.225 g, 0.425 g and 0.625 g PGA. The relationship of PGA loadings in comparison with the Richter Scale Magnitude and Modified Mercalli Intensity scale (MMI) are presented in Table 1.

| PGA (g)   | Richter Scale Magnitude | MMI Scale | MMI observations             |
|-----------|-------------------------|-----------|------------------------------|
| 0.039 - 0.092 | 4 - 5                  | V         | Sleepers awakened            |
| 0.092 - 0.18   | 5 - 6                  | VI        | Trees sway, some damage from falling objects |
| 0.18 - 0.34    | 6                      | VII       | Cracking of walls            |
| 0.34 - 0.65    | 6 - 7                  | VIII      | Some damage to buildings     |

3.2. Modal and Respond Spectrum Analysis
Modal simulation is conducted after the static simulation. Then, at the final load step, time-history is defined as input at the loading node. The time-histories from Aydin and Tosya are chosen as hypothetical seismic loadings to replicate the long-wave earthquakes because the maximum PGAs are within the range of magnitude 6.0 which are suitable for the region of responsibility in this study.

4. Results and Discussion
All the extracted results are from the deformation contours at the cross-section of Murum dam. Notable deformation at the lower part of the dam is detected when the load is 0.425 g PGA. Deformation about the value of 0.04 m can be observed at the mid-crest section in figure 3. The RSA results for seismic load at 0.625 g PGA (period 1.5s for Aydin and 1.6s for Tosya) exhibit greater value for the distribution of deformation ranging from 0.04 m to 0.07 m around the mid-crest section. Compared to our previous studies, the deformation yields are smaller [10,12]. It should be reminded that the results are generated from RSA without considering the 5% damping. This shows that the inclusion of reservoir introduces water compressibility that reduces the hydrodynamic pressure and add natural damping to the dam-reservoir-foundation system. Which means the water component absorbs the seismic load during static deformation as explained by Lin et. al. [15]. Overall, values obtained from both static and RSA agree with the crack model for seismic failure of concrete dam [16] and the crack profile of Konya dam [17]. From the results, the tensile zone generates from within the reservoir bed, extending to the heel of the dam foundation. High equivalent stress accumulates at the bottom of the dam because the foundation of the concrete dam is rigid and unable to deform copiously compare to the high deformation of the mid crest section. The deformation and stress values exceed the tensile resistances of concrete structure [18]. This points out there is a likelihood that the mid crest and foundation of the dam are severely damaged at 0.625g PGA as shown in figure 4 and figure 5. These results not only exhibit potential structural failures of Murum dam due to seismic hazard from magnitude ≥5.0 earthquake with the return period about 20 years but also the damage from magnitude ≥6.0 earthquake with the return period 150 years.

5. Conclusion
In conclusion, Murum dam is designed to withstand not more than 0.1g PGA seismic excitation. Therefore, notable hazard patterns are observed when the structure is introduced with hypothetical seismic loads that replicates the plausible earthquake originating from the Crocker fault system. The inclusion of reservoir body into the RSA envisaged clearly that the development of tensile zone is more rapid at the reservoir bed compare to dam foundation itself due to hydrodynamic pressure.
contrast of high deformation at mid crest and high stress at the dam-reservoir bed indicates the likelihood of seismic failure at 0.625g PGA shaking.

Figure 3. Static deformation of Murum dam at seismic loading 0.225g, 0.425g and 0.625g

Figure 4. Spectrum analysis deformation of Murum dam at 0.625g for Tosya and Aydin seismic load.

Figure 5. Equivalent stress distribution of Murum dam at 0.625g for Tosya and Aydin seismic load

6. References
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