Effects of Chiangrai earthquake to Mae Ngat dam from instrument interpretation and finite element simulation

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ABSTRACT

This is a study about the stress, displacement and factor of safety of Mae Ngat Dam. According to the field study and the analysis by finite element method in a 2D nonlinear plane strain, using the Elasto-Plastic soil model with Mohr-Coulomb failure criteria to analyze acceleration, pores water pressure, deformation and factor of safety. The analysis was done using dynamic method with the intensity that had happened according to the earthquake in Phan, Chiangrai, in northern part of Thailand, where the earthquake measured 6.3 Richter. The location of Mae Ngat Dam is 150 kilometers away from the epicenter. It was found from the model under seismic force, that the acceleration had even diffusion. The highest acceleration was at the crest of the dam. There was mostly horizontal displacement, analyzing 5.7 centimeters and the most vertical displacement was analyzed at 3.3 centimeters. According to the earth zone dam seismic force, the factor of safety was 1.856, which was higher than the minimum criteria of the safety factor by the Department of Irrigation 1.500. The seismic force had not much effected to the dam. It can be concluded that Mae Ngat Dam is still safe from this earthquake.

Keywords: earth dam, earthquake, finite element, dynamic

1 INTRODUCTION

Earthquakes are natural disasters that cause direct damage to engineered constructions such as buildings, roads, bridges, and dams, causing loss of life and property. According to studies of earthquakes in Thailand, both the study of active faults by the Department of Mineral Resources and the statistic compilation of earthquake occurrences by Thai Meteorological department, it was found that the North and the Northwest areas have faults which may cause earthquakes measuring 5-6 on the Richter scale. If an earthquake of this intensity occurs nearby local communities, it may cause destruction to life and property. The 6.3 Richter earthquake in Northern Thailand on May 5, 2014 at 18:08 pm caused immeasurable damage to the city and the surrounding areas. The centre is located in Mae Law, Phan District, Chiangrai province. (Fig. 1). The Dam instruments are installed at the dam to measure the acceleration

Fig. 1. Epicenter of earthquake is located in Mae Law, Phan District, Chiangrai province.

In the past, most of the operating dams in northern Thailand were designed and constructed based on the Pseudo-Static Method, which does not consider the actual seismic force. As the analysis hypothesis based on the Pseudo-Static Method cannot analyze the actual seismic force, it is necessary to analyze the factors of dam safety by using the response from dynamic force because the results of that analysis are more accurate. In addition, there has been further development of modeling analysis with the finite element method (FEM) and computer usage. This allows for more
detailed and accurate analysis. This research focuses on the analysis of the effects caused by the earthquake force that was obtained from the epicenter to evaluate the seismic safety of Mae Ngat Dam.

2 SITE DESCRIPTION AND INSTALLATION

2.1 Mae Ngat Dam

Mae Ngat Dam was an earth-filled embankment dam with a clay core. It is a zoned earth dam consisting of 4 parts: (1) Core zone, (2) Random one, (3) Miscellaneous, (4) Filter zone and (5) Rock fill zone (as in Fig. 2). The dam was built to block the Mae Ngat waterway at Cho lae sub district, Mae Taeng district, Chiang Mai. The dam’s height is 59 meters and the length is 1,590 meters. The types of soils used in the construction of Mae Ngat Dam were CL and MH. The dam’s construction began in 1977 and was completed in 1984. The cross section of the main dam and its layout is shown in Figure 2.

![Fig. 2. Typical cross section of the Mae Ngat dam](image)

2.2 The dam’s materials and properties

The data of the zoned-earth dam in this study was collected to acquire detailed information of both the construction and the timing of water retention by testing the qualities of the materials both on the field and in the laboratory by Vikromprasit (1987) and collecting the samples of soil in the core zone for additional laboratory testing. The acquired information was analyzed to select representatives of the current materials to be able to set properties in creating a model that is the closest to the current soil conditions, so it can be used to analyze the behavior of the dam when affected by dynamic force. Properties of materials of the dam are displayed in Table 1 and Table 2.

![Table 1. Properties of soil in Mae Ngat dam](image)

2.3 Instrumentation

With the cooperation of Royal Irrigation Department, the dam instrumentations, Piezometers and Accelerometers (USACE (1995)), were installed to measure the acceleration and the pore water pressure at Mae Ngat Dam in January 2014 in the dam and the mountain next to it (Regional Irrigation Office 1 (2013)).

- 50 Electronic Piezometers were installed to measure the pore water pressure in the dam at the locations according to the plan in Figure 3.
- Accelerometers were installed in the middle and on the crest of the dam to measure the acceleration of the dam according to the plan in Figure 4.

![Fig. 3. Position of piezometer installation in the dam](image)

![Fig. 4. Position of accelerometer installation](image)

3 METHOD

The data used in the analysis came from the soils used in the dam construction which were tested in the field and the laboratory. The data collected from the piezometers and accelerometers were used to create the dam model at Station 0 + 180 using Mohr-Coulomb model by finite element method (FEM) to study the response of the dam to earthquakes. Material models of Mae Ngat Dam used as 2D plane strain problem. The
PLAXIS program was used to analyze the model. The selected elements were triangular with 15 nodes and 12 stress points (Fig. 5) from Brinkgreve and Vermeer (1998). The water level in the dam was analyzed while the water retention level was normal and Figure 7 shows the phreatic line of Mae Ngat Dam (Cedergren (1977)). The water pressure was set to hydrostatic pressure. Then, the experiment was analyzed under dynamic force (Desai and Christian (1977)).

Fig. 5. Triangular elements with 15 nodes and 12 stress points.

Fig. 6. Mae Ngat dam model using finite element method (FEM) consists of 845 elements and 6947 nodes.

Fig. 7. The model using finite element method shows the phreatic line of Mae Ngat dam.

4 THEORY

4.1 Dynamic analysis

In this study, we analyzed with time history analysis method. This method is suitable for analyzing the behavior of the structure as close to reality with according to the acceleration of the ground. The equations of motion used as equation (1) by numerical methods proposed by Newmark (1959).

\[
M \ddot{u} + C \dot{u} + Ku = F
\]  

(1)

Here, \(M\) is the mass matrix, \(u\) is the displacement vector, \(C\) is the damping matrix, \(K\) is the stiffness matrix and \(F\) is the load vector. The displacement (\(u\)), the velocity (\(\dot{u}\)), and the acceleration (\(\ddot{u}\)) can vary with time which includes the following steps.

Step 1 Calculate the acceleration at the start time \(t = 0\) by using equation (2)

\[
\ddot{u}_0 = \frac{p_u - c\dot{u}_0 - ku_0}{m}
\]  

(2)

Step 2 determined the time \(\Delta t\)

Step 3 calculated \(k\) from equation (3)

\[
k = k + \frac{\gamma}{\beta \Delta t} c + \frac{1}{\beta (\Delta t)^2} m
\]  

(3)

When \(\gamma = \frac{1}{2}, \beta = \frac{1}{4}\) for Average acceleration method

\(\gamma = \frac{1}{2}, \beta = \frac{1}{6}\) for Linear acceleration method

Step 4 calculated parameter \(a\) and \(b\) from equation (4) and (5)

\[
a = \frac{1}{\beta \Delta t} m + \frac{\gamma}{\beta} c
\]  

(4)

\[
b = \frac{1}{2\beta} m + \Delta t \left( \frac{\gamma}{2\beta} - 1 \right) c
\]  

(5)

Step 5 calculated all parameter from equation (6) – (10)

\[
\Delta \dot{p}_j = \Delta p_j + a \dot{u}_i + b \ddot{u}_j
\]  

(6)

\[
\Delta u_j = \frac{\Delta \dot{p}_j}{k}
\]  

(7)

\[
\Delta \dot{u}_j = \frac{\gamma}{\beta \Delta t} \Delta u_j - \frac{\gamma}{\beta} \dot{u}_j + \Delta t \left( 1 - \frac{\gamma}{2\beta} \right) \dddot{u}_j
\]  

(8)

\[
\Delta \dddot{u}_j = \frac{1}{\beta (\Delta t)^2} \Delta u_j - \frac{1}{\beta \Delta t} \dot{u}_j - \frac{1}{2\beta} \ddot{u}_j
\]  

(9)

\[
u_{i+1} = u_i + \Delta u_i
\]

\[
\dot{u}_{i+1} = \dot{u}_i + \Delta \dot{u}_i
\]

\[
\dddot{u}_{i+1} = \dddot{u}_i + \Delta \dddot{u}_i
\]  

(10)

Step 6 Back to calculate the next time \(i + 1\), we will be the response of the structure.

4.2 Finite element method

The finite element analysis was performed under plane strain conditions through \(\Delta u - p\) formulation, the effect between the solid and fluid phases was carried out (Cook (1989). The governing equation of motion of coupled solid–fluid problem can be expressed as:

\[
L^T \sigma - \rho \ddot{u} + \rho \dddot{u} = 0
\]  

(11)
\[ m^T \ddot{\epsilon} = \text{div}\dot{\epsilon} + \left( \frac{n}{K_w} \right) \dot{p} \]  

(12)

Where the total stresses (\( \sigma \)), the body loads (\( b \)), and the acceleration (\( \ddot{u} \)) and the differential operator (\( L \)) are time dependent. \( L \) is given as

\[
L' = \begin{bmatrix}
\frac{\partial}{\partial x} & 0 & \frac{\partial}{\partial y} \\
0 & \frac{\partial}{\partial y} & \frac{\partial}{\partial x}
\end{bmatrix}
\]

(13)

Additionally

\[
\sigma = \sigma' + mp, m = \{1 \ 1 \ 0\}^T
\]

(14)

\[
\dot{\epsilon} = -k(\text{grad}p - \rho_w (b - \ddot{u}))/\rho_w g
\]

(15)

Here, \( \sigma \) is total stress, \( \sigma' \) is effective stress, \( p \) is pore pressure, \( k \) is coefficient of permeability, \( g \) is gravitational acceleration and \( \rho_w \) is density of water.

5 RESULTS

The accelerometer at Mae Ngat Dam captured the acceleration of 0.019 g (X-axis), 0.032 g (Y-axis) and 0.038 g (Z-axis). These data were used to analyze the behavior of the Mae Ngat Dam. The Plaxis program could show the acceleration, excess pore pressure, deformation, and factor of safety from the soil properties which seismic data that were entered.

5.1 Acceleration

According to the analysis using finite element method, the highest acceleration was at the crest of the dam in the front. It was 0.006g at the set time; 5 seconds. This was the result from the input acceleration that could be measured in the dam if the epicenter was at Phan District, Chiangrai and the earthquake measured at 6.3 Richter.

Considering the acceleration diffusion pattern in the dam, its vibration, while the acceleration was occurring at the highest horizon, the dam’s crest, displaced to its front like a mass that was in the center of the dam, holding to the dam’s base. It was strong and the acceleration was spreading evenly from the crest above water to the last stages of the current. The acceleration was lowest at the core of the phreatic line, close to the base of the dam.

For the acceleration, according to the vertical line in the middle of the dam crest (Fig. 8), the acceleration at the 45-50 meter height of the dam on both sides of it was highest. When comparing the highest acceleration result with the results of the studies by Soralump (2009a, b). It was found that the seismic acceleration at the crest of the dam would be highest.

5.2 Excess pore water pressure

It was found that the effects towards the increasing pore water pressure, while the earthquake was occurring, were only slightly changed regarding to the seismic intensity. It was also because of the shape of the model, which was an incremental model, so the pore water pressure raised only little more than its static condition during the earthquake. The most excess pore water pressure that could be calculated at random zone at the base of the dam during the earthquake was 150 – 350 kN/m². As the incremental model subsided in layers, the soils were very tight and it affected the acceleration and displacement. It was found that the earthquake that gave the seismic acceleration was in impulse load with a short vibration and affected the safety ratio.

5.3 Displacement

The displacement from this earthquake is shown in Figure 10. The results showed that the model had both horizontal and vertical displacements. The most displacement of the model affected by the earthquake occurred in the core of the dam at the crest.
Table 3 shows the comparison of displacement results from the model under static and dynamic loading. Where total displacement is $U_t$, horizontal displacement is $U_x$, and vertical displacement is $U_y$.

Table 3. Comparison of displacement results from the model under static and dynamic loading.

| Model         | Most displacement (m.) |
|---------------|-------------------------|
|               | $U_t$       | $U_x$     | $U_y$     |
| Static loading| 0.016       | 0.014     | 0.008     |
| Dynamic loading| 0.060     | 0.057     | 0.033     |

Horizontal displacement at different timings with regard to the height of the horizontal lines from the base of the dam shows there were most reactions towards horizontal displacement in the middle of the dam crest in comparison to other height levels. The total of displacement is 0.060 meters.

5.4 Factor of safety

According to the results of the dam’s safety ratio from the model under static and dynamic loading, there were no effects to the dam’s safety ratio as it was changed only slightly. Most importantly, the safety ratio was under the set standard of an earth zone dam.

Table 4. Factor of safety

| Model         | F.S. |
|---------------|------|
| Static loading| 1.856 |
| Dynamic loading| 1.631 |

6 CONCLUSIONS

Considering the results of the increasing pore water pressure while the earthquake was occurring at the dam, the random zone, the center, and area by the base of the dam were the areas that water percolated. In the case that the pore water pressure was higher and the Effective Stress of the soils decreased, from the analysis of the pore water pressure that got highest in the random zone and the center of the dam and the base while the earthquake was occurring, measured 150-350 kN/m². From the earthquake case it showed that water was able to go into soils. If the pore water pressure was high, it might have caused the effective stress of the soils to decrease. In the study under this analysis, the effective stress still showed that the soils consolidated. Therefore, the soils from the dam we studied did not become liquid at the area we were considering.

According to the model with finite element method used to analyze seismic force against the base of the dam, it was found that the highest acceleration was at the crest of the dam in the front. It was measured at 0.006g at the set time; 5 seconds if the earthquake was measuring 6.3 Richter. Considering the acceleration diffusion pattern and the vibration of the dam, while the acceleration was occurring at the highest horizon, at the crest of the dam, displaced to the dam’s north, holding to the dam base. The acceleration was spreading evenly from the crest of the dam above water to the last stages of the current and the base. The acceleration was lowest at the core of the phreatic line, close to the base of the dam. The acceleration was highest at a height of 45-50 meters along the vertical line, in the middle of the dam on both sides of its crest. The results showed that the model had both horizontal and vertical displacements. The displacement of the model affected by the earthquake occurred at the front and the back of the dam. The area with most displacement was in the core at the dam’s crest. The displacement plane was at a depth close to the base of the dam at 59 meters from the crest of the dam. Because the soils in the said areas had dilative behavior, which causes the soils to have more ability to deal with shear force, so they did not displace in the random zone. According to the model, the front of the dam displaced 5 - 12 centimeters after the 6.3 Richter earthquake. Lastly, when considering the safety factor of the dam, it was found that the safety factor of the model, analyzed under static force and dynamic force, was changed slightly. It decreased from 1.856 to 1.631. Most importantly, the factor of safety was on the set standard of an earth zone dam, which has a safety factor not less than 1.5.

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