Seismic Hazard Assessment for Thuong Tan-Tan My Quarries (Vietnam)

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Abstract

This paper presents the seismic hazard assessment for Thuong Tan-Tan My quarries in Di An commune, Binh Duong province, Vietnam. Combination methods of gravity and magneto-telluric were used to estimate the dip angle and the width of the seismic source. The highest water column of 160 m will cause direct stress on the reservoir bottom with a maximum value of 1535.600 kPa and Coulomb stress of 68.693 kPa (at a depth of 2 km). The typical components of natural earthquake hazard (Mn.max = 5.0, depth of 10 km) in Thuong Tan - Tan My reservoir have the following values: peak ground acceleration PGA = 0.073 g ÷ 0.212 g; peak ground velocity PGV = 2.662 cm/s ÷ 7.984 cm/s; peak ground displacement PGD = 0.706 cm ÷ 1.918 cm at 10% probability of exceedance in 50 years. The typical components of triggered earthquake hazard (Mtr.max = 3.5, depth of 6 km) in Thuong Tan - Tan My reservoir have the following values: peak ground acceleration PGA = 0.024 g ÷ 0.172 g; peak ground velocity PGV = 0 ÷ 5.484 cm/s; peak ground displacement PGD = 0.061 cm ÷ 0.461 cm at 10% probability of exceedance in 50 years.

Keywords: quarry, Thuong Tan, Tan My, seismic source, triggered earthquake, maximum credible earthquake, incremental stress, Coulomb stress, seismic hazard

1. Introduction

Thuong Tan-Tan My building stone quarries consist of 17 quarries (13 quarries in Thuong Tan commune and four quarries in Tan My commune) located in Bac Tan Uyen district, Binh Duong province, Vietnam. These are open-pit quarries, exploiting Andesite extrusive sedimentary rocks (aged T3-J) under the weathered overburden of approximately 1m, on the terrain of 10-20 m height. Currently, these 17 quarries are exploited at different levels, from -30 m to -100 m (Fig. 1). Due to the great demand for building stones, the Binh Duong Provincial People’s Committee has proposed connecting Thuong Tan-Tan My quarries for exploitation to -150 m and then converting this pit into a reservoir. According to the proposed plan, the connection and expansion of Thuong Tan-Tan My quarries will create a pit of 37.0 km² with a depth of over 160-170 m (up to the level of -150m and the terrain height of 10-20 m).

One of the important tasks in evaluating the environmental impact on the exploitation method at Thuong Tan-Tan My quarries is the seismic hazard assessment which is assigned to the Institute for Applied Geophysics - VUSTA (Vietnam Union of Science and Technology Association). This paper concisely presents the methodology and results of this task with the following contents: determination of seismic source; assessment of maximum credible earthquake; calculation of incremental stress and Coulomb stress in case of water impoundment; and seismic hazard assessment for Thuong Tan-Tan My quarries.

UAV technology has been used to collect topographic data for related researches (Dieu Tien Bui, et al., 2017; Nguyen Quoc Long, et al., 2019; Bui, X.N., et al., 2019; Long, et al., 2020).

2. Determination of seismic source and assessment of maximum credible earthquake

Thuong Tan-Tan My quarries are located in the Sai Gon River fault zone, dividing the Da Lat - Can Tho structural block into two sub-blocks (Hung Cat Nguyen, et al., 2009): Da Lat in the north and Can Tho in the south. The fault acts as a dynamic hinge in Cenozoic between two different tectonic regimes: uplift, denudation during the Cenozoic in Da Lat sub-block in the northeast and subsidence, Cenozoic sedimentary fill, with the greatest thickness of 2100 m (Tra Cu basin) in Can Tho sub-block. The depth of influence of this fault zone is through the Earth’s crust (over 30 km), and the sphere of influence is 20÷30 km. This fault zone nearly coincides with the photo lineament length-density anomaly strip and the DEM-Lineament length-density anomaly reaches 200÷300 m/km2 (Linh Do Van, et al., 2008). The dextral displacement amplitude of rivers based on results of Landsat image analysis in 2002 is 500÷2000 m (Linh Do Van, et al., 2008). The largest vertical displacement amplitude of the Cenozoic sedimentary basement is 330÷446 m (Linh Do Van, et al., 2008). The latest research results (Linh Do Van, et al., 2008; Hung Cat Nguyen, et al., 2009; Nam Bui Xuan, et al., 2020) show that:

- The Sai Gon River fault zone is likely to be active in the modern period, including the Sai Gon River main fault and two accompanying faults: Dong Nai River and Thien Tan -
Determination of the structure of seismic source

A detailed assessment of seismic source includes structure (width, length, depth); dip angle of fault; and fracturing characteristics of rocks (through density and resistivity values). These are important parameters used to assess the magnitude of earthquakes which can possibly occur. In this paper, the authors have proposed using a combination of methods to determine the seismic source as follows:

1/ The length of the seismic source was determined on the basis that (Trieu Cao Dinh, 2010; Trieu Cao Dinh, Vinh Nguyen Duc, 2012) the source segment (fault) is defined as a boundary dividing structural blocks of the Earth's crust with different composition and geophysical characteristics, and dividing gravitational and magnetic fields with the certain contrast. This boundary causes sudden changes in the depth and the altitude of basic boundary surfaces in the Earth's crust and sedimentary layers. They are clearly shown on modern topography, on satellite images or DEM map (Hung Cat Nguyen, et al., 2009), creating special topographic and geomorphologic elements or controlling the formation of Quaternary and modern sedimentary basins, with manifestations of earthquake, landslide, and neotectonic and modern deformations.

2/ The width, dip angle and fracturing characteristics of rocks of the source were determined using highly-detailed gravity method (gravimeter CG3, made in Canada) and magneto-telluric (AGCOS-Advanced Geophysical Operations and Services Inc., made in Canada) (Fig. 1):

a- Highly-detailed gravity measurement was carried out along two profiles (at the scale of 1:25000) in Thuong Tan-Tan My quarries in order to calculate the maximum horizontal gradient (Gmax) and normalized full gradient (GH) of Bouguer gravity anomaly, for determination of fault locations (Trieu Cao Dinh, 2005; Kha Tran Van, et al., 2018; Nam Bui Xuan, et al., 2020).

b- Magneto-telluric measurement was conducted on two profiles (at the scale of 1:25000) perpendicular to the Thien Tan - Binh Son active fault zone (nearly coinciding with gravity profiles), serving the study on structural characteristics of this seismic source (Fig. 1).

c- Structural model of Thien Tan - Binh Son seismic source to a depth of 12 km is described in Figure 2. Based on the results of this study, we can evaluate the structural characteristics of seismic source, which can affect Thuong Tan-Tan My quarries, as follows: source length L = 4.8 km (Trong Cao Dinh et al., 2018); source width W = 2.8 km (Figure 2b), and dip angle of fault α = 75° (Fig. 2b).

Assessment of maximum credible earthquake occurrence

1/ The maximum natural earthquake (Mn.max) in the Thuong Tan – Tan My quarries and adjacent area

Vietnamese seismologists often use empirical formulas from Wells and Coppersmith (1994) and Trieu Cao Dinh (2002, 2010) in assessing the maximum credible earthquake. Although these two formulas have different coefficients, they always give similar results (Hung Cat Nguyen, et al., 2009; Trong C. D., 2016; Nam Bui Xuan, et al., 2020). These two formulas were also applied in estimation of the maximum credible natural earthquake in the Thien Tan - Binh Son source segment, which shows Mn.max = 5.0. This value is consistent with the previous research results (Hung Cat Nguyen, et al., 2009; Trong Cao Dinh, et al., 2018; Nam Bui Xuan, et al., 2020).

2/ The maximum triggered earthquake (Mtr.max) in the Thuong Tan – Tan My reservoir after impoundment:
After the Thuong Tan – Tan My pit is exploited to -150 m, the water will be impounded, which can generate triggered earthquake (Gupta H.K, 2002; Trieu C. D., et al., 2014; Trong C. D., et al., 2016). Currently, there is no perfect formula for predicting the maximum magnitude of the triggered earthquake in the reservoir; however, $M_{tr,max}$ is always supposed to be smaller than $M_{n,max}$ with the difference of at least one magnitude unit (M) (Gupta H.K, 2002; Trieu Cao Dinh, et al., 2014; Trong Cao Dinh, et al., 2016). Trong Cao Dinh, et al. (2016) suggested that $M_{tr,max}$ does not exceed the value $(bn/bkt)\times M_{n,max}$ ($bn$ and $bkt$ are the b values in the function of frequency and natural earthquake magnitude, and that of frequency and triggered earthquake magnitude, respectively; Gutenberg–Richter function). $M_{tr,max}$ approximates to $(H_{tr}/H_{n})\times M_{n,max}$ (Trong Cao Dinh, et al., 2016). Supposing that the thickness of the active layer of the triggered earthquake ($H_{tr}$) and of the natural earthquake ($H_{n}$) is related to the maximum credible earthquake magnitude, $M_{tr,max}$ value in Thuong Tan-Tan My reservoir will not exceed 3.5 (The thickness of the active layer of natural earthquake in south Central Vietnam is about 17 km and that of the triggered earthquake in Vietnam is about 8 km).

3. Calculation of incremental stress and Coulomb stress in case of water impoundment

Calculation of incremental stress on the reservoir bottom after the impoundment

Both 2D and 3D problems can be used to calculate the incremental stress field and subsidence of the reservoir bottom. In the case of 3D problem, the reservoir was divided into the area elements of a x a km2 by a set of orthogonal straight lines. After determining the water depth ($h_i$) for each area element, we had the vertical force $F_i = \rho g a^2 h_i$ at the centre of each area that can replace the water column pressure. With
the X'X axis towards the east, the Y'Y axis towards the north and the Z'Z axis downwards, three normal stress components and one shear stress component at any point P were calculated according to the following formulas (Kalpna G., Chander R., 2000; Kalpna G., Gupta H.K., 2008; Kalpna G., Tuan T.A., Rao N.P., 2016):

\[ \sigma_x = \frac{F}{2\pi R} \left( 1 - \frac{3z^2}{R^2} \right) \]
\[ \sigma_y = \frac{F}{2\pi R} \left( 1 - \frac{3y^2}{R^2} \right) \]
\[ \sigma_z = \frac{F}{2\pi R} \left( 1 - \frac{3z^2}{R^2} \right) \]
\[ \tau_{xy} = \frac{F}{2\pi R} \left( \frac{1}{R} + \frac{x}{R^2} + \frac{y}{R^2} \right) \]
\[ \tau_{xz} = \frac{F}{2\pi R} \left( \frac{1}{R} + \frac{z}{R^2} + \frac{x}{R^2} \right) \]
\[ \tau_{yz} = \frac{F}{2\pi R} \left( \frac{1}{R} + \frac{z}{R^2} + \frac{y}{R^2} \right) \]

(1)

Where: \( v \) is Poisson’s ratio; \( R=\sqrt{x^2+y^2+z^2} \) - the distance from the origin to the point \( P(x,y,z) \) and its projection given by \( r=\sqrt{x^2+y^2} \).

To add the distribution of F forces, they were converted to Cartesian coordinate system according to the correlation:

\[ \sigma_x = \sigma_0 \sin^2 \theta + \sigma_0 \cos^2 \theta \]
\[ \sigma_y = \sigma_0 \cos^2 \theta + \sigma_0 \sin^2 \theta \]
\[ \tau_{xy} = \tau_{xy} \cos \theta \sin \theta \]
\[ \tau_{xz} = \tau_{xz} \cos \theta \sin \theta \]
\[ \tau_{yz} = \tau_{yz} \cos \theta \sin \theta \]

(2)

Where: \( \theta = \arctan(y/x) \) is calculated from the east to the north (counterclockwise).

Stress is considered as the result of total loading on a point collected by taking the total distribution of all F forces for six stress components: \( \sigma_x, \sigma_y, \sigma_z, \sigma_{xy}, \sigma_{yz}, \sigma_{zx} \).

From these parameters, we selected the normal downward stress \( \sigma_n \) and the maximum shear stress \( \tau_{max} = (\sigma_1-\sigma_3) \).

In addition, under the pressure of reservoir load, the vertical subsidence \( \Delta d \) (m) due to the effect of total F force was calculated by the formula:

\[ \Delta d = \frac{F}{2E\pi R} \left[ \frac{(1+\nu)^2}{R^2} + 2 \frac{(1-\nu^2)}{R} \right] \]

(3)

Where: \( E \) is Young’s modulus; \( R \) is the distance of point \( P \) from the origin. The subsidence is caused by all the point forces and the total subsidence \( d \) at point \( P \) is the result of reservoir load.

The calculation of incremental stress on the bottom of Thuong Tan-Tan My reservoir after the impoundment was carried out at the depths: 2 km, 4 km, 6 km and 8 km (the hypocenter of a triggered earthquake is usually located at a depth from 2 km to 8 km). Results of stress calculation at different depths with water columns of 130 m and 160 m (corresponding levels of reservoir bottom of -120 m and -150 m, dam height of 15 m at these levels, water rise of 5 m from dam crest) are presented in Fig. 3 & 4 and the maximum value of this incremental stress is shown in Tab.

**Calculation of Coulomb stress due to the effect of the water column on the bottom of Thuong Tan – Tan My reservoir**

According to Bell and Nur (1978), the change of Coulomb stress (\( \Delta S \)) caused by reservoir impoundment was determined as follows: \( \Delta S = \Delta \tau - \mu (\Delta \sigma_n - \Delta P) \), where \( \Delta \tau \) and \( \Delta \sigma_n \) correspond to the changes of shear stress and normal stress which are caused by reservoir loading on fault surface, \( \Delta P \) is the change of pore pressure, and \( \mu \) is the coefficient of friction. The increase of \( \Delta \tau \) and the decrease of \( \Delta \sigma_n \) mean that \( \Delta S \) has a positive value, which will stimulate the fault activity and vice versa.

**Tab. 1. The maximum value of incremental stress with different scenarios of reservoir depth**

| Scenario of reservoir depth | The maximum value of incremental stress at different depths (kPa) | \( \sigma_0 = 0.01 \)bar |
|---------------------------|---------------------------------------------------------------|-------------------------|
| 130 m                     | 1247.700                                                     | 767.690                 | 481.650                     | 314.870 |
| 160 m                     | 1535.600                                                     | 944.850                 | 592.800                     | 387.540 |

Fig. 5. Coulomb stress field caused by reservoir load at: a- depth of 2 km; b- depth of 4 km; c- depth of 6 km; and d- depth of 8 km (water column of 130 m)

Rys. 5. Pole naprężeń kulombowskich wywołane obciążeniem zbiornika na: a- głębokości 2 km; b- głębokości 4 km; c- głębokości 6 km; id- głębokości 8 km (słup wody 130 m)
versa. The role of pore pressure always promotes the fault activity due to the lubrication on the fault surface and decreases the shear stress component $\Delta \tau$.

Based on the above theoretical basis, the research team has written a program in Matlab language to calculate stress components and Coulomb stress caused by reservoir loading on the study area.

The reservoir was divided into small blocks, the parameters of length, width and depth at each block were determined. The fault parameters consisting of strike angle, dip angle and rake angle were taken into account to account for the change of stress field. In the study area, Thien Tan – Binh Son River right-lateral strike-slip fault near the reservoir is considered as an active fault, and the parameters of this fault (strike angle = 140°, dip angle = 75°, rake angle = 180°) were included in the calculation of Coulomb stress (Hung C. N, et al., 2009). The study area is divided into grid of 0.0018° x 0.0018°; with Poisson's ratio $\nu = 0.25$; Skempton's coefficient $B = 0.7$; coefficient of friction $\mu = 0.65$ (Tuan T. A, et al., 2017).

From the above input parameters, the calculations are based on the scenario in which the reservoir is fully impounded, and the tectonic stress field in the area is unchanged at the calculation time. Components of Coulomb stress field were calculated with reservoir depths of 130 m and 160 m at 2 km, 4 km, 6 km and 8 km depth, respectively (Tab. 2, Fig. 5 & 6). The results show that the areas with a positive value of Coulomb stress $\Delta S$ are at risk of a triggered earthquake when the reservoir is fully impounded. These results allow us to delineate the areas at risk of a reservoir-triggered earthquake.

### 4. Seismic hazard assessment for Thuong Tan-Tan My quarries

OQEngine software (using the function of ground motion attenuation from Campbell-Bozorgnia 2008 and seismic source model-SSM) was applied in seismic hazard assessment for Thuong Tan-Tan My quarries (GEM, 2020; Pagani, M., Monelli, D., Weatherill, G. A. and Garcia, J., 2014; Coppersmith, K., J. Bommer, K. Hanson, J. Unruh, R. Coppersmith, L. Wolf, R. Youngs, A. Rodriguez Marek, L. Al Atik and G. Toro, 2014; Marco Pagani, Julio Garcia, Valerio Poggi, and Graeme Weatherill, 2016).

The 10% probability of exceedance in 50 years was used in seismic hazard assessment (natural earthquake, $M_{n,max} = 5.0$; triggered earthquake, $M_{t,r,max} = 3.5$) for Thuong Tan-Tan My quarries, which is shown in Figures 7, 8 and 9:

- Natural earthquake with $M_{n,max} = 5.0$ will result in PSHA (10% probability of exceedance in 50 years) with the highest values at Thuong Tan-Tan My quarries as follows: peak ground acceleration PGA = 0.073 g ÷ 0.212 g; peak ground velocity PGV = 2.662 cm/s ÷ 7.984 cm/s; peak ground displacement PGD = 0.706 cm ÷ 1.918 cm.

| Scenario of reservoir depth | The maximum value of Coulomb stress at different depths (kPa) |
|-----------------------------|-------------------------------------------------------------|
| 130 m                       | 55,813 60,827 38,632 27,650                               |
| 160 m                       | 68,693 62,593 47,547 34,031                               |

Fig. 6. Coulomb stress field caused by reservoir load at: a- depth of 2 km; b- depth of 4 km; c- depth of 6 km; and d- depth of 8 km (water column of 160m)

Rys. 6. Pole naprężeń kulombowskich wywołane obciążeniem zbiornika na: a- głębokość 2 km; b- głębokość 4 km; c- głębokość 6 km; id- głębokość 8 km (słup wody 160 m)
- Triggered earthquake with Mtr.max = 3.5 will lead to PSHA (10% probability of exceedance in 50 years) with the highest values at Thuong Tan-Tan My quarries as follows: peak ground acceleration PGA = 0.024 g ÷ 0.172 g; peak ground velocity PGV = 0 ÷ 5.484 cm/s; peak ground displacement PGD = 0.061 cm ÷ 0.461 cm.

5. Conclusion

1. Within the Thuong Tan-Tan My quarries, there exist two seismic sources with the magnitude of natural earthquake Mn.max = 5.0, namely Dong Nai River and Binh Long - Binh Chau. The source segment that is likely to generate the triggered earthquake (directly connected to Thuong Tan-Tan My reservoir) has the following structural characteristics: 4.8 km length; 2.8 km width; rake angle = 180°; dip angle = 75° and Mtr.max = 3.5.

2. The highest water column of 160m will cause direct stress on the reservoir bottom with a maximum value of 1535.600 kPa and Coulomb stress of 68.693 kPa (at a depth of 2km). Compared to the breaking stress of rock in the earthquake, the calculated value is very small, only about 1%. It acts as the promoting mechanism and only matters when the natural stress reaches its limit.

3. The typical components of natural earthquake hazard Mn.max = 5.0 occurring at a depth of 10 km (10% probability of exceedance in 50 years) in Thuong Tan-Tan My reservoir have the following values: peak ground acceleration PGA = 0.073 g ÷ 0.212 g; peak ground velocity PGV = 2.662 cm/s ÷ 7.984 cm/s; peak ground displacement PGD = 0.706 cm ÷ 1.918 cm.

4. The typical components of triggered earthquake hazard Mtr.max = 3.5 occurring at a depth of 6 km (10% probability of exceedance in 50 years) in Thuong Tan-Tan My reservoir have the following values: peak ground acceleration PGA = 0.024 g ÷ 0.172 g; peak ground velocity PGV = 0 ÷ 5.484 cm/s; peak ground displacement PGD = 0.061 cm ÷ 0.461 cm.

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Ocena zagrożenia sejsmicznego dla kamieniołomów na rejonie Thuong Tan-Tan My (Wietnam)

W artykule przedstawiono ocenę zagrożenia sejsmicznego dla kamieniołomów na rejonie Thuong Tan-Tan My w gminie Di An w prowincji Binh Duong, Wietnamie. Do oszacowania kąta upadu i szerokości źródła sejsmicznego wykorzystano kombinację metod gravitacyjnych i magneto-tellurycznych. Najwyższy słup wody 160 m spowoduje bezpośrednie naprężenia na dnie zbiornika o maksymalnej wartości 1535,600 kPa i naprężeniu kulombowskim 68,693 kPa (na głębokości 2 km). Typowe składowe naturalnego zagrożenia trzęsieniem ziemi (Mn.max = 5,0, głębokość 10 km) w zbiorniku Thuong Tan-Tan My mają następujące wartości: szczytowe przyspieszenie gruntu PGA = 0,073 g ÷ 0,212 g; szczytowa prędkość gruntu PGV = 2,662 cm / s ÷ 7,984 cm / s; szczytowe przemieszczenie gruntu PGD = 0,706 cm ÷ 1,918 cm przy 10% prawdopodobieństwie przekroczenia za 50 lat. Typowe składowe wywołanego zagrożenia trzęsieniem ziemi (Mtr.max = 3,5, głębokość 6 km) w zbiorniku Thuong Tan-Tan My mają następujące wartości: szczytowe przyspieszenie ziemi PGA = 0,024 g ÷ 0,172 g; szczytowa prędkość gruntu PGV = 0 ÷ 5,484 cm / s; szczytowe przemieszczenie ziemi PGD = 0,061 cm ÷ 0,461 cm przy 10% prawdopodobieństwie za 50 lat.

Słowa kluczowe: kamieniołomy, źródło sejsmiczne, trzęsienie ziemi, maksymalne wiarygodne trzęsienie ziemi, naprężenie przyrostowe, naprężenie Coulomba, zagrożenie sejsmiczne