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THE IMPACT OF EARTHQUAKES OF TUNNEL LININGS: A CASE STUDY FROM THE HANOI METRO SYSTEM

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ABSTRACT: At present, systems of infrastructure are built and developed very strongly in Hanoi. The metro tunnels system is also being designed and built in Hanoi to meet the requirements of economic and social development. The paper uses the Wang's method, Penzien & Wu's method, HRM method and a two – dimensional numerical analysis method by Abaqus software to evaluate the impact of the strongest earthquake that could occur in Hanoi to the tunnel lining of Hanoi metro system, this impact could be the internal forces and state stress on the tunnel lining. Based on results obtained from assessing the impact of earthquakes to the tunnel lining in the Hanoi metro system, this paper has compared and commented to these results for the purpose of finding the most accurate results about the impact of earthquakes on the tunnel lining in the Hanoi metro system. These results and comments will be used in the design and construction tunnel in the Hanoi metro system under the impact of the strongest earthquake that could occur in Hanoi.

Keywords: Tunnel lining, earthquake, state stress, internal forces.

1. INTRODUCTION

Earthquakes are natural phenomenon that is difficult to predict and accurately calculates its impact on works within its limit of influence. The impact of earthquakes on the works can be do the deformation of works or works may be displaced. Works may be change or completely destroyed. Hanoi is the capital of Vietnam, where has got very many people and there are important works here. At present, the metro system that has been designed and built in Hanoi. Hanoi is located near Song La - Dien Bien and Red River faults with the strongest earthquake M_W = 6.5 richter [1]. Based on the geological and hydro-geological conditions in the central part of Hanoi and the parameters of earthquake, that may occur in the Hanoi area, this paper has been study and evaluate of the impact of the strongest earthquake on the lining tunnel in Hanoi metro system.

2. PARAMETERS OF EARTHQUAKES, SOIL AND TUNNEL SUBWAY IN HANOI

The groundwater level in Hanoi is quite high, in the central area of Hanoi, the hydrogeological and geological conditions are as follows: the ground water level is three meters below the surface; distributed from the ground surface to the bedrock at a depth of 48 m and there are usually six layers of soils. All parameters of layers soil in Hanoi center in Table 1 and in Fig.1.

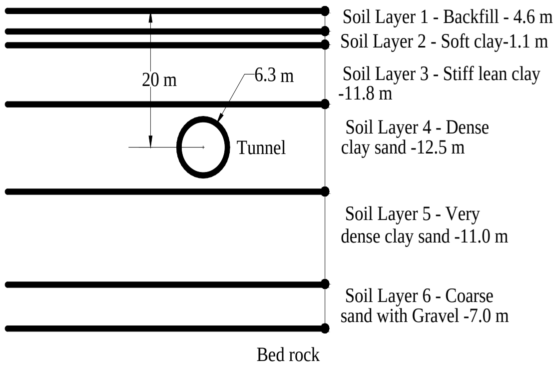

Fig.1 Layers soils of considered section

Parameters of tunnel in the Hanoi metro system [2]:

The tunnel is located at a depth of 20 m from the surface ground. The tunnel has got cross section is circular with the tunnel's radius R= 3.15 m, the tunnel lining is made reinforced concrete. The design parameters of the tunnel lining are listed below:

- Young's modulus E_l = 35500 MPa;
- Poisson's ratio ν_l = 0.15;
- Lining thickness t_l = 0.3 m.

Based on the data collected from the above studies, some characteristics of the strongest earthquakes that can occur in the Hanoi area are [1]:

- Earthquake with a maximum M_W of 6.5;
- Distance from the epicenter of the earthquake to Hanoi is 20 to 50 km and peak ground acceleration a_{max}= 0.2 g.

Table 1 Parameters of layers soil in Hanoi center [1]

Number of soil layers	Elastic module, E, MPa	Poisson's ratio, μ	Thickness of layer (h), m	Depths of soil layers, m	Density of the soil, ρ, g/cm3	Ground water level, m
1	9.25	0.41	4.6	4.6	1.75	
2	7.68	0.38	1.1	5.7	1.76	
3	15.3	0.35	11.8	17.5	1.81	3.0
4	35.02	0.33	12.5	30	1.78	
5	53.9	0.32	11.0	41	1.83	
6	65	0.3	7.0	48	1.86	

3. CALCULATION METHODS

3.1 Wang's Method [3]

In 1993, Wang based on closed form solutions recommended by Peck et al, proposed modified analytical equations in terms of axial force, bending moments and displacements under external loading conditions. Wang may be the first person in the world given equations that be used to calculation structural forces in the tunnel lining under seismic loading conditions.

In case full – slip at the soil – lining tunnel's, bending moment M and forces normal T can be written by Wang:

$$T = \pm\frac{1}{6}K_1\frac{E}{(1+\nu)}R\gamma_{\max}\cos\left[2(\theta+\frac{\pi}{4}\right] \quad (1)$$

$$M = \pm\frac{1}{6}K_1\frac{E}{(1+\nu)}R\gamma^2{}_{\max}\cos\left[2(\theta+\frac{\pi}{4}\right] \quad (2)$$

Where $K_1 = \dfrac{12(1-\nu)}{2F+5-6\nu}$ (3)

In case no-slip at the soil – the lining tunnel, only the normal forces T can be expressed by Wang [1993]:

$$T = \pm\frac{1}{2}K_2\frac{E}{(1+\nu)}R\gamma_{\max}\cos\left[2(\theta+\frac{\pi}{4}\right] \quad (4)$$

Where

$$K_2 = 1+\frac{F\left[(1-2\nu)-(1-2\nu)C\right]-\frac{1}{2}(1-2\nu)^2+2}{F\left[(3-2\nu)+(1-2\nu)C\right]+C\left[\frac{5}{2}-8\nu+6\nu^2\right]+6-8\nu} \quad (5)$$

$$C = \frac{E\left(1-\nu_s^2\right)R}{E_s t(1+\nu)(1-2\nu)} \quad (6)$$

$$F = \frac{E(1-\nu_S^2)R^3}{6E_S J_S(1+\nu)} \quad (7)$$

$$G = \frac{E}{2(1+\nu)} \quad (8)$$

In 2013, Kouretzis el al proposed an equation of the maximum bending moment in lining tunnel under no slip condition when effect dynamic loading, this to improve the Wang's method.

$$M_K = \pm(2-K_3-2K_4)\tau_{\max}\frac{R^2}{2} \quad (9)$$

$$\tau_{\max} = \pm V_{\max}\sqrt{\rho_{\max}G_{\max}} \quad (10)$$

Where $\tau_{\max}$ - the maximum free field seismic shear stress, $\rho_{\max}$ - density of the surround ground, $G_{\max}$ - the maximum ground shear modulus, $V_{\max}$ - the peak seismic velocity due to shear wave propagation.

$$K_3 = 1+\frac{(1-2\nu)(1-C)F-0.5(1-2\nu)C+2}{\left[(3-2\nu)+(1-2\nu)C\right]F+\left[0.5(5-6\nu)\right](1-2\nu)C+(6-8\nu)} \quad (11)$$

$$K_4 = \frac{\left[1+(1-2\nu)C\right]F-\left[0.5(1-2\nu)C\right]-2}{\left[(3-2\nu)+(1-2\nu)C\right]F+\left[0.5(5-6\nu)\right](1-2\nu)C+(6-8\nu)} \quad (12)$$

Where K_1 - full-slip lining response coefficient; K_2 - no-slip lining response coefficient; F - flexibility ratio of tunnel lining respectively; E_s - Young's modulus of tunnel lining respectively; C - compressibility ratio of tunnel lining respectively; ν_s - Poisson's ratio of tunnel lining respectively; R - tunnel radius respectively; J_s - inertia moment of tunnel lining per unit length of the tunnel (per unit width); t - thickness of tunnel lining respectively; ν

-Poisson's ratio of ground mass surrounding tunnel; E - Young's modulus of ground mass surrounding tunnel; G - shear modulus of ground mass surrounding tunnel; I - moment of inertia of the lining tunnel; γ_{max} - maximum free-field shear strain; θ - angle measured counter-clockwise from spring line on the right.

3.2 Penzien's Method [4]

Penzien & Wu (1998) and Penzien (2000) developed similar analytical solutions for the thrust moment and shear in tunnel lining. In case full-slip condition at the soil-lining, the normal forces T and bending moment M, that be defined by equations:

$$T = -\frac{12E_s I \Delta d^n_{lining}}{d^3(1-\nu_s^2)} \cos 2(\theta + \frac{\pi}{4}) \quad (13)$$

$$M = -\frac{6E_s I \Delta d^n_{lining}}{d^2(1-\nu_s^2)} \cos 2(\theta + \frac{\pi}{4}) \quad (14)$$

$$V = -\frac{24E_s I \Delta d^n_{lining}}{d^3(1-\nu_s^2)} \sin 2(\theta + \frac{\pi}{4}) \quad (15)$$

$$\pm \Delta d^n_{lining} = \pm R^n \Delta d_{free-field} \quad (16)$$

$$R^n = \pm \frac{4(1-\nu)}{\alpha^n + 1} \quad (17)$$

$$\alpha^n = \frac{12E_s I(5-6\nu)}{d^3 G(1-\nu_s^2)} \quad (19)$$

In the case of no-slip condition, the formulations are presented as:

$$\pm \Delta d_{lining} = \pm R \Delta d_{free-field} = R\frac{\gamma_{max} d}{2} \quad (20)$$

$$T = -\frac{24E_s I \Delta d_{lining}}{d^3(1-\nu_s^2)} \cos 2(\theta + \frac{\pi}{4}) \quad (21)$$

$$M = -\frac{6E_s I \Delta d_{lining}}{d^2(1-\nu_s^2)} \cos 2(\theta + \frac{\pi}{4}) \quad (22)$$

$$R = \pm \frac{4(1-\nu)}{\alpha + 1} \quad (23)$$

$$\alpha = \frac{24E_s I(3-4\nu)}{d^3 G(1-\nu_s^2)} \quad (24)$$

3.3 HRM Method [5, 6, 7, 8, 9, 10]

The HRM method has been given by Duddeck and Erdmann [1985], Takano [2000], Oreste [2007], ITA [1988], AFTES [1997b]. This method is part of the numerical methods category and simulates the interaction between the lining tunnel and environment material surrounding the tunnel by a number of independent "Winkler" type springs. When using the HRM method must the definition of the active loads that apply directly to the lining tunnel structure. Mashimo and Ishimura [2003] presented different methods that be used to calculation these loads. In case of having effect of seismic loading, necessary to estimate the active loads on the tunnel lining. Peinzen and Wu [1998] and Naggar et al. [2008] presented equations, these can be used to calculation of ovaling deformation of a circular tunnel during a seismic due to the in plane shear stresses caused by vertically propagating (notice that, in case of the seismic load on the tunnel lining, all the external loads are rotated counter-clockwise by 45^0 and the horizontal loads are in opposite directions). In this study, Matlab program was used to calculation for the internal forces on tunnel lining by HRM method.

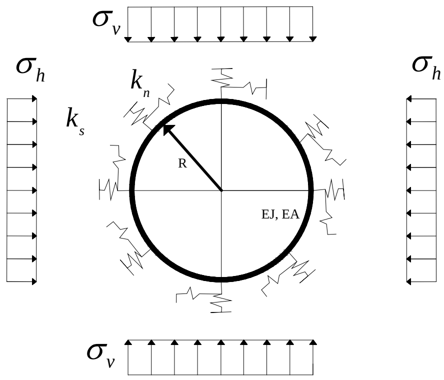

Fig. 2 Calculation scheme of tunnel lining with the HRM method. σ_v: vertical load in the model tunnel – surrounding ground; σ_h: horizontal load in the model tunnel – surrounding ground; k_n: normal stiffness of the interaction springs; k_s: tangential stiffness of the interaction springs; R: tunnel radius; EJ and EA: bending and normal stiffness of the tunnel lining.

3.4 2D numerical model

In case have seismic load, numerical models have recently been used more and more to model bored tunnels lining. With the numerical models, that can be possible to build tunnel models and material environments surrounding the tunnel with the close most natural parameters. In this study, the numerical model is built by means of the finite difference element program Abaqus (Simulia Corp). The soil environment surrounding the tunnel behavior has been assumed to be governed by an elastic perfectly - plastic constitutive model, based on the Mohr-Coulomb failure criterion. The tunnel lining behave linearly and elastically. The numerical analysis has been performed under regardless of the effect of gravity and groundwater conditions. A time history analysis has carried out using data of El Centro earthquake (with characteristics of the El Centro earthquake almost identical to characteristics of the strongest earthquake that can occur in the Hanoi) – $M_w = 6.5$ richter and be showed in fig. 3 [11]. All methods be caculation for case no-slip at the soil – lining tunnel's.

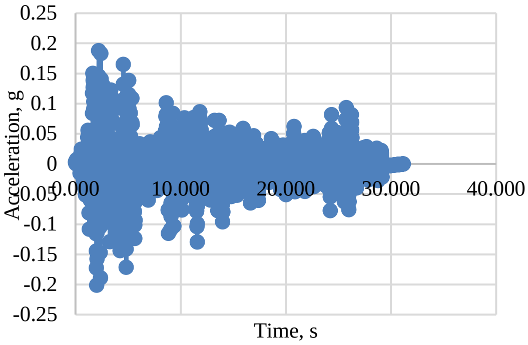

Fig.3 Data in El Centro earthquake

In the 2D numerical model, soil layers are replaced with a single soil layer with equivalent properties [12]:

- Young's modulus, E = 35.75 MPa;
- Poisson's ratio, = 0.34;
- Damping ratio is 5%.

The 2D numerical model is 180 m wide in the x-direction, 80 m in the z-direction.

Phases of the construction process of tunnel in this study:

- Phase 1 (model setup): This is the first step corresponds to the setup of the model, assignment of the plane strain boundary conditions, there is no reflection wave at the boundary of model and don't taking into consideration the influence of the gravity and groundwater. The model was divided two parts, part 1 contains the tunnel and the soil layer surrounding the tunnel, the second part is the area using infinite elements so that the model has not wave reflection phenomenon. (Figure 4, 5);

- Phase 2: Construction of the tunnel, include built parameters of soil layer and lining tunnel, assigning the lining tunnel's with layer soil link conditions (assumptions the continuous tunnel lining without joints). Setting up the pressure over the whole tunnel boundary on both tunnel structure and model's boundary, assign to the peak ground acceleration of the earthquake to the model (see Figure 5);

- Phase 3: The results obtained after running the model (see Figures 10, 11, 12)

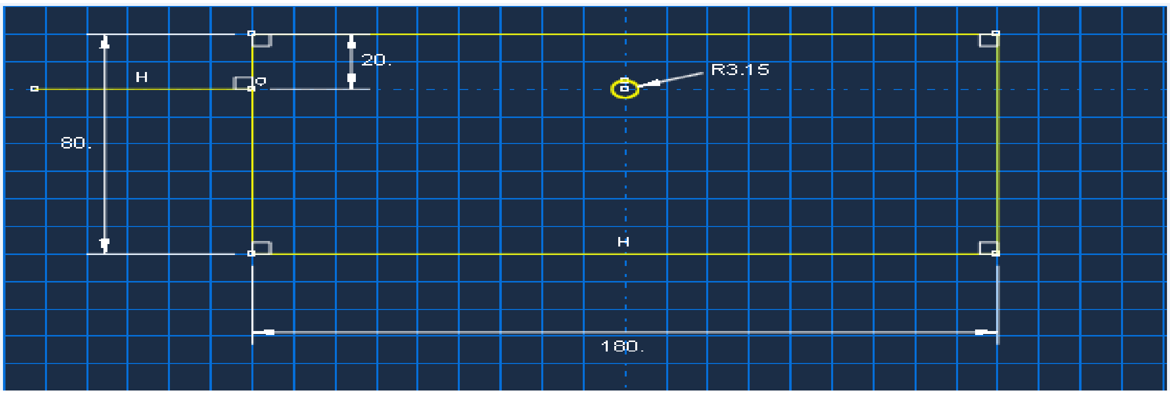

Fig.4 Geometry problem of the 2D numerical method – Abaqus software

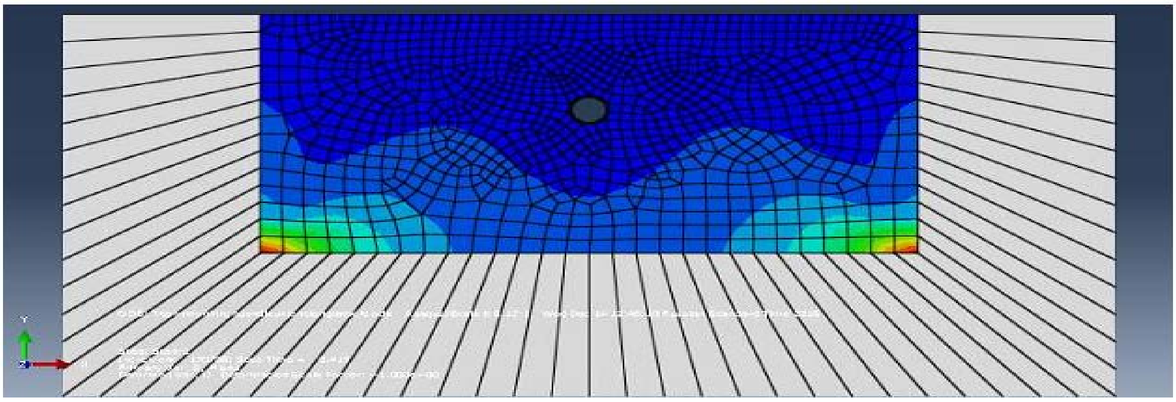

Fig.5 Tunnel model under consideration

4. RESULTS AND DISCUSSION

In table 2, analysis results be presented. The internal forces in lining tunnel (the bending moment and normal force) obtained from HRM method be presented in Figure 6, 7. Wang's method, Penzien &Wu's method in Figures 8, 9 and 2D model numerical in Figures 10, 11, 12.

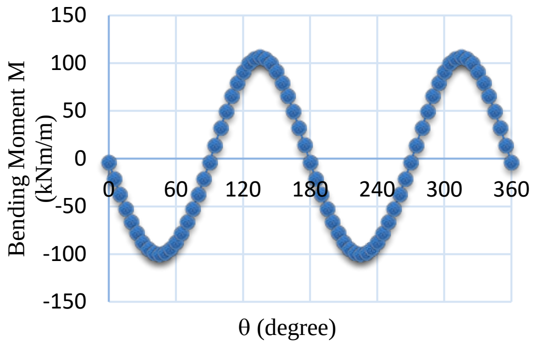

Fig.6 Bending Moment *M* in the lining tunnel by HRM method

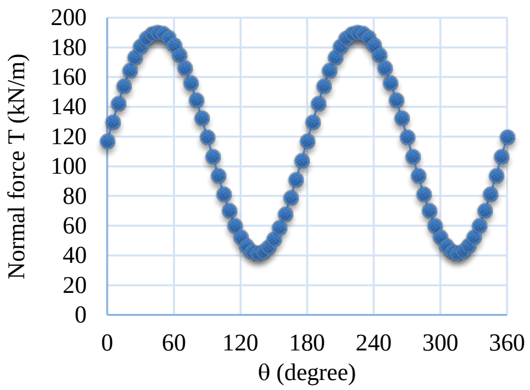

Fig.7 Normal force *T* in the lining tunnel by HRM method

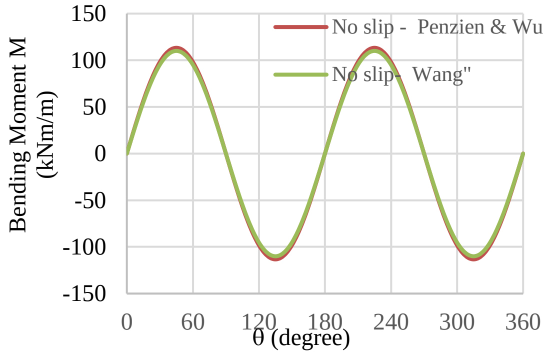

Fig.8 Bending Moment *M* in the lining tunnel by Wang's method and Penzien & Wu's method

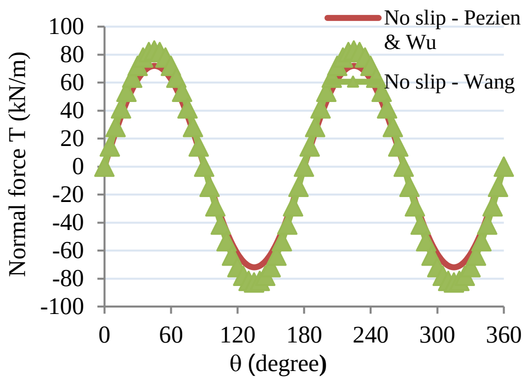

Fig.9 Normal force *T* in the lining tunnel by Wang's method and Penzien & Wu's method

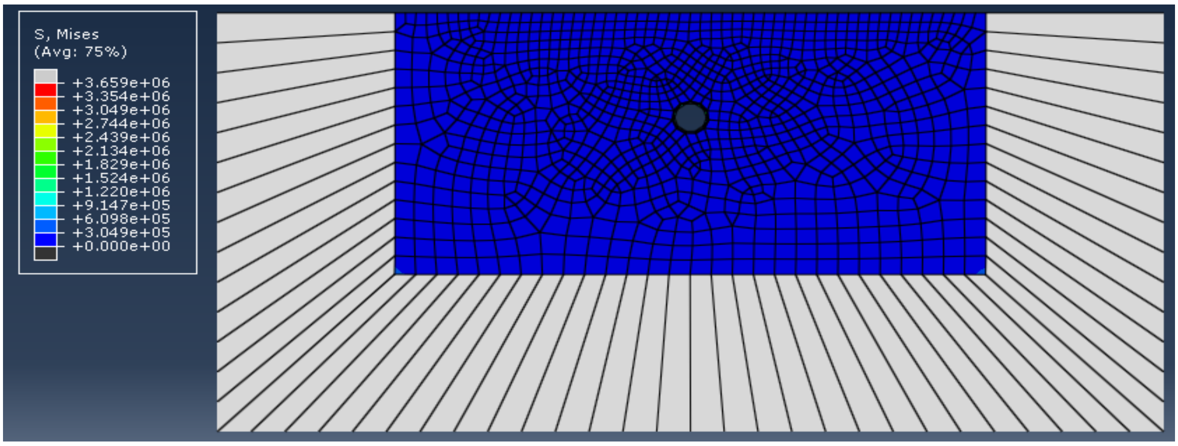

Fig.10 Result calculation of model tunnel's by 2D numerical method

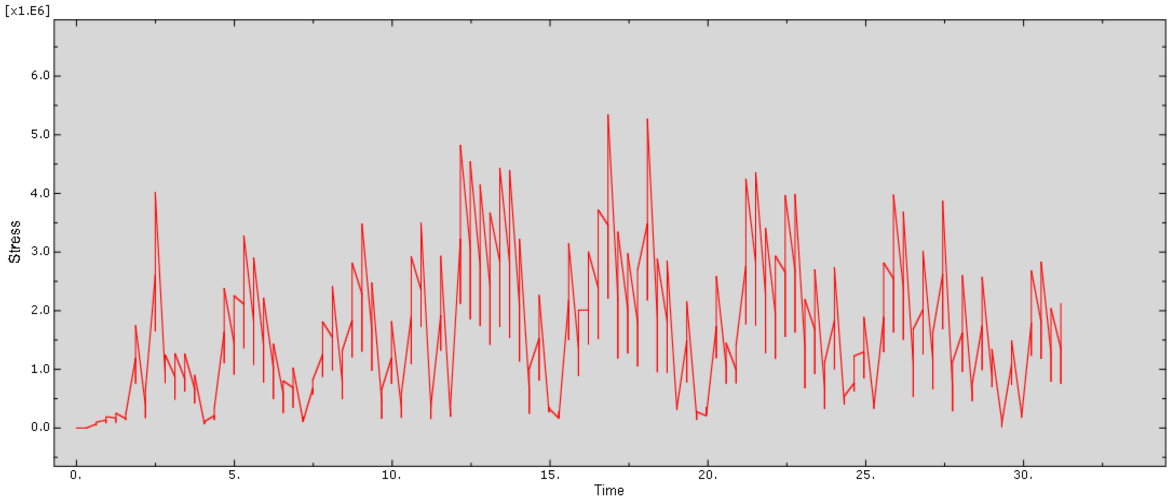

Fig.11 State stress on the tunnel lining in 2D numerical method

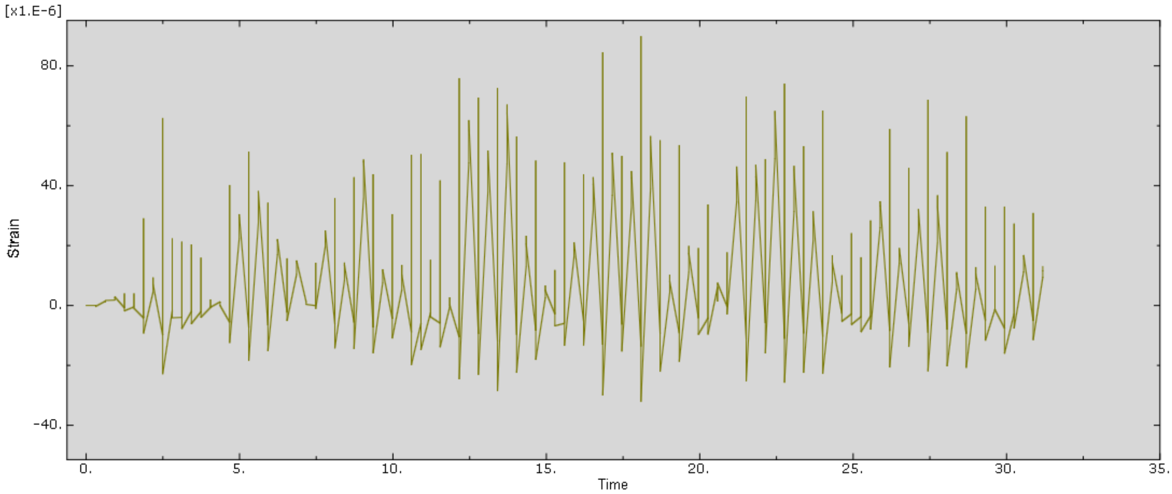

Fig.12 Strain of the tunnel lining in 2D numerical method

Table 2 Summary of analysis results

The internal forces in lining tunnel	Wang's method	Penzien & Wu's method	HRM method	2D numerical method
M (kN.m/m)	110.03	113.34	106.64	-
T (kN/m)	82.95	71.96	190.34	-
σ (MPa)	5.626	5.757	5.771	4.213

Note: Stress limit of tunnel lining, $[\sigma]_{\text{limit}} = 22\ MPa$

Results in Table 3 show that all stresses on the lining tunnel, which were calculated by analytical methods and numerical methods, are less than the limited stress values of the tunnel lining's material and the maximum stress obtained in 3 analytical methods are higher than that obtained with the 2D numerical method. This could be attributed to the fact that, in the numerical model, the direct influence of the soil environment surrounding the tunnel lining is considered. The 2D numerical model uses direct data from the earthquake, this is may be do results were received in higher accuracy than the results of analytical methods. Further, these are reasons that can be explained for these results: the soil layer surrounding tunnel has been assumed to be governed by an elastic perfectly-plastic constitutive model, based on the Mohr-Coulomb failure criterion and had got impact of damping ratio of soil and tunnel lining (damping ratio is 5% in this paper). The presence of damping ratio in the soil surrounding the tunnel lining and in the tunnel lining reduced the impact of earthquakes on the lining. This damping ratio is a main reason that was the vibration of the layer soil surrounding tunnel and vibration of tunnel lining decrease a value over time, therefore, the internal force on the tunnel lining is reduced. These reasons reduce the internal force that occurs in the lining. However, it should be noted, in results obtained from the 2D numerical model, displacement of the soil surrounding tunnel and tunnel lining under the effect of the earthquake about 2.1 cm. This displacement can make cracks, deformation and tunnel instability develop, although the internal force value by effect of earthquake in the tunnel lining is smaller than the durability of the tunnel lining up a lot.

5. CONCLUSIONS

In this paper, a lot of methods calculation about impact of earthquake to tunnel lining were used. Results of internal forces induced in the tunnel lining of Hanoi metro system determined using Wang's method, Penzien & Wu's method, HRM method and 2D numerical model–Abaqus software were presented and comparative. Under the impact of the earthquake, that has got strongest magnitude can occur in the Hanoi's area, the stress on the tunnel lining of the Hanoi metro system is smaller than value of the stress limit of the tunnel lining ($\sigma < [\sigma_{\text{limit}}]$ =22 MPa) and can be concluded that the tunnel lining (with selected characteristics) could operate safely under the impact of earthquake waves. However, analyses pointed out some differences in the internal forces on the lining tunnel, these are bending moments and normal forces have been determined by analysis methods and numerical method. There are quite large differences in results of stress on the tunnel lining between the analytical methods and the 2D numerical method. These are explained by the reasons:

1. The 2D numerical method demonstrates the interconnection and interactions of soil surrounding the tunnel and lining;
2. The 2D numerical method has used the soil surrounding tunnel as be an elastic perfectly-plastic constitutive model based on the Mohr-Coulomb failure criterion and the tunnel lining is linear elastic model (In analysis methods were to consider layer soil surrounding tunnel and the tunnel lining as be elastic material model);
3. The 2D numerical method taken into account the effect of the damping, through the damping ratio, in this study is 5%.

Results received by have been calculated using analytical methods and 2D numerical methods using the Abaqus software have confirmed the safety of tunnel in Hanoi metro system under the impact of earthquakes. However, it should be noted that in the results of the 2D numerical method there is a displacement of the tunnel and the soil surround the tunnel, this displacement may be does not break the tunnel lining but can make cracks, deformation of the tunnel lining and the tunnel could be loosed qualities when tunnel be used.

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