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DIFFERENT BEHAVIOUR OF CIRCULAR AND RECTANGULAR TUNNELS UNDER THE IMPACT OF EARTHQUAKES: A CASE STUDY FROM THE TUNNEL OF HANOI METRO SYSTEM

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ABSTRACT: Currently, the metro system is built in Hanoi, the capital of Vietnam. Hanoi's metro system was designed to be shallow that of near-surface (with an average depth of ground is H = 20 m). Hanoi is located in the Northern part of Vietnam, where it can be influenced by the highest magnitude of earthquakes is up to Mw = 6.5 Richter, so the study of the effects of earthquakes to the tunnel's stability in the Hanoi metro system is necessary. The paper studied and calculated for two cases of the tunnel's cross-section of the Hanoi metro system is circular and rectangular under effects of the earthquake, this has been the strongest earthquake may have the impact to Hanoi. Based on the results obtained, the paper has given comments on the effects of earthquakes to tunnel's stability in studies of two case and given suggests about the cross-section shape of the tunnel in Hanoi metro system that may be used to under the effect of the earthquakes.

Keywords: Behaviour, tunnel circular, tunnel rectangular, earthquake, impact.

1. INTRODUCTION

Earthquakes can destroy or destabilize works and infrastructure in the area, where earthquakes have got impacts. Hanoi is between two major fault systems: the Red River fault system and the Son La - Lai Chau - Dien Bien fault system [1]. The distance from Hanoi to these two fault systems is not large and valuable from 20 to 50 km. Thus, the area of Hanoi may be affected by the earthquake, that has the magnitude is up to M_w = 6.5 Richter [1]. Hanoi metro system is one of the important constructions be built in Hanoi. Tunnels in Hanoi metro system, these may be affected by earthquakes. Current, there are many types of tunnel cross sections that are used to design and constructions for tunnels in the metro system, such as the cross-section of the tunnel is a circular, rectangular, dome... In this paper, the authors used two the cross-sectional shapes for the tunnel in Hanoi metro system: a circular cross-section and a rectangular cross-section to study and calculate for the stability of the tunnel under effects of the strongest earthquake in Hanoi. The methods had been used in the paper are the analytical methods of Wang [2], Penzien [3], Wood [4, 5] and 2D numerical methods using Abaqus Similar software and Matlab software that was used to in HRM method.

2. CHARACTERISTICS OF GEOLOGICAL AND TUNNEL FROM HANOI METRO SYSTEM

Hanoi is the capitol and the second largest city in Vietnam with about 8 million inhabitants. Hanoi is located in the Red River delta and has the groundwater level is three meters below the surface. According to the authors [1], the Hanoi center area can be affected by the strongest earthquakes with a maximum magnitude M_w = 6.5 Richter, peak ground acceleration of a_{max} = 0.2g. The tunnel of Hanoi metro system in the Hanoi center that has an average depth of H = 20 m and has a cross-sectional area of approximately S=31 m^2 [6]. Distributed from the ground surface to the bedrock at a depth of 48 m and there are usually six layers of soil. The parameters of the tunnel in Hanoi metro system and the layers of soil in the Hanoi center-surrounding the tunnel, these were drawn in Fig.1. In this paper, the study and calculations for two cases: The first case, the tunnel cross-section is circular with a diameter of the tunnel D = 6.3 m. The tunnel's cross-section is rectangular with a dimension of 5.5mx5.5m in the second case.

In both two case of the tunnel's cross-section is circular and rectangular, the parameters of the tunnel lining include:

- The tunnel lining is made by reinforced concrete;
- Young's modulus E_l = 35500 MPa;
- Poisson's ratio ν = 0.15,
- The thickness of the tunnel lining t = 0.35 m.

The geological conditions of layers soil in central Hanoi, where the tunnel of Hanoi metro system has been shown in Table 1 [7, 8]:

Table 1 Parameters of layers soil in Hanoi center

Number of soil layers	Elastic module, E, MPa	Poisson's ratio, μ	Thickness of layer (h), m	Measured SPT blow count, N	Density of the soil, ρ, g/cm^3
1	9.25	0.41	4.6	2	1.75
2	7.68	0.38	1.1	1	1.76
3	15.3	0.35	11.8	3	1.81
4	35.02	0.33	12.5	7	1.78
5	53.9	0.32	11.0	10	1.83
6	65	0.3	7.0	12	1.86

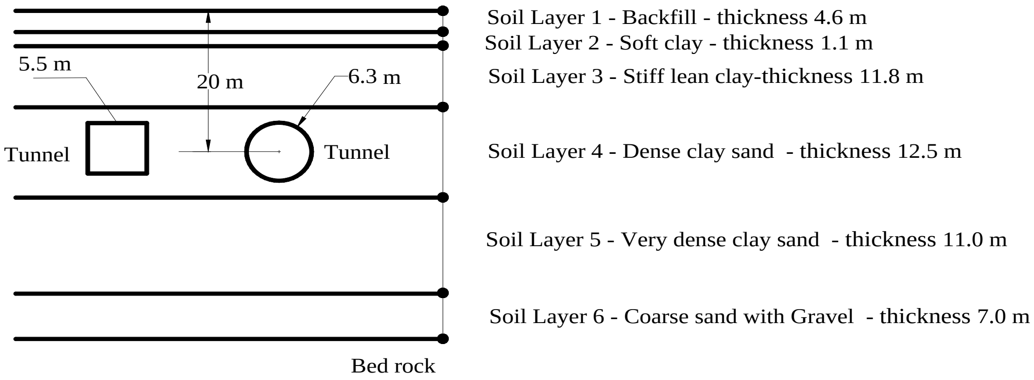

Fig.1 Tunnel and layers soils of considered section

3. METHODS CACULATION FOR TUNNEL LINING

3.1 Methods calculation for circular tunnel

3.1.1 Wang's method

In 1993, Wang (Wang, 1993) [2] proposed a calculation method for tunnels with circular cross-sections (circular tunnel) under the influence of the earthquake. In Wang's method, the internal force values that appear in the envelope in the tunnel lining are represented by the equations for determining the moment M and forces normal T. In Wang's method, has two cases of full-slip and no-slip at the soil–tunnel lining.

3.1.2 Penzien's method

In 1998 and 2000, Penzien and Wu [4] improved Wang's formulas to calculate for the tunnels have circular cross-sections under the influence of earthquakes. In the method of calculating the internal force appearing in the tunnel lining under the influence of earthquakes, Penzien also divided into two cases as with Wang's approach: Full-slip and no-slip at the tunnel lining with the surrounding soil environment).

3.1.3 HRM method

The HRM method introduced by Orsten in 2003 [9] (Orsten, 2003). It was essentially a numerical method to the calculation of tunnels with circular cross-sections under the influence of earthquakes. In this method, the tunnel structure is split into beam elements, each of which is defined by two limit nodes. In HRM method, the interaction between the lining and the soil surrounding the tunnel is reflected through independent "Winkler" type springs. The associated springs are represented by the normal and tangential stiffness as well as the load acting on the springs.

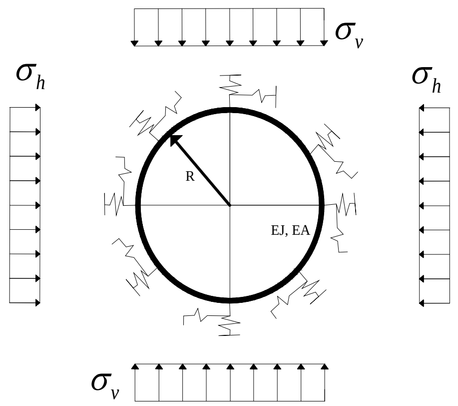

Fig.2 HRM method. σ_v is vertical load in the model tunnel lining–soil; σ_h is horizontal load in the model tunnel lining–soil; k_n is normal stiffness of the interaction springs; k_s is tangential stiffness of the interaction springs; R is tunnel radius; EJ and EA is bending and normal stiffness of the tunnel lining [8]

In case of having effect of earthquake, (Peinzen and Wu., 1998) and (Naggar et al., 2008) [10, 11] introduced formulas, these could be used to calculation for ovaling deformation of a circular tunnel during effect of earthquake due to the in-plane shear stresses caused by vertically propagating (in case of the seismic load on the tunnel lining, all the external loads are rotated counterclockwise by 45^0 and the horizontal loads are in opposite directions).

3.1.4 2D numerical method

Abaqus software had been used to set up a tunnel model that had a circular cross-section under the influence of the earthquakes. In this method, ignoring the effects of groundwater and gravity had been able to accurately study the effect of earthquakes on the tunnel lining and only consider the case of non-slip at the tunnel lining with the soil environment. In this method, two zones were created in the model of studying the impact of earthquakes to the tunnel. Zone 1 is the model of a tunnel with it's depth appropriate to the actual design of the tunnel and the soil environment surrounding. In this zone, the soil environment is a homogeneous, isotropic and elastic or elastic perfectly-plastic constitutive model. Zone 2 is the boundary's area, which is the area created by the infinite elements so that seismic waves these affect to the tunnel when propagated to the boundary will be transmitted straight without reflected back to the tunnel. This causes exactly when calculating the effect of earthquakes on the stability of the tunnel. In the 2D numerical model, soil layers are replaced with a single soil layer with equivalent properties [8]: Young's modulus of soil, E = 35.75 MPa; Poisson's ratio, μ = 0.34; the damping ratio D = 5% (in case of the soil layer surrounding tunnel is elastic perfectly-plastic).

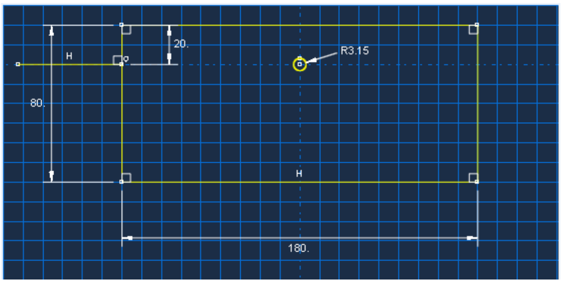

Fig. 3 Model of tunnel and soil layer [7]

Data of El Centro earthquake had been used to in the paper (with characteristics of the El Centro earthquake almost identical to characteristics of the strongest earthquake that could occur in the Hanoi center)–M_w = 6.5 Richter and be showed in Fig. 4 [12].

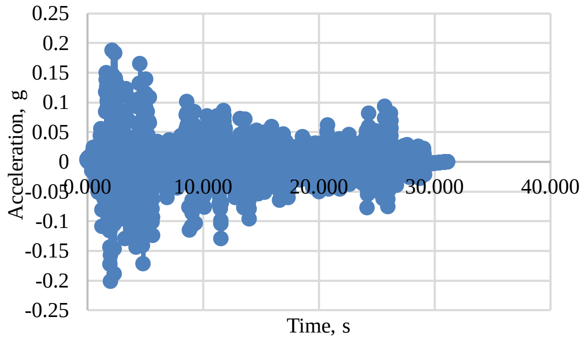

Fig. 4 Data of El Centro earthquake

3.2 Methods calculation for rectangular tunnel

3.2.1 Wang's method

In 1993, Wang also introduced a calculation method for tunnels with rectangular cross-sections under the influence of the earthquake [2]. In this method, Wang relies on the deformation of the soil environment under the effect of earthquakes to calculate the corresponding deformation of the tunnel lining through the coefficient of influence R and the flexibility ratio F_r of the system soil-structure. Calculation steps in Wang's method:

- Determine the free-field peak shear strain of the soil at the average depth of the structure of the tunnel;
- Determine the elastic and post-elastic stiffness of the tunnel's structure;
- Evaluation of the racking deformation of the tunnel's structure from results of the free-field strain, structure stiffness, and soil-structure interaction curves;
- Determine for the member forces in the tunnel's structure.

3.2.2 Wood's method

On the basis of Wang's method (Wang, 1993), Wood [3, 4] had given the calculation method for tunnels with rectangular cross-sections. The content of Wood's method is defined by equations:

$$T_s = T_1\left[\frac{H_s}{50}\right]\sqrt{\frac{100\rho_s}{2G_s}} \quad (1)$$

$$u_s = u_1\left[\frac{H_s}{50}\right]^2\left[\frac{100\rho_s}{2G_s}\right] \quad (2)$$

$$\varepsilon_s = \varepsilon_1\left[\frac{H_s\rho_s}{G_s}\right] \quad (3)$$

$$R = \frac{\Delta_{si}}{\Delta_{ff}} \quad (4)$$

$$f_{st} = \frac{\Delta}{P} = \frac{H^2}{24K_w} \frac{1}{\left[1 - \frac{2+3r+3jr}{2+2r(2+2j+3jr)}\right]} \quad (5)$$

$$F_r = \frac{f_{st}}{f_s} \quad (6)$$

$$f_s = \frac{H}{LG} \quad (7)$$

$$M_f = \frac{6\Delta K_w}{H}\left[\frac{j(3+q)}{j-(2j+q)(2+q)}\right] \quad (8)$$

$$M_r = \frac{6\Delta K_w}{H}\left[\frac{j(3+q)(2+q)}{j-(2j+q)(2+q)}+1\right] \quad (9)$$

Where:

$K_w = \frac{EI_w}{H}$; $K_w = \frac{EI_w}{H}$; $K_r = \frac{EI_r}{H}$; $r = \frac{K_r}{K_w}$; $q = \frac{1}{r} = \frac{K_w}{K_r}$; E is Young's modulus for the structure material and I_w and I_r , I_f are the moments of inertia per unit length of the wall, roof and floor respectively; T_s, u_s, ε_s , G_s are period, displacement strain and shear modulus of soil layer; T_1, u_1 and ε_1 are the reference soil layer values; ρ_s is soil density; G is shear modulus in the soil at the level under consideration; f_{st} is elastic flexibility of lining; R is the shear strain deformation ratio; F_r is the flexibility ratio; K_w is wall stiffness; K_r is roof stiffness; K_f is floor stiffness; q is ratio wall/roof stiffness; j is ratio floor/roof stiffness; r is ratio roof/wall stiffness; M_r is the moment at the top corner of structure; M_f is the moment at the bottom corner of structure.

Based on the characteristics of the rigid base-bed rock that the tunnel was above on as well as the technical characteristics of the tunnel structure, Wood has devised a process for calculating the impact of earthquakes on the tunnel rectangular's structure when this tunnel works under the impact of earthquakes as follows:

- Determine and calculate the average shear modulus of soil over the height of the tunnel's structure;
- Determine the tunnel's structure stiffness and flexibility ratios of tunnel's structure. Modify the stiffness parameters of tunnel's structure if necessary;
- Calculate the flexibility ratio F_r of the system soil-structure and influence ratio R;
- Determine for the shear deflection of the tunnel's structure from the interaction shear strain, then calculate the moment on the tunnel's structure under the effect of earthquakes;
- Correct the calculated bending moments on the tunnel's structure by used to ratios F_r and use relevant charts;
- Calculate the flexural strength capacities of the tunnel's structure sections;
- From the internal forces in tunnel's structures under the impact of the earthquakes, determine the stresses in the tunnel lining.

3.2.3 2D numerical method

The tunnel model has a rectangular cross-section of 5.5mx5.5m in size with the tunnel lining characteristics and depth in the soil layers as described in section 2 had been to set up using the Abaqus Similar software. In this method, the case study is no-slip at the tunnel lining with soil and regardless of the effect of gravity and groundwater conditions. This model is also divided into two zones with the same features as the model of the tunnel with the circular cross-section. The stages of this method include:

- Phase 1 Building the tunnel model, tunnel lining and soil layer surrounding with their parameters;
- Phase 2 Assign boundary conditions, setting up the pressure on both tunnel structure and model's boundary, assign to the peak ground acceleration of the earthquakes to the model, include built parameters of soil layer and tunnel lining, assigning the tunnel lining with layer soil by link conditions;
- Phase 3 Identify effects of earthquakes on the tunnel and given the results obtained of the model.

Note. There are two cases: In case of the layered soil surrounding tunnel is elastic or in case of the layered soil surrounding tunnel is elastic perfectly-plastic and had the damping ratio D = 5%.

4. RESULTS AND DISCUSSIONS

The results of calculating the impact of the earthquake on the tunnel lining were presented in Table 2 and Table 3. The internal forces appearing in the tunnel lining include M moment and T normal force. The stresses appear in the tunnel lining these were calculated through the forces internal in the tunnel lining and compare the results obtained by different methods calculation for two cases: The tunnel's cross-section is circular and rectangular. In both cases, the soil layer around the tunnel was elastic, homogeneous, isotropic or elastic perfectly-plastic. Based on the results of these methods calculation for each case of, a comparison for the effects of the strongest earthquake that can occur in the Hanoi center to the tunnel lining of the two cases was made.

Table 2 Analysis results of different calculation methods – circular tunnel

The internal forces in lining tunnel	Wang's method	Penzien's method (reference case)	HRM method	2D numerical method	
		Elastic		Elastic	Plastic
M (kN.m/m)	110.03	113.34	113.67		
% difference with the reference case - M	3.01	-	0.29	-	-
T (kN/m)	82.95	71.96	190.84	-	-
% difference with the reference case -T	13.25	-	165.26	-	-
σ (MPa)	5.626	5.757	6.11	5.721	4.119
% difference with the reference case - σ	2.275	-	6.18	0.625	28.452

In case of the tunnel cross-section is circular, the results of calculating the internal forces in tunnel lining under the influence of earthquake by the Wang's method, Penzien's method and HRM method these were presented in Figures 5 to 8 [8].

Using 2D numerical method by Abaqus software, results of calculating the internal forces in the tunnel lining under the influence of earthquake were presented in Figures 9 to 18 for both cases of the tunnel cross-section is circular and rectangular.

Table 3 Analysis results of different calculation methods – rectangular tunnel

The internal forces in lining tunnel	Wood's method (reference case)	2D numerical method	
	Elastic	Elastic	Plastic
M_{max} (kN.m/m)	145.89	-	-
σ (MPa)	7.145	6.912	4.725
% difference with the reference case - σ	-	3.434	33.867

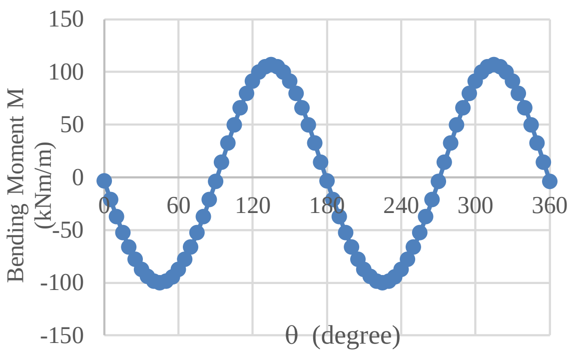

Fig.5 Bending moment M in the tunnel lining by HRM method

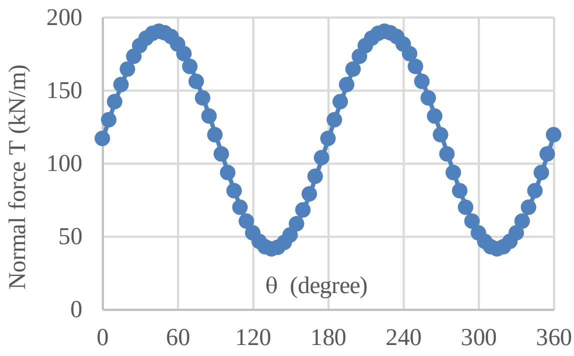

Fig.6 Normal force T in the tunnel lining by HRM method

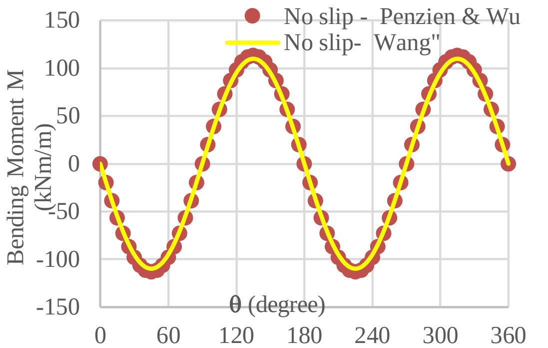

Fig.7 Bending moment M in the tunnel lining by Wang's method and Penzien & Wu's method

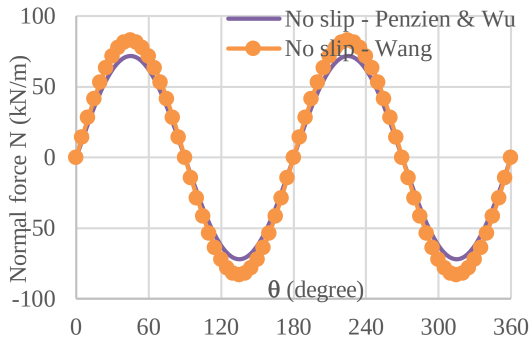

Fig.8 Normal force T in the tunnel lining by Wang's method and Penzien & Wu's method

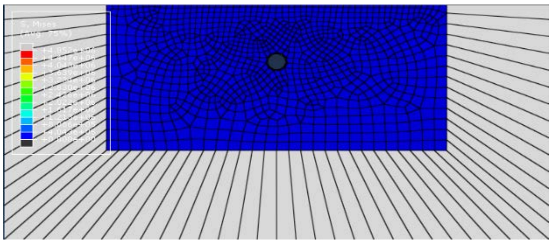

Fig. 9 Result calculation for model tunnel's by 2D numerical method-circular tunnel

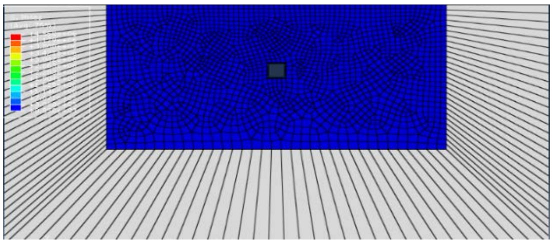

Fig. 10 Result calculation for model tunnel's by 2D numerical method-rectangular tunnel

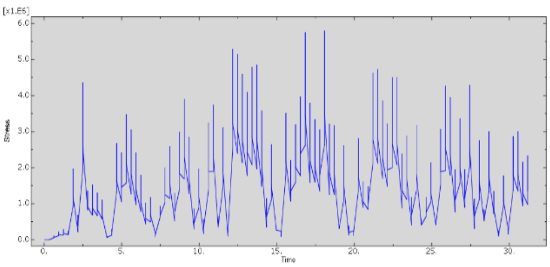

Fig. 11 State stress in the tunnel lining-circular tunnel

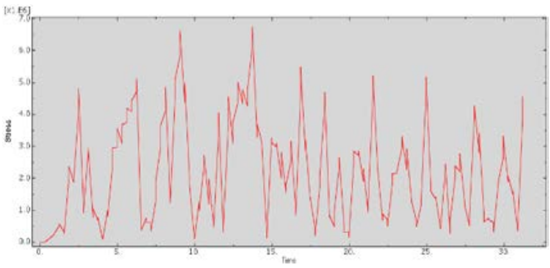

Fig. 12 State stress in the tunnel lining-rectangular tunnel

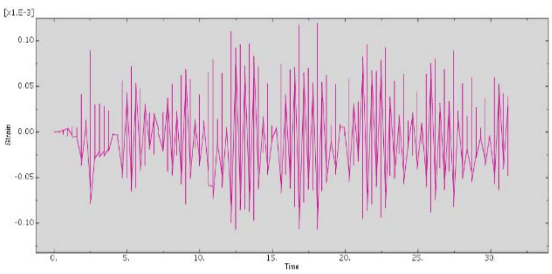

Fig. 13. Strain of the tunnel lining-circular tunnel

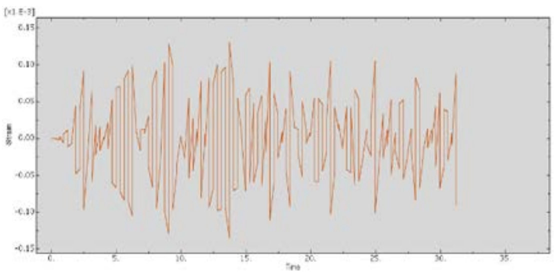

Fig. 14 Strain of the tunnel lining-rectangular tunnel

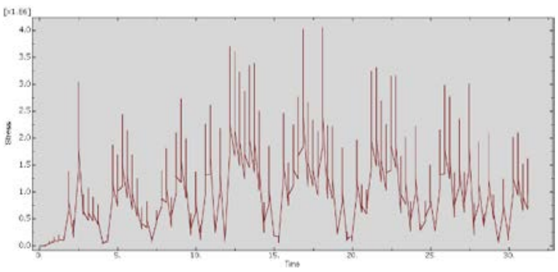

Fig. 15 State stress in the tunnel lining-circular tunnel&plastic

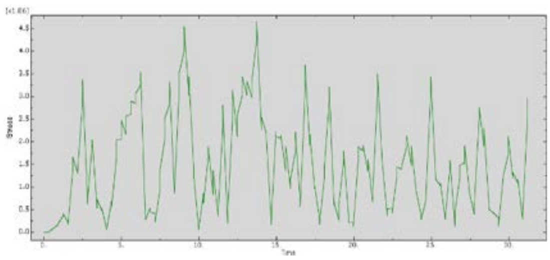

Fig. 16 State stress in the tunnel lining-rectangular tunnel &plastic

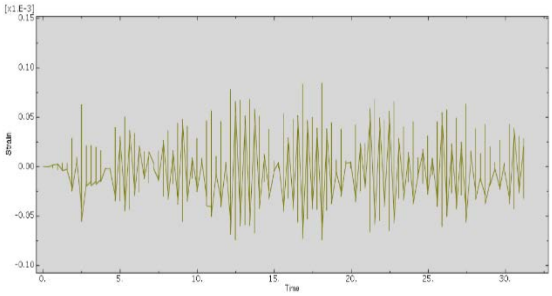

Fig. 17 Strain of the tunnel lining-circular tunnel & plastic

Based on the results obtained in Table 2 and Table 3, could see these: In the case of the cross section of the tunnel is circular and the soil environment surrounding tunnel is elastic, the stress values appear in the tunnel lining under the impact of the earthquake according to Wang's method σ = 5.626 MPa, this stress had difference compared to the stress of results in the Penzien's method-reference method is 2.275% (the stress values appear in the tunnel lining by Penzien's method σ = 5.757 MPa), HRM method used to the Matlab program and had given the stress in the tunnel lining σ = 6.11 MPa, the difference compared to the stress of results in the Penzien method is 6.18%. The 2D numerical method using Abaqus software had the stress value in the tunnel lining σ = 5.721 MPa, the difference in comparison with the stress in the Penzien's method is 0.625%. All differences of methods are not large, this confirms the accuracy of the calculation methods. When the soil environment surrounding tunnel is elastic perfectly-plastic, by using the 2D numerical method, received the value stress in the tunnel lining σ = 4.119 MPa and had the difference in comparison with the value stress in the Penzien's method (calculation for the soil environment is elastic) is 28.892 %. In case of the cross-section of the tunnel is rectangular and the soil environment surrounding tunnel is elastic. The maximum stress values appearing in the tunnel lining σ = 7.145 MPa, according to the Wood's method. Using the 2D numerical method by Abaqus software when the soil environment is elastic and elastic perfectly-plastic, comparing two values maximum stress in tunnel lining under the impact of the strongest earthquake that can occur in the Hanoi center (σ = 6.912 MPa and σ = 4.725 MPa) with the value maximum stress in the tunnel lining according to Wood's method. In case the soil environment is elastic, the difference value is 3.434%, this difference is not large. When the soil environment is elastic perfectly-plastic, the difference value is 33.867%. Note, in both methods calculation the corner point is the connection point for the components of the tunnel lining (the beam roof with wall column) that had the maximum value stress in the tunnel lining.

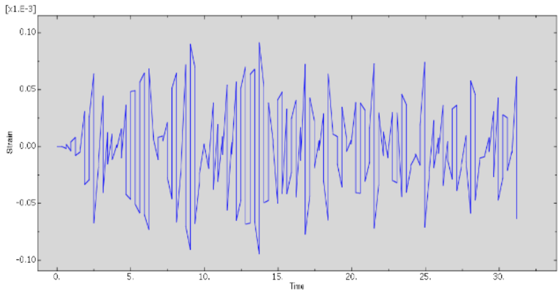

Fig. 18 Strain of the tunnel lining-rectangular tunnel & plastic

Comparison of the maximum stress values in the tunnel lining-circular tunnel with the maximum stress value in the tunnel lining-rectangular tunnel. When the soil environment is elastic, the difference of the values stress is 19.426% (the value stress of Penzien’s method was reference value) by using analysis methods and the difference of the values stress is 17.231% by using the 2D numerical method. When the soil environment is elastic perfectly-plastic, the difference between the stress values in the tunnel lining by used to the 2D numerical method to calculate is 14.712 % (the value stress in case of the circular tunnel was reference value). Based on the results obtained, it could be seen that there is a large difference between the stresses in the tunnel lining in two cases of and given conclusion: the cross-sectional shape of the tunnel has the large influence to stress values in the tunnel lining when the tunnel works under the impact of the earthquakes.

5. CONCLUSIONS

Earthquakes one of the most unpredictable natural phenomena and very hard to research. Earthquakes could cause large impacts on the stability of works in the area that it affects. In this paper, analytical methods and 2D numerical methods were used to calculate the impact of the strongest earthquake that can occur in the Hanoi center to tunnel of Hanoi metro system in Hanoi center by two cases of the cross-section of the tunnel lining is circular and the cross-sectional tunnel lining is rectangular when the soil environment surrounding the tunnel is elastic or elastic perfectly-plastic. Comparing the results in two cases, the following conclusions can be given:

- Under the influence of the strongest earthquake that can occur in the Hanoi center, the tunnel lining with selected characteristics could still work in a stable and sustainable manner in both cases of the cross-section of the tunnel lining is circular and the cross-sectional tunnel lining is rectangular (the stress in tunnel lining in two cases, these have values are less than the value limit stress of material lining’s ($\sigma \leq \sigma_{limit} = 22$ MPa);

- In cases of the tunnel lining has cross-section is circular, the stress value appearing in the tunnel lining is less than the stress value in the tunnel lining in the case of the tunnel has a cross-section is rectangular under the influence of the earthquakes. This is explained by the reasons, in the case of the tunnel has the rectangular cross-section, the stresses in the tunnel lining were concentrated in the corner points these are the connection points for the components of the tunnel lining these are the roof beams, floor beams, and wall columns. The stress was concentrated at these points will reduce the bearing strength of the tunnel lining. In case of the tunnel lining has the circular cross-section, the stress in the tunnel lining is uniformly distributed in the cross-section of tunnel lining. In addition, comparing the strain of the tunnel lining under the influence of the earthquake in two cases of, it could be seen that in case of the tunnel lining has a circular cross-section, the strain of the tunnel lining $\varepsilon = 10^{-4}$ when the soil environment surrounding the tunnel is elastic and $\varepsilon = 0.8.10^{-4}$ when the soil environment surrounding the tunnel is elastic perfectly-plastic. These values strain is smaller than values strain of the tunnel lining in case the cross-section of the tunnel lining is rectangular $\varepsilon = 1.5.10^{-4}$ when the soil environment surrounding the tunnel is elastic and $\varepsilon = 10^{-4}$ when the soil environment surrounding the tunnel is elastic perfectly-plastic. Based on this result, it can be argued that tunnels have a circular cross-section could work better than tunnels these have rectangular cross-section respectively under the influence of earthquakes;

- When the soil layer surrounding tunnel is elastic perfectly-plastic, the value of the stresses in the tunnel lining under the influence of the earthquake is smaller than the stresses in the tunnel lining in case of the layered soil surrounding tunnel is elastic. When the soil layer surrounding the tunnel has been assumed to be working as an elastic perfectly-plastic and under the influence of earthquakes, the soil layer can move and deform favorably than when the soil layer is working in an elastic state. The presence of damping ratio in the soil surrounding the tunnel lining and in the tunnel lining reduced the impact of earthquakes on the tunnel lining. This damping ratio is the main reason of that was the vibration of the soil layered surrounding tunnel and vibration of tunnel lining had been decreased the values over time, therefore, the internal force on the tunnel lining is reduced. These reasons reduce the stress that occurs in the tunnel lining.

6. ACKNOWLEDGMENTS

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