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A Numerical Method for the Design of the U-Shaped Segmental Tunnel Lining under the Impact of Earthquakes: A Case Study of a Tunnel in the Hanoi Metro System

NGUYEN Chi Thanh[1, *], DO Ngoc Anh[1], PHAM Van Vi[1], GOSPODARIKOV Alexandr[2]

[1] Hanoi University of Mining and Geology, 18 Vien street, Hanoi, Vietnam
[2] Saint Petersburg Mining University, Saint Petersburg, Russia Federation

Corresponding author: nguyenthanh.xdctn47@gmail.com

Abstract. Circular tunnels are usually encountered when excavation tunnel. However, the U-shaped tunnel lining is used a lot in practice because of it's advantages. However, there are not many studies in the world to calculate and design for underground structures with U-shaped tunnel lining, especially in the case of tunnels being affected by earthquakes. This paper proposes a new numerical-HRM method approach for the analysis of U-shaped segmental tunnel lining under the impact of earthquakes. Hanoi is the capital of Vietnam, this is a big city with more than 8 million people. Hanoi is located between two major fault systems, the Red River fault system and the Son La-Dien Bien-Lai Chau fault system. Therefore, the Hanoi area is assessed as likely to be affected by earthquakes of magnitude $M_w = 6.1$ up to 6.5 Richter. The Hanoi metro system is constructed by TBM and the U-shaped segmental tunnel lining is also one of the types of tunnel lining considered for use in the construction of metro tunnels in Hanoi. The improved HRM method has been used to investigate the effect of joints in the tunnel lining from the Hanoi system metro under the impact of earthquakes is conducted considering from the results of the tunnel lining behavior in terms of bending moment (M), normal forces (N) and tunnel lining displacements (δn) in both cases: the U-shaped continuous tunnel lining and the U-shaped segmental tunnel lining.

Keywords: Numerical method, U-Shaped segmental tunnel lining, Impact of earthquakes, Hanoi metro system

1. Introduction

In the construction process and the design for tunnels, the U-shaped tunnel lining is used a lot by its construction ability, usability, and bearing capacity. Some researchers in the world have conducted research and calculations for the U-shaped tunnel lining to serve the needs of using this type of tunnel lining in underground constructions in hydroelectricity, transportation, and infrastructure. Yin and Yang, (2000) together with the topology optimization method [1], Barpi et al., (2011) with a method for the study of the U-shaped tunnel lining based on a fuzzy approach and the bedded-beam-spring model [2], Some other authors with the Hyperstatic Reaction Method (HRM) [3, 4, 5, 6, 7, 8]. In which, the HRM method is a numerical method that is quite focused on developing and used because of its advantages, such as fast calculation results, simple input parameters, ease to use. However, there is still no study using the HRM method to calculate the U-shaped segmental tunnel lining affected by earthquakes.

In fact, could use numerical methods with software such as FLAC^{3D}, Plaxis^{2D}, Abaqus^{2D}, etc. studying and calculating the effect of earthquakes on the U-shaped segmental tunnel lining. However, the use of these software requires a large initial investment, the computer configuration used must be strong enough, the time to build the tunnel model that is affected by the earthquake, and processing research results for quite a long time. The HRM method, one numerical method was developed and used to calculate the U-shaped continuous tunnel lining by Nguyen et al., (2020) [7] which used the following theories: the reaction of soil mass around the tunnel caused by the deformation of the tunnel lining that is a function of the tunnel lining stiffness. This reaction is determined using the geometrical parameters and mechanical characteristics of the tunnel lining. The active loads depend on the displacements in the tunnel lining along with the structure/ground interface.

The ground is linked with the tunnel lining through two types of springs: normal springs and tangent springs. Sections of the segmented lining of the tunnel are linked through joints. These joints work through characteristic stiffnesses, including K_{R0} is rotational stiffnesses, K_A is axial stiffness and radial stiffness K_R.

This paper presents the HRM method and provides some improvements to the methodology so that the method could calculate the U-shape tunnels when the tunnels are affected by earthquakes, in both cases of the U-shaped continuous tunnel lining and the U-shaped segmental tunnel lining.

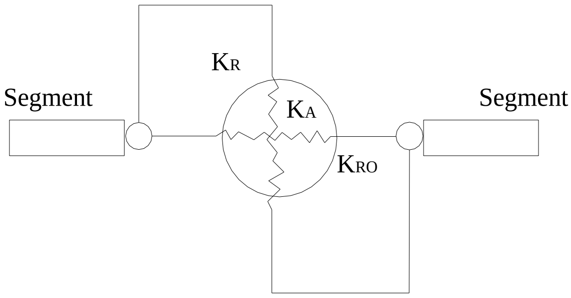

Fig. 1. Joint and properties.
K_{R0} is rotational stiffnesses, K_A is axial stiffness and radial stiffness K_R.

2. Hyperstatic Reaction Method for the U-shaped tunnel lining

The HRM method was proposed and developed by; Oreste, 2007 [3]; Do, 2014 [4, 5, 6]; Du et al., (2020) [9]; Duddeck and Erdmann (1985) [10]; Leca and Clough (1992) [11]. Firstly, the HRM method was used to calculate the circular tunnel. This is a numerical method that is likely to account for the effects of the ground's parameters, these can change under load, and to 2014, Do et al. [4] have used the HRM method in cases of circular tunnels are affected by static load and in case of the circular tunnels are affected to dynamic loads with the tunnel lining is segmental lining.

2.1. The HRM method for the U-shaped continuous tunnel lining

Du et al., (2020) used the HRM method to calculate and design for the U-shaped tunnel lining in case of the continuous tunnel lining and under static load [9]. Nguyen et al., 2020 [7] improved the HRM for use in the design of the U-shaped tunnel lining in the case of that the tunnel is affected by an earthquake and the tunnel lining is continuous.

In the HRM method, the tunnel lining interacts with the ground by springs. There are two types of springs used: tangential springs and normal springs. The tunnel lining in the HRM method is represented by a number of one-dimensional elements. The "*i*" element in the tunnel has two nodes. The length of each element is the distance between the two bounding nodes of that element, with the parameters of the tunnel element, including the inertia modulus *J*, area *A* of the element transversal section, the elastic modulus *E*, and length are parameters of each element in the tunnel lining [6].

The interaction between ground mass and the tunnel lining could be analysed through springs distributed over the nodes and applied active loads. When the displacement of the nodes in the elements of the tunnel lining under the effect of external load is determined, it is possible to determine the stress occurring inside the elements of the tunnel lining [12]:

$$Z_i * S_i = R_i + G_i \tag{1}$$

where S_i is the vector displacements at node "*h*" and node "*j*" of the element "*i*" (Fig. 5); G_i is the external nodal forces of the element "*i*"; R_i is the forces at nodal applied by the neighboring elements.

$$\begin{bmatrix} \frac{E.A}{L_i} & 0 & 0 & -\frac{E.A}{L_i} & 0 & 0 \\ & \frac{12.E.J}{L_i^3} & \frac{6.E.J}{L_i^2} & 0 & -\frac{12.E.J}{L_i^3} & \frac{6.E.J}{L_i^2} \\ & & \frac{4.E.J}{L_i} & 0 & -\frac{6.E.J}{L_i^2} & \frac{2.E.J}{L_i} \\ & & & \frac{E.A}{L_i} & 0 & 0 \\ & & & & \frac{12.E.J}{L_i^3} & -\frac{6.E.J}{L_i^2} \\ & & & & & \frac{4.E.J}{L_i} \end{bmatrix} \begin{bmatrix} u_{h,i} \\ v_{h,i} \\ \theta_{h,i} \\ u_{j,i} \\ v_{j,i} \\ \theta_{j,i} \end{bmatrix} = \begin{bmatrix} R_{xh,i} + G_{xh,i} \\ R_{yh,i} + G_{yh,i} \\ R_{zh,i} + G_{zh,i} \\ R_{xj,i} + G_{xj,i} \\ R_{yj,i} + G_{yj,i} \\ R_{zj,i} + G_{zj,i} \end{bmatrix} \tag{2}$$

With *K* is the matrix of the global stiffness, *K* in the global Cartesian reference system had been setup:

$$Kq=F \tag{3}$$

$$\begin{bmatrix} (k_{n,a}+k_{1,a}) & k_{1,b} & 0 & 0 & 0 & k_{n,c} \\ k_{1,c} & (k_{1,d}+k_{2,a}) & k_{2,b} & 0 & 0 & 0 \\ 0 & k_{2,c} & (k_{2,d}+k_{3,a}) & k_{3,b} & 0 & 0 \\ 0 & 0 & k_{3,c} & (k_{3,d}+k_{4,a}) & ... & 0 \\ 0 & 0 & 0 & .... & ... & k_{n-1,b} \\ k_{n,b} & 0 & 0 & 0 & k_{n-1,c} & (k_{n-1,d}+k_{n,a}) \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \\ ... \\ q_n \end{bmatrix} = \begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \\ ... \\ F_n \end{bmatrix} \tag{4}$$

The sub-matrices of k_i , each of which has 3 × 3 dimension with $k_{i,a}$; $k_{i,b}$; $k_{i,c}$, $k_{i,d}$ are the sub-matrices of k_i :

$$k_i = \begin{bmatrix} k_{i,a} & k_{i,b} \\ k_{i,c} & k_{i,d} \end{bmatrix} \tag{5}$$

$q_1, q_2, q_3, \ldots, q_n$: the sub-vectors composed of the three displacements of each node in the element of the tunnel lining. $F_1, F_2, F_3, .., F_n$: the sub-vectors composed of the three external forces applied to each node of the element.

$$\begin{aligned} K^*_{3i-2,3i-2} &= K_{3i-2,3i-2} + k_{n,i}.\cos^2(\frac{\alpha_{i+1}}{2}+\frac{\alpha_i}{2}-\frac{\pi}{2}) + k_{s,i}.\sin^2(\frac{\alpha_{i+1}}{2}+\frac{\alpha_i}{2}-\frac{\pi}{2}) \\ K^*_{3i-1,3i-1} &= K_{3i-1,3i-1} + k_{n,i}.\sin^2(\frac{\alpha_{i+1}}{2}+\frac{\alpha_i}{2}-\frac{\pi}{2}) + k_{s,i}.\cos^2(\frac{\alpha_{i+1}}{2}+\frac{\alpha_i}{2}-\frac{\pi}{2}) \\ K^*_{3i-1,3i-2} &= K_{3i-1,3i-2} + (k_{n,i}-\mathrm{k}_{s,i}).\sin(\frac{\alpha_{i+1}}{2}+\frac{\alpha_i}{2}-\frac{\pi}{2}).\cos(\frac{\alpha_{i+1}}{2}+\frac{\alpha_i}{2}-\frac{\pi}{2}) \\ K^*_{3i-2,3i-1} &= K_{3i-2,3i-2} + (k_{n,i}-\mathrm{k}_{s,i}).\sin(\frac{\alpha_{i+1}}{2}+\frac{\alpha_i}{2}-\frac{\pi}{2}).\cos(\frac{\alpha_{i+1}}{2}+\frac{\alpha_i}{2}-\frac{\pi}{2}) \end{aligned} \tag{6}$$

where "*i*" is the number of the generic node; $k_{s,i}$ is the stiffness of the tangential interaction spring connected to node "*i*" of the element; $k_{n,i}$ is the stiffness of the normal interaction spring connected to node "*i*" of the element; α_i and α_{i+1} are the angle between the local systems and global reference systems, for element *i* and for element *(i + 1)* in the tunnel lining.

By two ways: through the active loads that have an effect on the tunnel lining and through the normal springs and tangential springs over the nodes of the tunnel lining. The interaction between the tunnel lining with the ground was setup.

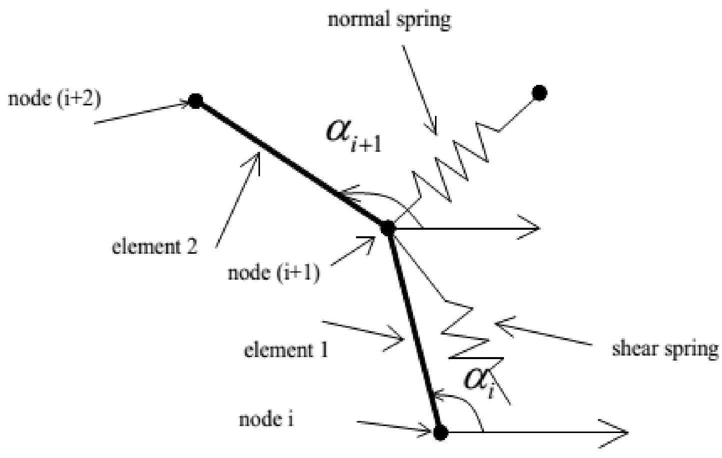

Fig. 2. The tunnel lining-soil surrounding interaction through the Winkler springs linked to support nodes of the tunnel lining.

The equation about the relationship between the deformation of the tunnel lining and the reaction pressure was given [3]:

$$p = p_{\lim} * (1 - \frac{p_{\lim}}{p_{lim} + \eta_0 \delta}) \tag{7}$$

where p is reaction pressure (MPa), $p_{\lim}$ is the maximum reaction pressure of ground (MPa), η_0 is the initial stiffness of the ground (N/m^3), δ is deformation of the tunnel lining (m).

The relationship between the initial normal stiffness ground and tangential stiffness ground had determined by the equation [13, 14]:

$$\eta_{n,0} = \beta \frac{1}{1+\nu} * \frac{E}{R} \tag{8}$$

$$\eta_s = \frac{1}{3} \eta_n \tag{9}$$

where E is Young's modulus of the ground (MPa); ν is Poisson's ratio of the ground; R is the tunnel radius (m); β is the dimensionless factor, β could be known as a function depending on factors such as: the grounds elastic modulus, the elastic modulus of the tunnel lining, the thickness of the tunnel lining. In this study, β=2; η_s is the tangential stiffness of the ground.

$$p_{n,\lim} = \frac{2c * \cos\omega}{1-\sin\omega} + \frac{1+\sin\omega}{1-\sin\omega} * \Delta\sigma_{\text{conf}} \tag{10}$$

$$\Delta\delta_{conf} = \frac{\sigma_h + \sigma_v}{2} * \frac{\nu_s}{1-\nu_s} \tag{11}$$

The maximum shear reaction pressure was determined:

$$p_{s,\lim} = \frac{\sigma_h + \sigma_v}{2} * tg\omega \tag{12}$$

$$\sigma_h = K_0 * \sigma_v \tag{13}$$

$$k_{n,i} = \frac{p_{n,\lim}}{\delta_{n,i}} * \left(1 - \frac{p_{n,\lim}}{p_{n,\lim} + \eta_{n,0}.\delta_{n,i}}\right) * \frac{(L_{i-1} + L_i)}{2} \tag{14}$$

$$k_{s,i} = \frac{p_{s,\lim}}{\delta_{s,i}} * \left(1 - \frac{p_{s,\lim}}{p_{s,\lim} + \eta_{s,0}.\delta_{s,i}}\right) * \frac{(L_{i-1} + L_i)}{2} \tag{15}$$

$$\tau = \gamma_c * G \tag{16}$$

where G is the shear modulus of the ground (MPa); τ is shear stress (MPa) and γ_c is shear strain (%); σ_v and σ_h are the respectively vertical and horizontal loads effect to the tunnel lining (MPa); K_0 is the lateral earth pressure coefficient; $k_{n,i}$ and $k_{s,i}$ are the stiffnesses of each spring in the ground interaction with the tunnel lining [15-19].

The HRM method has been improved [7] when using the HRM method to calculate and design for the U-tunnel, the continuous tunnel lining and effected by earthquakes. The cross-section of the U-tunnel is now divided into five regions. Each region is determined by the centre corners of the cross-section tunnel as shown in Figure 3, when dividing the tunnel lining into 360 elements, each element that has been determined by a corresponding angle ϕ=1 degree at the point centre of the cross-section tunnel. According to Nguyen et al., (2020) [7], the length of each element of the tunnel lining will be changed according to the respective angle φ, that had been made by the vertical line and the location of the element on the tunnel lining, rotate counter-clockwise.

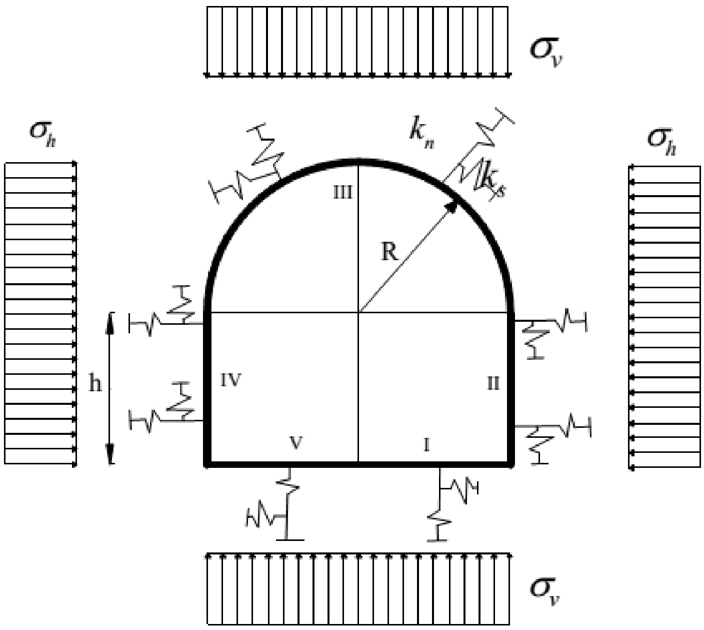

Fig. 3. Calculation diagram of tunnel lining with the HRM method in case the U-shaped tunnel lining σ_v -vertical load in the model tunnel–surrounding soil; σ_h -horizontal load in the model tunnel–surrounding soil; k_n -normal stiffness of the interaction springs; k_s -tangential stiffness of the interaction springs; *R*-tunnel radius; *EJ* and *EA*-bending and normal stiffness of the tunnel lining.

In the region I, the length of elements, when $0^0 \le \varphi \le arctang(\frac{R}{h})-1$:

$$L_1 = h*\left[\text{tang}\left(\frac{3.1415*\varphi}{180}+\phi\right)-\text{tang}\left(\frac{3.1415*\varphi}{180}\right)\right] \quad (17)$$

In the region II, the length of elements in the region II, $arctang(\frac{R}{h}) \le \varphi \le 90^0$:

$$L_2 = R*\left[\text{tang}\left(\frac{3.1415*(90-\varphi)}{180}\right)-\text{tang}\left(\frac{3.1415*(90-\varphi)}{180}-\phi\right)\right] \quad (18)$$

In the region III, the length of elements in the region III, when $90^0 \le \varphi \le 269^0$:

$$L_3 = 2*R*\sin\left(\frac{\phi}{2}\right) \quad (19)$$

In the region IV, the length of elements in the region IV is determined by the equation, when $270^0 \le \varphi \le 270^0 + arctang(\frac{h}{R})$:

$$L_4 = R*\left[\text{tang}\left(\frac{3.1415*(\varphi-270)}{180}+\phi\right)-\text{tang}\left(\frac{3.1415*(\varphi-270)}{180}\right)\right] \quad (20)$$

In the region V, $270^0 + arctang(\frac{h}{R}) \le \varphi \le 359^0$, the length of elements:

$$L_5 = h*\left[\text{tang}\left(\frac{3.1415*(360-\varphi)}{180}\right)-\text{tang}\left(\frac{3.1415*(360-\varphi)}{180}-\phi\right)\right] \quad (21)$$

where *R* is the radius of the dome; *h* is the length of the column of the tunnel.

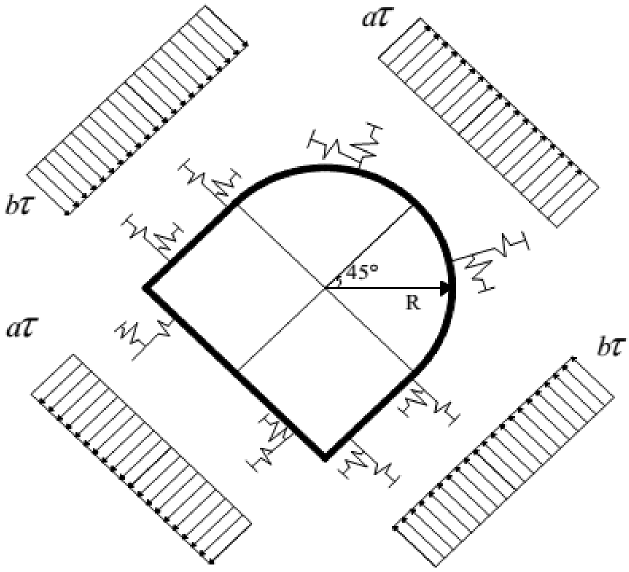

Fig. 4. The external load applied to the tunnel under the effect of earthquakes in the HRM method in case the U-shaped tunnel.

In case the tunnel is affected by an earthquake, as in case the static load diagram on the tunnel lining but the horizontal load components are in opposite direction, the external loads have the impact to tunnel lining are rotated counter-clockwise 45^0. Parameters in the equations for determining the diagram of the load acting on the tunnel under the impact of an earthquake are: The parameter "*b*" = 5, the parameter "*a*" depends on the tunnel radius R-the circular tunnel cross-section has the equivalent area than the area of the U-shaped tunnel cross-section and can be defined using the following the equation [7]:

$$a = -0.7\ln(R) + 0.885 \tag{22}$$

2.2 The HRM method for the U-shaped segmental tunnel lining

In this paper, the author used the formulas to calculate the fixity factor of joints in the segmental tunnel lining r_j (which is used extensively in semi-rigid frame analysis and determined at each link node of the tunnel lining element), which could describe the working of the segmental tunnel lining [4] to improve the HRM method in case of the HRM method has been used to calculate the U-shaped segmental tunnel lining under the impact of an earthquake.

$$r_j = \frac{1}{1 + \frac{3E_s J_s}{K_{RO} L_i}} \tag{23}$$

The joints can work between two cases: joints are a pinned link with fixity factor $r_j = 0$ and a fully rigid connection is unity with the fixity factor $r_j = 1$. The joints are considered semi-rigid links with a fixity factor of between zero and unity ($0 < r_j < 1$).

Working of joints in the segmental tunnel lining is shown in the equation:

$$K_i^{SR} = z_i * C_i \tag{24}$$

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$$C_i = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{4r_2 - 2r_1 + r_1 r_2}{4 - r_1 r_2} & \frac{-2L_i r_1 (1 - r_2)}{4 - r_1 r_2} & 0 & 0 & 0 \\ 0 & \frac{6(r_1 - r_2)}{L_i (4 - r_1 r_2)} & \frac{3r_1 (2 - r_2)}{4 - r_1 r_2} & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{4r_1 - 2r_2 + r_1 r_2}{4 - r_1 r_2} & \frac{2L_i r_2 (1 - r_1)}{4 - r_1 r_2} \\ 0 & 0 & 0 & 0 & \frac{6(r_1 - r_2)}{L_i (4 - r_1 r_2)} & \frac{3r_2 (2 - r_1)}{4 - r_1 r_2} \end{bmatrix} \quad (25)$$

where K_i^{SR} is the stiffness matrix of member "*i*"; L_i is the length of the element "*i"*; C_i is the stiffness matrix of the element "*i*" was represented by a semi-rigid correction matrix; rotational stiffness modulus at two ends of the element K_{RO1} and K_{RO2}.

It should be noted that, in the calculation of the U-shaped segmental tunnel lining, due to the change in the length of the elements of the tunnel lining, the fixity factor of joints in the tunnel lining is also changed.

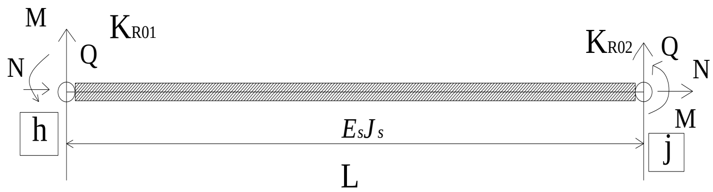

Fig. 5. The beam-type finite element in the tunnel lining with reference to the local Cartesian coordinates.

3. A case study: calculation for the tunnel lining from Hanoi metro system

3.1 Characteristics of earthquakes, soil and tunnel in Hanoi metro system

The hydrogeological and geological conditions of the Hanoi center are as follows in Table 1. In the Hanoi center, the groundwater level is three meters below the surface.

Tab. 1. The properties of the ground in Hanoi center [7, 17].

Number of soil layers	Elastic module of soil, *E*, MPa	Poisson's ratio of soil, μ	Thickness of soil layer (d), 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

The parameters of the tunnel in the Hanoi metro system are shown in Table 2: the tunnel has a depth of between 15 and 20 m below the ground surface. The U-shaped tunnel with the size is shown in Figure 7, the radius of the dome *R* with the length of the column-wall *h*, *R*=*h*=2.95m. The tunnel lining is reinforced concrete with properties in Table 2. In the case of the segmental tunnel lining with joints. Arrange 6 joints

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at the positions at the reference angle is 0^0, 60^0, 120^0, 180^0, 240^0, 300^0 (the reference angle is 0 degrees to the horizontal).

The strongest earthquakes that can occur in the Hanoi center have properties [7, 20]: highest magnitude M_W=6.5 Richter; distance from the epicenter of the earthquake to Hanoi is 20 km to 50 km and peak ground acceleration amax = 0.2g. In this method, using data of El Centro earthquake (Fig. 7).

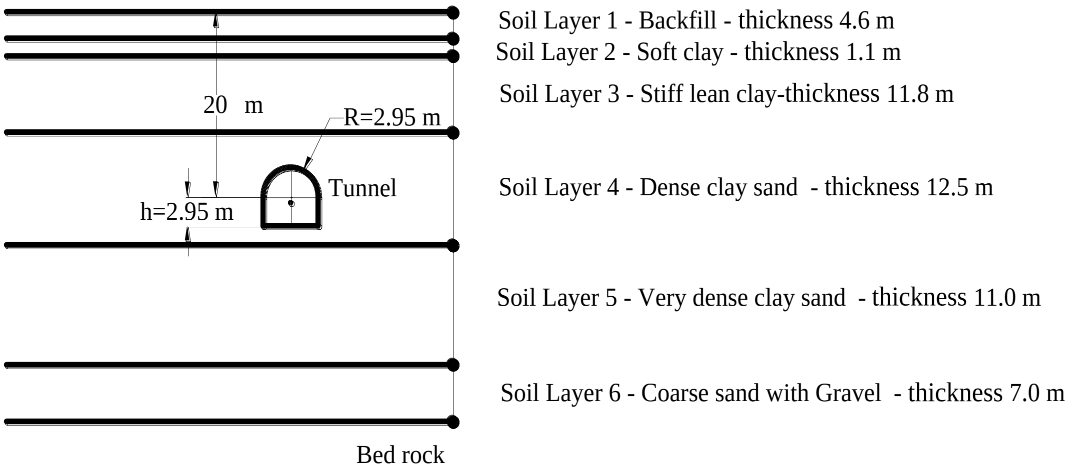

Fig. 6. Parameters of ground and tunnel.

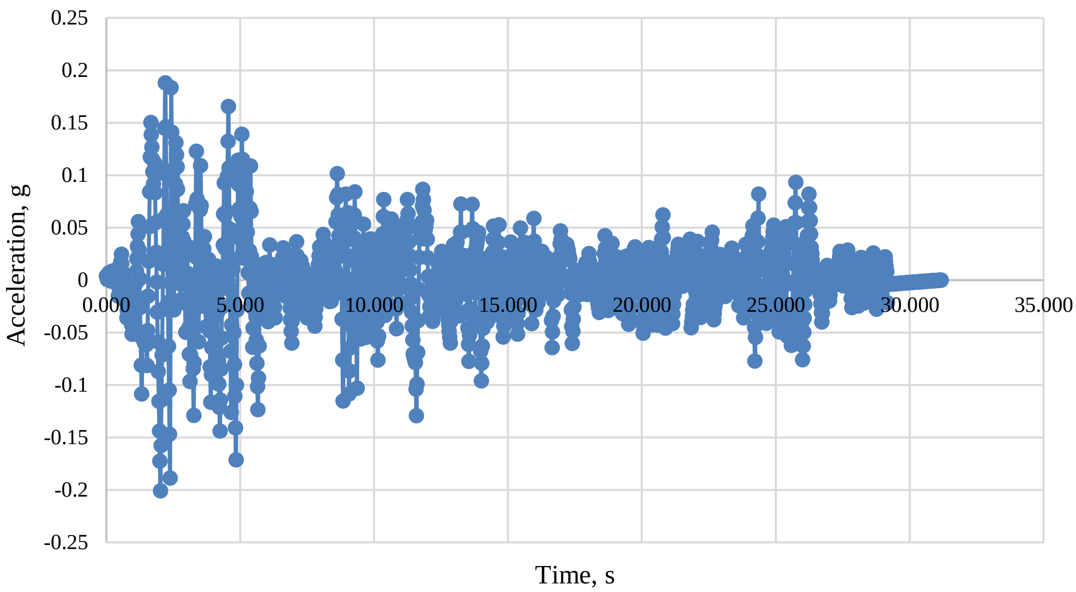

Fig. 7. Data of El Centro earthquake [21, 22, 23, 24, 25].

Tab. 2. The parameters of the tunnel lining [7].

Young's modulus E_l	MPa	35500
Poisson's ratio v_l	-	0.15
Lining thickness t	m	0.35
Overburden H	m	20
The radius of the dome R	m	2.95
The length of the column-wall h	m	2.95

3.2 Results and Discussions

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In the case of the continuous tunnel lining, the finite element method Abaqus^{2D} (FEM) and the HRM method are used to calculate for the tunnel from Hanoi metro system in Hanoi central. In HRM method and FEM, there is no influence of the groundwater on the tunnel model. The tunnel lining and the surrounding ground are considered to be an environment elastic, homogeneous, and isotropic. The characteristics of surrounding ground: $E = 37.75$ MPa, Poisson's ratio $\nu = 0.34$.

Phases of the construction process of the tunnel and soil in the FEM:

Phase 1 - Set up the model: setting up the model and assigning boundary conditions and the initial stress state. There is no reflection wave at the boundary of the model (using the CINPE4 infinite elements);

Phase 2 - Excavation tunnel: The excavated ground inside the tunnel boundary is deactivated. It should be mentioned that there is not influence of the groundwater on the tunnel model and the soil. All the external loads caused by the soil were applied to the tunnel lining in order to consider the worst case of tunnel lining stress.

Phase 3 - Installation of the tunnel lining: the tunnel lining is activated on the tunnel boundary (the continuous tunnel lining). Set up to the peak ground acceleration of the earthquake in the model;

Phase 4 - Run the model with conditions established in the above phases and obtain the results.

Table 3, and Figures 9, 10, 11, 12 indicate small differences for the maximum stress, the maximum bending moment and maximum displacement in the tunnel lining obtained by the HRM method and the FEM (Abaqus^{2D}). The HRM method gives the maximum stress which is 7.415% smaller than those of the FEM (Abaqus^{2D} model). The differences of the maximum bending moment and maximum displacement in HRM method are 5.84% and 2.513%. These differences are not big.

Tab. 3. Analysis results of different methods for the U-shaped continuous tunnel lining.

The internal forces in tunnel lining	HRM	The FEM (reference case)
M_{max} (kN.m/m)	273.60	289.6
σ_{max} (MPa)	14.821	15.92
Maximum displacement of the tunnel lining	5.365	5.39
% difference with the reference case		
ΔM	5.84	-
$\Delta\sigma$	7.415	-
Δd	2.513	-

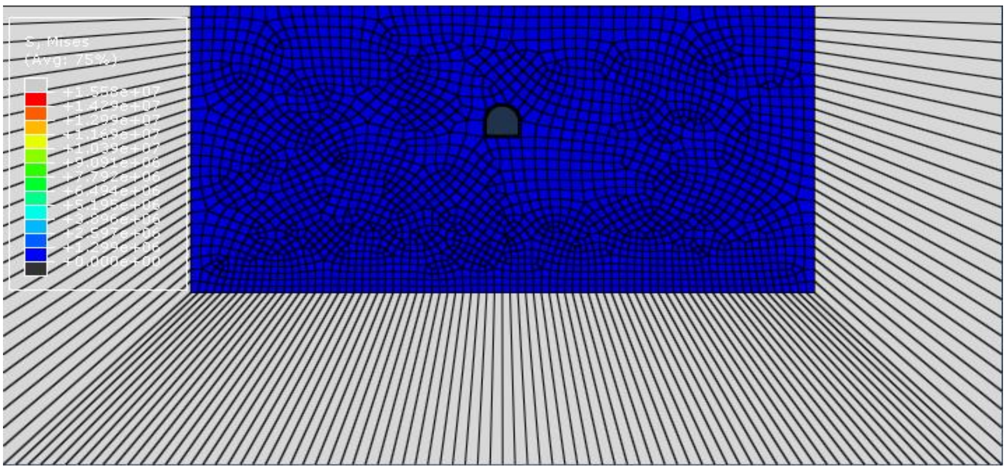

Fig. 8. Model the U-tunnel continuous lining by the FEM.

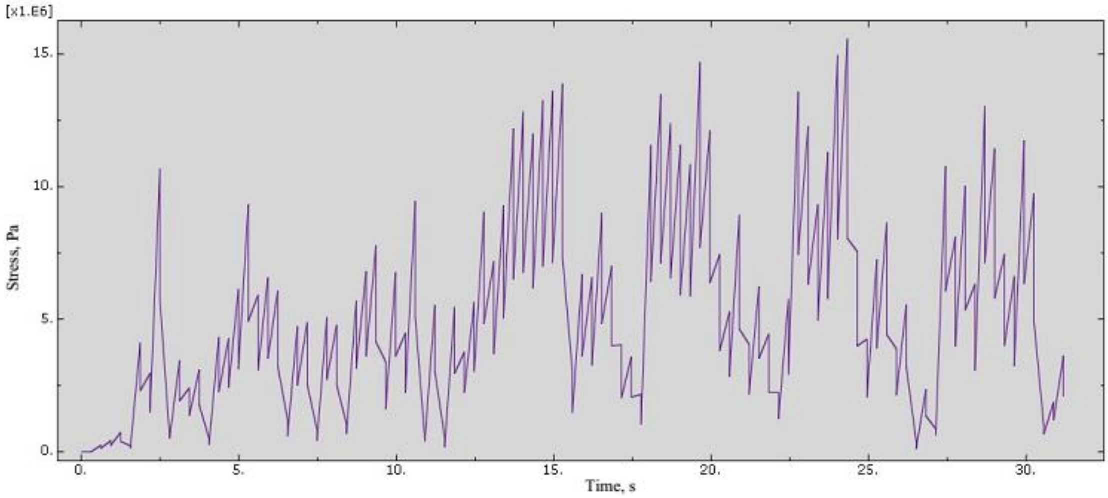

Fig. 9. State stress on the one point in the U-tunnel continuous lining by the FEM.

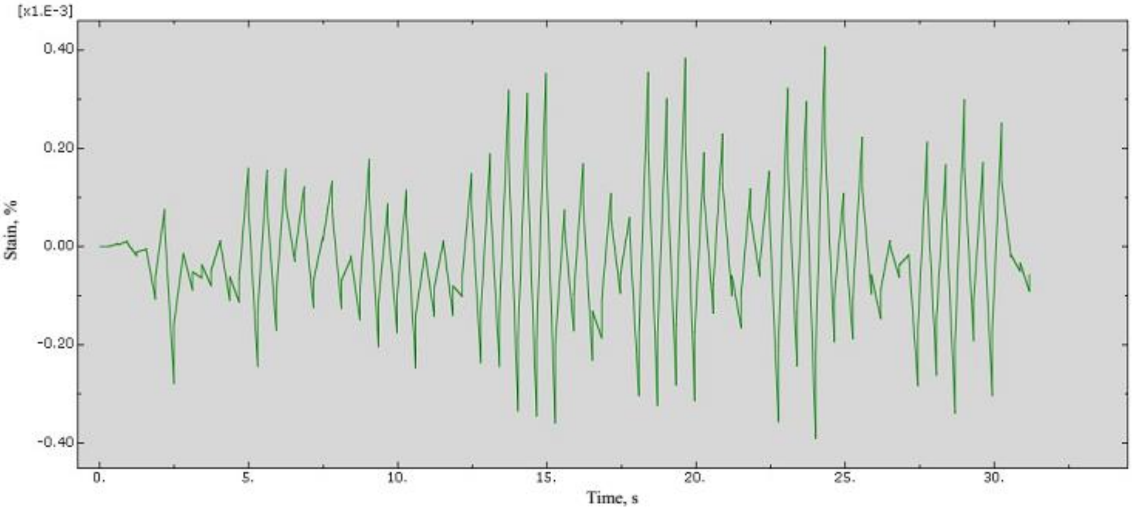

Fig. 10. Strain of the one point in the U-tunnel continuous lining by the FEM.

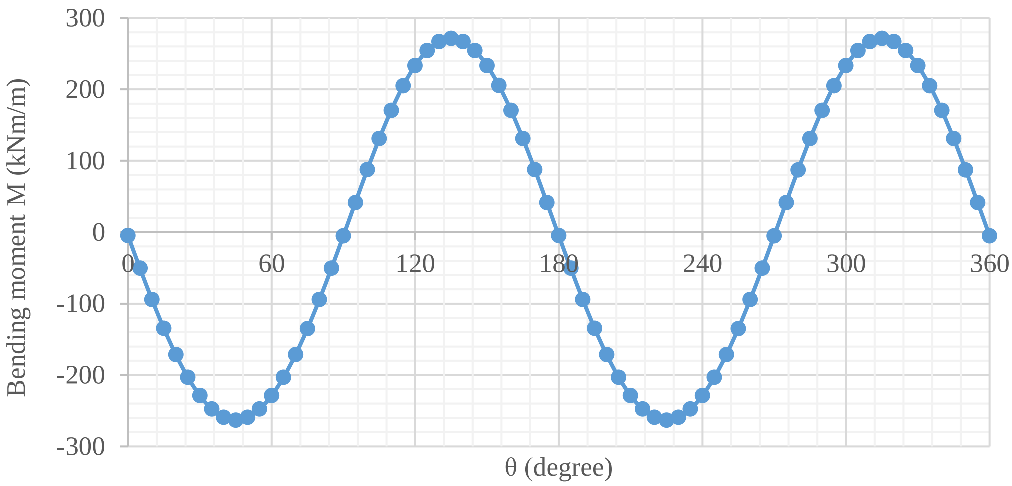

Fig. 11. Bending moment M in the tunnel lining by HRM method in case of the U-tunnel continuous lining.

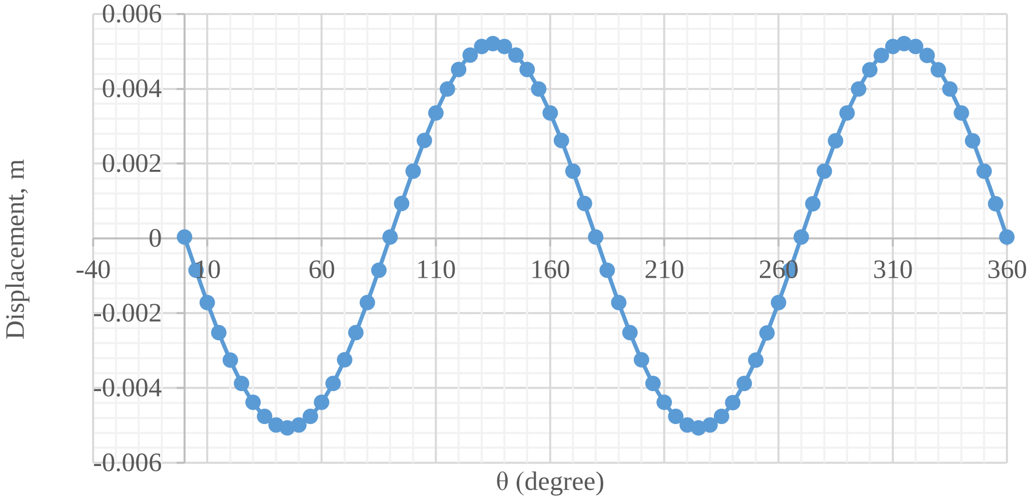

Fig. 12. Displacement of the tunnel lining by HRM method in case of the U-tunnel continuous lining.

In case the segmental tunnel lining with joints, using the HRM method to calculate the tunnel of the Hanoi metro system when the tunnel under the effect of the strongest earthquake that may occur in Hanoi centre. In the tunnel lining cross-section, 6 joints were evenly distributed, and the tunnel lining cross-section is made up of 6 segments that were distributed evenly along the tunnel border. The joints of the tunnel lining these are located at angles of 0°, 60°, 120°, 180°, 240° and 300°, measured counter-clockwise from the spring line on the right. These results are shown in Table 4, and Figures 13, 14, 15, 16.

Tab. 4. Analysis results in case the U-shaped segmental tunnel lining.

The internal forces in the tunnel lining	The continuous lining (reference case)	The segmental tunnel lining			
		λ=1.5	λ =1	λ =0.5	λ =0.25
M- Maximum bending moment (kN.m/m)	273.60	256.90	251.20	238.0	220.90
% difference with the reference case -M	-	6.104	8.187	13.011	19.261
T-Maximum normal force (kN/m)	465.28	462.40	461.70	460.0	457.60
% difference with the reference case -T	-	0.619	0.769	1.134	1.65
σ -Stress (MPa)	14.821	13.904	13.623	12.971	12.127
% difference with the reference case -σ	-	6.187	8.083	12.482	18.176
d- Maximum displacement, (mm)	5.932	7.699	8.935	12.422	18.765
% difference with the reference case -d	-	29.787	50.623	109.41	216.355

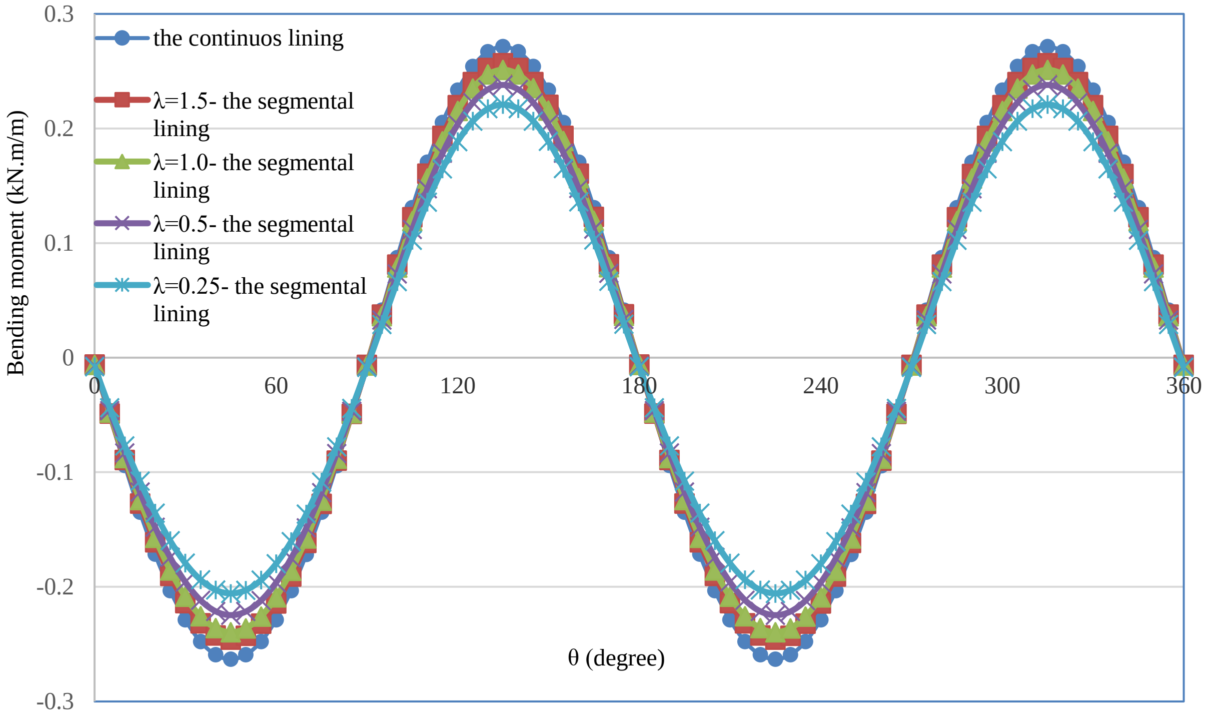

Fig. 13. Bending moment M in the U-shaped segmental tunnel lining by the HRM method.

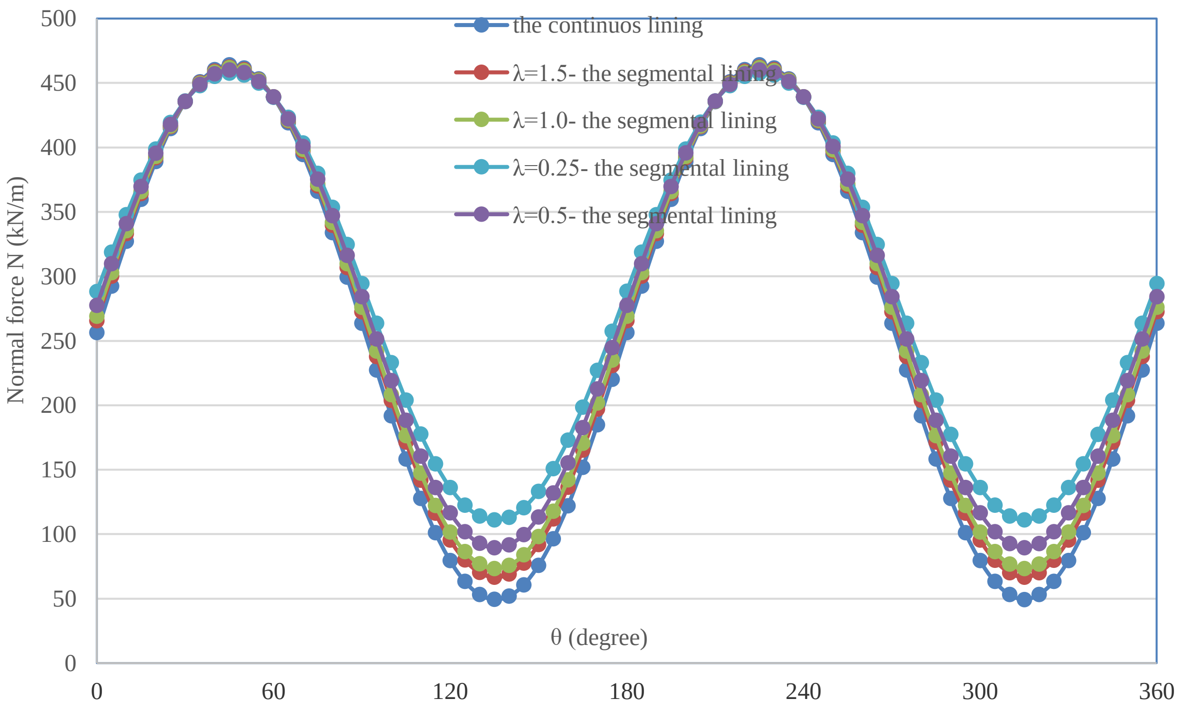

Fig. 14. Normal force in the U-shaped segmental tunnel lining by the HRM method.

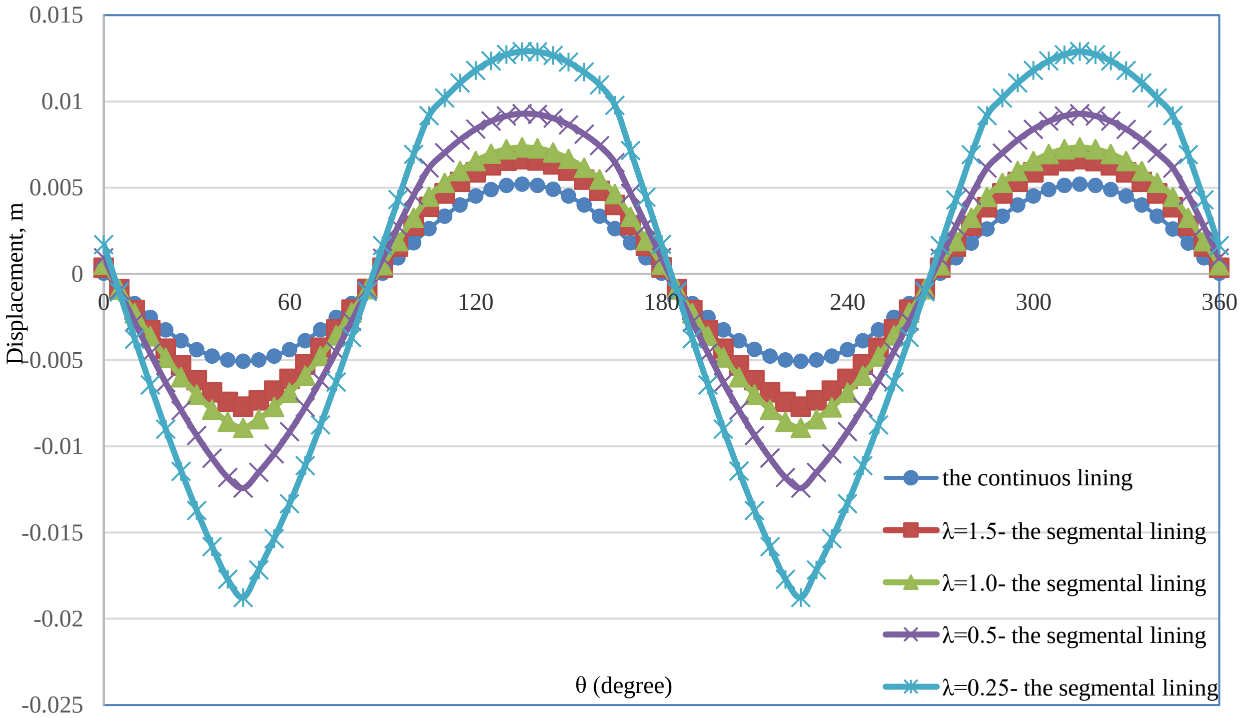

Fig. 15. Displacement of the U-shaped segmental tunnel lining by the HRM method.

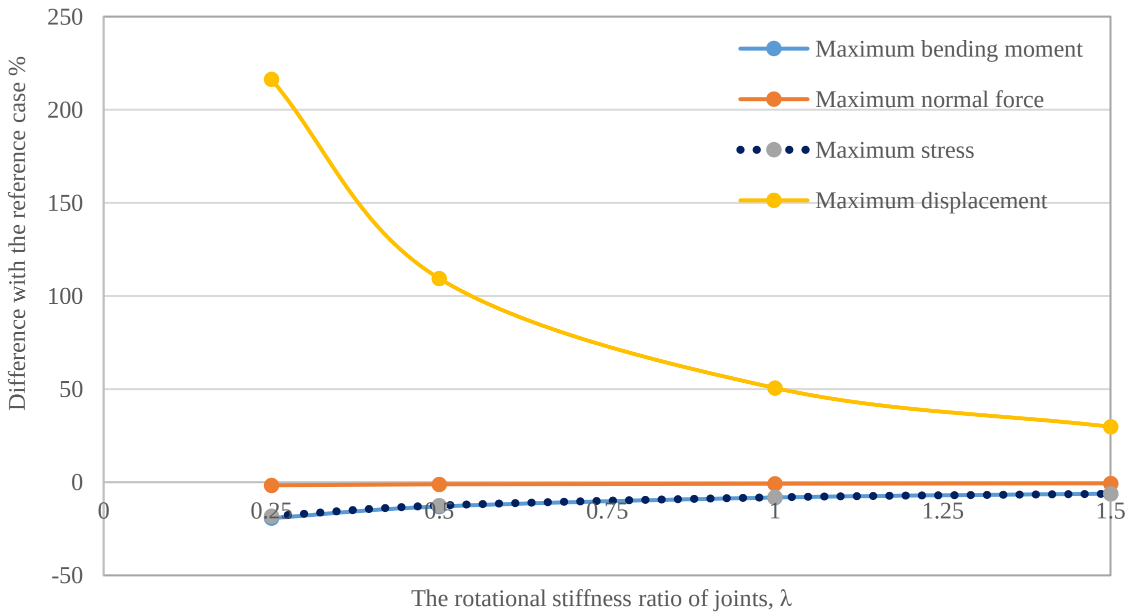

Fig. 16. Effect of the rotational stiffness ratio of joints on the internal forces and displacements on the U-shaped segmental tunnel lining.

The results in the case of the continuous tunnel lining are reference values. When the rotational stiffness ratio of joints has a value λ=1.5, the maximum bending moment in the tunnel lining with the reference case is 6.104%, smaller, the maximum normal force with the reference case is smaller 0.619% and the absolute maximum displacement with the reference case is 29.787%, bigger.

When the rotational stiffness ratio of the joints has a value λ=1.0, the maximum bending moment in the tunnel lining with the reference case is 8.187%, smaller, the maximum normal force with the reference case is smaller 0.769% and the absolute maximum displacement with the reference case is bigger 50.623%.

With the rotational stiffness ratio of the joints has a value $\lambda = 0.5$, the maximum bending moment in the tunnel lining with the reference case is 13.011%, smaller, the maximum normal force with the reference case is smaller 1.134% and the absolute maximum displacement with the reference case is bigger 109.41%.

When the rotational stiffness ratio of the joints has a value $\lambda = 0.25$, the maximum bending moment in the tunnel lining with the reference case is 19.261%, smaller, the maximum normal force with the reference case is smaller 1.65% and the absolute maximum displacement with the reference case is 216.355%, bigger.

On the basis of the above analysis, it is reasonable to conclude that:

- The internal force and the displacement of the tunnel lining when the tunnel is effected by the earthquakes depend on the rotational stiffness ratio of the joints in the tunnel lining;

- In both cases, the tunnel lining is continuous and the tunnel lining is segmental, the maximum stresses in the tunnel lining under the effect of the strongest earthquake that can occur in the central of Hanoi is less than the limited stress value of material tunnel's (σ_{limit}=22 MPa), so the tunnel could work safely and stable under the influence of the strongest earthquake that can occur in Hanoi center.

4. Conclusions

This study proposed some improvements of the method numerical HRM for designing the U-shaped segmental tunnel lining under the impact of earthquakes. The paper mentioned the influence of the geometrical parameters and mechanical characteristics of the tunnel lining on the content of the HRM method. In the case of the continuous tunnel lining, the internal forces in the tunnel lining under the impact of the strongest earthquake that can occur in the Hanoi center were calculated by using the improved HRM method and the FEM. The difference in results of the two methods is not large and the maximum stress value that occurs in the tunnel lining under the influence of the strongest earthquake is located at the intersection of the column and the dome of the tunnel lining. On the base these results above, it can confirm the accuracy of the HRM method when HRM method was used to design the U-shaped tunnel under the impact of an earthquake with the outstanding advantage of the HRM method: the time calculation is very short (10s to 15s); the input data is simple and easy to access.

In case of the segmental tunnel lining under the effect of the earthquake, the improved HRM method was used to calculate the U-shaped segmental tunnel from the system Hanoi metro. On the basis of the internal forces in the tunnel lining and the displacement of the tunnel lining with the rotational stiffness ratio of joints in the lining respectively, the conclusion that can be drawn is that:

- When joints have a big rotational stiffness ratio, the internal force in the tunnel lining is big and vice versa;

- When joints have a small rotational stiffness ratio, the displacement of the tunnel lining has a value big and vice versa.

This means the rotational stiffness ratio of the joints is directly proportional to the internal force and stress in the lining and inversely proportional to the displacement of the tunnel lining. With the presence of joints, if the tunnel lining has big displacement, the internal forces in the tunnel lining that has value small and vice versa. The presence of joints in the tunnel lining could increase the flexibility of the tunnel lining and could increase the stability of the tunnel under the impact of an earthquake.

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