A NUMERICAL SIMULATION OF THE TUNNEL LINING BEHAVIOUR UNDER THE IMPACT OF HIGH TEMPERATURE DUE TO FIRES

Tran Nam Hung[1,*], Nguyen Thi Thu Nga[1]

[1]*Le Quy Don Technical University*

Abstract

The fires in tunnels can cause high temperature and can seriously affect tunnel structure. Study on the work of tunnel lining under impact of high temperature is a challenge for predicting the safety as well as proposing measures to repair the structures after the fires. This study aims at analysis of stress-strain state in the tunnel lining that subjected to the large changes of temperature due to the fires. The analysis is relied on numerical simulations by finite element method with the assumptions of the plane strain problem for a deep tunnel. The thermo-hydro-mechanical coupling behavior for the lining and the surrounding medium is used in the simulation. The results obtained show that the influence of the high temperature on the stress-strain state of the lining is significant and the region of the lining near tunnel wall can be damaged.

Keywords: *Tunnel lining; fires; thermo-hydro-mechanical behavior; finite element method.*

1. Introduction

The number of fire incidents occurring in tunnels is quite large, even in developed countries where traffic safety and fire safety are given great attention [1, 2]. Although the risk of vehicle accidents in the road tunnel network is often lower than the one on the others, the catastrophe potential related to road tunnel fire is higher [3, 4]. Due to traffic volume increases and more and longer tunnels are being built, the risk of vehicle fires in the tunnels may increase [4]. The zone where occurs fires in the tunnels is an enclosed space that impedes dissipation of heat and smoke as well as restricting access to firefighters [3, 5]. On one hand, fire in the tunnel causes traffic obstruction, threatens human life and assets safety. On the other hand, the impact of high temperatures caused by fire results in damage for structures that affect its bearing capacity and shorten the life of the construction (Figure 1). Studying the effect of the temperature due to the fires on the tunnel structures should be considered in the context of the increasing the number of underground traffic works, especially road and subway tunnels in Vietnam.

[*] Email: tranhung@lqdtu.edu.vn
https://doi.org/10.56651/lqdtu.jst.v3.n01.83.sce

Many studies on the effect of fire temperature on the work of the tunnel lining have been carried out and are mainly based on two main approaches [5-9]. While some works focused on estimation of the operation of tunnel under the influence of temperature based on theoretical calculations [5, 7-9], the others conducted experimental studies on the lining structure in the fire [6]. Numerical calculations primarily refer to the tunnel lining and surrounding medium based on a dry material model under the impact of temperature changes whereas due to expensive costs, experimental studies are often limited by certain conditions of fire temperature and structural materials [6].

In fact, the tunnel lining and surrounding medium are partially or fully saturated materials. Thus, if the tunnel is subjected to the change of temperature, the interaction between mechanical, hydraulic and thermal phenomena will occur. In Vietnam, structural research under the impact of high temperatures, and especially considering the behavior of porous materials according to a thermo-hydro-mechanical coupling model, is still very limited [10]. This paper will be devoted to the study of the effect of the temperature caused by small and average fires on the work of the tunnel lining based on an isotropic thermo-hydro-mechanical behavior.


Figure 1. Concrete thickness of the liner segments of the Channel tunnel (France-England) has been completely expelled after the fire in 1996.

2. Constitutive equations of thermo-hydro-mechanical behavior model of porous medium

A porous material is a medium including 3 phases of solid, liquid and gas in which the void of the medium may be partially or fully saturated. When subjected to mechanical and thermal loadings, its behavior becomes very complicated due to the interaction of the phases. In such a medium, the thermal load induces a strong interstitial thermal pressure that can significantly affect the hydraulic and mechanical responses of the material [11]. Concretely, the thermal stresses generated will combine not only with mechanical stresses but also with stresses due to coupled hydro-thermal phenomena (changes in pore pressure). Indeed, the change in temperature can significantly affect the distribution of pore pressure because of the large volume expansion of the pore fluid. In turn, increasing of pore pressure causes changes of effective stresses as well as heat transfer in the medium. For its part, the effective stresses counteract the pore pressures, fluid and heat transfers, especially liquid transfer. Depending on the permeability of the material, the process of thermal diffusion may be faster or slower than the diffusion of fluid, leading to the behavior of the medium may be governed by a fully or partially thermo-hydro-mechanical coupling [12].

For the purpose of reducing presentation, we do not present here fully the relationships of thermodynamic theory for the thermo-hydro-mechanical behavior model of the material (interested reader could consult for more details in [13]). In this section, we present only some basic equations related to the main parameters of such a model used in the paper.

The effective stress model of Biot for the porous material is used in the present work in which the effective stress is expressed through total stress and pore pressure [13]:

$$\sigma' = \sigma + b.\pi \tag{1}$$

Note that, in this study the conventional sign of solid mechanics is used with positive tensile stress. In equation (1), σ' and σ express the effective and the total stresses respectively; *b* is the Biot coefficient; π is the equivalent pore pressure that is a function of water saturation and fluid pressure in the interstitiel:

$$\pi = \begin{cases} \int_{S_w}^{1} S_w(p_c)dp_c & \text{if} \quad S_w < 1 \\ p_w & \text{if} \quad S_w = 1 \end{cases} \tag{2}$$

where p_c is the capillary pressure and p_w is the water pore pressure. The capillary pressure related to the water pore and gas pressures p_g by the following relationship:

$$p_c = p_g - p_w \tag{3}$$

The water saturation plays an important role in describing hydro-mechanical behavior. According to Van Genuchten (1980), the water retention curve $S_w(p_c)$ depends on two parameters (P_r and n) according to the equation:

$$S_{\mathrm{w}}\left(p_c\right)=\left[1+(p_c/P_r)^n\right]^{(1-n)/n} \tag{4}$$

For a given relative humidity *RH*, the capillary pressure is evaluated from Kelvin's law assuming perfect gases:

$$p_c=\frac{\rho_w.R.T}{M_w^{ol}}\ln(RH) \tag{5}$$

where R, ρ_w, M_w^{ol} are respectively the constant of perfect gases, the unit weight and molar mass of water.

During the process of heat transfer in the porous medium, its porosity φ varies according to the following relationship:

$$d\varphi=\left(b-\varphi\right)\left(d\varepsilon_V-3\alpha_0 dT+\frac{dp_{gz}-S_w dp_c}{K_s}\right) \tag{6}$$

where $d\varepsilon_V$ is the change of volumetric strain, α_0 is the coefficient of thermal expansion of the porous medium, dT is the change in temperature and K_s is the bulk modulus of the solid phase. One has the relationship between the Biot coefficient, bulk modulus of the solid phase and the drainage bulk modulus of the porous material K_0 as follows:

$$b=1-K_0/K_s \tag{7}$$

It can be seen that, the effective stress defined by Terzaghi will be obtained, corresponding to b = 1, is a special case of Biot effective stress when $K_0=K_s$.

The Fourrier equation for heat transfer in 3-dimensional Cartesian coordinate system is:

$$\lambda^T\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)=\rho_0 C_P\frac{\partial T}{\partial t} \tag{8}$$

In equation (8), λ^T, ρ_0 and C_P, respectively, are the thermal diffusion coefficient, unit weight and specific heat capacity of the porous material. Within the framework of a coupled thermal-hydro-mechanical model, the coefficient of heat diffusion λ^T is evaluated by the expression:

$$\lambda^T=\left(1-\varphi\right)\lambda_{\mathrm{s}}^T+\varphi S_{\mathrm{w}}\lambda_{\mathrm{w}}^T \tag{9}$$

in which λ_{s}^T, λ_{w}^T denote respectively diffusion coefficients of solid and liquid phases that depend on the temperature.

Darcy fluid diffusion equation in Cartesian 3-tridimentional coordinate system is written:

$$\lambda_{w}^{H}\left(\frac{\partial^{2} p_{w}}{\partial x^{2}}+\frac{\partial^{2} p_{w}}{\partial y^{2}}+\frac{\partial^{2} p_{w}}{\partial z^{2}}\right)=\rho_{w} \frac{\partial \xi}{\partial t} \tag{10}$$

where ξ is the change of fluid volume per unit volume of the porous material. The diffusion coefficient of the liquid is determined from the formula:

$$\lambda_{w}^{H}=\frac{K^{\text{int}}(\varphi) k_{w}^{rel}\left(S_{w}\right)}{\mu_{w}(T)} \tag{11}$$

in which K^{int} being intrinsic permeability that is one of characteristics of the porous medium and being a function of the porosity; μ_{w} being the dynamic viscosity of water and depends on the temperature; k_{w}^{rel} being the relative permeability of water and depends on water saturation S_{w}.

One has the relationship between diffusion coefficient and water permeability coefficient k_w below:

$$k_{w}=\lambda_{w}^{H} / \rho_{w} g \tag{12}$$

where g is gravitational acceleration.

3. Numerical simulation of the tunnel under high temperature loading

Let us consider a circular tunnel at depth of 500 m excavated in a saturated clay stone formation with the radius of r_0 = 3,5 m. The tunnel lining with the thickness of 0,5 m is composed by concrete B60. The calculation parameters of the lining are given in Table 1. The properties of the rock mass are chosen as in [14]. The initial stress field with vertical and horizontal components are $\sigma_v = \sigma_h$ = -12,5 MPa.

The numerical solution is based on finite element method and implemented on Code_Aster software. This is an open source code for numerical simulation in structural mechanics, developed mainly by research and development department of Electricity of France (EDF). Code_Aster is a powerful software in simulating multi-physical phenomena including the coupled thermo-hydro-mechanical behavior.

It is assumed that the problem satisfies the conditions of plane strain, i.e., the length of the fire along the tunnel is large enough. The evolution of the tunnel excavation and installation of the lining are numerically simulated relied on the convergence-confinement method proposed by Panet [15]. Assuming that the lining is installed at the tunnel face corresponding to the rate of stress release (λ) reaches 50%. Henceforth, the lining and rock mass work simultaneously. The numerical calculation procedures are carried out so that at the beginning of the lining installation, the displacement of the lining is zero. In the model, we use the 8-point quadrilateral finite element with 4 corner nodes for degrees of freedom of displacement and 4 midpoint nodes of the edges for degrees of freedom of pore pressure and temperature. Assuming also that the temperature is imposed uniformly along the tunnel wall circumference. Because of the symmetry of the model through tunnel axis, only a quarter one is used in the simulation. The geometry model and boundary conditions are illustrated in Figure 2a in which Φ_h and Φ_T denote respectively hydraulic flux and thermal flux.

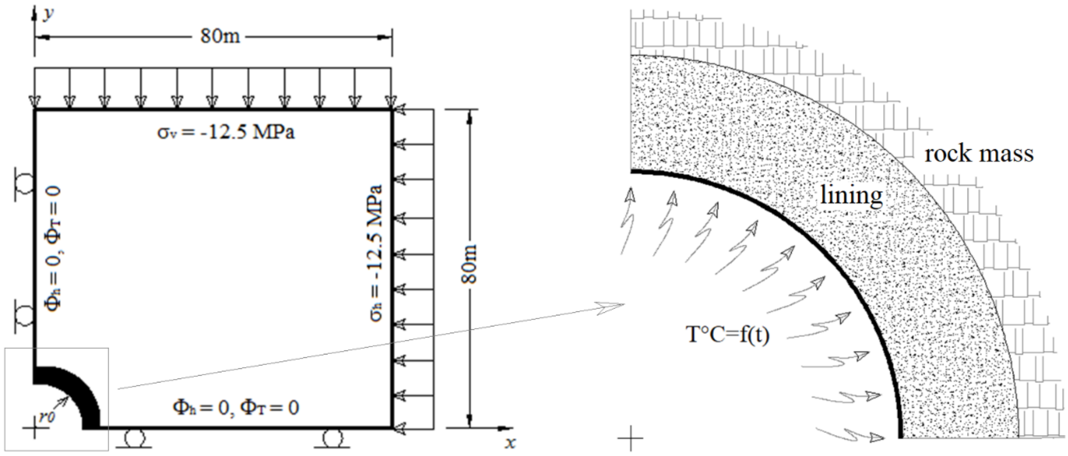


Figure 2. Geometry model and boundary conditions of the tunnel used in numerical simulation (a), and temperature acting on the tunnel wall (b).

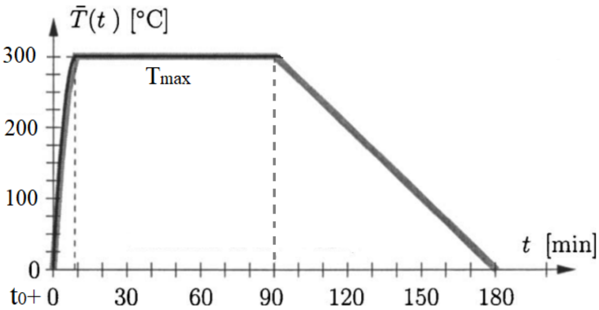


Figure 3. Evolution of temperature imposed on the tunnel wall, assuming t_0 is the beginning instant for heating the tunnel wall.

Several studies showed that, when occurring fires in the tunnel the temperature increases very quickly. In many cases, the temperatures can reach over 1000°C in just few minutes [6-9]. However, concrete is a material with mechanical properties that change much at high temperatures. According to [16], when the temperature is over 400°C, the physio-mechanical properties of the concrete change significantly. Therefore, simulation of the work of the concrete at high temperatures is very complicated. In present paper, we only study the behavior of the concrete lining subjected to low-average temperatures, around 300°C. With respect to such temperature, for the sake of simplicity, one supposes that the behavior of the concrete is still in the limit of linear elasticity. Fig. 3 describes the temperature function acting on the tunnel wall.

In fact, the concrete is often partially saturated by water. In this study, the saturation degree of the concrete is taken as 60%.

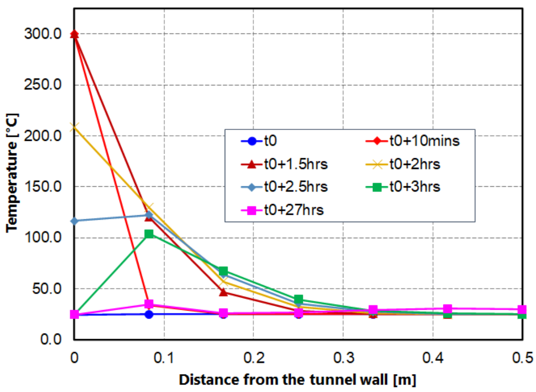
Table 1. Calculation parameters of the lining concrete

Parameters		**Symbol**	**Unit**	**Concrete B60**
Mechanical	Compressive strength	*Rc*	MPa	60
	Young modulus	E_0	MPa	40000
	Poisson coefficient	ν		0,25
Water transfer	Permeability	*K*	m^2	$1{,}0\times10^{-18}$
	Porosity	*f*	%	15
Heat transfer	Heat diffusion coefficient	λ	$W.m^{-1}.K^{-1}$	2
	Specific heat capacity	*Cp*	$J.kg^{-1}.K^{-1}$	1043
Thermo-hydro-mechanical properties	Biot coefficient	*b*	-	0.8
	Thermal expansion coefficient	*a*	K^{-1}	$2{,}6\times10^{-5}$
	Water retention curve (Van-Genuchten)	*Pr*	MPa	2
		m	-	$m = 1\text{-}1/n$
		n	-	1,54

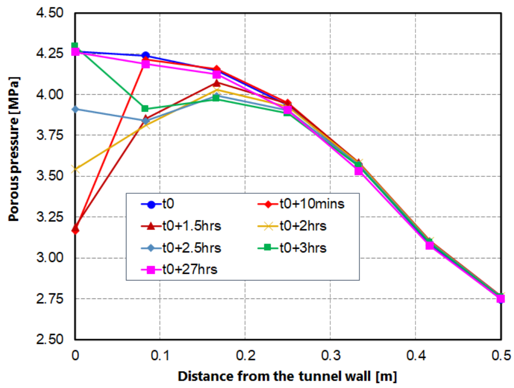
4. Results and disscusion

Figure 4a shows the temperature in the lining over time with t_0 being the beginning instant of heating the tunnel wall. It can be seen that, the temperature in the vicinity of the wall increases rapidly according to the one on the wall. Furthers, the high temperature only appears in the range of the 0,15m from the wall where the highest one reaches around 75°C. Beyond this zone one can consider the concrete working at normal temperature.

Figure 4b shows that the capillary pressure always appears (here is the pore pressure with positive sign) because of the unsaturated state of the concrete. At the distance of 0,18 m from the wall, the capillary pressures are always maintained at large values (around 4,0 MPa). This is most likely due to the influence of both mechanical and thermal phenomena on the hydraulic phenomenon in contrast to the vicinity of the tunnel wall where large oscillations of capillary pressure and thermal one are observed, and the rest region of the lining where there is not much influence of the temperature.



a)



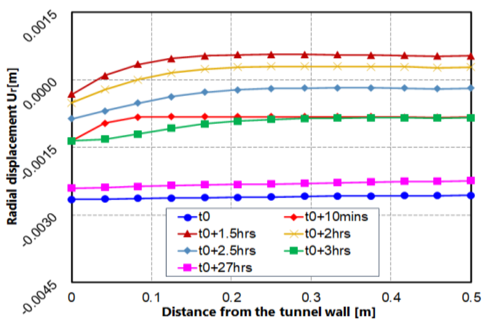
b)

Figure 4. Temperature (a) and pore pressure (b) in the tunnel lining at instants: t_0, t_0+10 minutes, t_0+1,5 hours, t_0+2 hours, t_0+2,5 hours, t_0+3 hours and t_0+27 hours.

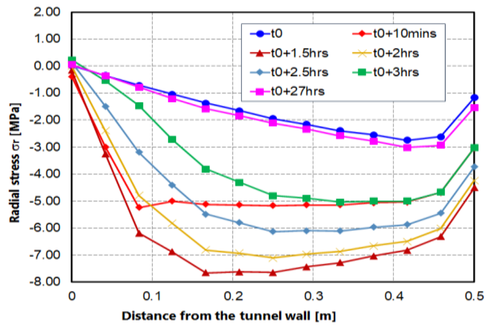
Figure 5 shows the displacements and stresses in the tunnel lining. Figure 5a shows radial displacement while Figures 5b, 5c and 5d show radial stress, tangential stress and longitudinal stress.

Figure 5a indicates that, at the instant t_0, due to the loading transported from the rock mass the lining displaces towards the tunnel center, i.e., the radial displacement of the lining take the maximum negative value (according to the sign convention in this work). When the temperature increases, the lining displaces away from the tunnel center. This is explained by the thermal expansion of the lining with respect to the heat source (tunnel center-line).

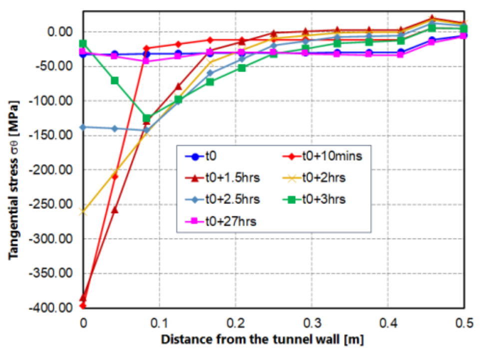
Figures 5b, 5c, 5d show that the stresses increase with the rising of temperature and vice versa. This is because as the temperature increases, thermal deformation causes thermal stress, and the pore pressures (including pore water pressure and capillary pressure) impact on the solid phase which promotes increasing of effective stresses. The large value of radial stress is observed in the zone around 0,2 m from the tunnel wall. The tangential and longitudinal stresses take as the highest values on the tunnel wall (approximately 400 MPa). In comparison with the radial stresses, the tangential and longitudinal stresses are much greater and they exceed greatly the compressive strength of concrete. Observating the value of pore pressure (Fig. 4b), it does not exceed 4,5 MPa while the tangential and longitudinal stresses can reach hundreds MPa at the highest temperature. This proves that the influence of hydraulic phenomena on these stresses is not much, but mainly from thermal one. Indeed, under the influence of high temperature the concrete expands. However, due to the characteristic of the tunnel structure, the length is much greater compared to the width and height, so this expansion is restricted in longitudinal direction. Furthermore, the tunnel lining is donut in shape, so it is also restricted in the tangential (ortho-radial) deformation. Since these reasons, the stresses in these two directions are very large. We also conducted simulations with lower temperature levels, for example, with T_{max} = 200°C and 250°C, one obtained also these stress values greater than the compressive strength of concrete. This phenomenon occurs not only for tunnel lining but also for some other structures that are restricted by deformation under high temperature.



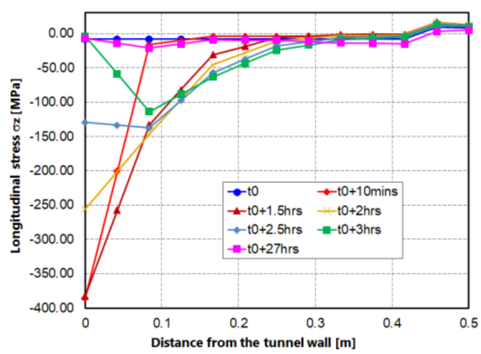
a)



b)



c)



d)

Figure 5. Stress and displacement in the tunnel lining:
radial stress (a); radial stress (b); tangential stress (c); and longitudinal stress (d).

Figures 5c and 5d indicate that the zone of the lining around the 0,2m from the tunnel wall can be damaged by longitudial and tangential stresses. This conforms with the results of Mindeguia [16]. Practical observations show that the lining concrete after the fire is often damaged in the form of breakage.

5. Conclusions

The present paper conducted the numerical simulations for lined circular tunnel at depth under high temperature due to the fires. The thermo-hydro-mechanical coupling behavior for plane strain model is used. Based on the results obtained, some comments could be proposed:

- With respect to the average fire where the maximum temperature about 300°C as in this study, heat flux transfers from the tunnel wall to inside and maintained it at high temparature at the depth of 0,15 m.

- Subjected to the effect of temperature load, the stress - strain state in the tunnel lining changes significally. Particularly, the compressive longitudinal stress and the tangential stress of the lining increase greatly and exceed the compressive strength of concrete. The region from the tunnel wall to a depth of about 0,2 m can be damaged by these stress. Although only numerical simulations with specific assumed conditions, the results illustrated the thermal stress field in the lining and its evolution mechanism. This can help in evaluation of the operation safety as well as in the decision to repair the lining structure after fires.

- Multi-physical thermal-hydro-mechanical model can be used to simulate the behavior of concrete under high temperature.

- The extension of this work to introduce a 3D model with different temperatue levels and geometry conditions as well as considering the nonlinearity of concrete at high temperature will be right perspective.

Acknowledgements

This research was funded by National Foundation for Science and Technology Development (NAFOSTED), Vietnam under grant number 107.01-2017.307. The authors wish to thank the editors and two anonymous reviewers for their constructive comments on earlier versions of this article.

References

1. Beard, A., and Carvel, R. (2005). *The handbook of tunnel fire safety*, Thomas Telford, London.
2. Nævestad, T., Meyer, S. (2014). A survey of vehicle fires in Norwegian road tunnels 2008-2011. *Tunn. Undergr. Space Technol., 41*(2), pp. 104-112.
3. Mashimo, H. (2002). State of the road tunnel safety technology in Japan. *Tunnel. Underground Space Technol., 17,* pp. 145-152.
4. Haack, A. (2002). Current safety issues in traffic tunnels. Tunnel. *Underground Space Technol. 17,* pp. 117-127.
5. Caliendo, C.P., De Ciambelli, M.L., Meo Guglielmo, M.G., Russo, P. (2013). Simulation of fire scenarios due to different vehicle types with and without traffic in a bidirectional road tunnel. *Tunn. Undergr. Space Technol., 37,* pp. 22-36.
6. Hong-peng Lai, Shu-yong Wang, Yong-li Xie (2014). Experimental research on temperature field and structure performance under different lining water contents in road tunnel fire. *Tunnelling and Underground Space Technology, 43*, pp. 327-335.
7. Pichler, C., Lackner, R., and Mang, H. A. (2006). Safety assessment of concrete tunnel linings under fire load. *J. Struct. Eng., 1326*, pp. 961-969.
8. Caner, A., Zlatanic, S., and Munfah, N. (2005). Structural fire performance of concrete and shotcrete tunnel liners. *J. Struct. Eng., 13112*, pp. 1920-1925.
9. Caner A, Böncü A. (2009). Structural fire safety of circular concrete railroad tunnel linings. *J. Struct. Eng. ASCE 2009, 9,* 1081-92.
10. Nguyễn Trọng Dũng, Phạm Đức Thọ, Hồ Anh Cương (2017). Mô phỏng ứng xử Thủy-nhiệt của vật liệu bê tông bằng phương pháp mô hình lưới. *Tạp chí Khoa học công nghệ Xây dựng, 3/2017* (in Vietnamese).
11. Ghassemi A., Diek A. (2002). Porothermoelasticity for swelling shales. *Jour. Petro. Sci. Eng., 34*, 123-135.
12. Fjaer E., Holt R.M., Horsrud P. (2008). *Petroleum related rock mechanics*. Second Edition. Amsterdam; London: Elsevier. ISBN: 9780444502605.
13. Coussy O. (1995). *Mechanics of Porous Continua*. Wiley.
14. Charlier R., Collin F., Pardoen B, Talandier J., Radu JP., Gerard P. (2013). An unsaturated hydro-mechanical modelling of two in-situ experiments in Callovo-Oxfordian argillite. *Eng. Geol., 165*, pp. 46-63.
15. Carranza-Torres C., Fairhurst C. (2000). Application of the convergence-confinement method design to rock masses that satisfy the Hoek-Brown failure criterion. *Tunn. Undergr. Space Technol., 15*(2):187-213.
16. J.C. Mindeguia (2009). *Contribution expérimentale à la compréhension des risque d'instabilité thermique des béton*. PhD Thesis, Université de Pau et de pays de l'adour, France (in French).

MÔ PHỎNG SỐ SỰ LÀM VIỆC CỦA VỎ HẦM DƯỚI TÁC DỤNG CỦA NHIỆT ĐỘ CAO SINH RA DO HỎA HOẠN

Tóm tắt: *Sự cố hỏa hoạn trong các đường hầm có thể ảnh hưởng nghiêm trọng đến kết cấu vỏ chống. Nghiên cứu sự làm việc vỏ chống dưới tác động của nhiệt độ do các đám cháy là rất cần thiết trong việc dự báo sự an toàn của công trình cũng như đề xuất các biện pháp sửa chữa kết cấu sau hỏa hoạn. Bài báo tập trung phân tích trạng thái ứng suất-biến dạng trong kết cấu vỏ chống dưới tác động của sự thay đổi nhiệt độ do hỏa hoạn sinh ra. Các phân tích được dựa trên các mô phỏng số bằng phương pháp phần tử hữu hạn với các giả thiết của bài toán biến dạng phẳng cho một hầm đặt sâu. Mô hình ứng xử kết hợp nhiệt-thủy-cơ được sử dụng cho kết cấu vỏ chống và môi trường xung quanh hầm. Kết quả nhận được chỉ ra rằng ảnh hưởng của nhiệt độ cao do hỏa hoạn đến ứng suất-biến dạng vỏ hầm là rất lớn và vùng bê tông lân cận vách hầm có thể bị phá hủy.*

Từ khóa: Vỏ chống hầm; hỏa hoạn; ứng xử kết hợp nhiệt-thủy-cơ; phương pháp phần tử hữu hạn.

Received: 07/4/2020; *Revised:* 19/5/2020; *Accepted for publication:* 17/6/2020

❑