ANALYZING THE INFLUENCE OF THE EXPLOSION DEPTH ON THE STRESS-STRAIN BEHAVIOR OF CIRCULAR TUNNEL IN SATURATED SOIL

Dinh Viet Thanh[1,*], Vu Ngoc Anh[1]

[1]*Le Quy Don Technical University*

Abstract

This paper presents the effects of the explosion depth on the stress-strain behavior of circular tunnel in saturated soil with 2 approaches: experiment and numberical method (SAP2000 ver 12.0). The result of experiment and numerical methods indicate the factors on the declining of explosion energy for design the tunnel in saturated soil subjected to blast loading purpose.

Keywords: *Circular tunnel; saturated soil; declining of explosion energy; blast loading.*

1. Introduction

In recent years, Vietnam has built more and more underground works in urban areas. These are structures that can be used to make shelter under war conditions or against natural disasters. To ensure these factors, it is necessary to calculate the types of urban underground works affected by blasting load. However, up to now, the study of the impact of explosions on the new tunnel structure has mainly focused on the explosion in an infinite environment. Therefore, the study of the effects of explosive waves at explosion depths with different blasting loads acting on circular tunnel located is saturated soil a necessary issues. Solving this problem will contribute to predicting the extent of explosive energy loss in the case of shallow explosions compared to those in the infinite environment. The results serve as a basis for the design and evaluation of underground structure located in saturated soil under the effect of blasting load.

This study focuses on the influnce of the depth of explosion on the stress-deformation state of circular tunnel in saturated clay.

2. Theoretical basis

Currently, there are 2 points of view analyzing the behavior of deep underground structures under blasting load: ignore the explosion and expansion of explosive products; taking into account the entire process of explosion and expansion of explosive products.

* Email: vietthanhdinh2008@gmail.com
https://doi.org/10.56651/lqdtu.jst.v3.n01.84.sce

In the first approach, ignoring the process of explosion and the expansion of explosive products, using the models of M.A. Sadovsky, Brode (1955), Newmark và Hanse (1961) or calculated according to US standards UFC 3-340-02. Blasting load is calculated in advance and entered into the model calculated at a certain boundary as dynamic load. This method is suitable to calculate the underground structure in the infinite medium and ignore the loss of explosive energy on the ground level.

The second approach is to consider the entire process of explosion and expansion of explosive products (fully coupled method). When environment of occurrence of plastic deformation, here are applied two basic models to establish the relationship between stress and strain tensile. The application of a model to a real environment involves the nature of the research process.

Within the scope of the paper, due to the explosion test with small model and small amount of explosion (diameter of tunnel model 114 mm, the amount of explosion has a weight of $3 \cdot 10^{-3}$ kg), when changing the stress state in the domain of the loads little, the deformation of many media is elastic and its properties are characterized by generalized Hooke's law, that is, the medium to be surveyed as a linear elastic medium, whereby the relationship between the components stress and strain are linear [1, 2].

2.1. Analyze the effect of the explosion in the soil environment

On the effects of explosions in infinite medium

When exploding in an infinite environment, shockwave forms and propagates to a short distance from the explosion center (usually 3 ÷ 7 times the radius of explosion), then quickly transforms into compressed waves. The compression wave differs from the shock wave in that there is no leap on the surface of the wave, at first the pressure increases gradually and then decreases (Figure 1). The maximum pressure in the compression wave after the destructive zone of the concentrated explosion is [3]:

$$\Delta P_{\max} = \Pi \left(\frac{r_0}{r} \right)^{\alpha} \tag{1}$$

where Π and α - the coefficients depend on the properties of soil and its physical state (look up tables: $\Pi = 65000; \alpha = 2,8$); r_0, r (m) - radius of charge and distance from explosion center to the study site.

Explosion radius r_0 is calculated using the formula: $r_0 = \dfrac{\sqrt[3]{C}}{18,7}$ (2)

Time to maintain the effect of the compression wave is calculated by the empirical formula:

$$\tau = 10^{-2} (r + \sqrt[3]{C}) \tag{3}$$

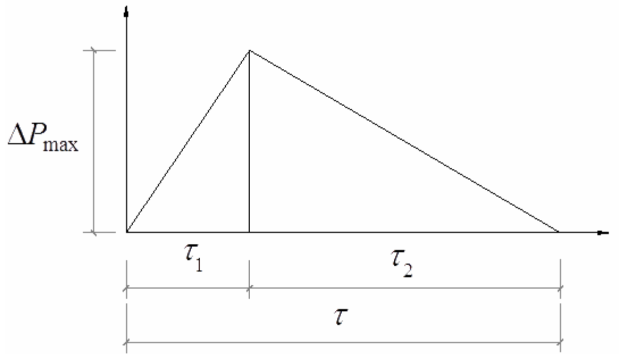

Figure 1. Compressed wave pressure graph over time

The time of pressure increase from zero to maximum is determined by the formula:

$$\tau_1 = \frac{r - 0,6\sqrt[3]{C}}{a_0}\left(\frac{a_0}{a_1} - 1\right) \tag{4}$$

Time to reduce the pressure: $\tau_2 = \tau - \tau_1$

where *r* is the distance from the explosion center to the calculated point on the structure, m; *C* is explosive weight, kg; a_0 is the velocity of propagation of the compressed wave in the soil during the elastic phase; a_1 is the velocity of propagation of the compressed wave in the soil during the plastic phase; for clay [4]: $a_0 = 150 \div 300$ m/s; $a_1 = 100 \div 150$ m/s.

Explosion effect in soil near the ground

When exploding in the soil at a certain depth (explosive near the ground), the effect of explosion in addition to depending on the type of rock, explosive properties and explosive volume, it depends greatly on the system. The amount of compaction above the surface of the explosive quantity can be interpreted as the depth of burial of the explosive when the explosive is placed in the soil. At this time, the destructive radius is calculated by the following formula [4]:

$$R_P = m.K_P\sqrt[3]{K_T.C} \tag{5}$$

where R_P is the radius of destruction; m is the compaction coefficient (tabulation); K_P is the coefficient for the destructive area (look up table); K_T is the factor for using explosion, for TNT is $K_T = 1$; *C* is explosive weight (kg).

Analysis of formula (5) indicates that the depth of burial proportional to the compaction factor. This reflects the rule that the more shallow the medicine is buried, the greater the loss of explosive energy into the air environment and the smaller the effect of the compression wave spreading in the soil and vice versa. However, in reality, there is no method to predict the pressure of compressed waves when the center explodes near the ground in saturated clay.

2.2. Calculation of Underground structures under the blasting load in soil by FEM

The calculation of underground structures under the impact of the load caused by the explosion often uses numerical methods, the most common of which is the finite element method (FEM). FEM is a solution on the basis of discrete structure into elements, linked together at nodes, the unknown number is the displacement at the nodes, from these displacements we will determine the stress state, deformation of the element. Dynamic analysis of the structure of the building under dynamic load in general by FEM often leads to solving equilibrium dynamic equations [6]:

$$\left[\overline{M}\right]\left\{\ddot{\overline{u}}\right\}+\left[\overline{C}\right]\left\{\dot{\overline{u}}\right\}+\left[\overline{K}\right]\left\{\overline{u}\right\}=\left\{\overline{F}\right\} \tag{6}$$

where: $\left\{\ddot{\overline{u}}\right\},\left\{\dot{\overline{u}}\right\},\left\{\overline{u}\right\}$ are the vector of acceleration, velocity, displacement node; $\left[\overline{M}\right],\left[\overline{C}\right],\left[\overline{K}\right]$ are the mass matrix, the drag matrix, and the stiffness matrix, respectively; $\left\{\overline{F}\right\}$ is the node load vector in the overall coordinate system.

To solve the system of differential equations of motion, we can use many different methods such as: direct integration method, center differential method,... in which direct integration method is a widely applied method. The method of direct integration using the system of equations (6), the term "direct" here implies that the integral does not use any further transformations. The basic ideas of this method group are:

- Instead of finding a system that satisfies equation (6) at all times *t*, we try to find the system that satisfies the above relation at a series of discrete points spaced at a regular interval Δt small enough. As is known, dynamic analysis is essentially a static analysis from time to time taking into account the inertial and drag forces. Thus all static solver technologies can be applied to solve the system of dynamic equations.

- Depending on the specific method of selection, one represents the derivative of the displacement, that is the representation of acceleration and velocity in a finite number of displacement values at the time before and after the time of calculation. The mathematical nature of the direct integration method is to differentiate the system of differential equations.

The group of direct integral methods has many solutions such as: center differential method, Houbolt integral method, Newmark integral method, Tetra-Wilson method, etc. In the paper, the analysis will use the Newmark's direct integration method to solve the system of structural equations of the structure.

3. Experimental

3.1. Select experimental research method

In fact to experiment with explosions in an infinite environment is hard to accomplish. Therefore, to evaluate the effect of the compressive wave intensity due to an explosion in an infinite environment on the buried structures, we use the FEM method (numerical test) and the explosion test method in the miniature model in the field for explosions near the ground level with increasing depth of explosion.

3.2. Numerical tests determine the stress-deformation state of a structure when explosive detonation concentrates in an infinite environment

Input data:

To determine the stress-deformation state in the tunnel model of a circular section buried in saturated clay, we calculate the stress in the tunnel structures at the locations shown in Figure 2 (crown of the tunnel - position 1); bottom of pit - position 3; sides of tunnel - positions 2 and 4) with the following input data:

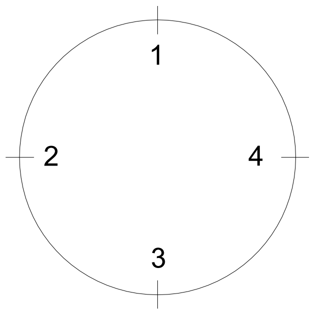

Figure 2. Location of stress survey points in tunnel cover

Tunnel model is a circular steel tube, outer diameter is 114 mm; inner diameter is 110 mm, thickness is 2 mm; tube length 600 mm; elastic modulus E = 200000 MPa. The explosive $3 \cdot 10^{-3}$ kg is buried in saturated soil, the distance from the explosion to the crown of the tunnel model, respectively, 0,38; 0,35; 0,3; 0,25; 0,2; 0,1 m.

Suppose the explosions concentrated in saturated soil are exploding in an infinite environment (explosive energy is not lost on ground levels). Now using the formulas

(1), (2), (3), (4) we determine the compressive wave load over time acting on the tunnel as follows (Table 1):

Table 1. Input parameters for 6 load cases

Row	Distance from charge to the crown of the tunnel (m)	Load $\Delta P_{\max}$ (kN/m^2)	τ (s)	τ_1 (s)	τ_2 (s)
1	0,38 (r_1)	120	0,0053	0,0015	0,0038
2	0,35 (r_2)	150	0,0049	0,0013	0,0036
3	0,30 (r_3)	230	0,0045	0,0011	0,0034
4	0,25 (r_4)	390	0,0039	0,0008	0,0031
5	0,20 (r_5)	730	0,0034	0,0006	0,0029
6	0,10 (r_6)	5100	0,0025	0,0001	0,0024

From the field test data, then look up the table [5] we determine the elastic resistance coefficient for saturated soil k_0 = 20 MN/m^3.

Modeling

Because the tunnel length is many times larger than its cross section dimension, the authors use the plane strain model. The calculation method is based on Finite Element Method, by using the commercial software SAP2000 ver 12.0. Modelling by separating the structure from the environment, the structure is discrete and linearized into bar elements (Figure 3), the surrounding soil environment is modeled according to Winkler by nonlinear elastic spring (Figure 3 - Gap link).

Figure 3. Gap model- springs are subject to only-compression

The stiffness of links is determined by the following formula:

$$k_r = k_0.b.l_i \tag{6}$$

where k_r is the axial stiffness of the link; k_0 is the soil elastic resistance coefficient; b is the width of the modeling tunnel section; l_i is the remaining size of the contact area of the structure with the rock replaced by the joint.

Calculation results:

Analysis of 6 cases of load applied to the structure as indicated above, the maximum stress results obtained at the survey points are as follows (Figure 4, Table 2):

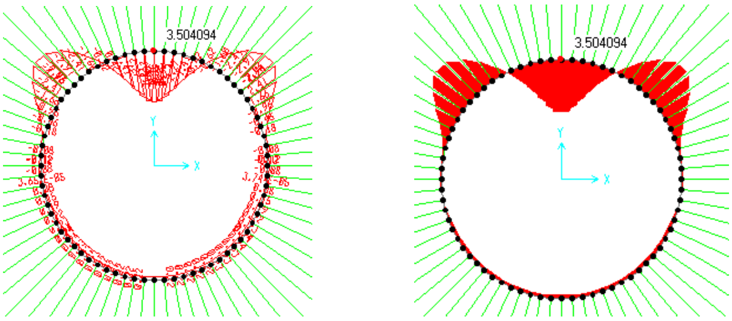

Figure 4. Maximum bending moment in the tunnel structure when the amount of explosion is 0,38m (r_1) from the top of the tunnel (crown of tunnel)

Table 2. Maximum bending moment and stress results for 6 load cases

Row	Distance from explosive to tunnel crown (m)	Maximum bending Moment (10^{-3} kN.m)			Maximum stress $\sigma^{(1)}_{max}$ (MPa)		
		Point 162 (1)	Point 144 (2); 198 (4)	Point 198 (3)	Point 162 (1)	Point 144 (2); 198 (4)	Point 198 (3)
1	0,38 (r_1)	0,082	0,044	0,041	12,3	6,6	6,15
2	0,35 (r_2)	0,104	0,0677	0,068	15,6	10,15	10,25
3	0,30 (r_3)	0,156	0,0987	0,103	23,4	16,8	15,45
4	0,25 (r_4)	0,267	0,145	0,139	40,05	21,75	20,85
5	0,20 (r_5)	0,504	0,281	0,270	75,6	42,15	40,50
6	0,10 (r_6)	3,504	2,08	1,850	525,6	312	277,50

3.3. Explosive test in the field

a. Describe the experimental model

Experimental modelling: Tunnel model is a circular steel tube, outer diameter is 114 mm; inner diameter is 110 mm, thickness is 2 mm; tube length 600 mm; elastic modulus E = 200000 MPa (Figure 5).

Test medium: Saturated soil is inherited, using from National Science and Technology project, code ĐTĐL.CN-32/18-C.

Clay materials with mechanical and physical characteristics determined in the laboratory through actual field sampling are shown in Table 3. The thickness of clay in the tank is 1,5 m; The test tank is made of reinforced concrete with a width of 6m, a length of 6m and a depth of 2,5 m to ensure resistance to deformation and watertightness, then pour each layer of clay with a thickness of 25 cm to 40 cm and then compact it with a compacted dress until the thickness of the clay layer is 1,5 m (Figure 6). Underground construction model is buried in the middle of the tank with a depth of 40 cm. After burying the tunnel, pump water into the flooded basin to the surface of the soil to saturate the clay.

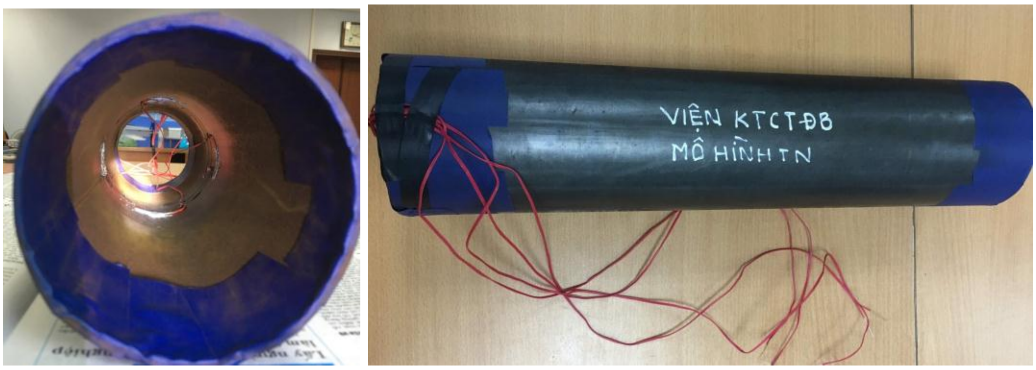

Figure 5. Experimental tunnel model

Table 3. Physical and mechanical properties of saturated clay

Parameters	**Unit**	**Sample 1**	**Sample 2**	**Sample 3**	**Average**
Density (Δ)		2,727	2,731	2,721	**2,726**
Humidity limit pasty (W_L)	%	56,35	54,91	52,60	**54,62**
Moisture limited plasticity (Wp)	%	14,63	12,81	12,78	**13,41**
Natural moisture (W)	%	28,74	28,74	29,27	**28,91**
Plasticity index (I_p)	%	41,72	42,09	39,83	**41,21**
Consistency (B)		0,338	0,378	0,414	**0,377**
Natural density (γ)	kN/m^3	19,19	19,22	19,23	**19,21**
Internal friction angle (φ)	degrees	27,76	27,15	27,34	**27,42**
Cohesion (C)	kN/m^2	21,34	21,45	21,26	**21,35**
Compaction coefficient (a_{1-2})	cm^2/kG	0,027	0,026	0,027	**0,027**
Deformation module (E_{1-2})	kN/m^2	1225	1275	1212	**1237**

Experimental equipment:

Strain gauges: Including 4 deformation probes at 4 positions 1, 2, 3, 4 according to the diagram shown in Figure 2 and Figure 4.

Multi-purpose dynamometer NI and electronic computer (laptop) to read and write deformation data when conducting experiments.

Figure 6. Model of saturated soil test tank and image after explosion with a depth of 0,05 m of explosion

Experimental load:

Experimental load is the dynamic load due to explosions from concentrated explosive, the amount of explosion is $3 \cdot 10^{-3}$ kg.

b. Experimental content

Step 1: Fabrication of underground steel constructions, installing deformation probes into 4 positions 1, 2, 3, 4 (Figure 2, Figure 5) and sealing the two ends of the tunnel with the purpose of not allowing water to enter in the tunnel during the experiment;

Step 2: Burring the tunnel into the saturated clay in the testing tank. The distance from the ground level to the crown of the tunnel is H = 0,4 cm. Then compact the clay on the top of the tunnel, keeping it in place and in position before starting an explosion;

Step 3: Conduct explosion experiments with 6 separate explosions, each time detonating 1 concentrated explosion with a volume of $3 \cdot 10^{-3}$ kg. The distance from the charge to the crown of the tunnel is 0,38 m; 0,35 m; 0,30 m; 0,25 m; 0,20 m and 0,10 m, which corresponds to the depths of charge, respectively; 0,02 m; 0,05 m; 0,10 m; 0,15 m; 0,20 m and 0,30 m. Each result of measurement was recorded through the NI multichannel dynamometer and electronic computer (laptop).

c. Experimental results

From the results of the test, we received the deformation of the tunnel at the 4 locations where the head of the strain gauge (top 1), the bottom of the tunnel (position 3), the sides of the tunnel (positions 2 and 4), on that basis, the highest stresses in the structure can be determined at the four locations (Table 4). From there, there is a relationship between the stress and depth of burial as well as the stress and distance from the amount of explosion to the top of the tunnel (position 1).

Table 4. Maximum strain and stress at survey locations

Row	Distance from explosive to tunnel crown (m)	The largest distortion				Maximum stress - $\sigma^{(2)}_{max}$ (MPa)			
		Location 1	Location 2	Location 3	Location 4	Location 1	Location 2	Location 3	Location 4
1	0,38 (r_1)	0,000036	-0,000024	0,000021	-0,000020	7,117	-4,835	4,133	-4,072
2	0,35 (r_2)	0,00005	-0,000039	0,00004	-0,00004	9,997	-7,849	7,239	-7,109
3	0,30 (r_3)	0,000083	-0,000060	0,000061	-0,000062	16,560	-11,916	12,216	-12,427
4	0,25 (r_4)	0,000157	-0,000092	0,000085	-0,000086	31,360	-18,344	16,918	-17,170
5	0,20 (r_5)	0,000323	-0,000185	0,000174	-0,000173	64,576	-37,01	34,77	-34,643
6	0,10 (r_6)	0,012888	-0,013317	0,011318	-0,014956	2577,5	-2663,4	2263,6	-2991,3

4. Analysis of experimental results

From the results of calculating the maximum stress in the structure at 4 survey points (1); (2); (3); (4) according to the FEM method (Table 2) and the field test method (Table 4) we find that in the case of the center of explosion from 10 cm of tunnel crown (the 6th explosion), the stresses in the structure are greater than steel allowable stress. This is explained by the fact that the tunnel is now within the destructive radius of the explosion (10 cm distance < R_P = 0,12 m - according to equation (5), we calculate the destructive radius for the concentrated blast of $3 \cdot 10^{-3}$ kg TNT: < R_P = 0,12 m).

Therefore, within the scope of this paper, we only focus on the analysis for the remaining 5 cases, the distance from the amount of explosion to the roof of the tunnel is: 0,38; 0,35; 0,30; 0,25; 0,20 m (equivalent to 3,8; 3,5; 3; 2,5 and 2 times the diameter of the experimental model).

The graph of the relationship between the maximum stress in the structure and the distance from the amount of explosion to the top of the tunnel is shown in Figures 7, 8, 9 respectively.

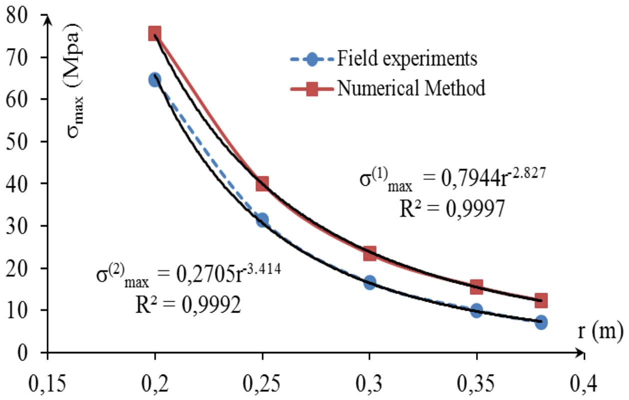

Figure 7. Relationship diagram between stress at point (1) and distance from charge to the top of tunnel

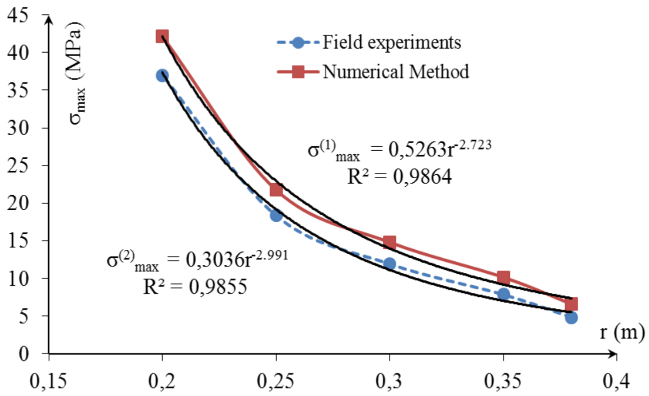

Figure 8. Diagram of stress relation at point (2) and point (4) with distance from charge to tunnel roof

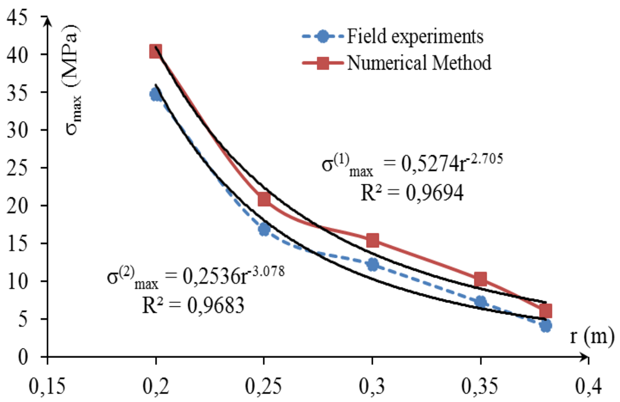

Figure 9. Relationship diagram between stress at point (3) and distance from charge to the top of the tunnel roof

The maximum stress ratio in the structure when exploding near the ground level ($\sigma^{(1)}_{\max}$) and exploding in the infinite environment ($\sigma^{(2)}_{\max}$) is shown in Table 5.

Table 5. Maximum stress ratio in structure when exploding near ground level (field experiments) and exploding in infinite environment (numerical method)

Row	Depth of drug buried (m)	Distance from explosive to the tunnel roof (m)	Location 1			Location 2, 4			Location 3		
			$\sigma^{(1)}_{max}$ (MPa)	$\sigma^{(2)}_{max}$ (MPa)	$\frac{\sigma^{(2)}_{max}}{\sigma^{(1)}_{max}}$	$\sigma^{(1)}_{max}$ (MPa)	$\sigma^{(2)}_{max}$ (MPa)	$\frac{\sigma^{(2)}_{max}}{\sigma^{(1)}_{max}}$	$\sigma^{(1)}_{max}$ (MPa)	$\sigma^{(2)}_{max}$ (MPa)	$\frac{\sigma^{(2)}_{max}}{\sigma^{(1)}_{max}}$
1	0,02 (W1)	0,38 (r_1)	12,30	7,12	**0,579**	6,60	4,84	**0,733**	6,15	4,13	**0,672**
2	0,05 (W2)	0,35 (r_2)	15,60	10,00	**0,641**	10,15	7,85	**0,773**	10,25	7,24	**0,706**
3	0,1 (W3)	0,30 (r_3)	23,40	16,56	**0,708**	14,80	11,92	**0,805**	15,45	12,22	**0,791**
4	0,15 (W4)	0,25 (r_4)	40,05	31,36	**0,783**	21,75	18,34	**0,843**	20,85	16,92	**0,789**
5	0,2 (W5)	0,20 (r_5)	75,60	64,58	**0,854**	42,15	37,01	**0,878**	40,50	34,77	**0,822**

From the results shown in Table 5, we draw a graph of the relationship between the maximum stress ratio in the structure when exploding near the ground level ($\sigma^{(2)}_{max}$) and explosion in the infinite environment ($\sigma^{(1)}_{max}$) according to the dependence on depth. burying explosives (Figure 10).

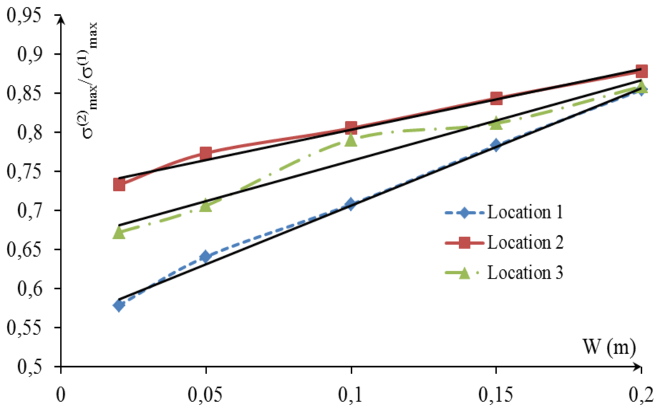

Figure 10. Relationship between $\frac{\sigma^{(2)}_{max}}{\sigma^{(1)}_{max}}$ *and depth of explosives W*

The relationship between the maximum stress in a structure when charges near the ground level (field testing method, w = 0,02÷0,2 m) and stress when exploding in an infinite environment (numerical method), depends on the depth of burial of explosives, can be approximated according to the following formulas:

- For point (1) is the crown of tunnel:

$$\frac{\sigma_{2\max}}{\sigma_{1\max}} = 0,567e^{2,11W}; \text{ w (m)} \tag{7}$$

- For point (2), (4) is the side wall of the tunnel:

$$\frac{\sigma_{2\max}}{\sigma_{1\max}} = 0,728e^{0,965W}; \text{ w (m)} \tag{8}$$

- For point (3) is below invert of tunnel:

$$\frac{\sigma_{2\max}}{\sigma_{1\max}} = 0,664e^{1,353W}; \text{ w (m)} \tag{9}$$

5. Conclusion

Based on explosion theory analysis, explosion results in the field when exploding near the ground and numerical results when exploding in an infinite environment allow the following conclusions and recommendations to be drawn:

- The closer the charge is placed to the ground, the smaller the intensity of the wave impacts on the tunnel structure and vice versa. This is consistent with the rule of explosion that the closer the explosive is placed to the ground, the greater the explosive energy is released into the air. Therefore, the smaller the amount of energy transferred into the soil, and vice versa, the deeper the depth of the explosion is corresponding to the case of explosion in the infinite environment, the greater the explosive affects on the tunnel structure and the intensity of the wave. Compression spread in soil reaches saturation value. From this, it can be drawn that the smaller the explosive quantity is applied, the smaller the stress value and deformation in the tunnel structure due to explosive wave will impact on the tunnel and vice versa.

- Recommendation: Because the experimental conditions are limited in the number of explosions, the results of the research can only be referenced in similar research works, but also for application in construction design calculations. Underground structures in explosive saturated soil environment should be rescued with more explosion experiments. The results of this study can be used to calculate and forecast the effects of explosions on shallow structures.

References

1. Nguyễn Hữu Thế (2017). *Nghiên cứu sóng nổ trong môi trường San hô và tác động của sóng nổ lên kết cấu công trình*. Luận án tiến sĩ kỹ thuật.
2. Trịnh Trung Tiến (2019). *Nghiên cứu tính toán công trình ngầm trong môi trường san hô bão hòa nước chịu tải trọng nổ*. Luận án tiến sĩ kỹ thuật.
3. Hồ Sỹ Giao, Đàm Trọng Thắng, Lê Văn Quyển, Hoàng Tuấn Chung (2010). *Nổ hóa học - Lý thuyết và thực tiễn*.
4. Nguyễn Trí Tá, Vũ Đình Lợi, Đặng Văn Đích (2008). *Giáo trình Công sự tập 1*.
5. Nguyễn Tương Lai, Vũ Văn Tuấn, Vũ Anh Tuấn, Mai Đăng Nhân, Cao Văn Ho (2017). *Nền và móng công trình*.
6. Bathe K.J. (1982). *Finite elements procedures in engineering analysis*. Prentice-Hall Inc., Englewood Cliff, New Jersey, USA.

PHÂN TÍCH ẢNH HƯỞNG CỦA CHIỀU SÂU NỔ ĐẾN TRẠNG THÁI ỨNG SUẤT - BIẾN DẠNG CỦA MÔ HÌNH CÔNG TRÌNH NGẦM TIẾT DIỆN TRÒN ĐẶT TRONG ĐẤT SÉT BÃO HÒA NƯỚC

Tóm tắt: *Bài báo nghiên cứu ảnh hưởng của chiều sâu đặt lượng nổ đến trạng thái ứng suất-biến dạng của công trình ngầm tiết diện tròn trong môi trường đất sét bão hòa nước bằng phương pháp thực nghiệm khi nổ và sử dụng Phần tử hữu hạn để khảo sát, phân tích và so sánh các kết quả. Từ kết quả của hai phương pháp có thể đưa ra được hệ số tổn thất năng lượng nổ trên bề mặt thoáng đến trạng thái ứng suất-biến dạng của kết cấu khi đặt các lượng nổ trong đất từ nông đến sâu. Kết quả nghiên cứu có ý nghĩa trong đánh giá các công trình ngầm nằm trong đất ngập nước dưới tác dụng của tải trọng nổ.*

Từ khóa: Mô hình hầm; chiều sâu nổ; khoảng cách từ lượng nổ đến nóc hầm; sét bão hòa nước; ứng suất trong vỏ hầm.

Received: 06/4/2019; *Revised:* 26/5/2020; *Accepted for publication:* 17/6/2020

❑