Effect of Surface Blasting on Subway Tunnels- A Parametric Study

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Abstract

During wars and crises, the underground tunnels are used as a safe space. Therefore, the stability and safety of them under a blast is of particular importance. In this paper, the Finite Difference Method has been used to study the influence of the change in geotechnical parameters and depth on surface blasting on subway tunnels. Results showed that increasing the internal friction angle, modulus of elasticity and cohesion of the soil reduced the effects of blast loads on the vertical displacement and bending moment in the center of tunnel crown. Furthermore, the results showed that increasing the depth of the tunnel reduced the effects of blast loading. Comparing all parameters collectively showed that the increase in the modulus of elasticity of the soil and depth of the tunnel is the most effective in reducing the influence of the blast loads on the vertical displacement and bending moment of the tunnel crown, respectively.

1. INTRODUCTION

In recent decades, tunnels and subway stations in addition to their main role in transportation have been used as shelters. Therefore, the safety of tunnels and underground structures against the blast loads has become an important issue which must be studied. Studies in this field can be divided into three categories: laboratory studies, field studies, and numerical simulations.

Because the test involves a lot of expenses and requires special equipment, fewer studies have been done in this area. Smith and Dallriva carried out experiments for evaluating the effect of surface blast on concrete buried arches [1, 2]. Blanchat, Ohno and De studied the effects of blast loads on underground structures by experimental tests [3-5].

Field studies in the area of the evaluation of effects of blast on underground structures in addition to high costs has other effects such as environmental pollution, hence, field studies undertaken in this area are limited. Among these tests, research by Ishikawa to investigate the behavior of three types of tunnels: straight tunnels, networked tunnels, and branch tunnels could be mentioned [6].

Due to the extreme limitations of laboratory and field studies, numerical simulations are the most acceptable options. On the other hand, since the blast physical process and wave propagation are very complex, accurate simulation of these phenomena requires the complex models for evaluation of the loading and responses of materials. The simulation processes and the effects of a blast on structures can be divided into three stages:

- The blast process and the formation of crater
- The blast wave propagation
- The response of the structure

Based on these three steps, numerical methods can be separated and classified into three categories: uncoupled, incomplete coupled, and complete coupled methods. In the uncoupled system, the free field stress histories are measured first and then these time histories are applied on the structure as boundary conditions for evaluating the structural response. Therefore, the interaction between the soil and the structure cannot be considered in a truly realistic way [7]. However, several numerical investigations were conducted to analyze the response of buried structures under explosion effects using an uncoupled system such, as Yang studies [8]. In the incomplete coupled method, the three above mentioned stages are reduced to two stages, with either the first two or the last two stages being used. The most important of the incomplete coupled methods are finite difference, finite element and hybrid methods. These coupled approaches consist of the dynamic soil-structure interaction and the coupling effect between the soil and the structure, but the blast loading is still defined in terms of stress or velocity time histories [7]. According to this method, Young examined the response of buried structures under surface blast loading versus depth and size of the structures [8]. Similarly, Gui studied the effect of soil damping and intensity of blast loading on tunnels [9]. Liu studied the nonlinear response of twin tunnels under blast loading [10]. Esmaeili and Falahzadeh studied the propagation of pressure waves from the explosions in soil and their effect on Tehran's subway tunnels [11]. Nagy et al. evaluated the effect of blasting depth in deep blast and the effect of surface blast on buried structures [12, 13]. Mirzeinali and Hashemi evaluated the effect of blasting on the subway tunnels by the finite difference method [14].

In a full coupled method, three-step procedures are considered in the model. Very recently, some numerical investigations have been reported for complete coupled numerical analyses using a combination of Smooth Particle Hydrodynamics (SPH) and the conventional FEM [15]. Sadegh Azar et al. evaluated the response of buried reinforced concrete structures under a surface blast using ANSYS-AUTODYN [7].

In most previous studies, effects of buried blasting on the tunnels or the effects of surface blasting on surface structures have been investigated. However, in this study, effect of surface blasting (such as terrorist explosions or explosion of weapons in surface) on subway tunnels has been evaluated. In this study, using the finite difference method, the authors have tried to evaluate the effect of the geotechnical parameters (internal friction angle, cohesion and modulus of elasticity) and depth on the performance of underground tunnels under surface blasting. These studies are performed in the incomplete coupled method category.

2. CHARACTERISTICS OF MODELS

2.1. Dimensions and boundary conditions

In this study for simulation and numerical analysis, the FLAC codes are used because of their capability on dynamic analysis of explosion. First, based on sensitivity analysis, semi-infinite soil medium dimensions of the models were chosen so that the performance of the boundary conditions due to reflected waves and stiffness has minimum effect on the results. Accordingly, width of the models were chosen between 120-180 meters, and height of the model, based on depth and dimensions of the tunnel, was chosen to be equal to 60 meters. Furthermore, to prevent the wave reflection from the boundaries, the wave energy absorbers were used at the boundaries (Fig. 1).

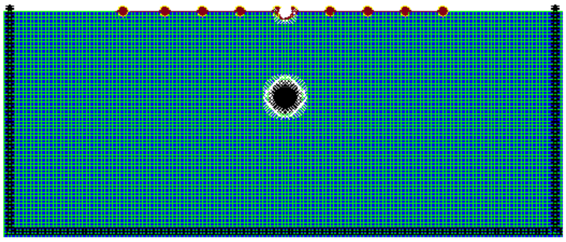

Figure1. Models loaded in FLAC code

2.2. Geotechnical properties

To simulate the soil behavior, the Mohr-Coulomb Constitutive Model was used. Properties of the soil in the base model are presented in Table 1. For parametric studies, the amount of desired parameter has been changed with constant value for other parameters.

Table1. Properties of soil in the base model

Parameters	Value
Cohesion (KPa)	30
Internal friction angle (Degree)	32
Modulus of elasticity (MPa)	80
Density (Kg/m^3)	1800

2.3. Characteristics of the tunnel

Diameters of subway tunnels drilled with TBM are about 9 m to 10 m. The diameter of these tunnels are chosen to be 9.4 m. Furthermore, it is assumed that the tunnel is located at a depth of 18 m. A 0.35 m thick reinforced concrete lining is considered in this study. The properties of concrete lining can be seen in Tab. 2. To simulate the behavior of soil- concrete interface, cohesion (C) and friction angle (ϕ) of this surface are calculated from equations 1 and 2:

$$C = \frac{2}{3} C_s \quad (1)$$

$$\tan\phi = \frac{2}{3} \tan\phi_s \quad (2)$$

Where C_s and ϕ_s are the cohesion and internal friction angle of soil, respectively.

Table 2. Properties of concrete lining

Type of material	Reinforced concrete
Thickness (m)	0.35
Poisson's ratio	0.17
Modulus of elasticity (GPa)	35
Density (Kg/m^3)	2446

3. BLASTING AND ITS LOADS

In the event of an explosion, a chemical reaction generates a large amount of gas in limited time. These gases greatly expand and drive the air around them to front. Consequently, the layer of air that is created in front of these gases is spread toward the outside environment. Thus, the blast wave is created and published in the air. As shown in Fig. 2, with distance from the source of the blast, pressure and shock wave decreases [16].

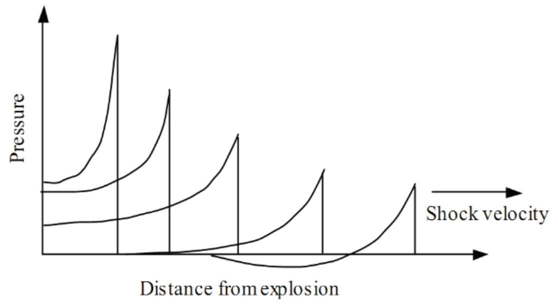

Figure 2. Blast wave propagation [16]

The resulting blast wave has two phases. In the first phase that is called the positive phase or pressure phase, the blast pressure is higher than the surrounding pressure. Then, this pressure reaches to atmospheric pressure and in the second phase, negative phase begins by creating suction.

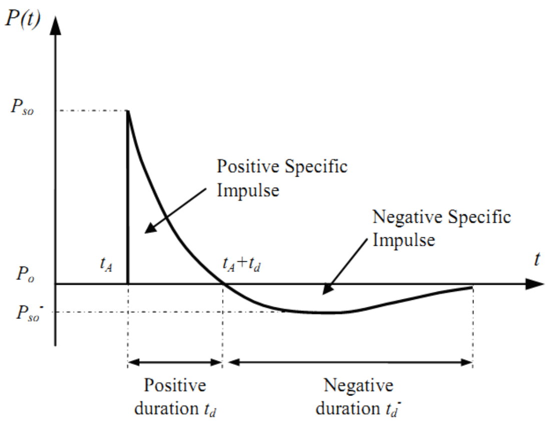

Figure 3. Blast wave pressure – Time history [17]

Fig. 3 shows a typical blast pressure profile. At the arrival time t_A, following the explosion, pressure increases to a peak value of overpressure, P_{so}, very rapidly. The pressure then decays to P_0 level at time t_d, then decays further to a negative pressure P_{so}^-. The quantity P_{so} is usually referred to as the peak side-on overpressure, incident peak overpressure, or merely peak overpressure [17].

Designers, for simplicity, use exponential or triangular-shaped pulse blasts for the design of structural members and neglect the negative phase (Fig. 4).

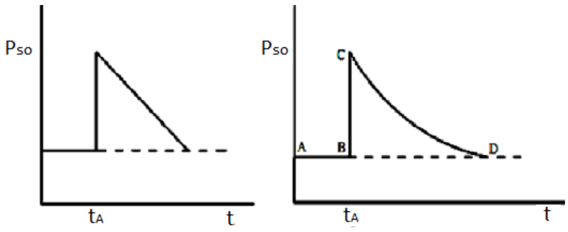

Figure 4. Simplified graph of blast wave pressure – Time history [18]

In most research, the structures are loaded under pressure over a simplified diagram without negative phase. The results show that for many computational purposes, these approximations are satisfactory. When the conservative approach is desired for the history of pressure, the exponential function can be converted to line 1 in Fig. 5. If one desires the impulse to be equal in both cases, line 2 is used. In this case, the areas beneath the exponential function and line 2 are equal [18].

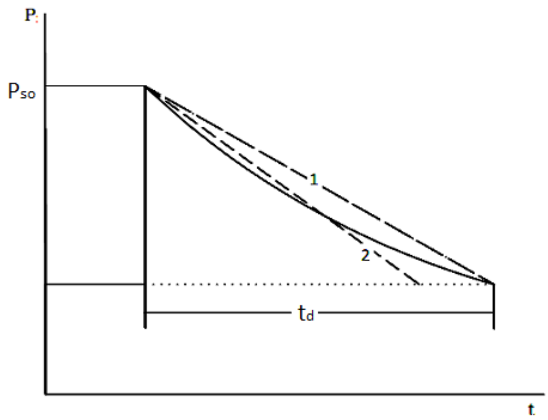

Figure 5. Blast wave profiles: real, conservative, impulse equality [18]

In this study, it is assumed that the explosive is TNT and its mass is 100 Kg. Furthermore, this explosive is placed on the ground surface and the explosion occurs on the ground surface (Fig. 6).

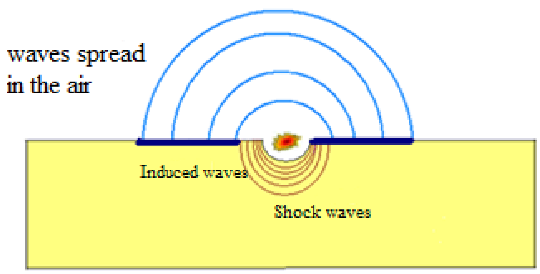

Figure 6. Waves of the explosion on the ground surface

As shown in Fig. 6, when an explosion occurs in ground surface, part of the energy of the explosion by shock waves is transmitted to the ground (crater wall). Another part of the waves spreads in the air in a hemispherical shape.

It should be noted that hemispherical waves that propagate in the air are similar entered pressure on the ground surface (induced waves) [19]. In most previous researches, only the pressures on the crater (the effect of shock waves) were considered and the effects of induced waves were ignored. But in this study, the combined effect of shock waves and induced waves are considered.

The peak value of overpressure, P_{so}, generated in a free field environment that produces the crater is given:

$$P_{so} = 0.0488 f_c \rho_s C \left(\frac{2.52R}{W^{1/3}} \right)^{-n} \tag{3}$$

Where f_c is the coupling factor which is given in Fig. 7, ρ_s is the density of the soil (Kg/m^3), C is the loading wave velocity (m/s), W is mass of explosive (Kg), R is distance to the explosion (m) and n is the attenuation coefficient (defined later on) [18].

The effectiveness of a weapon increases with the degree of coupling between the explosion and the ground, which is a function of its depth of burial. This effect is quantified by the incorporation of the coupling factor, f_c. Values for coupling factor are presented in Fig. 7.

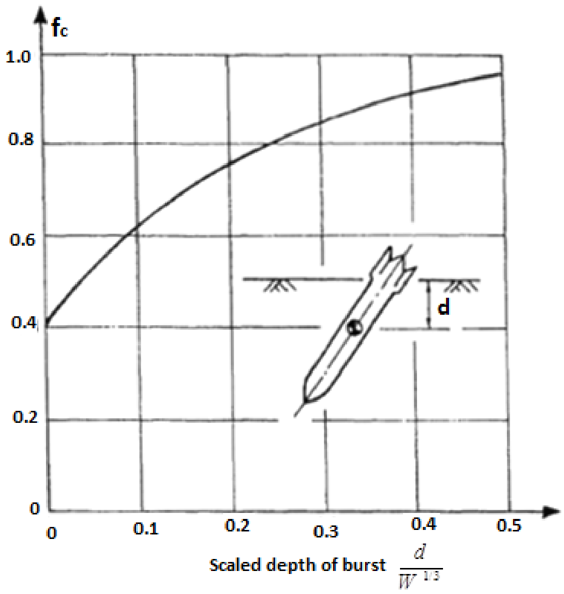

Figure 7. Values for the coupling factor- Scaled depth of burst [18]

The loading wave velocity C depends on both the seismic velocity and the peak particle velocity. At first, due to the high values of particle velocity, the C is high, but its value decays to the seismic velocity afterwards. The value adopted for C should never be less than c_s and is shown in Table 3 [18].

Table 3. Value for loading wave velocity (C) [18]

Soil	C
fully saturated clays	$C = c_s$
saturated clays	$C = 0.6c_s + \left(\frac{n+1}{n-2} \right) V_0$
sand	$C = c_s + \left(\frac{n+1}{n-2} \right) V_0$

The general term seismic velocity c_s is defined as follows:

$$c_s = \sqrt{\frac{E_s}{\rho_s}} \tag{4}$$

Where ρ_s is the density of the soil (Kg/m^3) and E_s is the modulus of elasticity of soil. Seismic velocities vary from 200 m/s for loose and dry sand to values more than 1500 m/s for saturated clays. The peak particle velocity V_0 at a range R from the bomb (explosives) is given:

$$V_0 = 48.8 f_c \left(\frac{2.52R}{W^{1/3}} \right)^{-n} \tag{5}$$

Some typical values of the attenuation coefficient for a range of soils are given in Table 4 [18].

Table 4. Attenuation coefficient (n) [18]

Soil	Attenuation coefficient (n)
Saturated clay	1.5
Partially saturated clay and silt	2.5
Very dense sand, dry or wet	2.5
Dense sand, dry or wet	2.75
Loose sand, dry or wet	3
Very loose sand, dry or wet	3.25

The arrival time t_A is given:

$$t_A = \frac{R}{c_s} \tag{6}$$

Where R is distance to the explosion (m) and c_s is seismic velocity (m/s). The duration of positive phase t_d is given:

$$t_d = 2\frac{I_0}{P_{so}} \tag{7}$$

Where I_0 is free field impulse [17]:

$$I_0 = 0.019 f_c \rho_s W^{1/3} \frac{C}{c_s}\left(\frac{2.52R}{W^{1/3}}\right)^{1-n} \tag{8}$$

To calculate the pressure histories caused by induced waves that are applied to the surface, it is assumed that these pressure histories are uniformly distributed in each circular strip of land around the crater (Fig. 8).

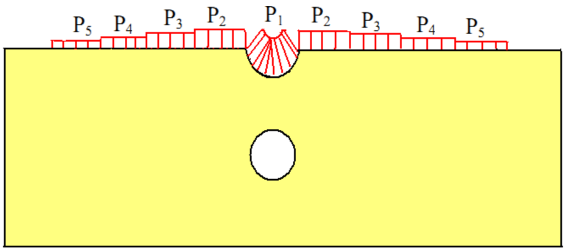

Figure 8. Pressures applied on the model

The width of each strip of land is 5 m and Fig. 9 is used to calculate the pressure histories. In Fig. 9, Z is the scaled distance that is calculated from equation 9:

$$Z = \frac{R}{W^{1/3}} \tag{9}$$

Where W is mass of explosive (Kg) and R is distance to the explosion (m) [16]. For each circular strip, the R is the distance from the center line of the strip to the center of the crater.

The parameters in Fig. 9 are: $T_s/W^{1/3}$: Scaled duration of positive phase ($ms/lb^{1/3}$), $i_s/W^{1/3}$: Scaled impulse of positive phase ($psi.ms/lb^{1/3}$), P_{so} : Peak value of overpressure (psi), $t_a/W^{1/3}$: Scaled arrival time of blasting wave ($ms/lb^{1/3}$), Z: Scaled distance ($ft/lb^{1/3}$).The calculated pressure histories are shown in Fig. 10.

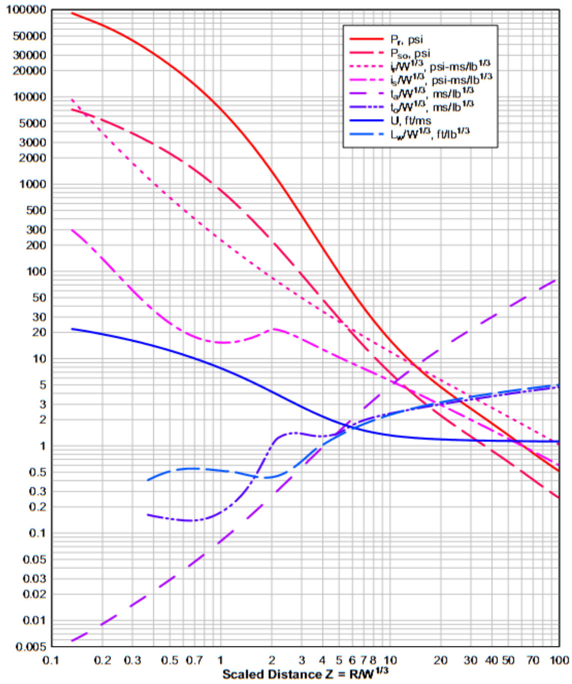

Figure 9. Positive phase shock wave parameters for a hemispherical TNT explosion on the surface at sea

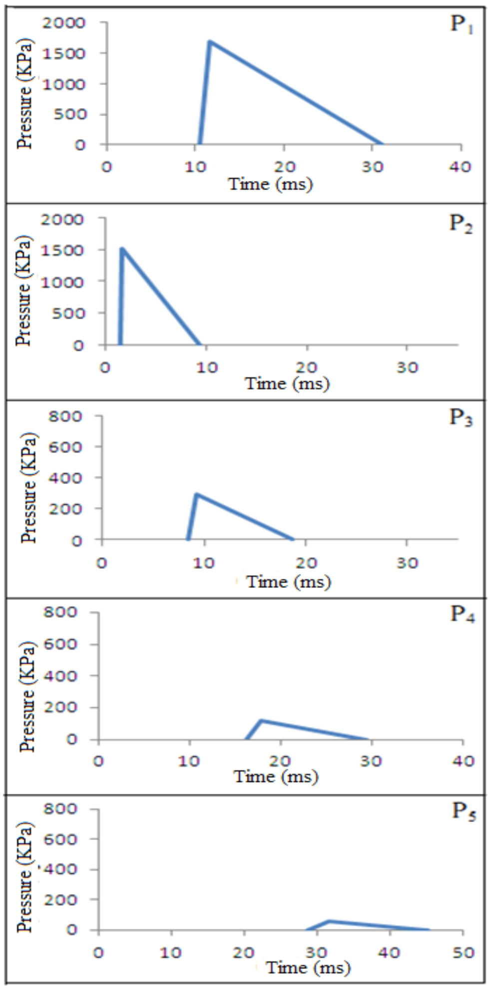

Figure 10. Calculated pressure histories

4. CRATER

The mechanism of crater formation is complex and this is due to the non-homogeneous nature of nonlinear and three-phase state of soil. To calculate the diameter of the crater, different equations by Kinney and Graham [20], Ambrosini and Luccioni were proposed [21, 22]. In this study, the diameter of the crater has been calculated with an equation offered by Kinney and Graham:

$$D = 0.8W^{1/3} \tag{10}$$

Where D is diameter of crater (m) and W is mass of explosive (Kg) [20]. Based on this equation, the calculated diameter of the crater is 3.7m.

5. RESULTS OF NUMERICAL SIMULATION AND ANALYSIS

Based on the above mentioned criteria, authors have used the FLAC code for numerical analysis of response of tunnel to blast loading for different geometrical and geotechnical parameters. Vertical displacement and bending moment in center of the tunnel crown have been considered as achieving parameters in parametric studies.

5.1. Effect of internal friction angle of soil

To evaluate the effectiveness of the internal friction angle in response of tunnel to surface blasting, effects of changing this parameter in range of 18 to 45 degrees have been studied. Results have been shown in Fig. 11. As seen in Fig. 11, increasing this parameter by 150%, the amount of vertical displacement under static load and combined effects of the static and blast loads have been shown to have decreased by 23% and 11% respectively.

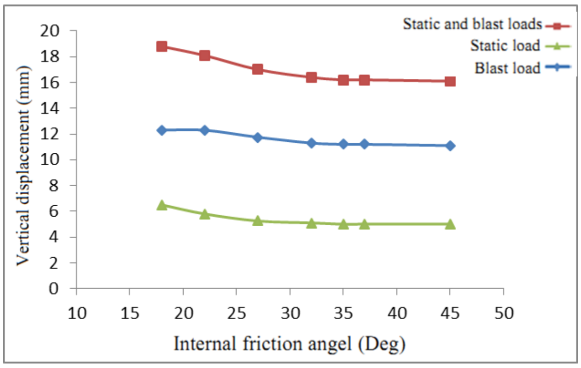

Figure 11. Vertical displacement of tunnel crown-internal friction angle of soil

Under the same situation, the bending moment in tunnel crown decreases by 7.2% and 53.5%, respectively. In other words, increases of this parameter cause reductions of bending moment by 42% under blast load merely (Fig. 12).

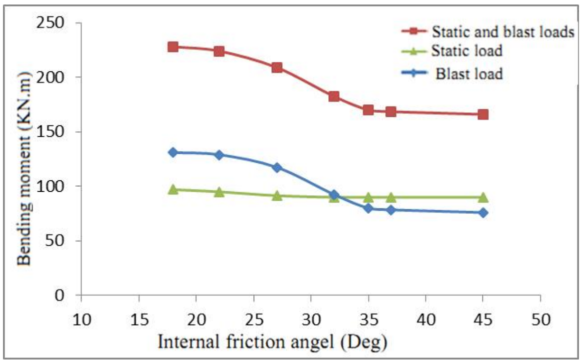

Figure 12. Bending moment in tunnel crown-internal friction angle of soil

5.2. Effect of soil cohesion

To evaluate the effect of cohesion of soil, values of this parameter ranging from 15 to 350 KPa has been considered. The results of the analysis showed that this parameter has a slight effect on the blasting effect (Fig. 13, 14). Similar results have been reported in previous studies for instance by Liu [10] and Esmaili and Falahzadeh [11].

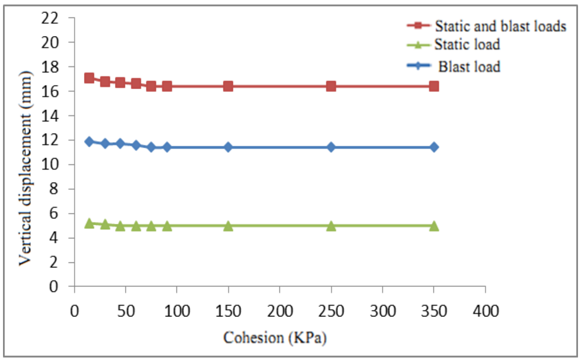

Figure 13. Vertical displacement of tunnel crown - the cohesion of soil

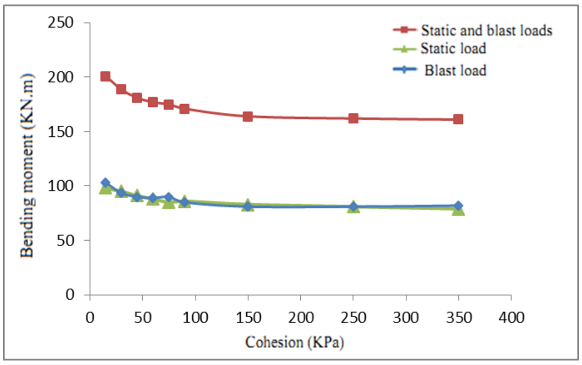

Figure 14. Bending moment in tunnel crown - the cohesion of soil

5.3. Effect of modulus of elasticity of soil

To investigate the effect of modulus of elasticity of soil, the parameter changes in the computing of the pressure on the crater (the effect of shock waves) must be considered. According to section 3, by increasing the modulus of elasticity, the over-pressure increases, but the continuity duration of wave increases. Histories of pressure that have been applied to the crater wall (the effect of shock waves) for soils with different modulus of elasticity are shown in Fig. 15. In this case, histories of pressure applied to the ground surface (P2, P3, P4 and P5) have been shown in Fig. 10.

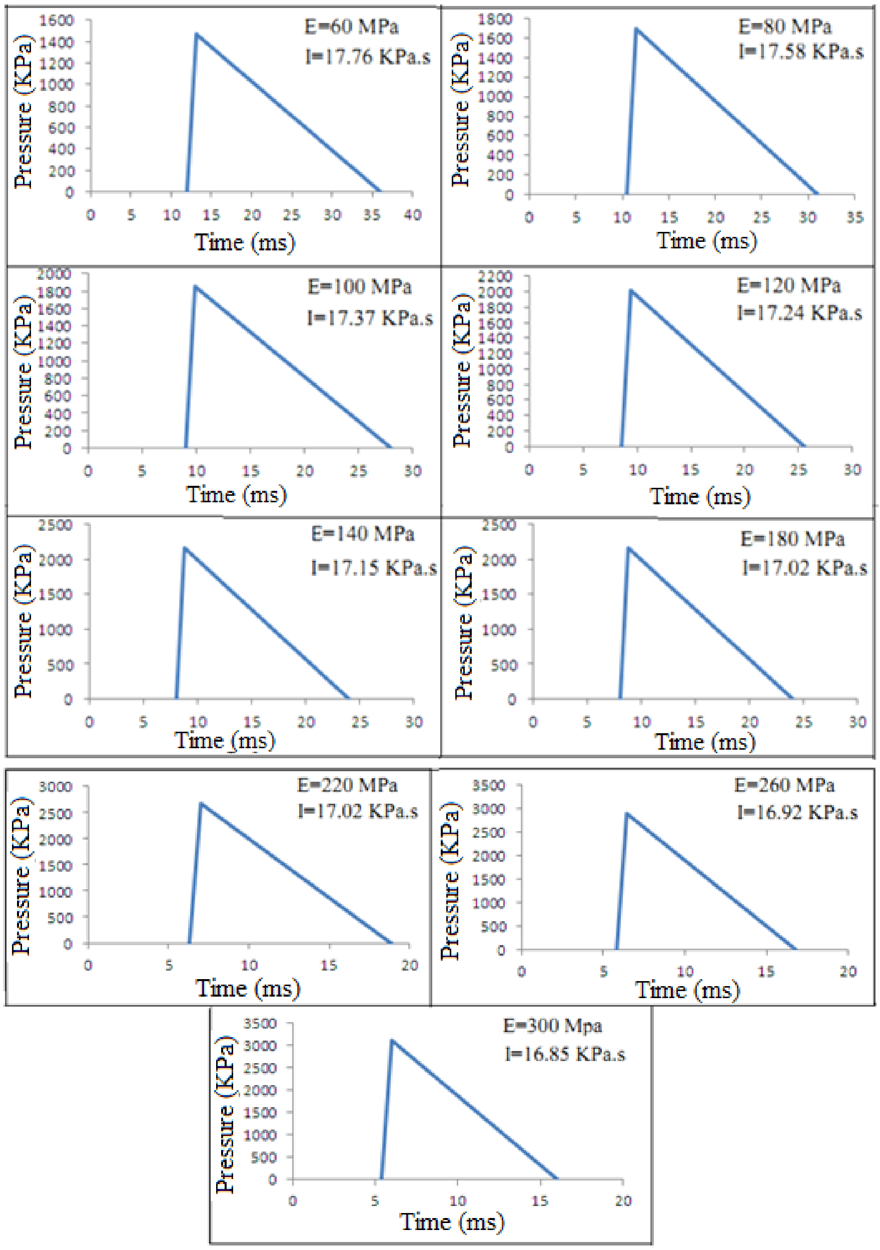

Figure 15. Pressure histories of the effect of shock waves exerted on the walls of the crater for soils with different modulus of elasticity

The results of the analysis shows that with a 400% increase in the modulus of elasticity of soil results in the reduction of vertical displacement under static load and combined effect of the static and blast loads by 66.6% and 55.2%, respectively. Inferring, increases of this parameter caused by the effects of blast loads decrease by 50% (Fig. 16). At the same time, the amount of bending moment decreases by 58% and 33% respectively. Thus, increases of modulus of elasticity caused by the effects of blast loads decrease by 14% (Fig. 17).

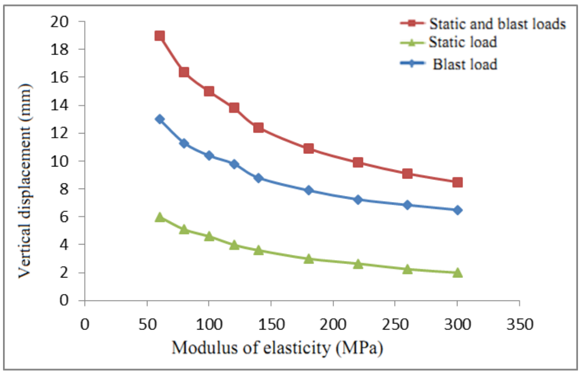

Figure 16. Vertical displacement of tunnel crown - the modulus of elasticity of the soil

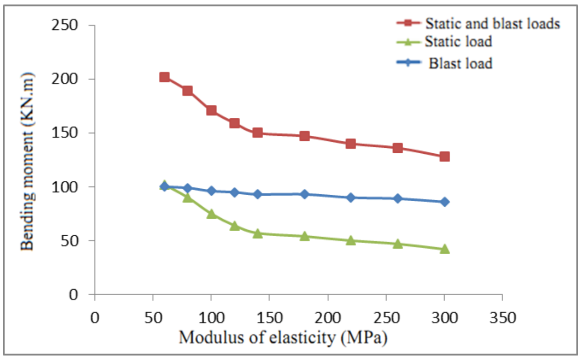

Figure 17. Bending moment in tunnel crown - the modulus of elasticity of the soil

5.4. The effect of depth of the tunnel

To investigate the effect of the depth of the tunnel, distance considered between the center of the tunnel crown and ground surface varies from 12 to 27 m. The results show that with increasing the depth of tunnel from 12 to 27 meters, the amount of vertical displacement under static load intensifies by 740%. Increases of this parameter caused by the effects of blast loads decrease by 43%. It should be mentioned, that for deeper tunnels, the effects of blast loads on tunnels decrease very rapidly, as shown in Fig. 18.

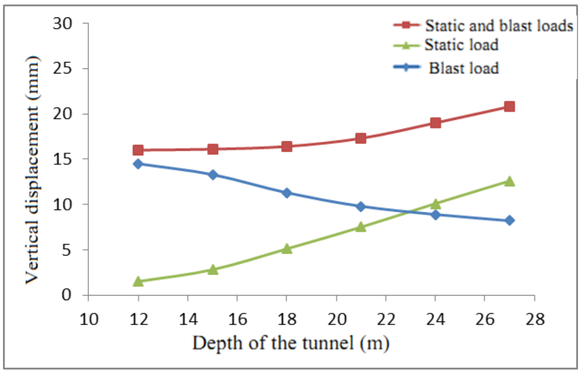

Figure 18. Vertical displacement of tunnel crown - depth of the tunnel

Fig. 19 shows the relationship between bending moment in tunnel crown versus depth of the tunnel. The results can be rationalized that by increasing the depth of the tunnel, the intensity of the wave pressures are reduced due to the damping effect of soil. Similar results have been reported in the literature, for instance studies by Hashemi and Mirzeynali [14], and Nagy et al. [12].

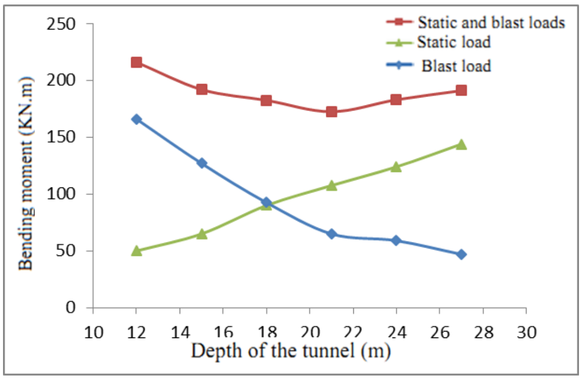

Figure 19. Bending moment in tunnel crown - depth of the tunnel

6. COMPARING ALL PARAMETERS COLLECTIVELY

So far, parametric studies of relevant issues have been presented. By showing all results in a single graph, the impacts of all parameters can be seen simultaneously in a so-called spider graph. First the values of these parameters are normalized according to equation 11 and then variations of the vertical displacement and bending moment at tunnel crown versus the changes in the normalized data are presented.

$$x_{norm} = \frac{x - x_{\min}}{x_{\max} - x_{\min}} \qquad (11)$$

That x_{norm} is the normalized value, x is the actual value, $x_{\max}$ is the maximum value and $x_{\min}$ is the minimum value.

The curve of the vertical displacement in tunnel crown versus to the change of the values of the normalized data is shown in Fig. 20. Considering this figure, increasing the modulus of elasticity of the soil is the most effective parameter in reducing the influence of the blast loads on the vertical displacement of the tunnel crown. Furthermore, increasing the depth of the tunnel has a significant effect on reducing the vertical displacement of the tunnel crown.

Curve of the bending moment changes versus to the change of the values of the normalized data is shown in Fig. 21. As shown in this figure, increasing the depth of the tunnels is most effective in reducing the influence of the blast loads on the bending moment. Furthermore, the cohesion of soil is more effective than other parameters.

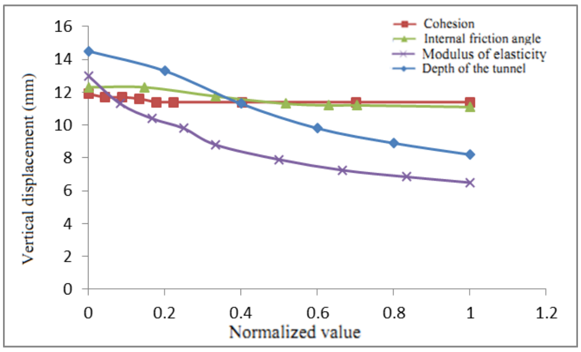

Figure 20. Vertical displacement of the tunnel crown- Normalized value

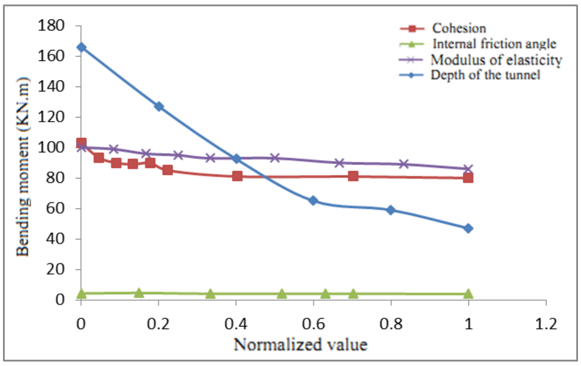

Figure 21. Bending moment in tunnel crown- Normalized value

7. CONCLUSIONS

In this study, authors have used the finite difference method to evaluate the influence of the change of geotechnical parameters and depth on effect of surface blasting on subway tunnels.

The effect of changing geotechnical parameters and depth of the tunnels, the behavior of underground tunnels under surface blast loading has been investigated. Based on analyses carried out, general results can be drawn as following:

- 150% increase in the internal friction angle of the soil has caused the effect of blast loads on the vertical displacement and bending moment in tunnel crown to decrease by 9.7% and 42%, respectively.
- Cohesion of the soil has negligible effect on the vertical displacement and bending moment in tunnel crown.
- 400% increase in the modulus of elasticity of the soil has caused the effect of blast loads on the vertical displacement and bending moment in tunnel crown to decrease by 50% and 14%, respectively.
- 125% increase in the depth of the tunnel has caused the effect of blast loads on the vertical displacement and bending moment in tunnel crown to decrease by 43% and 71.6%, respectively.
- Increase in the modulus of elasticity of the soil is the most effective in reducing the influence of the blast loads on the vertical displacement of the tunnel crown.
- Increase in the depth of the tunnel is the most effective in reducing the influence of the blast loads on the bending moment.

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