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Evaluation the Effect of Blast Pattern on Overbreak Area around the Miyaneh-Ardabil Railway Tunnel

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Abstract

Determining the appropriate blasting pattern is important to prevent any damage to the tunnel perimeter in conventional tunneling by blasting operation in hard rocks. In this research work, the LS-DYNA software and numerical finite element method (FEM) are used for simulation of the blasting process in the Miyaneh-Ardabil railway tunnel. For this aim, the strong explosive model and nonlinear kinematic plastic material model are considered. Furthermore, the parameters required for the Johnson-Holmquist behavioral model are based on the Johnson-Holmquist-Ceramic material model relationships and are determined for the andesitic rock mass around studied tunnel. The model geometry is designed using AUTOCAD software and Hyper-mesh software is applied for meshing simulation. After introducing elements properties and material behavioral models and applying control and output parameters in LS-PrePost software, the modeling process is performed by LS-DYNA software. Different patterns of blastholes including 66, 23, and 19 holes, with diameters of 40 and 51 mm, and depths of 3 to 3.8 m are investigated by three-dimensional FEM. The borehole pressure caused by the ammonium nitrate-fuel oil (ANFO) detonation is considered based on the Jones-Wilkins-Lee (JWL) equation of state in the LS-DYNA software. The outer boundaries of the model are considered non-reflective to prevent the wave's return. The results showed that LS-DYNA software can efficiently simulate the blasting process. Moreover, the post-failure rate of the blasting is reduced by more than 30% using the main charge with less explosive power and reducing the distance and diameter of contour holes.

1. Introduction

Today, tunnel excavation is performed by mechanized or conventional methods. The drilling-blasting method, as the most common example of conventional tunneling, is widely used in digging rock tunnels because of its low cost and high flexibility. Determining the appropriate blasting pattern is of great importance to prevent damage to the tunnel roof, floor, and walls. In general, in addition to the blasting pattern characteristics, the rock mass features also significantly affect the occurrence of adverse phenomena, e.g. post-failure and pre-failure in rocks around the tunnel. In the case of post-failure, which may be due to the unsuitable pattern or rock mass conditions, a considerable deal of time and cost must be assigned for improving damages due to the failure. Generally, post-failure and pre-failure can be affected by the rock's geo-mechanical properties, blasting parameters or a combination of both. Therefore, examining these parameters enables us to reduce the undesirable blasting phenomena in the tunnel.

Major requirements in tunnel excavation include investigating and analyzing tunnel stability and determining the optimal blasting pattern and required support. Some problems involved in tunnel construction are the complexity of elastoplastic behavioral models of rock masses, the uncertainty of the exact initial stresses, and dispersion in the laboratory results. However, apart

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from these problems, one can obtain results that are in good compatibility with the practical observations if the initial hypotheses regarding the numerical methods are compatible with the real problem. Today, numerical methods are widely used in modeling the stress-strain behavior of jointed rocks.

Certainly, developing a general model including jointed rock mass and all of its governing parameters is almost impossible. In the following, some studies in underground space stability analysis are mentioned.

Holmberg and Persson [1] studied the expansion of the damage caused by the explosion using the peak particle velocity (PPV) method. Saiang [2] evaluated the damage depth and the strength and stiffness parameters of the excavation damaged zone (EDZ) using FLAC and PFC software packages. The results revealed that the diameter of blast holes can lower the properties of the EDZ by 10 to 50%.

Saiang et al. [3, 4] investigated the effect of blasting on the rock mass around a shallow railway tunnel using the finite difference method (FDM) and FLAC 2D software. The results showed that blast induced damage around the tunnel was effective on the behavior of boundary stresses and land deformation. Furthermore, some damage types were identified around the tunnel and their mechanism was described.

Iverson et al. [5] studied the spread of damage caused by a single-hole blasting in a laboratory concrete block. This research work determined the EDZ in the range of 26 to 396 cm.

Wang et al. [6] examined the effects of the blasting wave on the fault rock mass using the hybrid FEM/DEM method and LS-DYNA and UDEC software packages. These authors applied LS-DYNA software to simulate the blasting process and UDEC software to model the blasting wave propagation in the faulted rock mass. They also investigated the relationship between rock fracture and fault parameters, including slope, stiffness, and internal friction angle (φ). The results showed that the hybrid FEM/DEM method can be a good choice for evaluating the blasting process in discontinuous and faulted rock mass. Haibo et al. [7] conducted a seismic and sound wave test to examine the effects of the blasting wave on the rock mass around the Linao Nuclear Power plant (LNPP). These researchers obtained very good results by numerical modeling using the LS-DYNA software. The modeling results were in good agreement with monitoring data. Eventually, based on the modeling results, a method was presented for the rock mass according to the propagation velocity safety threshold to reduce the rock mass EDZ.

Ondera et al. [8] applied numerical modeling to investigate the damage caused by the blasting in wells with fully decoupling charge. They also developed a hybrid stress blast model in FLAC software to simulate the blast, wave propagation, and rock fragmentation.

Yang et al. [9] conducted a numerical modeling for a deep tunnel drilled in Jinping using the LS-DYNA software. They especially emphasized the combined effects due to the stress redistribution in the rock mass around the tunnel and the damage caused by the blasting. They then analyzed the EDZ due to the blasting with a delay time of milliseconds. Yingji et al. [10] evaluated the failure mechanism in weak rock mass around large-scale railway tunnels. For this purpose, they applied physical and numerical methods. The results showed that the shear wedge along the main minimum stress has the least stability. A comparison of physical and numerical modeling results revealed that the damage structure model can be applied to determine the depth of the tunnel EDZ. Also, comparing the results of numerical modeling and field measurements indicated that the damage model can be used for identifying the weak rock mass displacements around tunnels. Xie et al. [11] investigated the destruction spreading mechanism in deep tunnels constructed by the drilling and blasting method. For this purpose, they first developed a shear stress and compressive damage model, followed by its use as a user-defined material model in LS-DYNA software. They also compared numerical results with existing field results to validate their method. The results showed that the main reasons for (interconnected) destruction or failure near the blasting holes are the stress wave concentration and the tensile waves reflected from free surfaces. Lateral pressure coefficients also affected the expansion direction of the tensile damage zone.

Eslami et al. [12] estimated the blasting damage in the tunnel of the Siah-bisheh pumped-storage power plant using numerical methods. They used 3DEC software for modeling the blast environment and blast holes and AUTODYN software for modeling the blast process. The results of AUTODYN software, such as blast wave, were used as input in the 3DEC software. Finally, numerical modeling results revealed that the blasting process can be examined before its implementation. Besides, a close estimate of the damage can be obtained using the two software of

3DEC and AUTODYN. Dang et al. [13] investigated the blasting effects on the surrounding rock mass and the adjacent old tunnel using the Abaqus/Explicit software. The 2D and 3D modeling results and their comparison with existing field data showed that numerical modeling provides a good estimate of the areas damaged by the blasting. Daraei et al. [14] estimated the post-failure in the tunnel of Qalajeh Road. The results of 2D modeling using Phase2 software showed a 40% difference from the field observations.

Verma et al. [15] estimated the EDZ of the rock mass around the underground space using the behavior of the ground vibration resulting from the blasting with an emphasis on the perimeter charge factor. This factor depends on the advancement factors, the confinement factor, and the maximum charge per delay.

Villalobos et al. [16] analyzed the stability of the Monte Seco Railway tunnel using ground-based laser scanner data and the FEM. The numerical modeling results showed an anisotropic behavior in the displacement pattern. In this study, the results obtained from parallel statistical models and impressions from ground laser scanners did not show a good overlap. The explanation is that they did not consider the factor intensity parameter in 2D generation DFN systems. Zou et al. [17] investigated the factors affecting the quality of different controlled blasting in rock tunnels. For this purpose, they used LS-DYNA software for 3D modeling. The results showed that the geological conditions and rock mass type have the greatest impact on the blasting quality. However, the loading rate and blasting speed can be considered secondary factors under certain conditions. Ali dadi et al. [18] estimated the damaged zone's thickness occurred due to tunnel excavation. These researchers modeled a circular tunnel using numerical modeling and FLAC 3D software. In this numerical modeling, the first 6 m of the tunnel was excavated mechanically, and 6 to 9 m was excavated by blasting. The results showed that the damage area caused by the blasting method was more widespread. Moreover, increasing the vertical position stress increased the damage zone radius in the tunnel walls, adhesion, internal friction angle, and the horizontal-to-vertical stress ratio and reduced the damage zone radius in the tunnel wall.

Chinaei et al. [19] applied numerical modeling to determine the Hoek-Brown failure criterion caused by the blasting around the tunnels. The results indicated that the explosion pattern has a significant effect on the amount of damage, so that by increasing the number of blast holes in a delay, the Hoek-Brown failure criterion increases, and with increasing the hole diameter, its value decreases drastically. Also, the results showed that the damage coefficient will decrease with the increase of the depth of the tunnel, and for better fragmentation of the rock, a stronger explosive material or an increase in the density of the explosive material will be needed. Some of the previous studies that are reported in the literature to evaluate the damaged zone caused by blasting operation in tunneling are summarized in Table 1.

1.1. Objectives and statement of problem

Despite the economic advantages involved in using explosives in constructing underground excavations, it is necessary to more deal with the damages and problems caused by rock mass explosions. According to mentioned studies, some of these problems are the rock mass instability and the increase in the area of destruction caused by the explosion, the increase in maintenance costs, delays resulting from the stoppage of operations, decreased the rate of advancement, and the increase in the overall costs of the project. Accordingly, in the present study, the Ardabil-Mianeh railway tunnel (Tunnel number 8) was selected as a case study for more investigation in this field and study the effect of blast pattern on damage and post-failure fate occurred around the Miyaneh-Ardabil Railway Tunnel. So, the main purpose of this study is to simulate the borehole pressure caused by the ammonium nitrate-fuel oil (ANFO) due to blasting operation by three-dimensional FEM. For this aim, LS-PrePost and LS-DYNA software are applied in order to determine the excavation damaged zone and overbreak volume in studied tunnel. Filed observations are available for validation of achieved results.

Section 2 of present research gives the information of considered case study. Methodology and 3D modeling of blast holes of Miyaneh-Ardabil Railway Tunnel are performed is section 3. Results and discussions are presented in section 4 and finally section 5 includes the conclusions.

Table 1. Literature review of damaged caused by blasting operation in tunneling.

Researchers	Applied method	The aim of the research
Holmberg and Persson [1]	Field and experimental analyzing of the seismic waves energy associated with ground vibration caused by explosion	Prediction and control of damage caused by the explosion in tunnels
Saiang [2]	Field methods, FLAC and PFC software	Evaluation the behavior of blast-induced damaged zone in hard rock tunnels
Saiang et al. [3, 4]	Numerical study by $FLAC^{2D}$	Mechanical properties of the damaged rock zone around tunnels in brittle rock
Inverson et al. [5]	A calibrated Hybrid Stress Blasting Model (HSBM)	The expansion of damage in a laboratory concrete block caused by a single-hole.
Wang et al. [6]	LS-DYNA and UDEC software packages	Assessment of blasting process in discontinuous and faulted rock mass
Haibo et al. [7]	Monitoring data and simulation with LS-DYNA software	Controlling of excavation damaged zone (EDZ) caused by blasting in construction of a nuclear power plant
Ondera et al. [8]	Numerical modeling by FLAC software	Investigation of damaged zone affected by the blasting in wells with fully decoupling charge.
Yang et al. [9]	Numerical modeling by LS-DYNA software	Progression of rock mass damage due to blasting in excavation of deep tunnels
Yingji et al. [10]	Physical model (Digital speckle correlation method (DSCM)) and numerical method ($FLAC^{3D}$)	Evaluation of failure mechanism in weak rock mass around large-scale railway tunnels
Xie et al. [11]	LS-DYNA software	Investigation of destruction spreading mechanism in deep tunnels constructed by the drilling and blasting method.
Eslami et al. [12]	3DEC software for modeling the blast environment and blast holes and AUTODYN software for modeling the blast process	Estimation of blasting damage in the tunnel of the Siah-bisheh pumped- storage power plant
Dang et al. [13]	2D and 3D modeling by Abaqus/Explicit software	Analysis of blasting effects at tunnel face on an existing adjacent tunnel
Daraei et al. [14]	Modeling using Phase2 software	Estimation of post-failure in the tunnel of Qalajeh Road
Verma et al. [15]	Developing an empirical correlation by data sets of 113 experimental blasts	Assessment of rock mass damage around the underground space caused by blasting
Villalobos et al. [16]	Ground-based laser scanner data and the FEM-RS2	Estimation of overbreak and stability of the Monte Seco Railway tunnel
Zou et al. [17]	3D modelling by LS-DYNA	Investigation of affecting factors on the quality of smooth blasting in rock tunnels
Ali dadi et al. [18]	Numerical modeling by $FLAC^{3D}$	Determination of damaged zone's thickness occurred due to tunnel excavation
Chinaei et al. [19]	Numerical modeling with LS_DYNA software	Calculation of Hoek-Brown damage factor caused by the blasting around the tunnels

2. Case Study

The project area is a part of the second section of Miyaneh-Ardabil railway line. This area has morphological characteristics resembling those of mountainous areas. This section is 20 km long along the impassable slopes of the northern shore of the Ghezel Ozan River. To complete this line, it is predicted to excavate 16 single-line tunnels with a height of 9 m and a width of 6 m. In this study, tunnel No. 8 was selected to investigate the blasting operations (Figure1). The length of this tunnel is about 960 m, starting from 210 + 366 km and ending at km 367 + 170. The main host rock of Tunnel No. 8 is an andesitic rock cut by a monzodiorite intrusive mass. Research has shown the spread of monzodiorite apophysis in multiple clusters on each side, altering andesitic rocks to varying degrees [20].

Different tunnel types and galleries have been selected based on the geological situation and geo-mechanical parameters, and finally using the rock mass classification system (RMR) and rock mass quality (Q), the tunnel excavation method is carried out in two stages of top heading and bench excavation such that the crown part of the tunnel has been drilled and blasted, and some advancement is made according to the geo-mechanical status. Then the floor is drilled and blasted. The length of the holes in the tunnel's crown is between 3 and 3.8 m. The arrangement and sequence of blastholes detonation is illustrated in Figure 2. In order to have a favorable fragmentation conditions for rocks throughout the blasting progression, existence of an empty hole for releasing the confining stresses is more applied. The numbers of advance holes, floor holes, and contour holes are 28, 10, and 19, respectively.

Figure 1. A view of the Miyaneh-Ardabil railway tunnel.

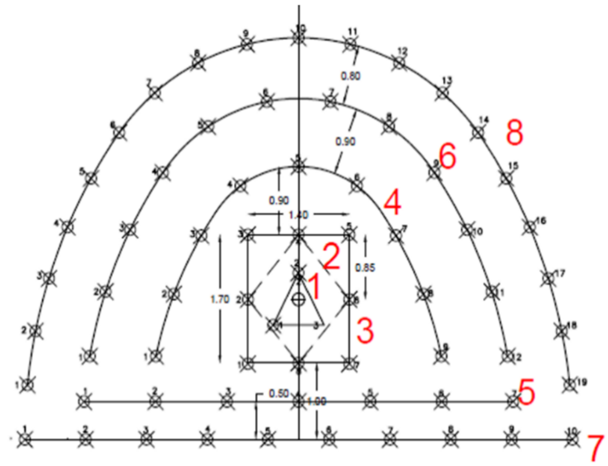

Figure 2. Blasting pattern in Miyaneh-Ardabil railway tunnels.

3. Methodology and 3D Modeling

Today, commercial software is used to simulate the blasting process using various methods. In software packages such as FLAC, UDEC, 3DEC, and PLAXIS, a blasting wave history is created in the form of a pressure-time diagram. This diagram represents the shock wave due to the detonation of the explosives. Afterward, this history is applied to the desired range or limits in the model to investigate the effect of the dynamic loading of a blasting. In the literature, other methods in addition to the above method have been proposed using hydro-codes such as ABAQUS, ANSYS, AUTODYN, and LS-DYNA. Considering the possibility of physical modeling of the material in these hydro-codes, this method can also be used for simulating the blasting process. Also, explosives are considered according to their physical and mechanical characteristics such as density and detonation velocity. To simulate the blasting process, a relation that expresses the explosion process and the resulting shock wave is necessary. This so-called equation of state is a relation between the pressure and volume of explosion products. In this respect, the Lagrangian solution method has some shortcomings, and excessive distortions occur in the model elements under loads with high strain rates such as using TNT. Therefore, other solution methods, such as the Eulerian method, Lagrangian-Eulerian coupling method, or smooth particle hydrodynamics method are used for this purpose. Finally, after investigating and comparing different numerical methods and existing software, FEM and LS-DYNA software were selected to model the blasting process in the Miyaneh-Ardabil railway tunnel.

In the dynamic loading speed, generated acceleration is usually large, and the inertial forces are significant, which are not considered in static loading. In addition, most materials show different behaviors in dynamic loading compared to static loading. In such circumstances, the circulation of the stress waves inside the material due to the high-velocity loading causes different stresses than the static state. As a result, impact mechanics must have a different approach compared to the strength of static materials. Hydro-codes are mechanical computational tools for continuous environments used for simulating the solids and fluid materials' response to dynamic loads (e.g. impact and blasting). LS-DYNA software has become one of the most powerful FEM softwares, with more than 200 types of material models and 13 types of state equations. In addition, it provides various methods for surface contact and a platform for analyzing the problems of blasting, impact, shock wave propagation, and object collision. Its reputation mostly lies in the simulation and analysis of nonlinear problems and dynamic loading using explicit FEM. This software also has implicit processing with limited capabilities that can be used to analyze structures and heat transfer in static problems. Lagrangian, Eulerian, Lagrangian-Eulerian coupling methods, and smooth particle hydrodynamics methods are among the methods available in this software. Considering the nature of the problem, the FEM-SPH coupling method was used in this study. To simulate the environment around and the rock mass, the FEM method was used. Moreover, the SPH method was used for modeling the explosive material.

Materials behavioral models are not merely outputs of some experimental data. Rather, they can express materials' mechanical and physical properties as realistically as possible. Today, many behavioral models are on the development path and are being updated to optimize numerical modeling. Behavioral models for materials with high loading rate, high strain rate, and high pressure (LHH) usually have more complex parameters, the calculation of which has been a major problem for researchers in recent years [21]. Behavioral models of materials in LS-DYNA software have different types depending on the analysis conditions, material type, and theories used in the solution. In the present numerical analysis, the strong explosive model and nonlinear kinematic plastic material model were used. Furthermore, the Johnson-Holmquist-Ceramics material model (JH-2) was used for rock materials.

High explosive material model is commonly used to model high-velocity high-explosive materials such as TNT. The model multiplies the explosion fractions of the state equation for explosive materials and controls the release of chemical energy to simulate the blasting process. Based on the explosive materials used in the Miyaneh-Ardibel railway tunnel, ANFO (i.e. the explosive material) was considered in this study as the main loading material in modeling. The explosive parameters of ANFO are given in Table 2.

Table 2. Explosive parameters related to ANFO [22].

Properties	ρ_e (Kg/m^3)	VoD (m/s)	P_{CJ} (MPa)
ANFO	850	3854	3278
ANFO	776	4084	3455

The Johnson-Holmquist material model was first proposed in 1992 by Johnson & Holmquist. The second version of this behavioral model was developed in 1994. This version performs well in modeling the mechanical behavior of brittle materials, such as ceramics, concrete, and rocks. The parameters required for the Johnson - Holmquist behavioral model are given in Table 3. These parameters are based on the Johnson - Holmquist - Ceramic (JH-2) material model relationships [23] and are determined for the andesitic rock mass around Tunnel No. 8 of the Middle-Ardabil railway.

Table 3. Parameters of Johnson-Holmquist Behavioral Model for Andesite.

Constants	Andesite	Constants	Andesite
Density (Kg/m^3)	2500	SFMAX	0.8
Shear modulus (GPa)	14.4	HEL (Hugoniot elastic model) (GPa)	4.5
Coefficient of Intact Strength A	1.21	P_{HEL} (HEL pressure) (GPa)	3.2
Coefficient of fractured Strength B	0.7	Bulk factor β	1
Strain rate parameter C	0.005	Damage factor D_1	0.005
Fractured strength parameter M	0.86	Damage factor D_2	0.7
Intact strength parameter N	0.78	Bulk modulus K_1 (GPa)	19.5
Reference strain rate	1	Coefficient of second pressure K_2 (GPa)	-23
Maximum tensile strength T (GPa)	11.15	Coefficient of third pressure (GPa) K_3	2980

The nonlinear kinematic plastic material model is a relatively simple behavioral model proposed by Lemaitre and Chaboche in 1990 for modeling the non-linear Kinematic Hardening paste behavior. This model also incorporates the nonlinear effect of Bauschinger, cyclic hardening, and ratcheting [24]. Table 4 presents the values of the required parameters in the behavioral model.

Table 4. Behavioral model parameters of nonlinear kinematic plastic [25].

Density (Kg/m^3)	Young's modulus (MPa)	Poisson rate	Initial yield stress (KPa)	Hardening kinematic modulus (MPa)	γ
1840	84.58	0.49	5.18	84.58	1814.63

An equation of state (EOS) is used for investigation the relationship of pressure and volume in hydrodynamic behavioral models. EOSs are used to calculate the pressure of these models, and their various forms can describe different material's density or volumetric expansion behavior. One of the most widely used EOS for explosive materials is JWL, which models the pressure generated by the blasting and released energy. This equation defines pressure as a function of relative volume and initial energy [21]. JWL EOS equation, as a high energy combustion model used in LS-DYNA, is given in Equation 1:

$$P = A(1-\frac{\Omega}{R_1V})e^{-R_1V} + B(1-\frac{\Omega}{R_2V})e^{-R_2V} + \frac{\Omega E}{V} \quad (1)$$

Where, P is amount of the pressure due to blasting, $V = \rho_0 / \rho_e$ is the relative specific volume of detonation products (the ratio of density of detonation products to explosive density), $E = E_0 / V$ is the specific internal energy of detonation products, A, B, R_1, R_2 and Ω are constants of JWL equation and also, E_0 is the initial specific internal energy [11].

The parameters related to the JWL for ANFO are shown in Table 5. These constants of JWL equation can be achieved by experiments. However, in present study, due to the lack of measurement instruments, these parameters are refereed to Sanchidrián et al. [22]. Moreover, details of JWL EOS in LS_DYNA, failure criterion and fundamentals of damage evolution is referred to [7, 9, 11, 22, 26-29].

Table 5. Parameters related to ANFO [22].

Properties	ρe (Kg/m^3)	A (GPa)	B (GPa)	R_1	R_2	Ω	E_0(GPa)
ANFO	850	266.799	3.435	7.037	1.159	0.39	1.731
ANFO	776	203.582	2.973	6.651	1.127	0.39	2.049

Due to the modeling limitations, only one blast hole is modeled and boundary conditions are applied accordingly. To determine the model dimensions tunnel cross-section and advance rate factors are considered. Under different boundary conditions, if model dimensions are selected about 10 times of tunnel cross-section and advance rate, the error percentage will be reduced to a minimum (less than 0.5%).

For this purpose, the model geometry is initially designed using the AUTOCAD software. Then the Hyper-mesh software is used for meshing simulation more appropriately, and easily. Figure 3 presents a schematic representation of the model.

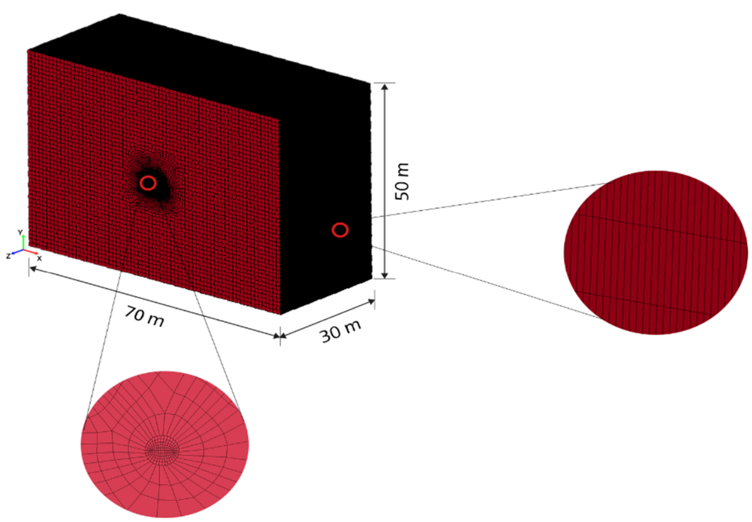

Figure 3. 3D finite element mesh.

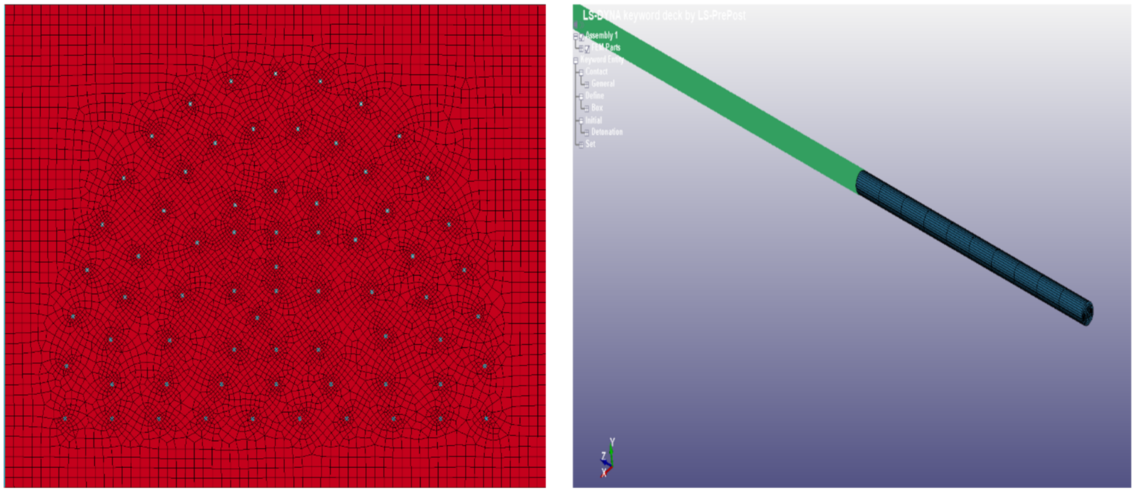

Figure 4. (a) Mesh modeling of 66 holes pattern and (b) Stemming and main charge modeling.

4. Results and Discussion

In this study, boundary conditions were considered non-reflective to bring the model closer to the real situation and prevent the reflection of the blast waves into the model within the infinite boundaries. Control parameters are also used for output controlling. The time step scale is one of the most important control parameters. For the stability of the numerical solution, the time step size for the temporal development must be smaller than the time stress wave takes to pass from the smallest lattice elements. In solving problems such as explosive loads where large deformations occur, the amount of time step changes during modeling. The time step scale coefficient for solving explosive problems is considered to be 0.67. Output parameters are also used to observe the modeling output results. D3THDT, D3PLOT and EXTENT BINARY outputs were used in this modeling. After introducing elements properties and materials behavioral models, and applying control and output parameters in LS-PrePost software, the modeling process can be performed. For this purpose, the created file (in K or Key format) is saved and transferred to the LS-DYNA software solution. Finally, after completing the modeling, the blasting process in modeling will be observable by calling the d3Plot file obtained from the software's modeling process. This modeling takes 37 days to analyze a model with 66 holes. The specifications of the heavy computing system used is given in Table 6.

Table 6. Heavy computing system specifications.

OS	RAM	Cpu
Microsoft Windows	128 GB	Intel(R) Xeon(R) CPU E5-2695 v3 @ 2.30GHz

After comparing the results of 66-hole and 19-hole models, only contour holes were modeled. The explanation is the nature of the phenomenon studied and studies conducted in this field and the lack of much difference between the results (less than 5%) [7,12]. Also, regarding the importance of the time step scale in blasting process modeling, especially using the SPH method, this value was changed from 0.67 (recommended by the software manufacturer) to 0.1 to enhance the modeling accuracy. The specifications of each model are shown in Table 7.

Table 7. Specifications of blasting models.

No. of holes	Diameter	Total number of model elements	Main charge	Model run time	Time step
66	51 mm	19800822	ANFO 850	37 days	0.67
19	51mm	6432440	ANFO 850	11 days	0.1
23	51 mm	7006445	ANFO 850	14 days	0.1
23	40 mm	6377165	ANFO 850	14 days	0.1
23	40 mm	6377165	ANFO 776	14 days	0.1

In the following, the blasting results in each model, with a tunnel cross-section and available field observations, are reviewed and compared. Figure 5(a) shows the desired cross-section for the tunnel, the cross-section of the tunnel after installation and support, and the cross-section obtained from the field observation. According to Figure 5, after recording the information related to each model in a certain area, the sections were drawn and compared with the desired section.

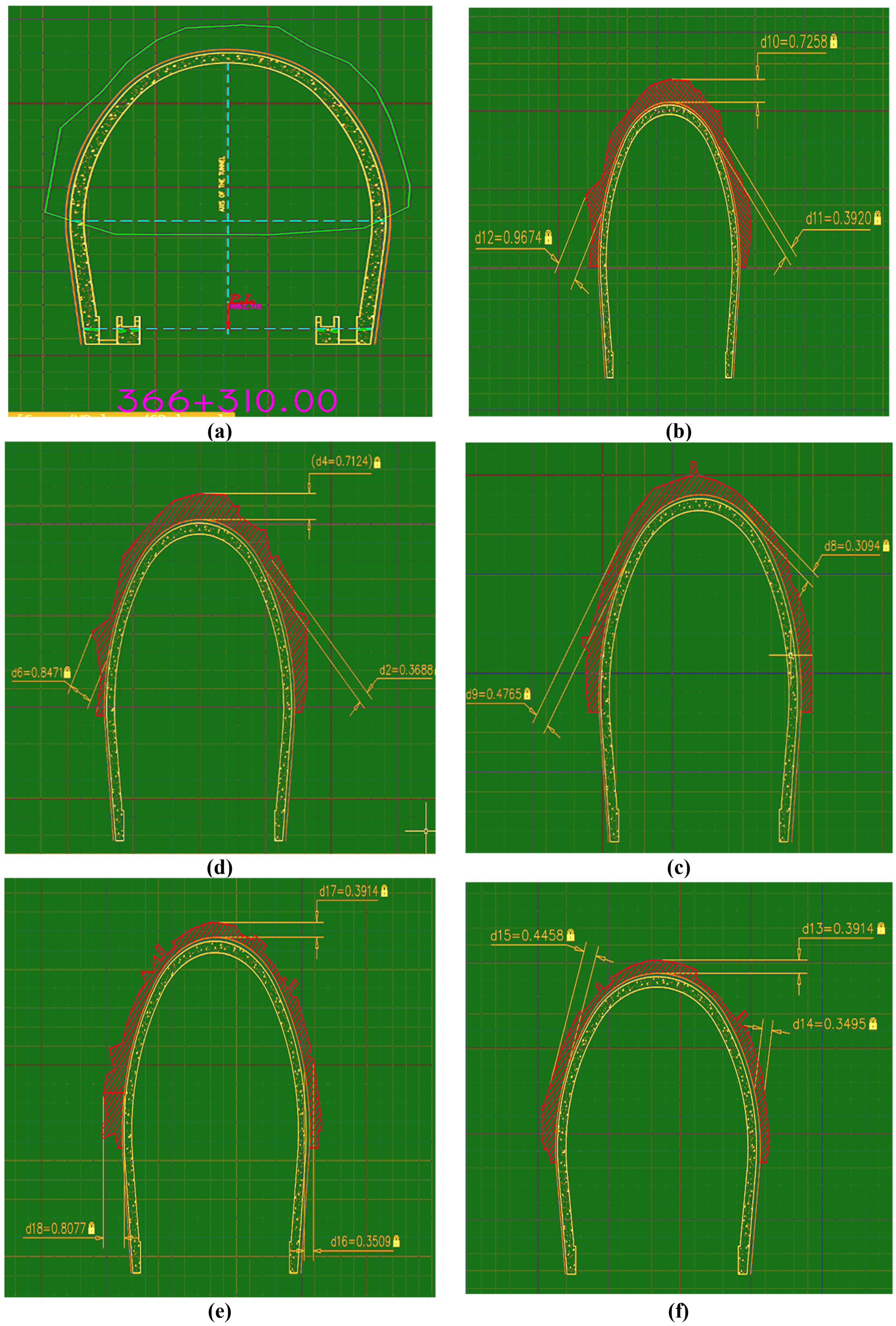

Figure 5. (a) Tunnel section and field survey information, (b) Modeling of 66 holes with the main charge of ANFO 850, (c) Modeling of 19 holes with the main charge of ANFO 850, (d) Modeling of 23 holes with the main charge of ANFO 850, (e) Modeling of 23 holes with the main charge of ANFO 850 and diameter of the hole is 40 mm, and (f) Modeling of 23 holes with the main charge of ANFO 776 and diameter of the hole is 40 mm.

Finally, obtained results by modeling the blasting operation and induced overbreak volume in this study are presented in Table 8.

Table 8. Comparison of obtained results from the modeling process and blasting in studied tunnel.

No. of holes	Diameter	Spacing	Main charge	Area of overbreak
66 holes (Tunnel section located in 310 + 366)	51 mm	76 cm	ANFO 850	8.32 m^3 (measured)
66 holes	51 mm	76 cm	ANFO 850	8.06 m^3 (simulated)
19 holes	51 mm	76 cm	ANFO 850	7.78 m^3 (simulated)
23 holes	51 mm	60 cm	ANFO 850	6.44 m^3 (simulated)
23 holes	40 mm	60 cm	ANFO 850	6.18 m^3 (simulated)
23 holes	40 mm	60 cm	ANFO 776	5.43 m^3 (simulated)

5. Conclusions

Drill and blast methods are frequently used in excavation of tunnels in hard rocks. Blasting pattern characteristics, as well as rock mass properties significantly affect the occurrence of overbreak around the tunnel. In order to reduce the blast-induced damaged zone, an appropriate blasting pattern is more important. So, from the minimum damage due to the explosives viewpoint, simulation and assessment of blasting process is favorably applied method.

Among the various methods for simulation of the blasting process, LS-DYNA software, as a software with high ability in this field, is used for simulation and the blasting analysis in the Miyaneh-Ardabil railway tunnel as case study.

The three-dimensional FEM simulation is performed by considering different patterns of blast holes including 66, 23, and 19 holes, with diameters of 40 and 51 mm, and depths of 3 to 3.8 m. The borehole pressure caused by the ammonium nitrate-fuel oil (ANFO) detonation is considered based on the Jones-Wilkins-Lee equation of state in the LS-DYNA software. The results showed the high ability of this software in simulation of the blasting process. First, by reducing the contour holes' distance, the overbreak volume around the tunnel due to blasting operation was reduced by 17%. Then, by simultaneously reducing the distance and diameter of contour holes, this value reached 20%. Finally, using the original load (with less explosive power) and reducing the distance and contour holes' diameter, the overbreak volume is reduced by more than 30%.

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ارزیابی تأثیر الگوی انفجار بر ناحیه تخریب اطراف تونل راه‌آهن میانه - اردبیل

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چکیده:

تعیین الگوی انفجار مناسب برای جلوگیری از هر گونه آسیب به محیط تونل در تونل‌سازی مرسوم با عملیات انفجار در سنگ های سخت حائز اهمیت می‌باشد. در این پژوهش از نرم افزار LS-DYNA و روش المان محدود (FEM) برای شبیه سازی فرآیند انفجار در تونل راه آهن میانه-اردبیل استفاده شده است. برای این منظور، مدل انفجار قوی و مدل مواد پلاستیک سینماتیک غیرخطی در نظر گرفته شده است. همچنین پارامترهای مورد نیاز برای مدل رفتاری جانسون - هلمکوئیست بر اساس روابط مدل جانسون - هلمکوئیست برای مواد سرامیکی بوده و برای توده سنگ آندزیتی اطراف تونل مورد مطالعه تعیین شده است. هندسه مدل با استفاده از نرم افزار اتوکد طراحی و از نرم افزار Hyper-mesh برای شبیه سازی مش‌بندی استفاده شده است. پس از معرفی خواص اجزا و مدل های رفتاری مواد و اعمال پارامترهای کنترلی و خروجی در نرم افزار LS-PrePost، فرآیند مدل سازی توسط نرم افزار LS-DYNA صورت گرفته است. الگوهای مختلف چال‌های انفجاری شامل ۶۶، ۲۳ و ۱۹ چال با قطرهای ۴۰ و ۵۱ میلی‌متر و عمق‌های ۳ تا ۳.۸ متری با روش المان محدود مورد بررسی قرار گرفته است. فشار چال ناشی از انفجار آنفو بر اساس معادله حالت جونز-ویلکینز-لی (JWL) در نرم افزار LS-DYNA در نظر گرفته شده است. به منظور جلوگیری از بازگشت موج، مرزهای بیرونی مدل غیر انعکاسی در نظر گرفته شده است. نتایج نشان داد که نرم افزار LS-DYNA قادر است فرآیند انفجار را به‌خوبی شبیه‌سازی کند. همچنین با استفاده از ماده منفجره اصلی با قدرت انفجاری کمتر و کاهش فاصله و قطر چال‌های انفجاری محیطی، حجم ناحیه تخریب اطراف تونل ناشی از انفجار بیش از ۳۰ درصد کاهش می‌یابد.

کلمات کلیدی: تونل‌سازی، روش المان محدود، نرم افزار LS-PrePost، نرم افزار LS-DYNA، ناحیه تخریب.