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Investigation of the specific charge variations in determining the optimal methods for drilling and blasting of tunnels

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Abstract
In this research, in order to compare and select the optimum patterns, two parameters of specific charge and specific drilling are used. Two explosive substances, including ammonium nitrate and fuel oil (ANFO) and Amulet, are used to charge the holes located on the cross-section of the tunnels in order to advance by 3 meters. Also, the cross-section of the selected tunnels was 19, 28, 32, 40, 48, 50, 65, and 76 square meters with horseshoe, circle and D-shaped. The diameter of the explosive hole is 48 mm for the Norwegian method and 51 mm for the two energy balance models and the Swedish method to compare them. A total of 160 designs are prepared for three types of limestone, sandstone and marl. The results obtained for two parameters of specific charge and special drilling for the selected rock material are completely opposite. Also, in the Swedish methods, according to the Amulet, the values of the calculated parameters are close to the energy balance model. Finally, according to the geomechanical parameters of the rock, for the Swedish method and the energy balance model in charging with amulet explosives, the energy balance model and the Holemberg-Persson method are proposed in the optimal design for the tunnel drilling and blasting pattern. In addition, for the Norwegian method and the energy balance model in charging the holes with ANFO, the energy balance model is prior to the Norwegian method. The amount of stemming of holes in different parts of the tunnel face is less for the Swedish method than the Norwegian and energy balance models.

Keywords
Angular and parallel cut; Specific charge; Specific drilling; Stemming; Optimum design.

Nomenclature			
ρ_r	Specific weight	A Cut	Angle Cut
v	Wave speed	P Cut	Parallel Cut
I_r	Impedance factor	EBM	Energy balance model
E	Specific surface energy	B	Burden
c	Rock coefficient	S	Spacing between the holes
RQD	Rock quality designation	σ_t	Uniaxial Compressive Strength
J_v	Number of joints	L	Advance
S_i	Distance between the joints	H	Depth of the hole
$D_{\text{charge diameter}}$	Explosive diameter	α	The angle of the holes in the cutting section
I	Density of the hole		

1- Introduction

In recent decades, mechanized tunnelling has been widely developed due to the many advantages of this method. However, despite the advantages of mechanized tunnelling methods due to the limitations of using this method, especially in terms of rock strength, the need for high investment, shape limitations, cross-sectional dimensions and tunnel curvature radius, highly skilled manpower, the method of drilling and blasting is still the dominant method for tunnel construction. The effective efficiency of the drilling and blasting method requires the design of a suitable blasting pattern, which is done in both parallel and angular cuts [1-6]. Various methods have been proposed to design the drilling and blasting pattern in both parallel and angular sections. These methods include the energy balance model with parallel and angular cutting, the Norwegian method (NTNU) with parallel cutting and finally, the Swedish method (nitronobel), which includes the Holemberg-Persson method with parallel cutting, Gustafson with angular cutting, Lopez with cutting Angular, Olafson with parallel cut and Konya with parallel and angular cut. In order to design the drilling and blasting patterns in the tunnel, since there is only one free surface, the cross-section of the tunnel is usually divided into three parts: cut, perimeter, and progress [7]. Initial explosions occur at the incision to create an opening in the tunnel cross section [8-10]. Various researchers have studied the design of the explosion pattern according to the vibrations caused by the explosion [11-13], optimization of the explosion parameters [14-16], rock throwing and the damage caused by it [17-18], the use of advanced electronic detonators [19-20] investigation of the explosion pattern in the peripheral part for the least damage to the rock mass [21-23]. Investigation of pre-failures and post-failures created in the tunnel [24-28], providing software for designing drilling and blasting patterns in the tunnel [29-30], crushing [31-33], etc. Young et al. (2020) have examined the angles of the charged holes in the cutting section (wedge cutting). The results of the research showed that due to the depth of cut, the volume of extractable rock, the size of broken rocks due to the explosion, vibration, drilling error, tunnel construction cost and other factors, wedge-cutting explosion with a slope of 65 to 69 degree can improve the rate of tunnel progress [34]. Man et al. (2018) investigated the tunnel's pattern of drilling and blasting according to the three types of designed cuts [35]. In the conducted design, cutting with parallel holes and cutting with angular holes (single wedge and double wedge) were used. The explosion results showed acceptable results for all three methods with respect to the exploitation ratio of the drilling holes. Also, the rock slag was uniform for single and wedge-cutting modes. Zhang et al. (2021) have conducted a laboratory study of the stemming of blasting holes on the size of rock fragments obtained from the explosion [36]. The test conditions were such that the holes were enclosed by steel plates around the granite sample. During the explosion, a high-speed camera was used to record the explosion process and monitor the gas emission. The conducted experiments have shown that if there is no gap between the explosive substance and the stemming (full stemming), the pieces of rock from the explosion will be smaller than when there is a gap between the explosive substance and stemming done in the hole (partial stemming). In addition, in the partial stemming done in the hole, a rapid outflow of gas from inside the explosion hole was observed. Zare'a and Bruland (2006) have studied the drilling and blasting patterns of tunnels according to Swedish and Norwegian methods with parallel cutting [37].

In both models, controlled blasting was used in the peripheral part, and a burn hole was used in the cutting part. The modelling results showed that in the Swedish method, the amount of burden in the progressive section is high. Because of this, fewer holes are used, and in the Norwegian model, the amount of charging holes is reported to be lower than in the Swedish model. Yimaz and Unlu (2013) have investigated the application of the modified Holemberg-Persson method in the design of tunnel drilling and blasting patterns [38]. The research results showed that in addition to using the modified Holemberg-Persson method in designing perimeter holes in the field of controlled blasting, this method can be used to select the appropriate combinations between the holes and the charging of the holes. Lou et al. (2020) have theoretically studied and numerically modelled wedge-shaped holes (V-CUT) and cutting aids by considering the rock properties, explosion parameters and angle of cut holes [39]. The results showed that if the length of the charging holes is less than 0.75 of the depth of the hole, there is no need to increase the area of the gap created by the cutting aid holes. Also, different rocks such as limestone, granite, shale, and sandstone have been shown to decrease the critical depth of the holes by increasing the angle of the cutting holes. Soroush et al. (2015) have studied and compared the basic parameters of the tunnel to design explosion patterns with respect to the same conditions in the diameter of the hole and the selected cross-section [40]. The design results showed that the number of holes for angular cutting was more than for parallel cutting. In addition, the specific charge for both cutting (angular and parallel) was approximately close to each other.

Previous research shows that most studies have been done in designing the tunnel drilling and blasting pattern for a specific cross-section or a part of the face. In the present research, the optimal design methods for tunnel drilling and blasting patterns are studied according to three types of limestone, sandstone and marl in 8 cross sections with different shapes for two explosives, ANFO and emulsion. A total of 160 designs were prepared without design software and regarding the 3-meter progress for comparison between methods. Also, the number of stemming holes in different parts of the face has been discussed for all methods. The diameter of the hole was 48 mm for the Norwegian method and 51 mm for the two energy balance models and the Swedish method.

2-Material and methods

2-1-Rock mass and geometric characteristics of tunnels

Table 1 shows three limestone, sandstone and marl specimens that have been used in this research. The amount of progress for all methods of designing the pattern of explosion and blasting in the tunnel was considered by 3 meters in order to compare the methods.

Tab.1. Geomechanical parameters of limestone, sandstone and marlstone

Type of rock	ρ_r $(^{kg}/_{m^3})$	v $(^{m}/_{s})$	I_r $(10^6\ ^{kg}/_{m^2 s})$	E $(^{kj}/_{m^2})$	c $(^{kg}/_{m^3})$	RQD	J_v	S_i (m)	σ_t MPa
limestone	2600	4000	10.4	1.47	0.4	65-70	3	0.4-0.7	70-80
Sandstone	2250	2750	6.19	1.18	0.4	75-90	1	1-3	20-170
Marl	2550	2500	6.37	1.10	0.4	50-90	1-2	0.3-1	50-100

In an ideal situation, the progressive value (L) is 95% of the length of the hole (H). Finally, the length of the hole in the parallel section is considered equal to 3.2 meters.

$$L = 0.95 \times H \rightarrow H = 3.2 \tag{1}$$

For angles that are proportional to the minimum angle of 60 degrees for cutting holes, the length of the hole is considered to be 3.7 meters.

$$L = Hcos\frac{\alpha}{2} \rightarrow H = 3.70 \tag{2}$$

According to Table 2, the geometric characteristics of the tunnels used in this research were horseshoe, circular and D-shaped, respectively.

***Table 2**. Geometric specifications of selected tunnels*

Cross Section (m^2)	*Tunnel Shaped*	*Tunnel Wide* (m)	*Arc height* (m)	*Arc length* (m)
76	horseshoe	15.84	6	21.33
65	horseshoe	12	5.5	20.1
50	horseshoe	11	6	18
48	D-shaped	8	2.38	9.85
40	D-shaped	7	1.7	8
32	horseshoe	7.5	5.3	15
28	circular	6	-	-
19	D-shaped	4.5	0.5	4.65

2-2-Holes charging

In this research, two explosive substances, ANFO and emulsion, are used to charge the holes. The length of the emulsion bullets used in the calculations is equal to 0.3 meters. The diameter of emulsion charges used in tunnel holes are 22, 27, 30, 35, 40 and 45 mm. According to equation (3), the charge density in the hole is calculated in proportion to the charge diameter.

$$I = A \times \rho_{Explosive} = \frac{\pi}{4} \times {D_{Explosive}}^{2} \times \rho_{Explosive} \tag{3}$$

Whereas parameter A is the cross-sectional area of the charge used, and $\rho_{explosive}$ is the density of the charge. The characteristics of the explosive substance used are presented in Table 3.

***Table 3**. Characteristics of used explosives substance*

Specific surface energy $(^{Mj}/_{kg})$	Impedance Factor $(10^6\ ^{kg}/_{m^2 s})$	Special Weight $(^{kg}/_{m^3})$	Type of Explosive
3.7	3.04	950	ANFO
4.52	5.4	1200	Emulsion

In the energy balance model, the charge diameter used in the progress and cutting section with assumed compression of charge is 48 mm in the hole, and when using the ANFO explosive, the charge diameter is considered to be the same as the hole diameter. For the Norwegian method, the charge diameter used in the hole with an explosive hole diameter of 48 mm is considered because of the use of ANFO explosives with compressed air. Also, for the Swedish methods, the amulet explosive was used to charge the holes because of different charge densities at the bottom and middle of the hole.

2-3-Drilling and blasting pattern design for a tunnel

In general, there are various methods for designing blasting patterns for tunnel faces, which are usually designed in two ways and developed with parallel and angular cuts. These methods include the Swedish, Norwegian and energy balance models. In each of the proposed methods for designing the drilling and blasting pattern in a tunnel, some advantages and disadvantages make there is no single method in tunnel blasting operations for different rock mass conditions. In the following section, the design methods for drilling and blasting patterns of the tunnel are investigated.

2-3-1-Parallel cut

The energy balance model, the Norwegian method, the Swedish method, the Holemberg-Persson method, the Olafson method, and the Konya method are among the methods defined as parallel cutting. The energy balance model (EBM) is a theoretical method that was developed based on the principle of explosion energy transfer to rock [40]. In this method, it is first necessary to determine how much energy the explosive transfers to the rock. The law of energy transfer is a function of the quality of the explosive, the energy-receiving rock (impedance factor) and the charge quality (coupling factor). In the energy balance model for the cutting section, the distance between the charge holes and the burn hole is calculated as a function of the diameter of the burn hole. So, each explosive hole should face the free surface created by the burn hole at least at an angle of 45 to 50 degrees. Also, the volume of the burn hole should have the necessary space to increase the volume of the broken rocks. In calculating the distance between the explosive holes and the burn hole created, it is assumed that the broken rocks associated with each hole must be moved before the next hole explodes. Also, since there is not enough space for the movement of rocks from the explosion, the maximum dimensions of the rocks from the explosion in the cutting section are considered to be 0.01 meters. In the Norwegian method, according to the parameter of blasting of the

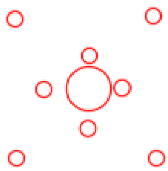
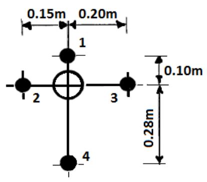
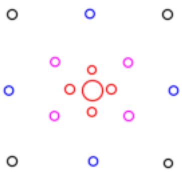
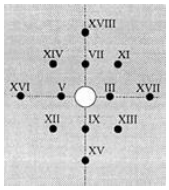
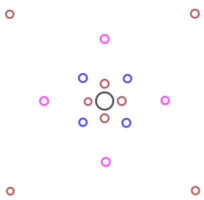
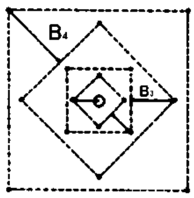
Locating cut holes in patterns	proposed pattern	Row	Reference
		**a**	[41]
		**b**	[37]
		**c**	[42]

***Figure 1**. Arrangement of holes in the cutting section. a) Energy balance model b) Norwegian method c) Swedish methods*

rock mass, to design the location of the holes in the cutting section, first, according to the length of the holes drilled in the working face, the required area for the cutting section is calculated to select the diameter of the burn hole. Then, the rock burden is calculated for the first four holes in proportion to the diameter of the burn hole. Figure 1 shows the arrangement of holes in the cutting section for the energy balance model and the Norwegian and Swedish methods. Also, for locating other holes, the burden-cutting section is determined according to the width of the free space base. In this study, according to Table 1, blasting was considered good for limestone, and blasting was considered poor for marl and sandstone. In the Swedish method, a four-section cut with parallel holes is used. Although how the rock breaks and the amount of crushing strongly depend on the type of explosive, the quality of the rock, the blasting conditions and the blasting, nevertheless, the distance from the center to the center of the blast holes and the burn hole (the first cut rock burden) can have a major impact on the result. In the Holemberg-Persson method, the amount of rock burden and linear density for the first four cut holes are calculated as Equations 4 and 5. Equation 6 is also used to calculate the burden of the remaining holes of the Holemberg method.

$$B = 1.7D_{burn\ hole} - E_p \tag{4}$$

$$I_1 = 55D_{burn\ hole}\left[\frac{B}{D_{burn\ hole}}\right]^{1.5} \times \left[B - \frac{D_{burn\ hole}}{2}\right] \times \frac{1}{PRP_{ANFO}} \tag{5}$$

$$B = 8.8 \times 10^{-2}\sqrt{\frac{x \times I_1 \times PRP_{ANFO}}{D_{explosive\ hole} \times C}} \tag{6}$$

whereas, E_p is the blasting error (m), H is the depth of the hole (m), $D_{explosive}$ hole is the diameter of the explosive hole (mm), D_{burn} hole is the diameter of the burn hole (mm), C is the rock constant, and PRP_{ANFO} is the relative weight strength of the explosive relative to ANFO. Next, Table 4 can be used to design the distance between the holes in the cutting section of the Olafson method. Also, in this method, the amount of hole density is calculated to calculate the density of the hole in the first four sections in proportion to the diameter of the burn hole and the distance from the center to the center of the burn hole with the charge holes. Then, to calculate the density of other cutting holes in proportion to the burden and the empty space created from the previous steps, the amount density of the hole is calculated.

***Table 4**. Calculations related to the cutting section in the Olafson method [43]*

Width opened	Burden	Section number
$X_1 = \sqrt{2}B_1$	$B_1 = 1.5D_{burn\ hole}$	*1*
$X_2 = \sqrt{2}B_2 \times 1.5$	$B_2 = \sqrt{2}B_1$	*2*
$X_3 = \sqrt{2}B_3 \times 1.5$	$B_3 = \sqrt{2}B_2 \times 1.5$	*3*
$X_4 = \sqrt{2}B_4 \times 1.5$	$B_4 = \sqrt{2}B_3 \times 1.5$	*4*

The Olafson method is used to design the cutting part of the Konya method. Also, in Figure 1, according to the burden calculated in each method, the location of the holes in the cutting section is done.

2-3-2-Angular cutting

The tunnel needs to be wide enough to achieve proper progress in angular cutting. If the tunnel width is low, progress is limited to 50% of the tunnel width [43]. The wedge angle in this method is at least 60 degrees, and if this angle decreases, the charge used in each hole should be increased, or a pair of V-shaped holes should be added in the direction of the depth or height of the tunnel. Figure 2 shows how to apply the burden in the cutting section of the face for design methods with angular cutting.

Row	located holes on the cross-section	Apply the rock burden
a		
b		

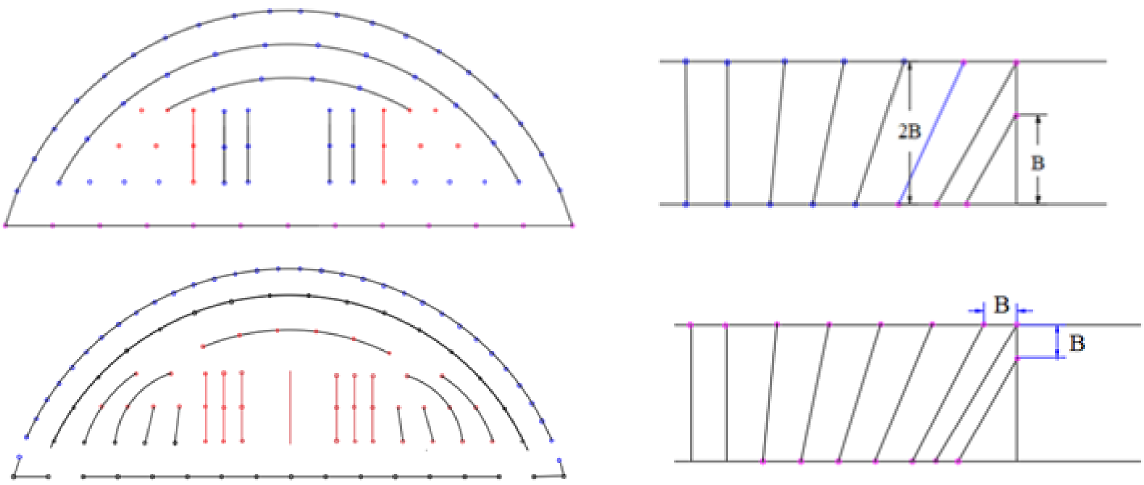


***Figure 2**. Applied rock burden in cutting sections for a) Swedish and b) energy balance models*

According to Figure 2, for Swedish methods, the rock burden is assumed to be approximately equal to half the depth of the hole in the event that, for the energy balance model, the computational burden of the cutting and advancing part is applied across the tunnel. For Swedish methods (Gustafson and Lopez), the amount of rock burden is determined by the diameter of the blast hole. For a hole diameter of 51 mm, the rock burden in the cutting section for Gustafson [44] and Lopez [41] methods is considered to be 2 and 1.73 m, respectively. In the Konya method, the rock burden is calculated according to the charge diameter, rock density and explosive substance density. Also, the inter-hole charge density for the Gustafson [44] and Lopez [41] methods is calculated as 50% of the bottom-of-hole charge. The density of inter-holes is not defined for the Konya method and the energy balance model.

2-3-3-Progressive and perimeter part

In addition to the cutting section, the tunnel face is divided into progressive and peripheral sections. In the progressive section, due to the explosion of the cutting holes, a new free surface has been created, and there is almost enough space to break the rocks; the dimensions of the largest piece of rock resulting from the explosion are considered to be 10 to 20 cm. In the energy balance model, the amount of computational rock burden in the progressive section is equal to the flanking distance between the holes. In the Norwegian method, the burden is considered to have a fixed value commensurate with the blasting ability of the rock. For the Swedish methods, the burden values for the Konya, Holemberg, and Olafson methods are calculated according to Equations 7, 8, and 9, respectively. For the Gustafson method, the burden is calculated according to the diameter of the explosive hole, and for the Lopez method, as for the Holemberg method, the amount of charge is calculated:

$$B = 0.012\left[\frac{2\rho_e}{\rho_r} + 1.5\right] \times D_{charge\ diameter} \tag{7}$$

$$B_{max} = 0.9\sqrt{\frac{q_1 \times PRP_{ANFO}}{\bar{C} \times f(S/B)}} \tag{8}$$

$$B = 0.88 \times I^{0.35} \tag{9}$$

whereas, ρ_e is the mass specificity of explosive substance (g/cm3), ρ_r is the mass density of rock (g /cm^3), $D_{charge\ diameter}$ is the explosive diameter (mm), f is correction coefficient, (S/B) is the ratio of flange distance to burden rock, C is rock coefficient, and I is considered the bottom density of the charge hole. In the perimeter part, because of the relatively large free surface due to the explosion of cutting holes and progressive holes, the largest dimension of the rock resulting from the explosion of perimeter holes is considered to be 40 cm or larger. For all design methods, emulsion explosive substances with a diameter of 22 to 30 mm were used in explosion holes with a diameter of 51 and 48 mm for less damage to the walls and roof of the tunnel. To carry out contour blasting in the perimeter sector, the diameter of the charge should be considered as 50% of the diameter of the hole or less than 50%. Also, the ratio between the flanking distance of the holes to the burden should be equal to 0.8 meters. Usually, in Swedish methods, according to the assumption of charging the whole hole, in a hole with a depth of 3.2 meters, the amount of 2.7 meters charged. According to Table 1 and rock composition, the amount of charge of environmental holes is calculated in meters for the energy balance model. In the Norwegian method, the charging density in the perimeter holes is considered to be 20 to 25% of the normal charging density [37].

2-4-Specific charge and specific drilling

Two parameters usually considered in the calculations of blasting patterns are powder factor (or specific charge) and specific drilling. These two parameters are considered to be the economic indices of blasting, facilitating the comparison of different patterns. The amount of explosive required to break one square meter or one ton of rock is the parameter referred to as the powder factor or the specific charge. The ratio of the total length of drilled holes on the tunnel face (in square meters) to the volume of the blasting-induced rocks (in cubic meters) is called specific drilling, the unit of which is meter per cubic meter. Based upon different circumstances, the specific charge varies dramatically, rising as the enclosure increases, the rock gets more rigid, and the unit of the tunnel cross-section declines [45]. The specific charge and specific drilling are in inverse proportion to the tunnel cross-section. The small cross sections, ranging from 10 to 50 square meters in area, have relatively high specific charges, as the cutting area where the charging is performed with higher density comprises a greater portion of the total cross-section. As the tunnel cross-section increases, the ratio of the cutting area to the total area of the tunnel face falls, and a greater percentage of the tunnel is charged using less substance, hence lessening the specific charge.

3-Results and Discussion

3-1-Energy balance method

Figure 3 shows the charts for the energy balance model based on the cross sections of the chosen tunnels for parallel and angular cuts using two explosives. In order to facilitate the comparison of different states in the energy balance method, the same charging conditions in different parts of the tunnel face are applied in all the chosen cross sections, involving the hole diameter, the hole length and the hole angle in the cutting area. In all charts drawn in this figure, ANFO with the angular cuts for the limestone has the maximum amounts for consumable charge, the number of holes, the specific drilling and the specific charge. Given the parameters in Table 1, in Figure 3(a), the charts pertaining to marl and sandstone are close to each other, and the values of the limestone charts are greater than those of the other two. Moreover, in Figure 3(b), for a tunnel cross-section ranging from 15 to 50 square meters, the results of the Energy Balance Model for both parallel and angular cuts with two explosives are very similar.

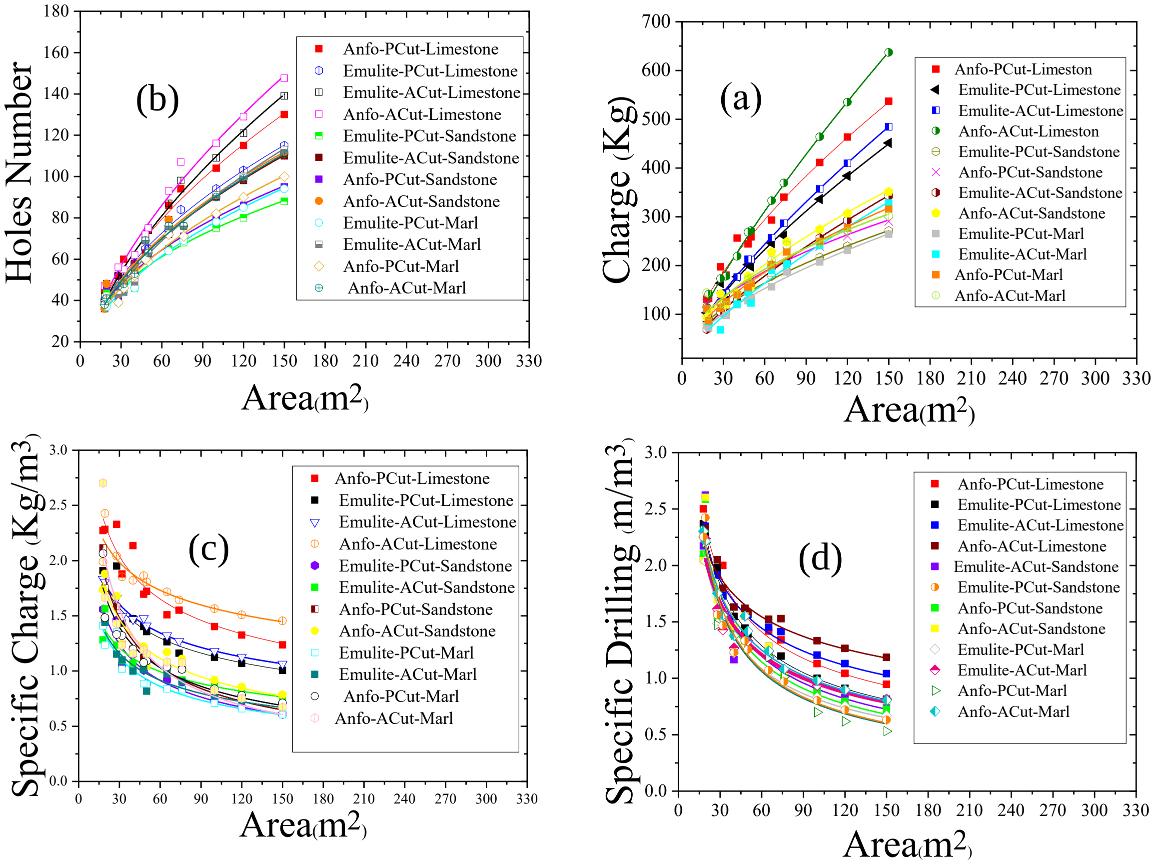


***Figure 3**. Chart of the Energy Balance Model based on the cross-section a) consumable charge b) number of holes c) specific charge d) specific drilling*

This is because, on the small cross-sections relating to a variety of tunnel forms, the values for the rock charge and spacing do not alter notably, resulting in equal numbers of the located holes on the tunnel cross-section for all the states considered in this method. Also, for the cross sections whose area is over 50 square meters, the rock charge and spacing between the holes for the limestone are smaller than those of the marlstone and sandstone, and more holes will thus be located on the cross sections containing limestone. Figures 3(b) and 3(c) represent different values for different states of the energy balance model when the cross-section area is between 15 and 50 square meters. Regarding Table 1, the specific surface energy and impedance factor for the limestone are bigger in relation to the marl and sandstone, so it can be said that in the energy balance model calculations, the number of holes, consumable charge and specific charge in the drawn charts will be greater for the limestone. In Figure 3(d), the falling trend of the specific drilling based on the cross section, has depicted a variety of rocks. The maximum and minimum values of the specific drilling for the explosive ANFO with angular cutting for the limestone and parallel cutting for the marl have been drawn, respectively.

3-2-Norwegian method

As shown in Figure 4, the values for the specific drilling, specific charge, consumable charge, and the number of holes based on the Norwegian method with parallel cutting for the limestone are less than those for the marl and sandstone. Regarding the fact that in this method, the rock mass blastability is used to measure the rock charge and the hole spacing, for the limestone with acceptable blastability, a smaller number of holes are located on the tunnel cross-section. That is why the results derived from the Norwegian method are completely in contrast to those observed in the energy balance method. Moreover, the rock explosiveness index was measured using laboratory tests conducted on small scales of rock samples. These tests might lead to acceptable results for the rocks without joints, such as mass granites, which are often found in Scandinavia. However, the small-scale laboratory tests do not manifest the properties of heterogeneous mass rocks with joints [46]. For this reason, Zare (2007) suggested that when the degree of fracture is very high, or the fracture is open, the explosiveness is expected to be weaker [46]. Moreover, when the joints are parallel or almost parallel to the tunnel, the explosiveness of the rock mass declines [46].

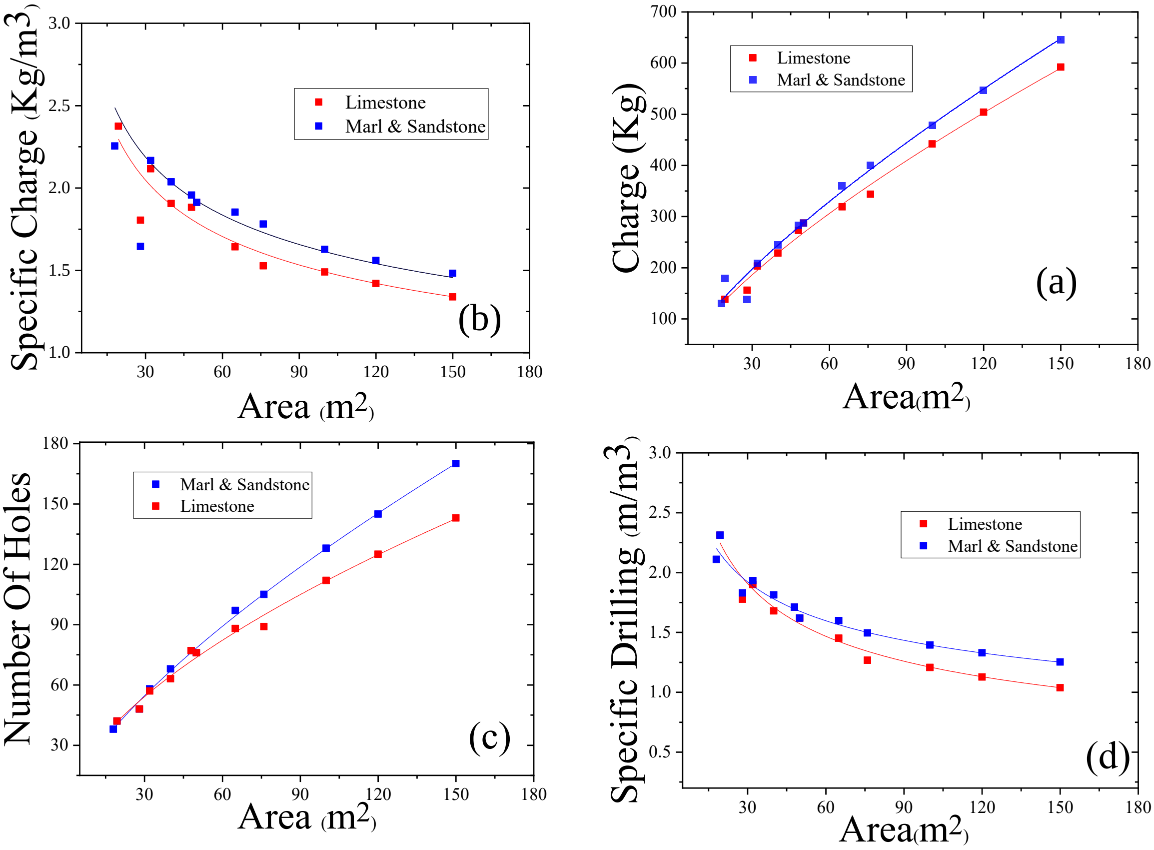


***Figure 4**. Charts of the Norwegian method based on the cross-section a) consumable charge b) specific drilling c) number of holes d) specific drilling*

3-3-Swedish methods

The charts relating to Swedish methods are drawn in Figure 5, with regard to the tunnel cross section for the explosive of emulsion. As the densities of bottom charges and column charges are not equal in this method, the charging has been done using only the explosive of Emolite. In Figure 5(a), the consumable charges for three methods, including Konya with angular cuts and Olafson, are almost equal, being the maximum. The consumable charges of Lopez and Holemberg are also nearly the same and minimum. For the cross sections between 10 and 50 square meters wide, the consumable charges of all methods are almost the same. Considering the results from Figure 5(a), in Figure 5(b), Konya and Olafson's methods have the highest values of the specific charges, and Holmberg and Lopez feature the lowest. In the diagram shown in Figure 5(c), the numbers of holes are almost equal for the two methods, Konya with parallel cut and angular cut, and also the maximum numbers of holes on cross sections pertain to Olafson with parallel cut, Gustafson with angular cut, Lopez with angular cut and Holemberg with the parallel cut. Finally, looking at Fig 5(d), the maximum value of the specific drilling is first related to the Konya method and then to Gustafson, Olafson, Lopez and Holemberg.

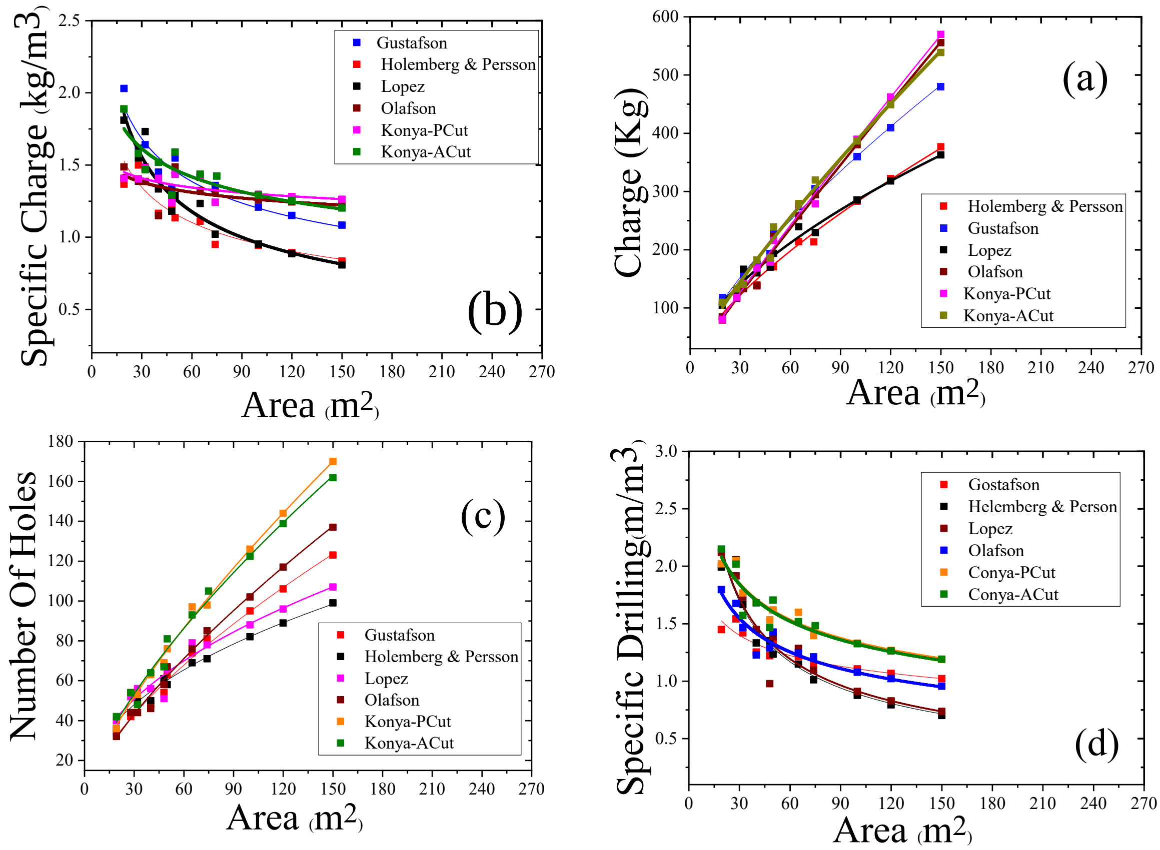


***Figure 5**. Charts of the Swedish methods based on the cross-section a) consumable charge b) specific charge c) number of holes d) number of specific drillings*

3-4-Stemming

One of the main functional parameters frequently used in different drilling and blasting methods in tunnels is stemming, quantified for each hole located in different parts of the tunnel face. In the Norwegian method, the amount of stemming in different sections of the tunnel face is defined as a function of the hole length [37]. In this way, stemming equals 10 per cent of the hole length for the cutting and bottom section, and for the other section, it is defined as 30 per cent of the hole length. Moreover, the quantity of stemming in most of the proposed approaches in the Swedish method is said to be 10 per cent of the blast hole [37]. For the energy balance method with parallel and angular cuts proportional to the location of Emolites in the hole, there has been no mention of the quantity of stemming in the holes. Figures 6 to 8 calculate the stemming values for different parts of the tunnel face. The shape diameters indicate the quantity of stemming, and the numbers ranging from 19.38 to 150 represent the tunnel cross section in square meters. Since the values of stemming for marl and sandstone are so close, a comparison of stemming parameters was drawn for limestone and sandstone.

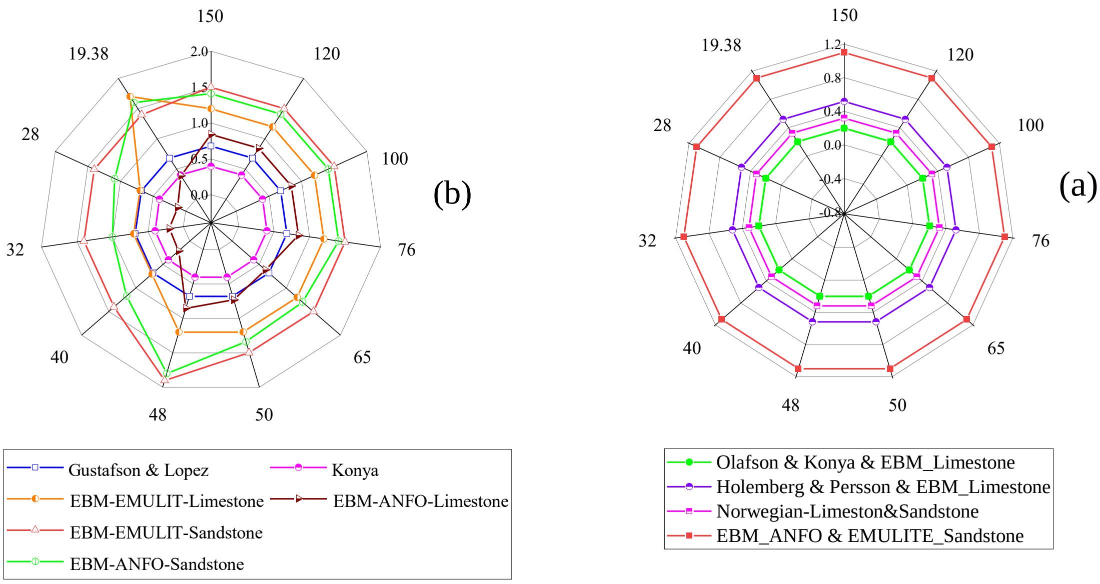


Figure 6. Stemming the holes in the cutting area a) parallel cut b) angular cut

In Figure 5(a), the minimum value of stemming proportional to parallel cut was calculated for three methods, including Olafson, Konya, and energy balance, with ANFO as the explosive. The maximum amount of stemming relating to the energy balance method with the explosives ANFO and Emolite has also been calculated for the sandstone. Furthermore, the results prove that the maximum values of stemming belong to Norwegian, Holemberg and energy balance methods with Emolite for the limestone, respectively. In part b, given the angular cuts, the amount of stemming varies for different tunnel cross-sections. The maximum stemming relates to the energy balance method for the sandstone using Emolite. For the Swedish methods with angular cuts shown in Figure 6(b), Konya indicates a lower stemming in relation to Gustafson and Lopez. Besides, in the energy transmission method, the stemming for the limestone and using Emolite is more than that using ANFO as the explosive. In Figure 7, the diagram illustrating the amounts of stemming for the holes around has been created using a variety of drawing techniques. Also, in the peripheral section, in order to lessen the damage to the walls and roof, Emolite, with a diameter between 22 and 30 millimeters, has been utilized instead of ANFO. According to Figure 7, the quantity of stemming for all the Swedish methods is considered to be the same at 0.5 m. The Swedish methods also need the minimum stemming in the peripheral holes. The stemming for the Norwegian method is more than for the Swedish methods. It can be seen that the stemming in the peripheral area for the energy balance method on the cross sections 50 to 150 square meters wide is more than the corresponding amounts for the Swedish and Norwegian methods.

Lastly, the maximum and minimum quantities of stemming in the peripheral area belong to the energy transmission and Swedish methods, respectively. Figure 8 indicates the quantities of stemming for the front part using parallel and angular cuts. In part a, the amount of stemming for the Swedish methods is less for the angular cuts than for the energy balance method. For the cross sections between 20 and 65 square meters wide, the stemming for the energy balance method using ANFO and sandstone has the highest value calculated so far. In Figure 8(b), the quantity of stemming in the holes of the front part with parallel cuts for the Swedish method is less than that for the Norwegian and energy balance methods.

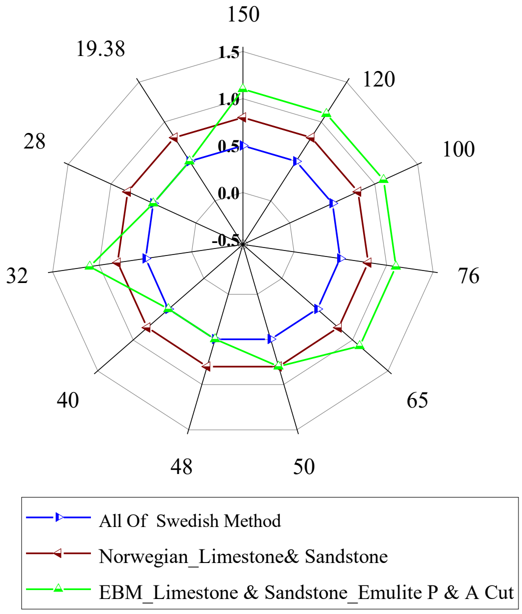


Figure 7. The quantity of stemming for the holes in the peripheral area using different methods for limestone and sandstone

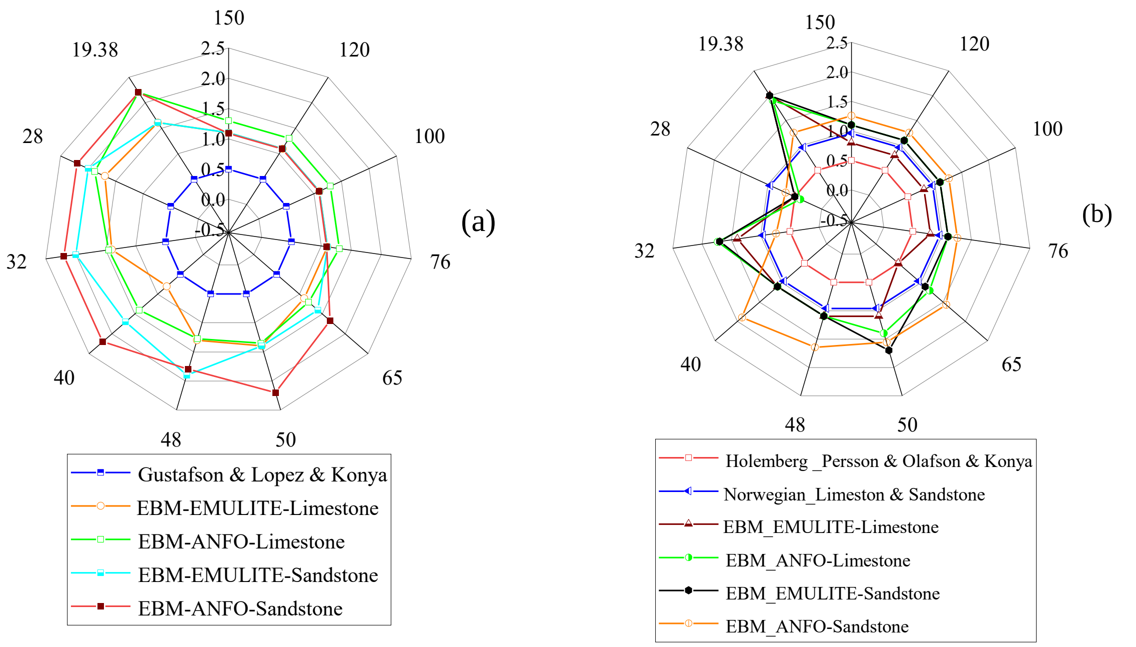


Figure 8. The quantity of stemming in the front part of the tunnel for the limestone and sandstone a) angular cut, b) parallel cut

3-5-Results comparison for drilling and blasting patterns methods

One of the paramount points in the Swedish methods is that charging occurs all over the length of the hole. Besides, unlike the energy balance and Norwegian methods, the rock texture is not taken into account in Swedish methods. That is why, for different types of rock, only one design is implemented for each cross-section. On the other hand, in the energy transmission method, different methods are used for each cross-section of different rocks with regard to the rock charge and spacing. The numerical values of the specific charge for the energy balance and Swedish methods are almost the same. Furthermore, comparing two methods, the Norwegian and energy balance model with ANFO, it was observed that the values of the specific charge for the Norwegian method were more than those for the energy balance method when the cross sections are large-scale (between 48 and 150 square meters). The values for the specific drilling in the energy balance and Norwegian methods with the explosive ANFO (limestone) are close to each other. For the marl and sandstone, the value of the specific drilling for the Norwegian method is more than for the energy balance method. Comparing the energy balance and Swedish methods, the values of the specific drilling are almost equal. Outlining the factors affecting the results of designing methods in parallel cut, it can be referred to the blast hole diameter, the charge diameter, the empty hole diameter, the hole length and the type of explosive used. In the methods for designing drilling and blasting patterns, the changing diameter is set equal to the hole diameter in the cutting and front sections. The empty hole's diameter for the energy balance method with parallel cut has been set to 102 millimeters, whereas for the Norwegian method, the diameter and the number of empty holes are calculated based on the hole length and the rock blasting capability. For the Swedish methods, the empty hole diameter is of paramount importance when determining the distance between the holes. In this research, the empty hole diameter is assumed to be 102 millimeters for the Swedish method.

4-Optimal pattern selection for a tunnel

A controversial issue in civil and mining engineering is how to find the optimal drilling and blasting patterns in the tunnel. One of the principal parameters used to seek an optimal pattern is the specific charge, which facilitates the comparison of different patterns. As the specific charge has direct associations with ground vibration, perimeter damage, over breaks and underbreaks, advance and grinding, it is required to work out its value in order to optimize the drilling and blasting patterns. Considering Figure 9(a), when contrasting the Swedish and energy transmission methods with Emolite as the explosive, in proportion to the specific drilling different values, it can be said that the lower the values of the specific surface energy and impedance factor are, the more the energy balance method is preferred to the Swedish, and as two parameters, the specific surface energy and impedance factor rise, Holemberg-Persson method gets more desirable than the energy balance model. In addition, Gustafson's method calculates a greater amount of the specific charge than all the Swedish and energy balance methods. For the methods, Lopez, Olafson and energy balance with the limestone, the values of the specific charge are very close, and considering the constraints existing for the methods, each of these methods might be used to design the drilling and blasting patterns for different cross sections. In Figure 9(b), the chart indicates the specific charges based upon the specific drillings for the energy balance and Norwegian methods using limestone. Given Table 1 and the parameter blastability, the values calculated for both methods are almost equal when the limestone is used, and no notable discrepancy is observed in their corresponding charts.

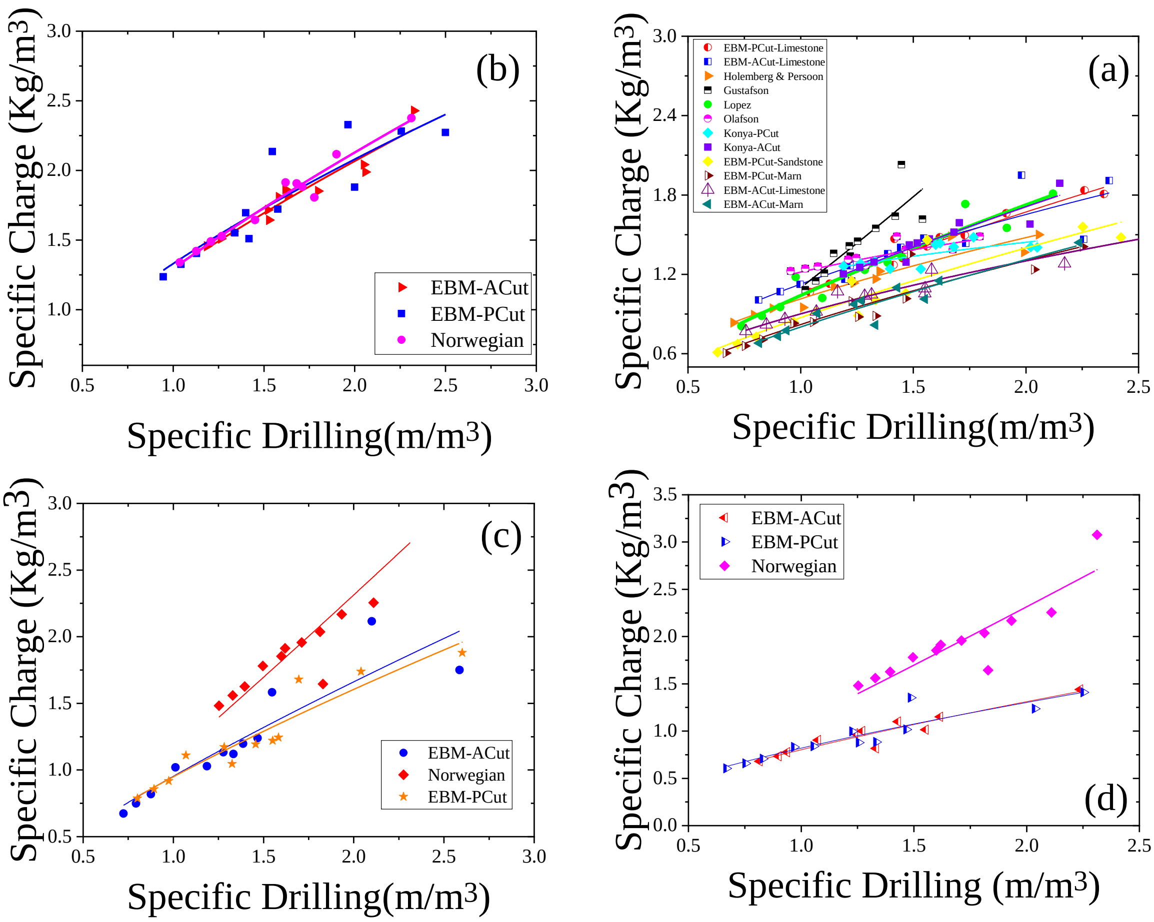


***Figure 9**. Specific charge vs. specific drilling a) Swedish and energy balance methods with Emolite as the explosive b) energy balance and Norwegian methods with ANFO in limestone c) energy balance and Norwegian methods with ANFO in sandstone d) energy balance and Norwegian methods with ANFO in marlstone*

For charts (c) and (d), when the rock in the energy balance method possesses a lower impedance factor and specific surface energy compared to limestone, a significant difference exists between the specific charges of the energy balance and Norwegian methods. In the Norwegian method, when the blastability is weak, more holes can be located on the cross sections. On the other hand, for the energy balance method, in accordance with the Norwegian method's prerequisites, a smaller number of holes are located on the tunnel cross-section. Considering the blastability of marlstone and sandstone, energy loss is more likely in this method in relation to the energy balance method. Because of this, the energy balance method is always preferred by the Norwegian when designing drilling and blasting patterns in the tunnel. Generally, when charging using Emolite, two methods of Holemberg-Persson and energy balance are suggested, and using ANFO as the explosive during charging, the energy balance method is used rather than the Norwegian method.

5-Conclusion

In the construction of a tunnel using explosives, a number of parameters must be taken into account, including advance rate, overbreak and underbreak, ground vibrations, the decline in the specific drilling and specific charge, rock fragmentation, prevention of secondary detonations etc., all of which can be easily optimized using an adequate drilling and blasting pattern. In this research, using the approaches for designing the drilling and blasting patterns in the tunnels, the parameters such as the specific charge, the specific drilling, the amount of the required explosive and the number of holes on different cross sections shaped like horseshoe, circle and D are calculated. These parameters are the general indices of blasting, which simplify the comparison of different patterns. The results indicate that in the energy balance method with angular cut, the consumable charge, the specific charge, the number of holes and the specific drilling are greater than when the cuts are parallel. In the Norwegian method, regarding the rock mass blastability parameter, the results are in contrast to the energy balance method using the aforementioned rocks. One of the reasons we can refer to is the large number of holes located on the tunnel cross sections using rocks with low blasting power. When implementing the Swedish and energy balance methods with the explosive Emolite to design optimal drilling and blasting patterns in the tunnel, two parameters of specific surface energy and impedance factor take part. When the values of these two parameters are bigger for a specific rock texture (limestone), the Holemeberg-Persson methods are preferred for the design, and if their values are trivial for the rock (marlstone and sandstone), the energy balance method is preferable. Amongst the two methods, energy balance and Norwegian, the energy balance is more acceptable than the latter. Finally, the value of stemming in all the Swedish methods is less than in the Norwegian and energy balance methods.

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