[Mansoura Engineering Journal](https://mej.researchcommons.org/home)

Volume 30 | Issue 3 Article 3

9-1-2021

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Recommended Citation
Belal, Adel (2021) "Rational Analysis for Vertical Side Wall Rock Tunnel Response Subtected to under Ground Explosion Load.," *Mansoura Engineering Journal*: Vol. 30 : Iss. 3 , Article 3.
Available at: https://doi.org/10.21608/bfemu.2020.131594

RATIONAL ANALYSIS FOR VERTICAL SIDE WALL ROCK TUNNEL RESPONSE SUBTECTED TO UNDER GROUND EXPLOSION LOAD

التحليل باستخدام علاقات منطقية للأنفاق الصخرية ذات الحوائط الرأسية نتيجة لتعرضها لأحمال تفجيرية أرضية

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ملخص البحث.

إن عملية تطوير واستنباط طرق تصميم الأنفاق في التربة الصخرية يتطلب دراسة وفهم لتأثير المتغيرات المختلفة المؤثرة على إنشاء الأنفاق. ولاستكمال عملية التصميم يجب الحصول على قيم وأشكال تقديرية للإجهادات والهبوط حول فتحة النفق . ولتحقيق ذلك يجب القيام بعمل نماذج رياضية يتم من خلالها دراسة المتغيرات المختلفة التي تؤثر على الأنفاق المعرضة لتفجيرات مختلفة ، علما بأن استخدام البرامج الجاهزة لهذه الأغراض يحتاج إلى تكلفة مادية عالية . وفى هذه المقالة تم استنتاج معادلات بسيطة لنفق ذو قطاع رأسي (Vertical side wall) اعتمادا على تحليل النتائج التي تم الحصول عليها من دراسة المتغيرات المختلفة التي تتم على النفق باستخدام طريقة العناصر المحددة بواسطة برنامج (AUTODYN) حيث أنة من أوسع البرامج المستخدمة في دراسة تأثير المفرقعات على المنشات المختلفة انتشارا. المتغيرات التي تم أخذها في الاعتبار في هذه الدراسة هي : بُعد المفرقعات عن النفق& أنواع الصخور المختلفة وأبعاد فتحة النفق .

ABSTRACT

Development and evaluation of a reliable explosion non-linear dynamic design method for rock tunnel systems require a through understanding of the parameters affecting the tunnels. Also, it is necessary to estimate the value and distribution of the stresses, deformations and damage that are likely to occur due to the expected explosion load. Accurate modeling of the complex tunnel response requires a large number of constitutive parameters, which are often difficult to integrate into an analytical or semi-analytical closed form formulation. Also, the non-linear computational simulation procedures need very expensive and complicated codes to perform the required non-linear dynamic analysis. Nevertheless, a major need still exists for alternative simple approaches to estimate the different responses of tunnels. In this study, simple equations have been developed for different responses of vertical side wall rock tunnel in different rock types based on a regression analysis of the results of a parametric study. This parametric has been performed for a tunnel in rock media under explosion loads. The main parameters that have been taken into consideration are type of rock, depth of tunnel, and tunnel span for constant weight of explosive charge. The numerical analysis of this study is carried out using finite element technique, the commercial software package AUTODYN 4.3 is used to perform three-dimensional nonlinear dynamic analysis used in this study. This program is probably the most extensively code dealing with explosive loads.

Key Words: Finite Element, Under Ground, Explosion Wave, Rock Soil, Tunnels

Accepted August 23, 2005.

1. MODEL CALIBRATION

In order to calibrate model results, a preliminary selected problem studied. The finite element package is used to create finite element models for the field test problem [7] as shown in Fig.1. A three-dimensional F.E. model is created for the same field test problem by using RHT. material model [3]. The transmit boundary condition is applied, and load cases are applied to this model as illustrated in Figure2. The field layout, as shown in Fig. 1, consists of a step charge hole with a total depth of 11m. The upper 6m of the charge hole has a diameter of 1.6m and the bottom 5 m has a diameter of 0.8m. The measuring point was placed at 25m distance from the eharge hole center. The test is carried out with an equivalent TNT charge weight 50 kg. The reliability of RHT material model performance has been demonstrated by its implementation into the commercially available soft ware. It exhibited qualitatively correct behavior to simulate the rock mass under explosive loading compared with measurements of field test problem and three-dimensional model agrees well with the field measurement as shown in Figure 3.

2. PARAMETRIC STUDY

A parametric study has been performed for a tunnel in rock media under explosion load. The main parameters that have been taken into consideration are; (1) Rock type, (2) Tunnel depth (location under ground surface), and (3) Tunnel span. These parameters have a great influence on the stresses and deformation in rock, and also internal forces in tunnels. In order to perform this parametric study a complete non-linear analysis has been accomplished for a three-dimensional finite element model. The rock media is assumed to be continuous, isotropic and homogeneous medium. RHT brittle material model is used to represent the non-linear dynamic response of rock [5].

2.1 Material Properties:

Table (1) provides the parameters values for the three rock classifications, hard, moderate and poor rock adopted in this study. Values of mechanical properties presented in the previous table were determined from numerous references [4] [6].

2.2 Tunnel Dimensions:

In order to demonstrate the effect of tunnel span (S) on the response of tunnel, three radii are used in this study; 6m, 9m, and 12m. Also, the effect of crown-detonation distance (D) are studied by using three distances between charge and tunnel crown; 10m, 15m and 20m as shown in Fig. 4

2.3 Model Description:

Fig. 5 shows the F.E. Mesh that is used in this study. Due to the symmetric conditions of this problem and to reduee the running time of the model, only a quarter of the domain is taken as a computation model. The model dimensions in the X and Y-axes are 5R and 7.5m respectively. The non-reflection boundary is given by transmitting the boundary conditions at ambient rock masses, the plane X=0 and Y=0 are treated as symmetric boundary. The number of elements that used in this model is presented in table (2) for all cases.
For all cases an explosive is located at 3m-distance bellow ground surface. Three points, crown, spring and invert point are used to study the displacement and internal forces.

3. RESULTS AND DISUSSION OF PARAMETRIC STUDY

To evaluate the effect of different parameters on the dynamic response of the vertical side wall tunnel under explosion load, a complete comparison between the dynamic responses of different models using different parameters is performed. This evaluation is based on damage indices of the rock media around the tunnel. These indices are, peak displacements and plastic strain time histories at three points crown, spring and invert.

3.1 Peak Displacements:

Fig. 6 shows the peak displacements at crown-point, when the D distance increase from 10m to 20m:

(1). For poor rock case the peak displacement reduce to 17%, 12% and 12% for R equal to 3,4.5, and 6m respectively.

(2). For moderate rock the peak displacement reduce to 24 %, 17% and 13% for R equal to 3, 4.5, and 6m respectively.

(3). The peak displacements for hard rock decrease to 34%, 17% and 12% for R equal to 3,4.5, and 6m respectively. Fig.7 shows the peak vertical displacements at spring and invert points. These displacement are small compared to the tunnel crown displacement especially for small distance D.

3.2 Plastic Strain Time History

Fig. 8 to Fig. 10 show the general response of the twenty-seven models. From these figures, the intensive radii of damage zone are about 9m for hard rock, 10m, and 13m for moderate and poor respectively. The damage zone reaches the upper part of the tunnel in the following cases:

(a) If distance D is less than 10m for any roek type

(b) If distance D is less than 15m for poor rock case

This damage level indicates excessive crack in the rock mass and possible failure of rock masses. That means, when the plastic strain excesses the failure strain, damage will occurred.

Fig. 11 shows the plastic strain time history at crown-point. From these figures, we can note that:

(1). For any span and any rock type, the plastic strain excesses the failure strain if D distance is little than 10m

(2). For D distance equal to 15m or less, only poor rock reaches failure strain at any span .

(3). If distance D equal to 20m or greater for all radii and rock type, the plastic strain does not reach the failure strain

4. NONLINEAR REGRESSION ANALYSIS

The commercial software Data Fit is used to determine the best-fit parameters for a model by minimizing a chosen merit function. The process is to start with some initial estimates and incorporates algorithms to improve the estimates iteratively. The new estimates then become a starting point for the next iteration. These iterations continue until the merit function effectively stops decreasing Analysis for rock displacements and plastic strain are performed.

4.1.1 Peak Displacement

The predicted equations for peak particle displacement of tunnel at crown and invert can be determined in the vertical direction as explained in table (3). However the predominant effect of the horizontal displacement is at the spring and can be determined from the same table. A comparison between the result of the predicted equations and FE-results is shown in figure (12) for all cases.

The predict equations of displacement at failure time are shown in table (4). The comparison between results of this equations and FE-results are shown in figure (13).

4.1.2 Peak Strain

Table (5) explains the predict equations of peak strain for different rock type.

5. CONCLUSION

Simple equations for estimation the displacements and strains of vertical side wall rock tunnel in different rock types have been developed. The estimating values computed by these equations showed a good agreement with the results of the Finite element complicated models.

The parametric study shows that, 10m crown-detonation distance for any rock type is not sufficient to secure the tunnel against high explosives, where the tunnel lining is essential in this case, but in case of 20m, rook thickness is enough to resist high load explosion for any rock type with any tunnel span. In the 15m crown-detonation distance cases, the depth of rock is enough to resist high load explosion for moderate and hard rock types and suffered from a remarkable damage level in poor rock case.

Also, this study shows that the intensive radius of damage zone depends on rock type and ductility of the rock not on tunnel span. The displacement at spring and invert point can be neglected compare with crown displacement.

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Table (1) Rock properties used in the parametric study

Rock Type	Rock Quality Design (RQD) %	Rock Mass Ratting (RMR) %	Density γ t/m^3	Modulus of elasticity E Gpa	Poisson ratio ν	Bulk Modulus K Gpa	Shear Modulus G Gpa	Unc. Com. Strength Mpa	Failure Strain
Hard	90	85	2.75	70	0.23	43.21	28.45	100	0.0025
Mod.	50-75	65	2.4	30	0.25	20	12	25	0.005
Poor	25-50	44	2.21	8.5	0.3	7.083	3.27	10	0.0075

Table(2) Number of elements in vertical side wall section FE model

D (m)	Tunnel span R(m)	Number of Rock solid element (lagrang)
10	6	38760
	9	42330
	12	44370
15	6	59220
	9	64155
	12	66975
20	6	75900
	9	81675
	12	84150

Table (3) the peak displacement of tunnel crown, spring and invert

Rock type	Vertical displacement at crown (cm)	Error %	Eq. No.
Poor	$\delta_{crown} = 2.406.e^{\frac{30}{D}}.\frac{R}{D}$	3.7	(1)
Moderate	$\delta_{crown} = 0.6385.e^{\frac{30}{D}}.\frac{R^{0.8}}{D}$	11.45	(2)
Hard	$\delta_{crown} = 0.2395.e^{\frac{30}{D}}.\frac{R^{0.8}}{D}$	20	(3)
General	$\delta_{crown} = 18.14.e^{\frac{30}{D}}.\frac{R^{0.8}}{D}.\frac{1}{(0.3E+0.9)^{1.4}}$	12.1	(4)
	Vertical displacement at spring (cm)		
General	$\delta_{spring} = 5.97\frac{1}{e^{0.0051D+0.331R+0.036E}}$	19.3	(5)
	Horizontal displacement at spring (cm)		
General	$\delta_{H-spring} = 1.377\frac{e^{0.119R}}{e^{0.1D+0.02E}}$	22.5	(6)
	Vertical displacement at invert (cm)		
General	$\delta_{invert} = 5.06\frac{e^{0.0126D}}{e^{0.45R+0.028E}}$	0.104	(7)

Table (4) the failure displacement at tunnel crown

Rock type	Failure displacement at crown (cm)	Error %	Eq. No.
Poor	$\delta_f = 9.367.e^{-\frac{3.411}{R}}$	0.167	(8)
Moderate	$\delta_f = 1.086.e^{0.098R}$	0.49	(9)
Hard	$\delta_f = 0.634.R^{-0.012R}$	12.2	(10)
General	$\delta_f = -0.829 + 1.134R + \frac{24.75}{E} - 0.547\log(R^2) - \frac{276.5}{E^2} +$ $32.11\frac{\log R}{E}$	0.5	(11)

Table (5) the peak strain at tunnel crown

Rock type	The strain at crown (cm)	Error %	Eq. No.
Poor	$\varepsilon_{crown} = 1880.D^{-4.6856}.1.158^{R}$	4.9	(12)
Moderate	$\varepsilon_{crown} = 6408.D^{-5.66}.R^{0.29}$	11.1	(13)
Hard	$\varepsilon_{crown} = 0.0452 - 0.005D - 0.00078R + 0.000154D^2 + 0.000316R^2$ $-0.0001D.R$	7.4	(14)
General	$\varepsilon_{crown} = 2.8\frac{e^{0.14.R}}{e^{0.377D+0.056E}}$	20	(15)

Where:-

δ_{crown} : Peak displacement at tunnel crown

δ_{spring} : Peak displacement at spring

δ_{invert} : Peak displacement at invert

δ_f : Failure displacement at tunnel crown

ϵ_{crown} : Peak strain at tunnel crown

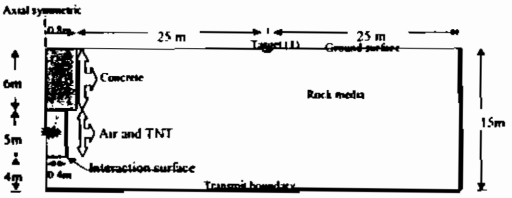


Fig .(1) Layout of test model

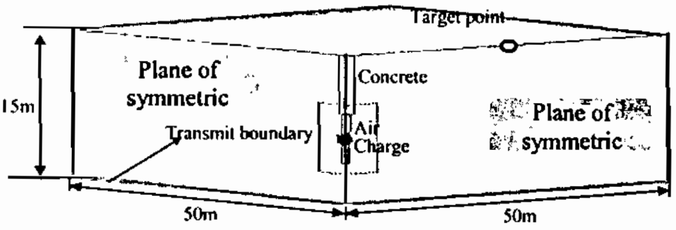


Fig. (2) 3D F.E. Mesh

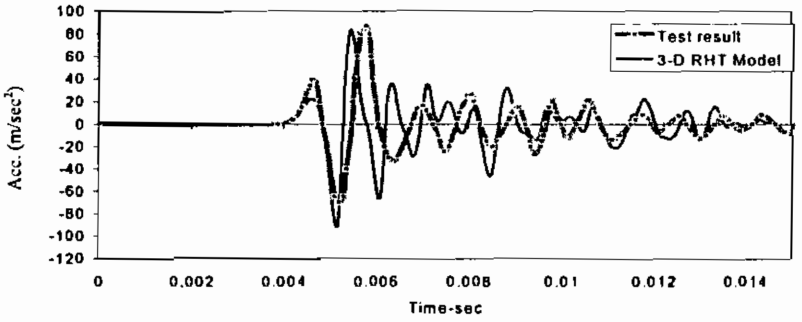
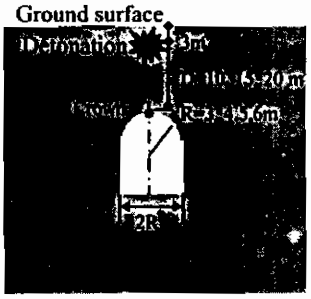


Fig. (3) Test versus finite element F.E, 2-D and 3-D. with RHT model response for horizontal acceleration at target point location



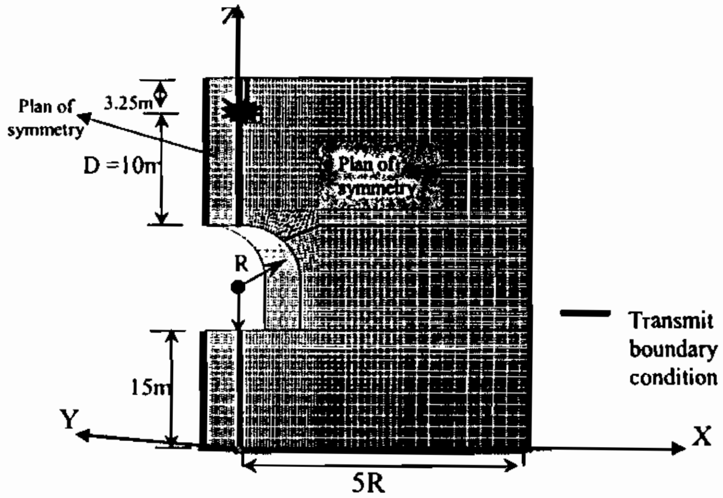


Fig. (4) VSW section of tunnel

Fig. (5) ATOUDYN-3D FE Mesh Vertical Side Wall Section Tunnel

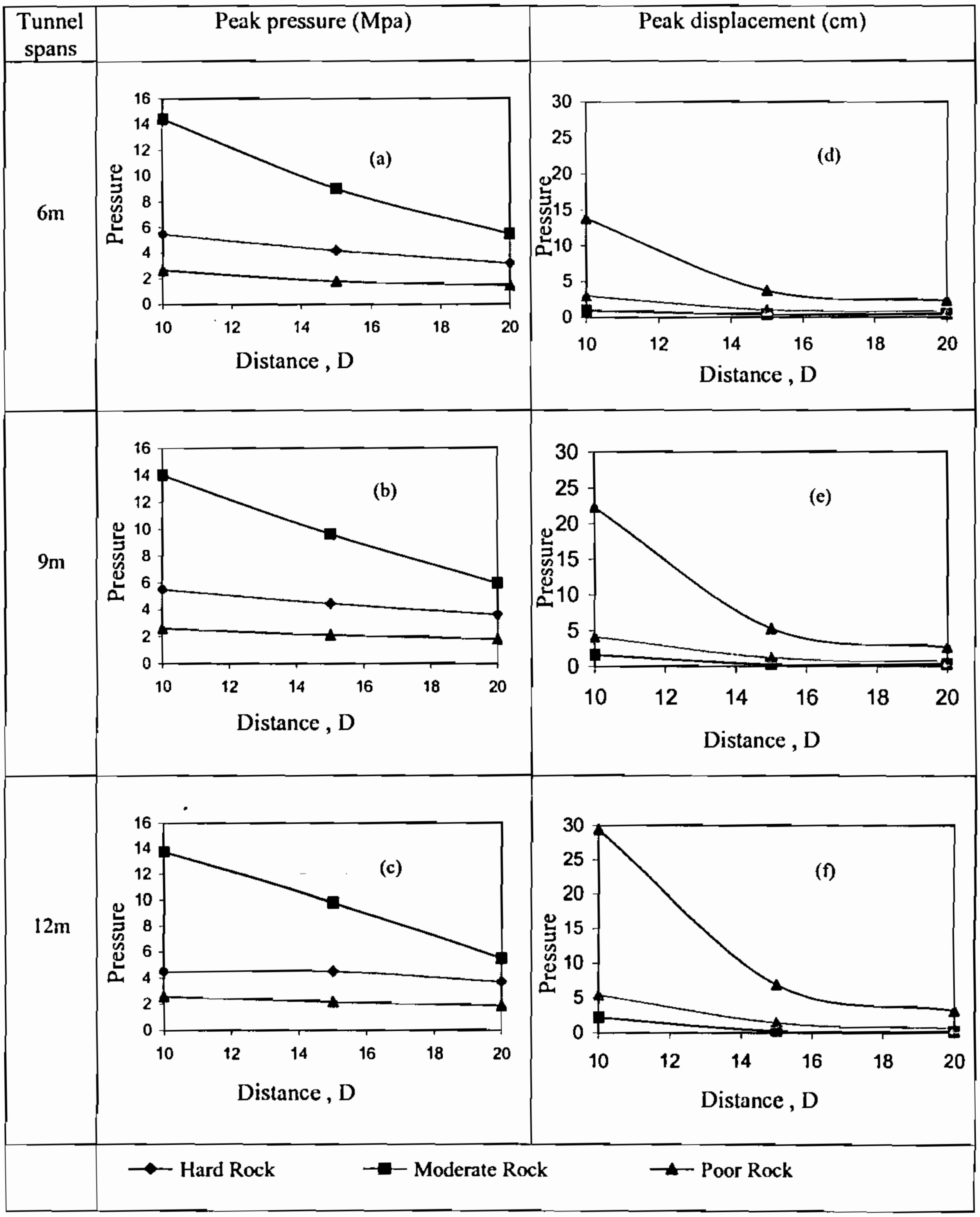


Fig. (6) Peak response pressure and displacement at tunnel crown versus crown-detonation distance for different rock types and tunnel radius

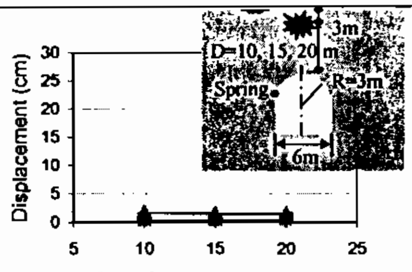
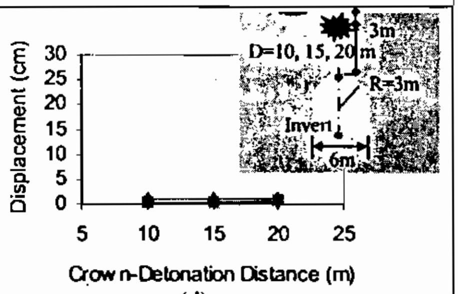
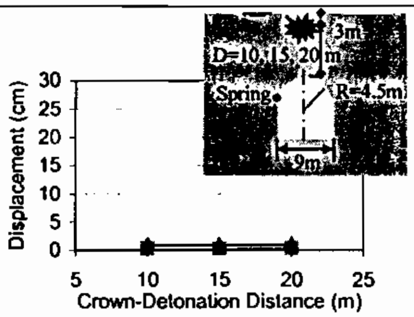
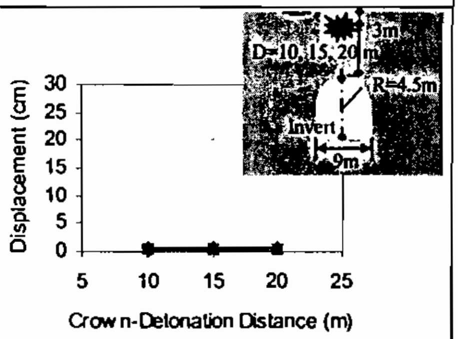
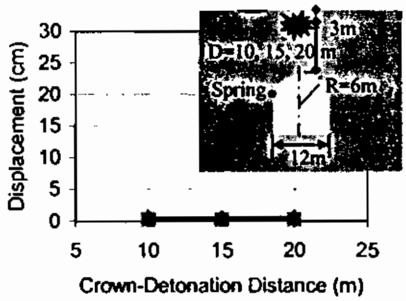
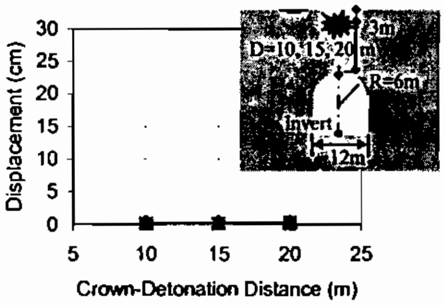
Tunnel Spans(m)	Spring Displacement (cm)	Invert Displacement (cm)
6	 (a)	 (d)
9	 (b)	 (e)
12	 (c)	 (f)
	—◆— Hard Rock —■— Moderate Rock —▲— Poor Rock	

Fig. (7) Peak displacement of spring and invert point versus crown detonation distance for different tunnel spans and rock type

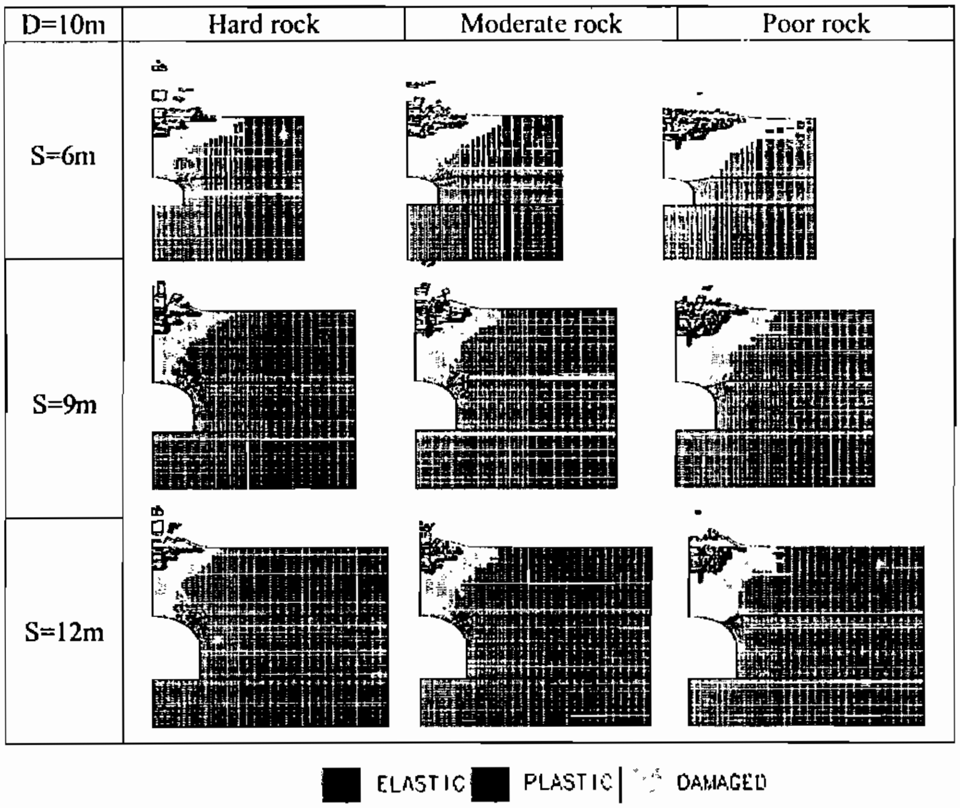


Fig. (8) The rock status case for different tunnel spans and rock types, D =10 m

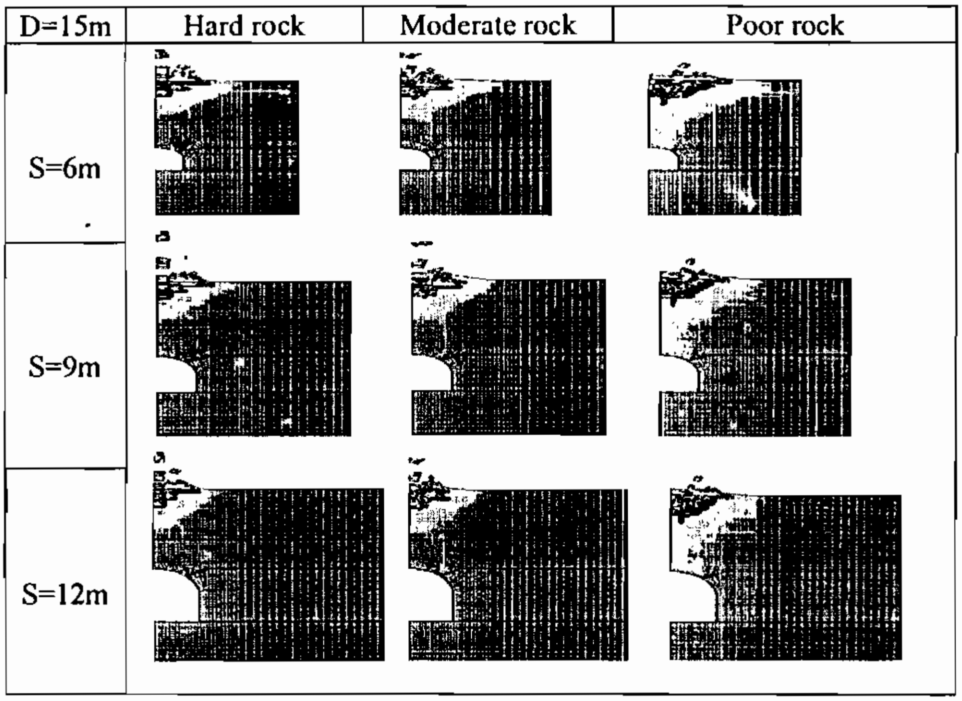


Fig. (9) The rock status case for different tunnel spans and rock types, D =15 m

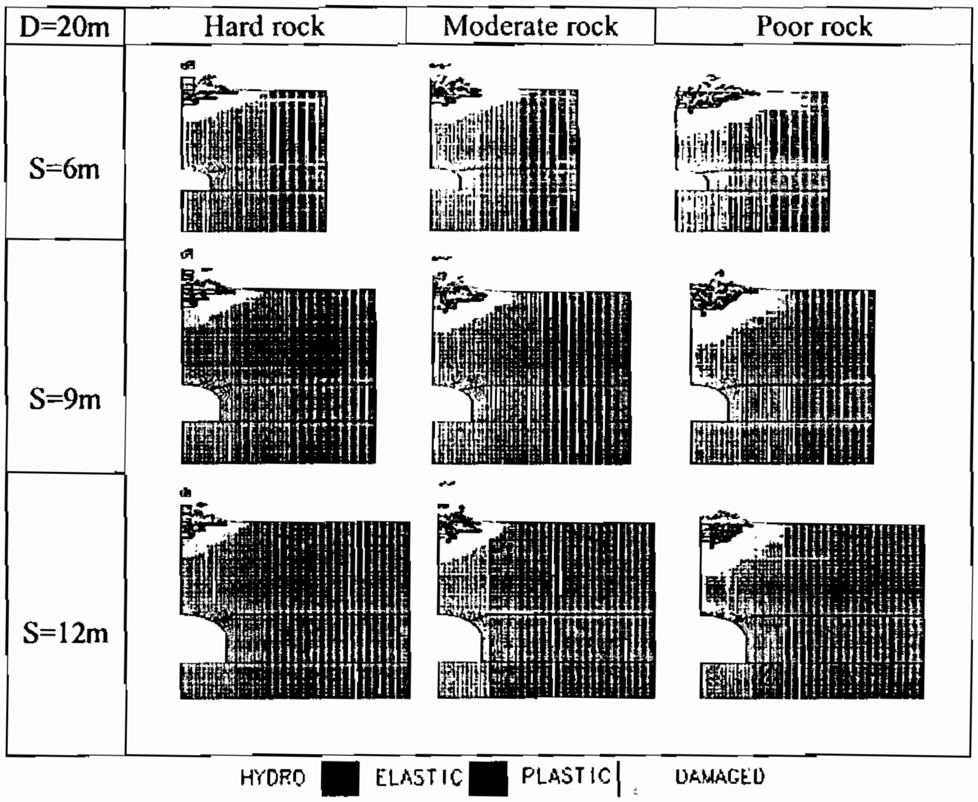


Fig. (10) The rock status case for different tunnel spans and rock types, D =20 m

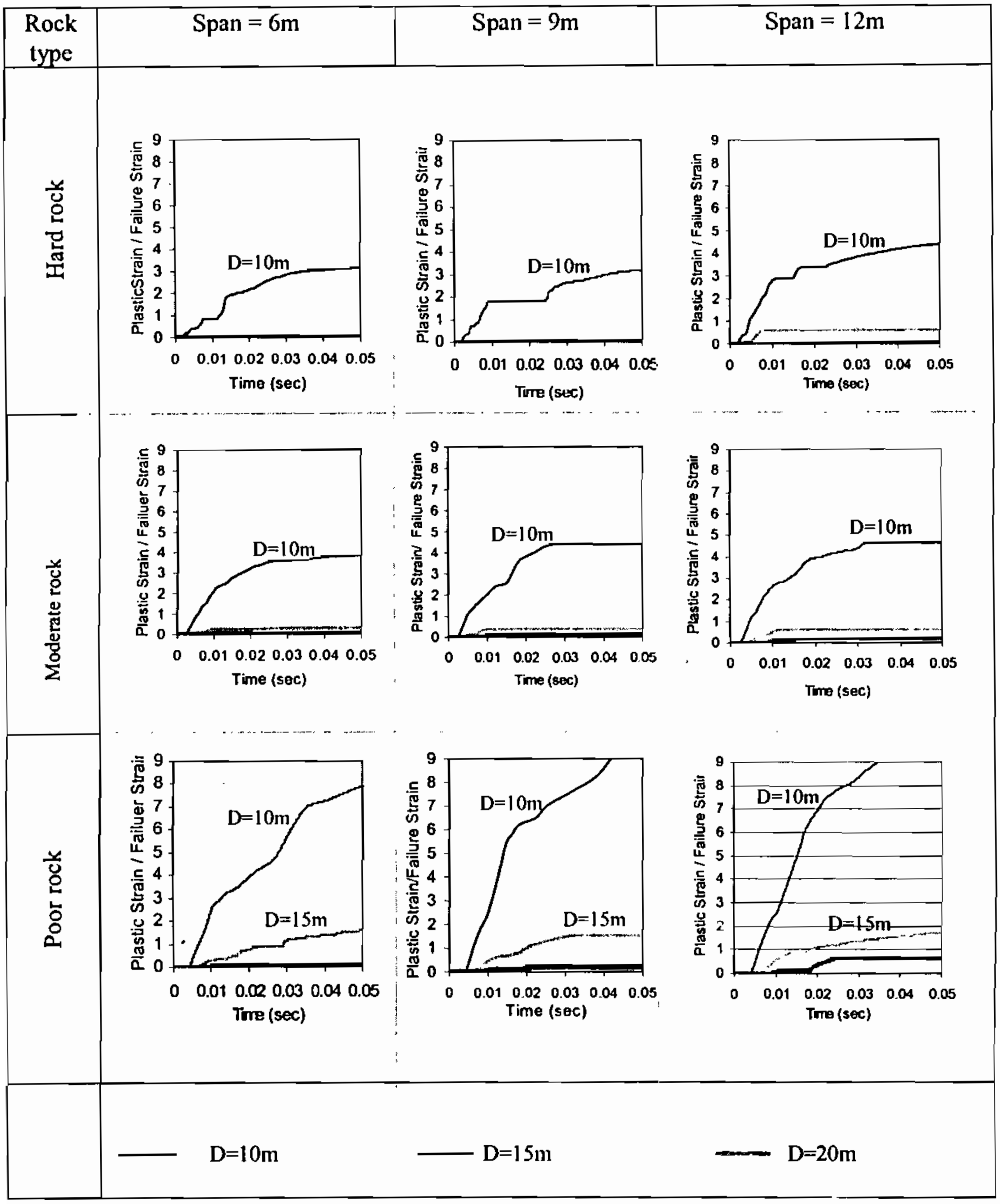


Fig. (11) Plastic strain time history / failure strain at crown tunnels for different rock type, different tunnel span and different crown-detonation distance

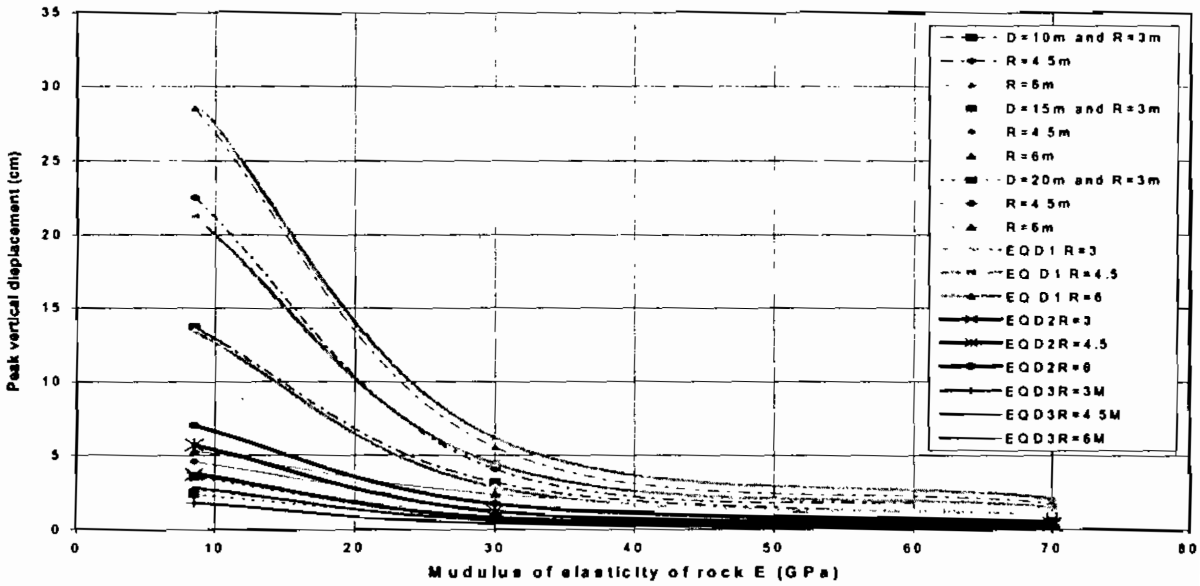


Fig. (12) Comparison of the peak displacement at tunnel crown between FE result and predicted equations for different rock type, tunnel radius and different crown-detonation distance

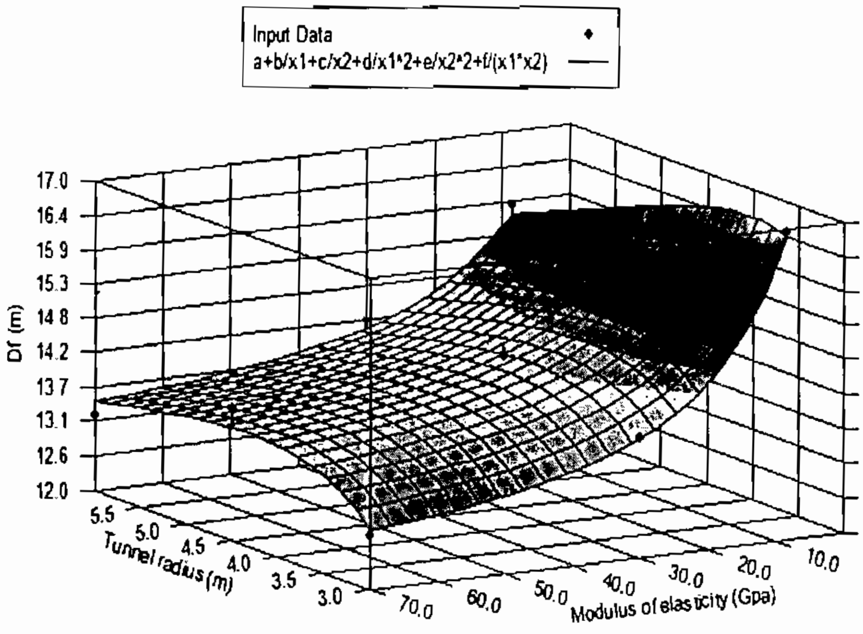


Fig. (13) The failure displacement at tunnel crown