ELASTIC AND KINEMATIC HARDENING PLASTIC BLAST INDUCED DEFORMATIONS OF UNDERGROUND TUNNELS BY THE FINITE ELEMENT METHOD

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الخلاصة

يتناول هذا البحث تحليل الاجهادات المتولدة على الأنفاق الواقعة تحت الأرض باستخدام طريقة العناصر المحددة. تم كتابة برنامج لاجراء هذا التحليل بناءاً على اشتقاقات صيغة الإزاحة.استعملت طريقة العناصر المحددة لحل معادلة التوازن الديناميكي وباستعمال التكامل في المجال الزمني (step-by-step time integration). تم اختيار نوع من الأحمال الديناميكية وهو حمل العصف النووي (nuclear blast loading) المسلط على سطح التربة.

لقد اخذ بنظر الاعتبار كل من المواد الاحتكاكية والحبيبية، الخرسانة والتربة .تم تمثيل التربة باستعمال أنموذج المرونة الخطية (Linear Elastic) وتم تمثيل الخرسانة باستخدام أنموذج المرونة الديناميكي. كما تم تمثيل التربة باستخدام أنموذج لدونة السطح المحيط (bounding surface plasticity). لقد اظهر التحليل تأثير انتقال موجات الإجهاد وانعكاسها و خاصة على المواد التي لا تتحمل أي شد، مثل التربة.

لقد حلل تأثير العصف النووي وذلك بوضع الحمل بصورة منتظمة على السطح. تم احتساب الاجهادات والازاحات في مقاطع مختلفة.

أعطى التحليل اللاخطي باستخدام أنموذج لدونة السطح المحيط نتائج جيدة مقارنة بالتحليل الذي يستخدم أنموذج المرونة. إن التحليل باستخدام أنموذج المرونة يستخدم كتخمين أولي للمسائل، ولكنه غير قادر على تمثيل التصرف الحقيقي تحت تأثير الأحمال الديناميكية.

ABSTRACT

This research deals with the stress analysis of typical underground tunnels using isoparametric finite elements. Enhanced software is used for predicting and analyzing this behavior by using a single-phase formulation. This software was developed from an original computer code named MIXDYN. The finite element method is used to solve the dynamic equilibrium equation with step-by-step time integration schemes. A selected type of dynamic load was chosen which is blast loading.

Frictional and particulate materials, i.e., concrete and soil, are considered. The soil and concrete structures are analyzed where a dynamic elastic model for concrete and a linear elastic one for soil

are used. The soil is further analyzed by a bounding surface plasticity model. The stress waves travel and the reflection effects especially in the no tension materials, i.e., soil are investigated.
The effects of blast loading are then analyzed hypothetically placing the explosion at the ground surface. The stresses and displacements are computed at different sections.
The nonlinear analysis utilizing the bounding surface plasticity characterization gave better predictions over the linear elastic model. The linear elastic model is proposed to be used as a first prediction of the problems encountered, but it is incapable of realizing the actual behavior under dynamic loads.

INTRODUCTION

In order to design structures supported by or buried into geological media for operating safely and surviving under extreme conditions, it is necessary to understand the dynamic behavior of soil. Almost all strong soil motions can be attributed to fault rupturing, that gives rise to earthquakes, and to man-made underground blasts. Other minor sources are man-related activities on the ground surface and powerful air blasts. Given the complexity of the problem, it is desirable to have basic and qualitative information on the relation between amplitude of soil motions and the magnitude of the disturbance for a variety of parameters. If a soil-structure system is loaded, displacement components in all directions are produced in the structure and in the soil below. The mutual dependency of the displacements is called soil-structure interaction.
The structure may either be loaded directly by forces or may be excited through the ground. In both cases, the vibrations and the residual deformations of the soil and the structure are mutually dependent (Al-Ani, 2001).
Various constitutive models are employed to represent the soil, the general analytical formulation for the solution scheme and of the bounding surface plasticity model was presented in the work of (Al-Damluji and Al-Ani, 2002).

FORMULATION OF THE SYSTEM OF DIFFERENTIAL EQUATIONS

Two categories of forces act on a deformable body in accelerated motion. The first is the externally applied load F_E. The second is the resulting force from motion. These forces are the inertia force F_R damping forces F_I and the internal resisting forces F_D. Therefore, the force equilibrium equation of motion can be written as (Bathe and Wilson, 1976):

$$F_I + F_D + F_R = F_E \tag{1}$$

The inertia force, according to Newton's second law, is a function of the mass and the acceleration:

$$F_I = m\ddot{u} \tag{2}$$

The damping force that represents viscous material damping is a linear function of the velocity:

$$F_D = c\,\dot{u} \tag{3}$$

where c is the proportionality constant. And finally the resisting force is a function of the stiffness and the displacement

$$F_R = K\,u \tag{4}$$

F_B The externally applied forces can be divided into two parts, the body forces and the surface traction forces F_T. Therefore, the force equilibrium equation becomes:

$$F_I + F_D + F_R = F_B + F_T \tag{5}$$

or,

$$m\,\ddot{u} + c\dot{u} + ku = F_B + F_T \tag{6}$$

The finite difference method or the finite element method together with the boundary conditions can be used in the solution of this equation. Generally, the problem is nonlinear if the stiffness matrix is nonlinear. Nonlinear behavior of structures may be divided into two types. The first is caused by nonlinear material properties (as in plasticity), i.e. material nonlinearity. The second is caused by changes in configuration (as in large deformations), i.e. geometric nonlinearity.
The classification "linear" and "nonlinear" is artificial. In physical reality, some nonlinear problems can satisfactorily be approximated by linear equations. Many problems in stress analysis and heat conduction are solved with quite good results by linear approximations. Nonlinear approximations are more difficult to formulate and the solution of the resulting equations may require 10-100 times the solution time as compared to linear approximations with the same degree of freedom (Al-Mashta, 1986).

GEOMETRY AND BOUNDARY CONDITIONS

The two-dimensional problem, which is considered herein, is the tunnel which is subjected to blast loading **Fig. (1)**. This figure shows the finite element meshes utilized in the analysis. Only half of the underground structure is considered due to symmetry. The dimensions are given in **Table (1)** and the number of elements and nodes are given in **Table (2)**.

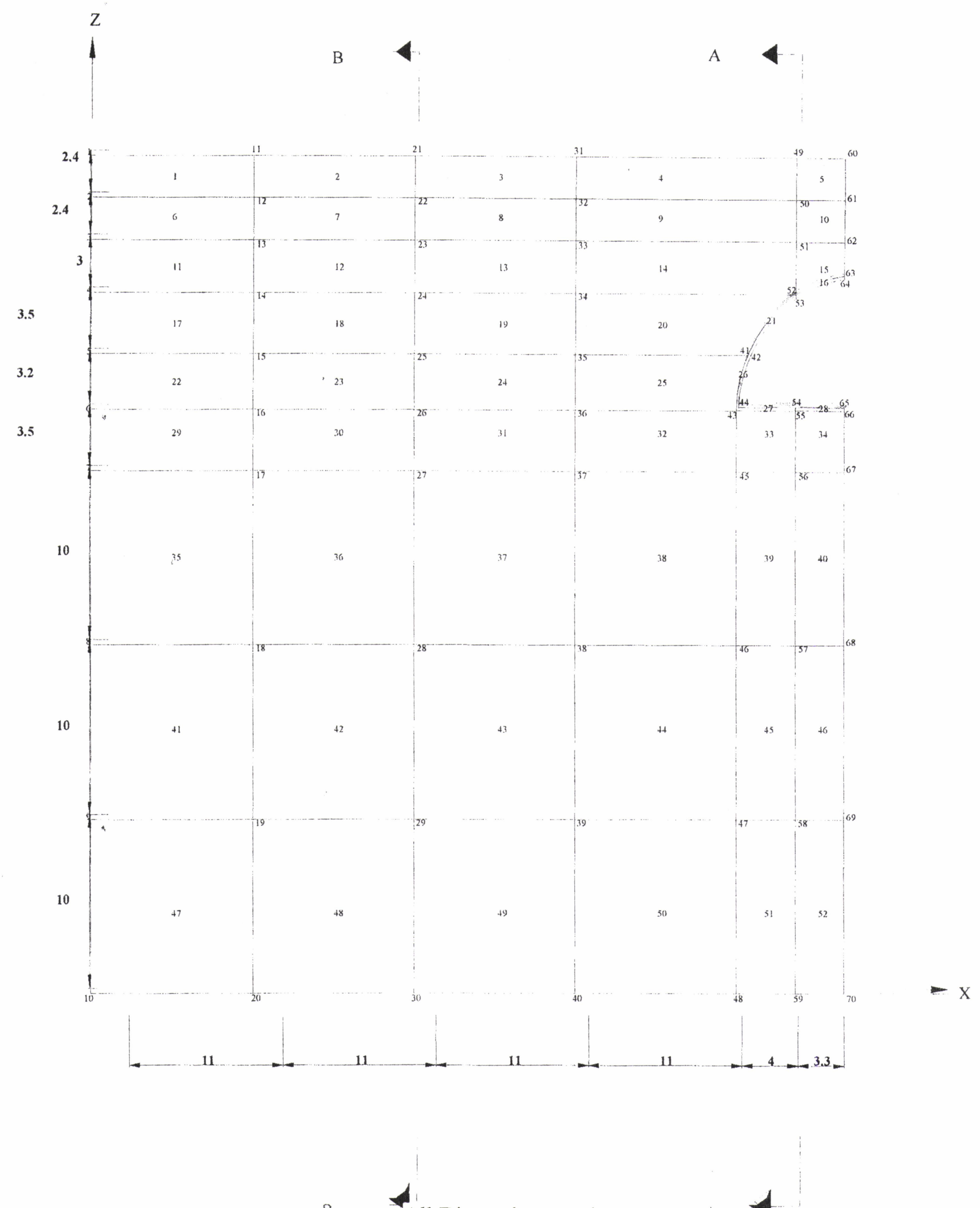
Table (1). Geometric Properties of the Underground Structure Used.

Tunnel	
Clear span(m)	7.3
Clear height(m)	6.1
Lining thickness(m)	0.2
Shelter	
Clear span(m)	3.0
Clear height(m)	3.0
Wall thickness(m)	2.0
Slabs thickness(m)	2.0

Table (2). Number of Elements and Nodes in the Soil and Structure.

Number of nodal points in soil and structure	70
Number of elements representing structure	5
Types of elements	4-node isoparametric elements

MATERIAL PROPERTIES



All Dimensions are in meters

Fig.(1). Finite Element Mesh for Analysis of Underground Openning System.

ATERIAL PROPERTIES

For the elastic analysis, Young's modulus E, Poisson's ratio and the mass density are only required, as given in **Table (3)**. But for the bounding surface plasticity analysis, additional material properties are required, the data used in the analysis are given in **Table (4)**. A high strength concrete used for the section of the tunnel with f'c = 48.4MPa whose data are given by Bazant and Tsubaki (1980) is adopted. The required set of data is presented in **Table (3)**.

Table (3.) Weald Clay and Concrete Properties (Data taken from Bazant and Tsubaki (1980)).

Property	Value	Unit
Concrete		
Young's modulus	**17384x10³**	**KPa**
Poisson's ratio	**.18**	
Mass density	**2.37**	**kN.sec²/**
Compressive strength f'c	**48.4x10³**	**KPa**
Clay		
Young's modulus	**20000**	**KPa**
Poisson's ratio	**0.30**	
Mass density	**2.0**	**kN.sec²/**

Table (4). Material Properties for the Bounding Surface Model (data taken from Levadoux (1980) and Whittle (1994)).

λ	0.184	___
κ	0.02	___
M_c	1.2026	___
M_e/M_c	0.8998	___
ν	0.35	___
P_L	30.4	KN/m^2
P_{atm}	101.4	KN/m^2
R_c	2.3	___
A_c	0.1	___
T	0.1	___
R_e/R_c	0.8	___
A_e/A_c	0.8	___
C	0.4	___
S_p	1.0	___
M	0.02	___
h_c	10.0	___
h_e/h_c	1.0	___
h_o	10.	___

RESENTATION AND DISCUSSION OF RESULTS

Linear Elastic Model

The Underground Openning System shown in **Fig. (1)** is subjected to a blast load at the ground surface. The loading is an overpressure due to a nuclear explosion equivalent to 1 MT yield. The peak overpressure is 2070 kPa. The rise time is equal to 0.006 second and the positive duration is 1.0 second, as shown in **Fig. (2)**.

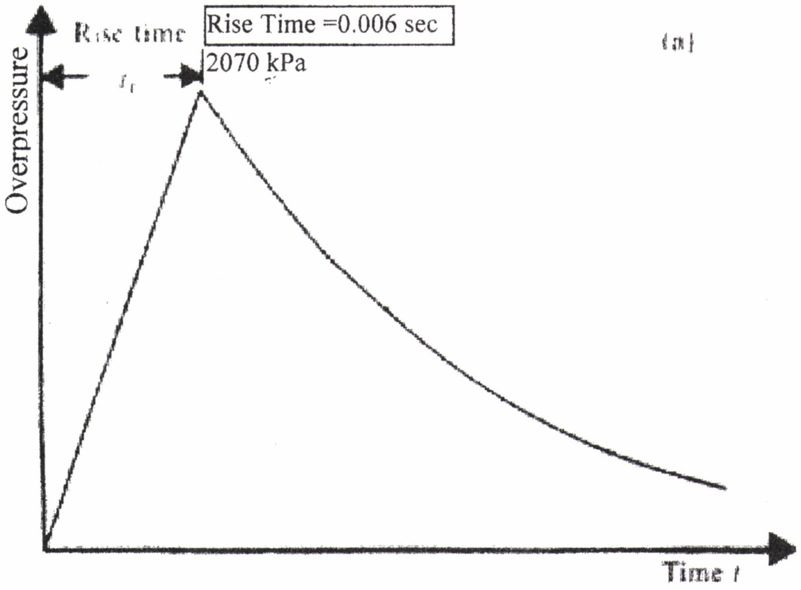


Fig. (2).Rise Time of Overpressure at a Point

Throughout this research an emphasis is made upon the importance of reflected stress from the impinging waves on the surfaces between two different materials and hence, effects of stiffnesses in the design of underground structures subjected to nuclear blast loadings.
The vertical and horizontal displacements for two different sections, namely sections A-A through the tunnel and B-B outside the tunnel, through the 7m deep tunnel are presented in **Fig. (3)** and **Fig. (4)**.
The horizontal displacements are much less than the vertical ones, and the ratio is between 1/10 to 1/100. The shapes of the vertical displacement curves in the two sections are approximately the same.
The vertical, horizontal and shear stresses are presented in **Fig. (5), (6)** and **(7)**, respectively. Those stresses are concentrated in the concrete elements due to their higher stiffness relative to the soil elements. The increments decreased as the distance increased away from the tunnel in the section that passes through it.

BOUNDING SURFACE MODEL

The bounding surface plasticity model accounts for the realistic behavior of materials under dynamic loads (Al-Sherefi, 2000). All the solutions presented under this heading have employed this model and their results are as follows.

THE 7M DEEP TUNNEL

The underground openning (tunnel system) of **Fig. (1)** is subjected to a blast load at the ground surface similar to the one outlined in section of the elastic linear model, but the bounding surface plasticity model is employed here. In **Fig. (8)** and **(9)**, the vertical and horizontal displacements are shown. It can be seen that the horizontal displacements are much less than the vertical ones, and the ratio is between 1/10 to 1/100 (as in the elastic case).

The distribution of the vertical displacements in a plane through the concrete elements, section A-A, is similar to the one in a plane not passing through the tunnel,section B-B.
The vertical, horizontal and shear stresses are concentrated in the concrete elements. These stress increments decrease as the distance increases away from tunnel.
The wave reflection on the tunnel's surface in the plane passing through it is obvious. The reflected waves from the bottom hard layer are more obvious in planes not passing through the tunnel. Vertical, horizontal and shear stresses are presented in **Fig. (10), (11)** and **(12)**, respectively.
The deformed shape of the tunnel system at the end of the blast load is as shown in **Fig (13).**

CONCLUSIONS

1- From the results presented in the previous sections, the following conclusions can be drawn:
2- The reflected stress waves are to be considered in the design of underground structures since they may be the major reason of failure.
3- The reflection of the waves is more obvious in the case of the 7m tunnel since the depth of the hard layer is only 48m, while for the case of the 18m deep shelter (Al-Ani, 2001), the depth is 57m.
4- The wave reflection on the underground surface in the plane passing through the underground structure is more pronounced. Other planes not passing through the underground structure show the wave reflections on the hard layer.
5- The results of the bounding surface model are the ones that should be adopted because they represent the realistic behaviour of the soil material under dynamic loads. Results of the linear elastic modes are useful for the sake of checking the analyses.

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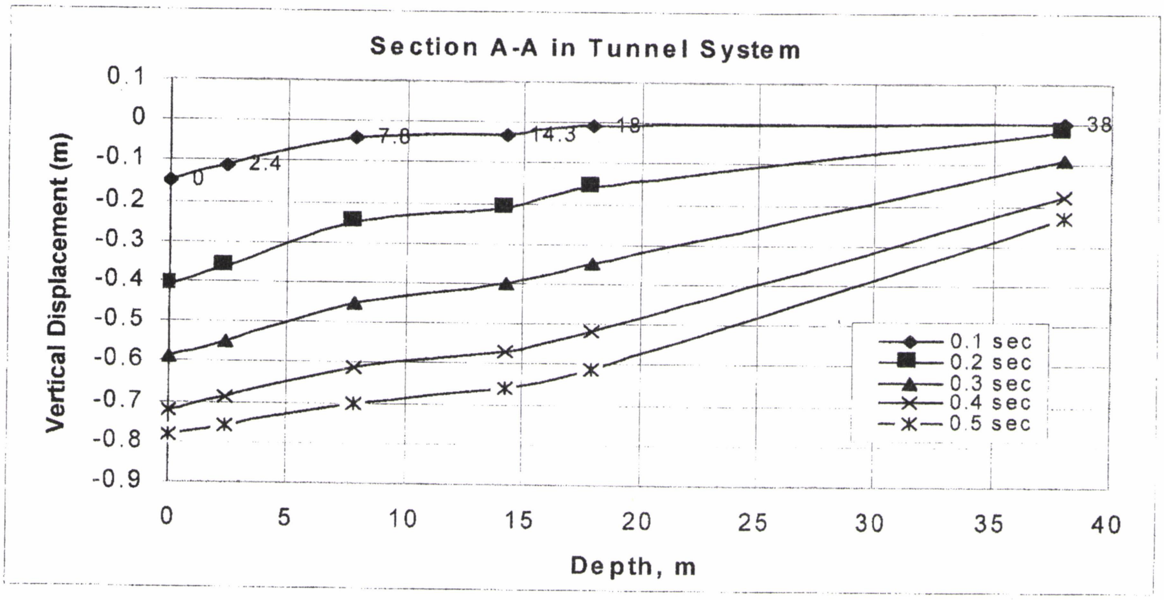
NOTATIONS

A	Shape parameter
A_c , A_e	Bounding surface model parameters
a	Bounding surface model parameter

C	Bounding surface model parameter
c	Constant
fc′	Uniaxial compressive strength of concrete
F_B	Body forces
F_D	Damping forces
F_E	Externally applied load
F_I	Inertia forces
F_R	Internal resisting forces
F_T	Surface traction forces
h_o, h_c, h_e	Hardening parameters
k	Stiffness matrix
m	Hardening parameter
M	Slope of the failure line in p-q plane
P_{atm}	The atmospheric pressure
R	Shape parameter
S_p	Elastic zone parameter
T	Shape parameter
λ	Slope of the virgin consolidation line
κ	Slope of the swelling line

ABBREVIATIONS

ASME = American Society of Mechanical Engineers,
FEM = Finite Element Method.



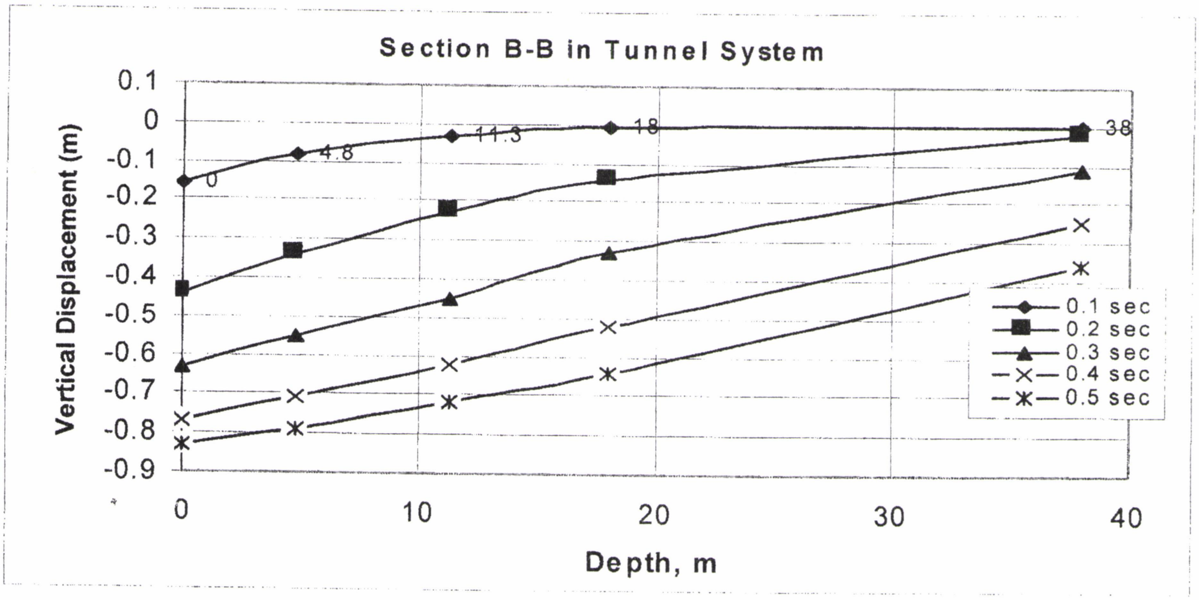
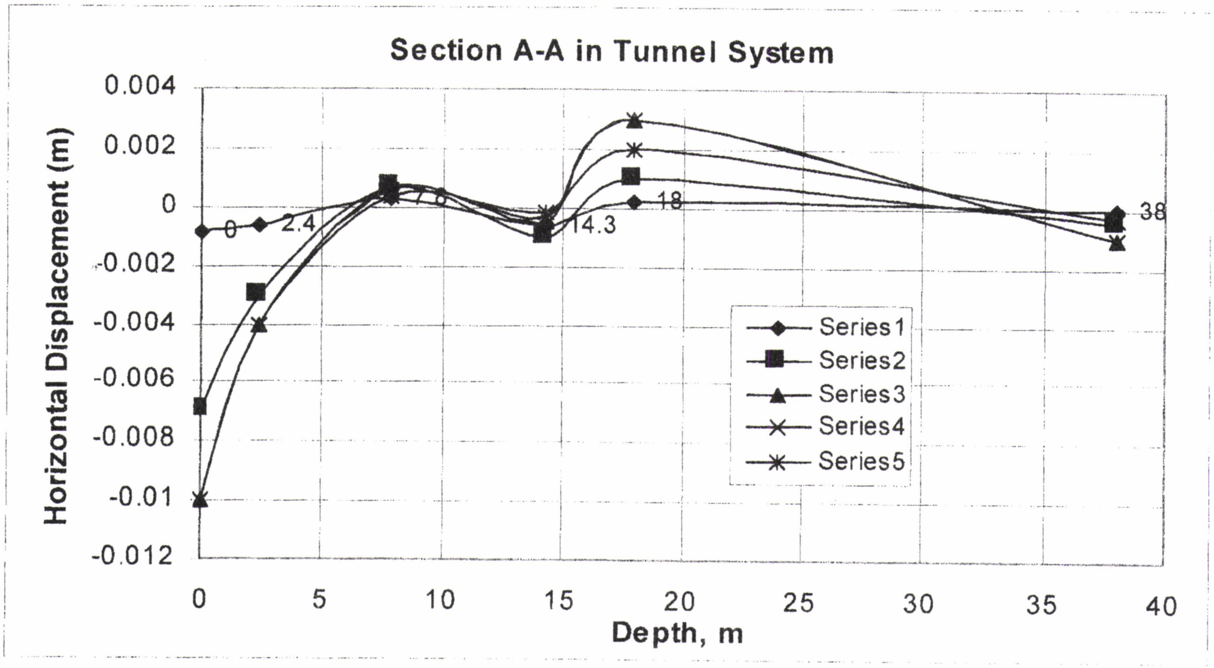


Fig. (3). Elastic Vertical Displacements of a 7m Deep Tunnel System Due to Blast Loading.



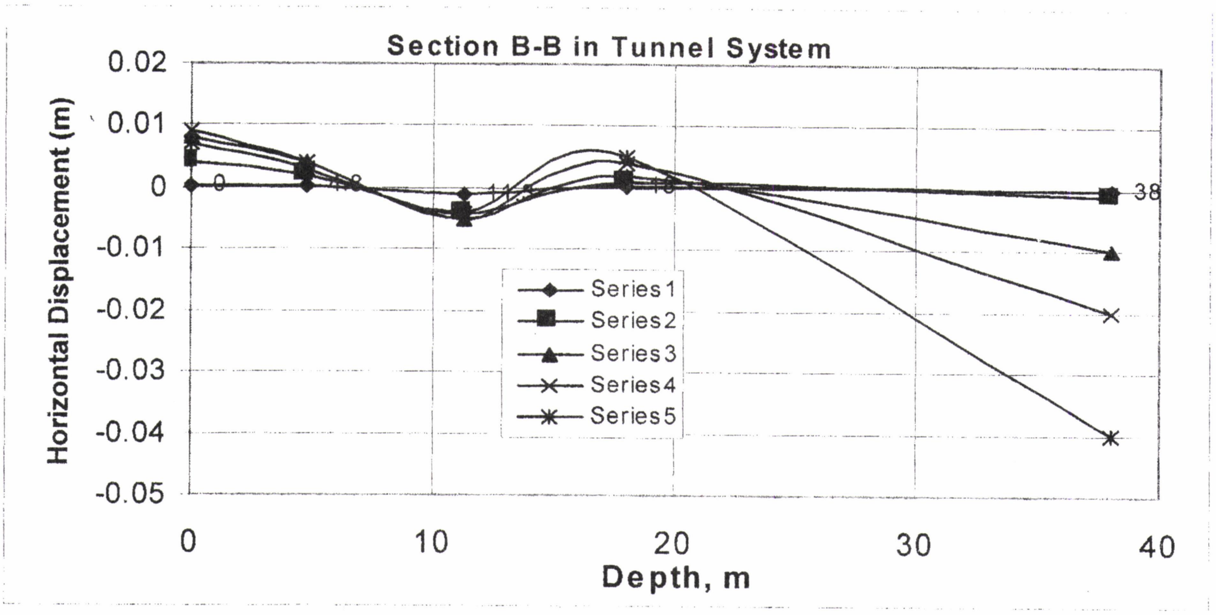
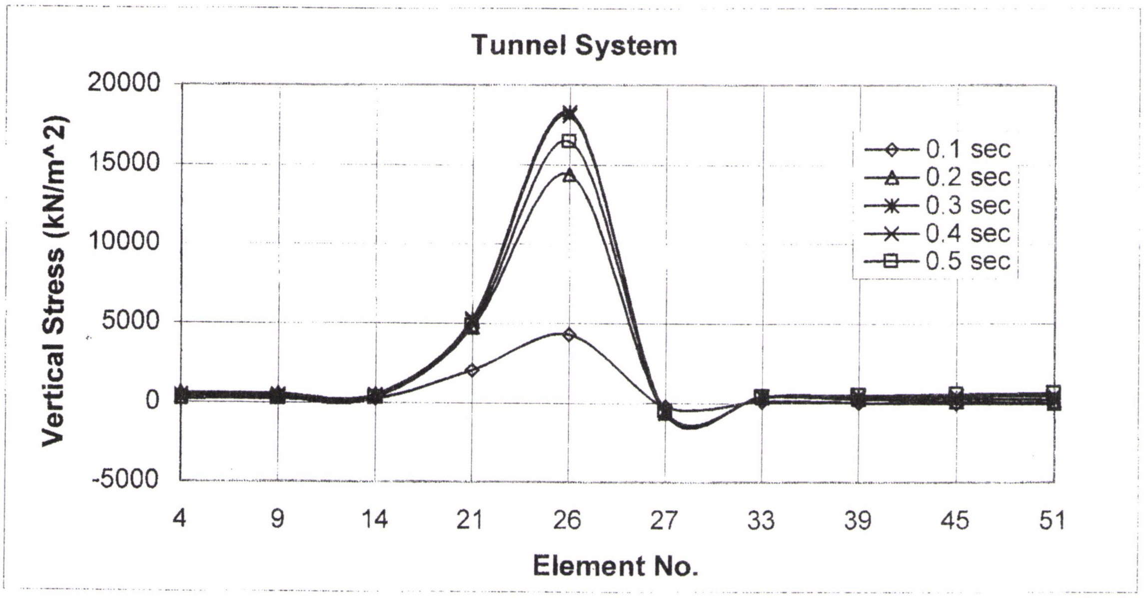


Fig. (4). Elastic Horizontal Displacements of a 7m Deep Tunnel System Due to Blast Loading.



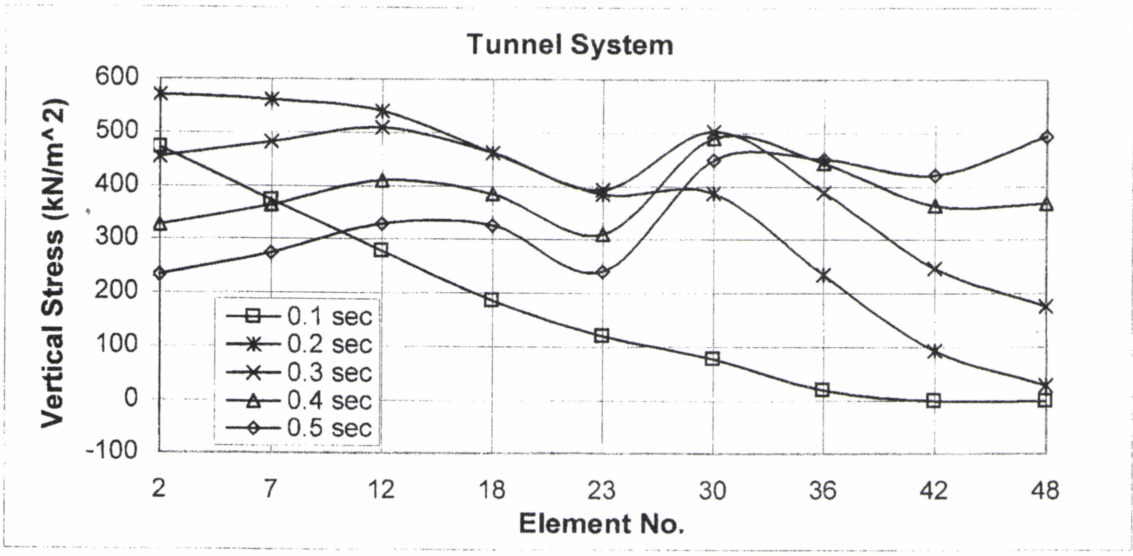
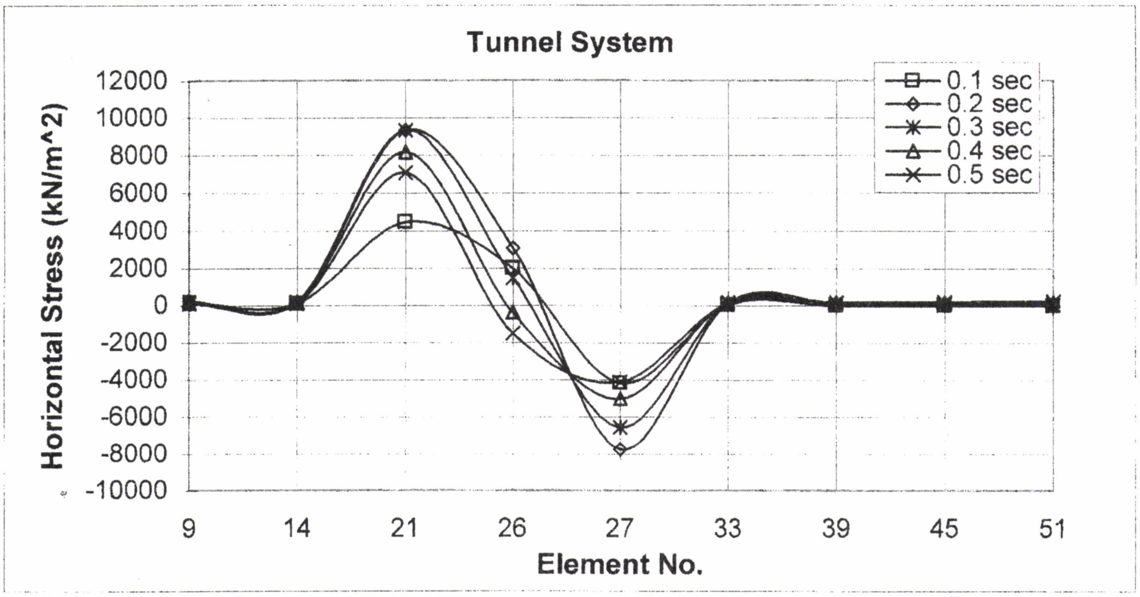


Fig. (5). Elastic Vertical Stresses in a 7 m Deep Tunnel System Due to Blast Loading.



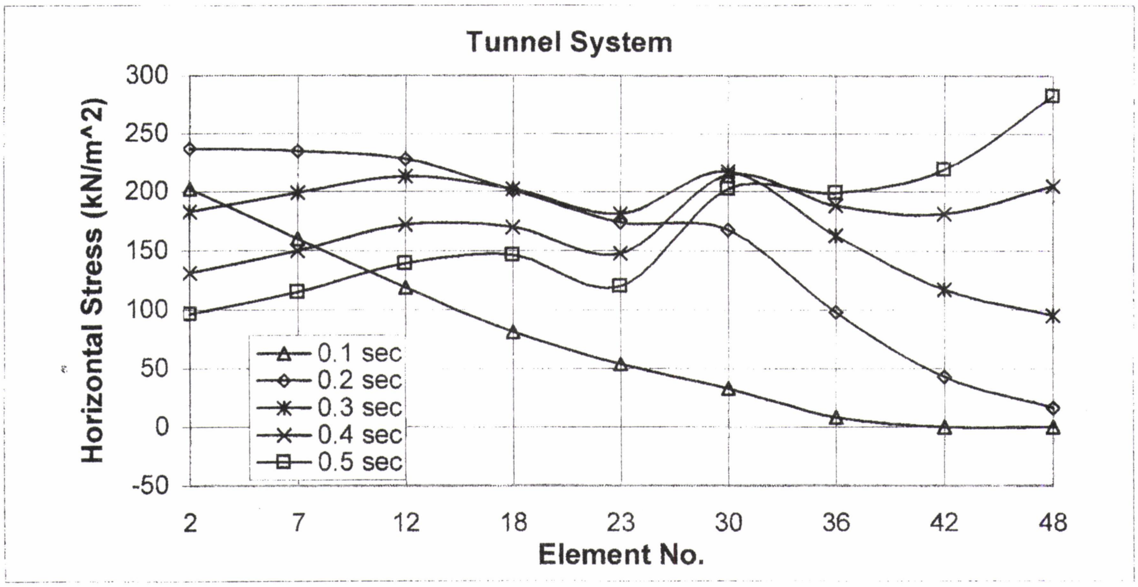
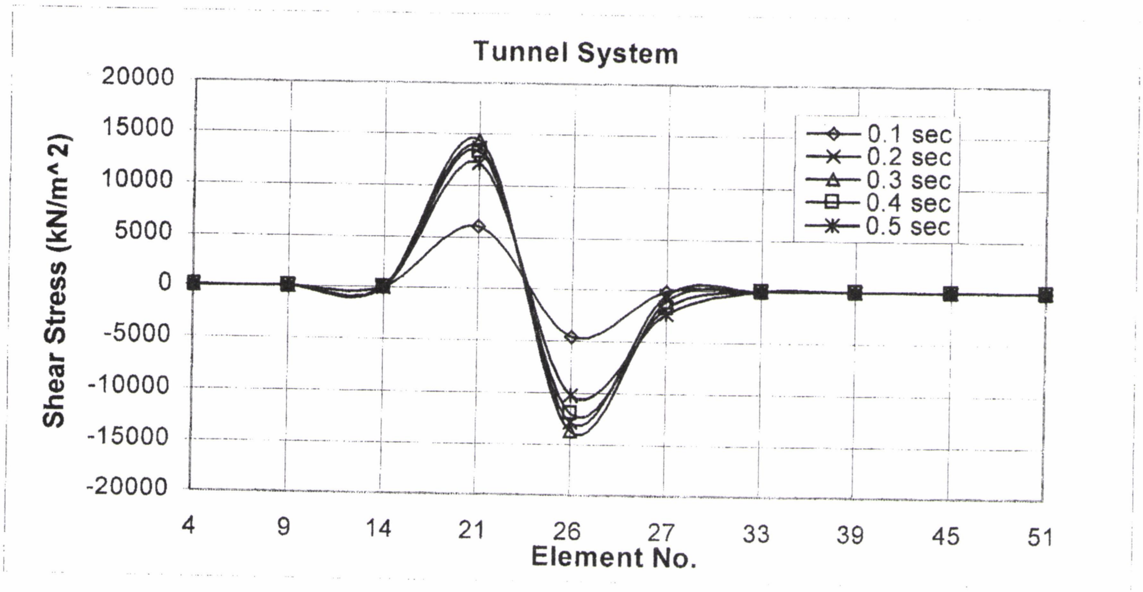


Fig. (6). Elastic Horizontal Stresses in a 7m Deep Tunnel System Due to Blast Loading



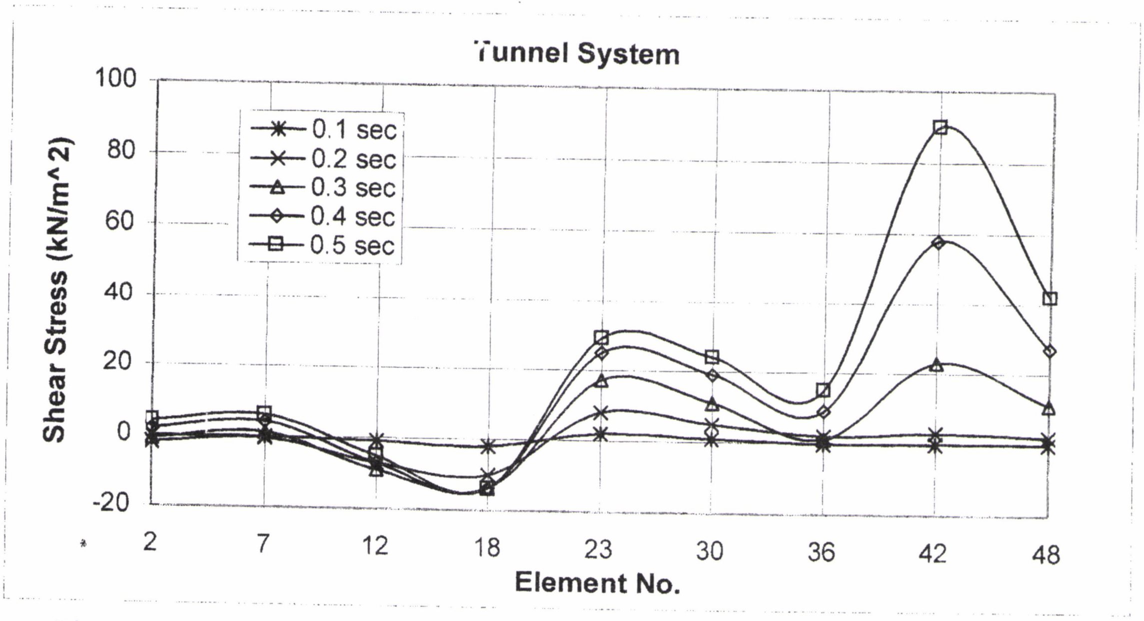
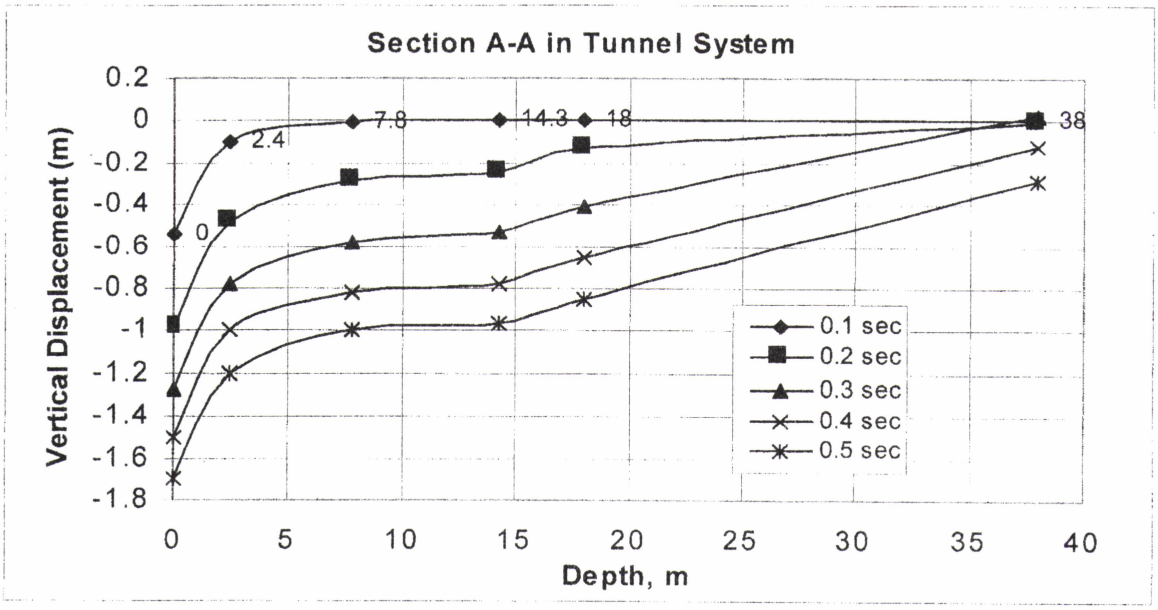


Fig. (7). Elastic Shear Stresses in a 7m Deep Tunnel System Due to Blast Loading



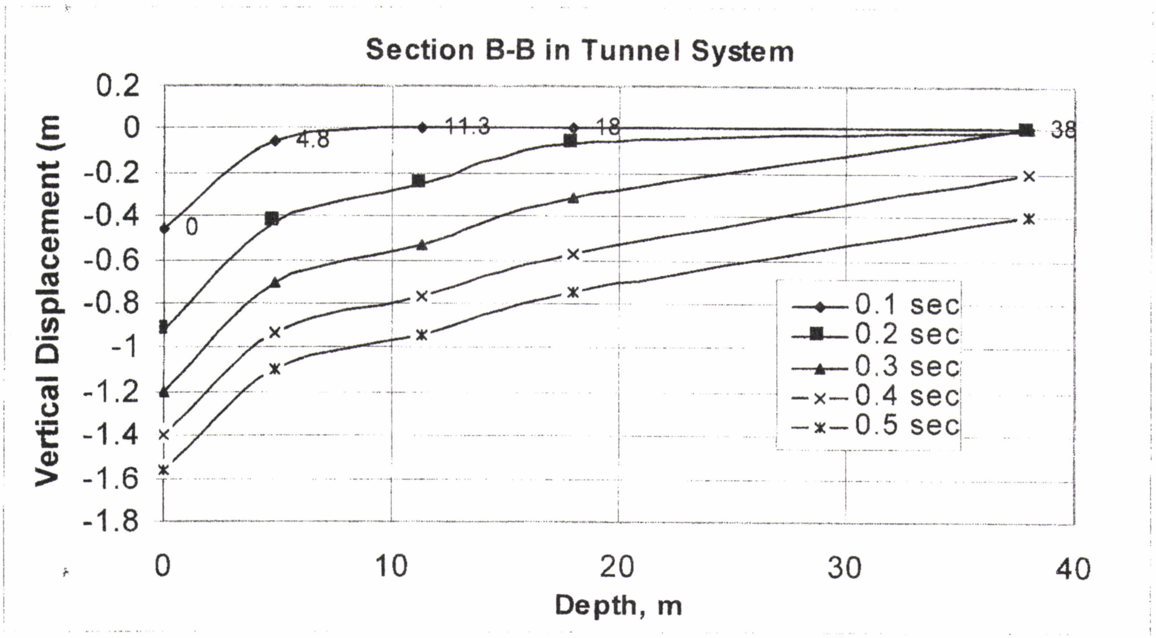
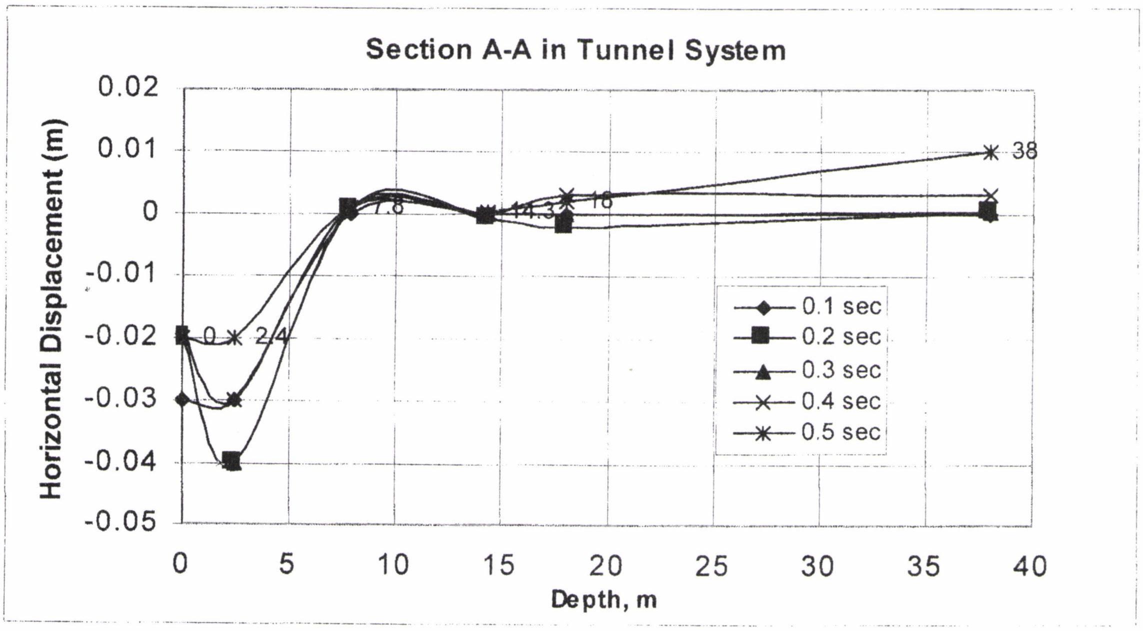


Fig. (8). Bounding Surface Model Displacements of a 7m Deep Tunnel System Due to Blast Loading



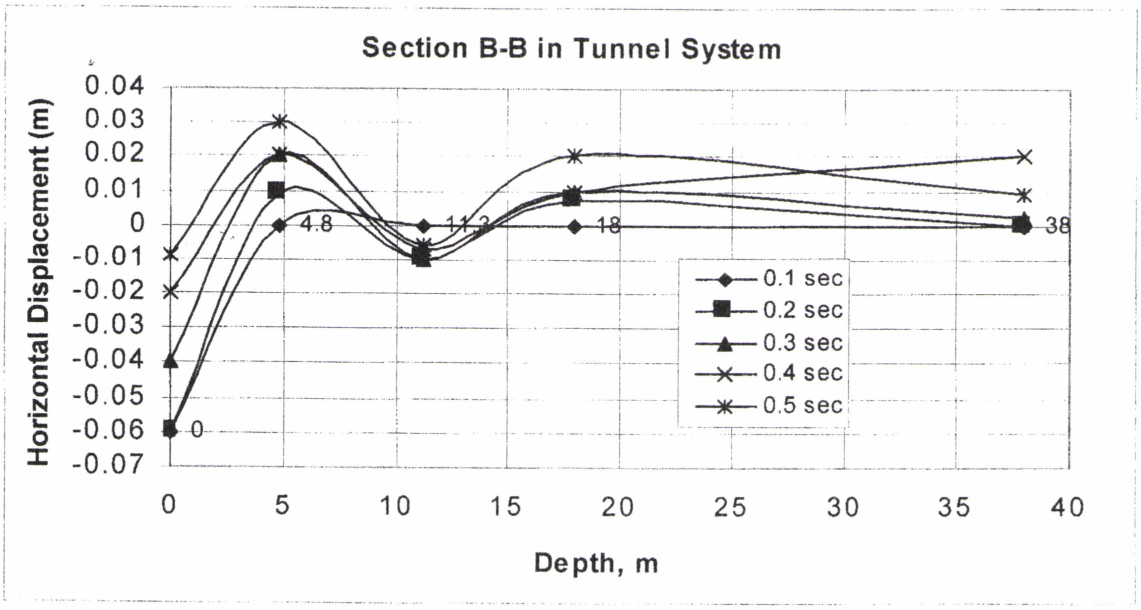
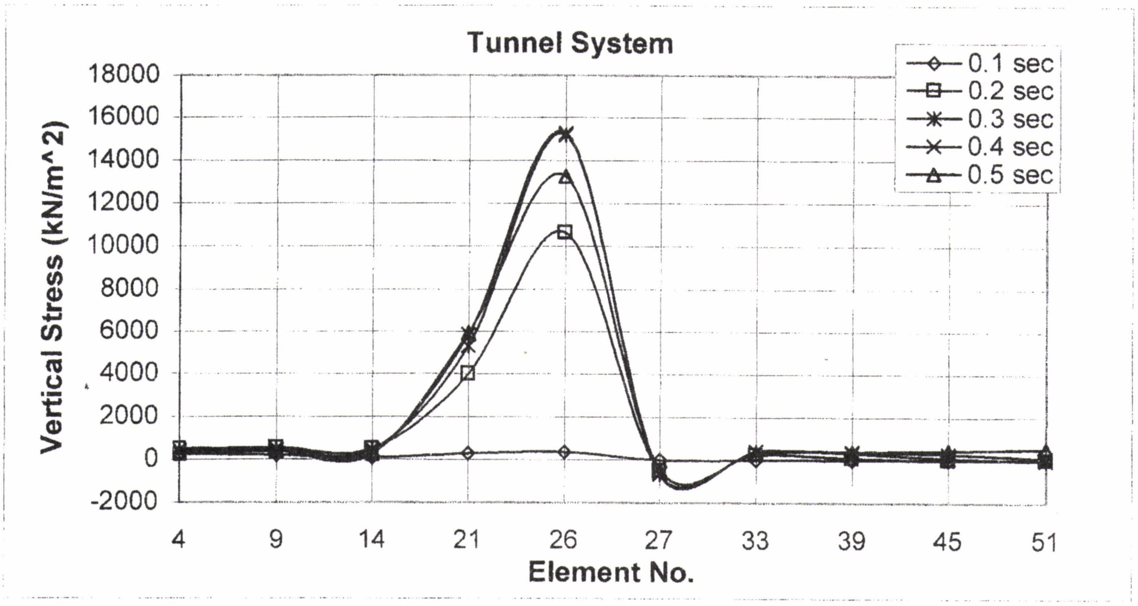


Fig. (9). Bounding Surface Model Displacements of a 7m Deep Tunnel System Due to Blast Loading



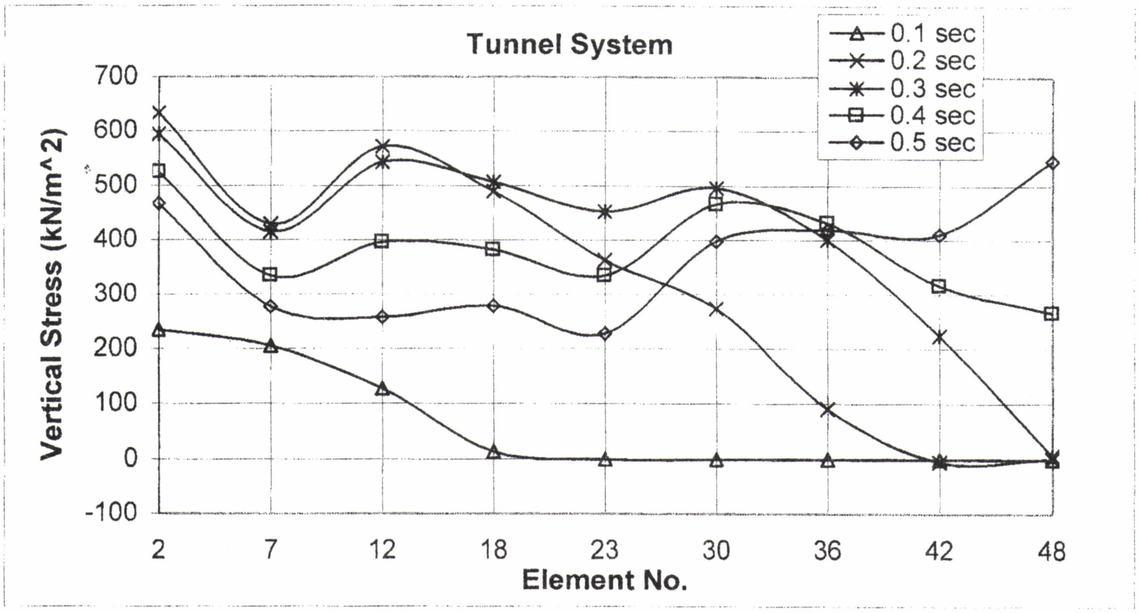
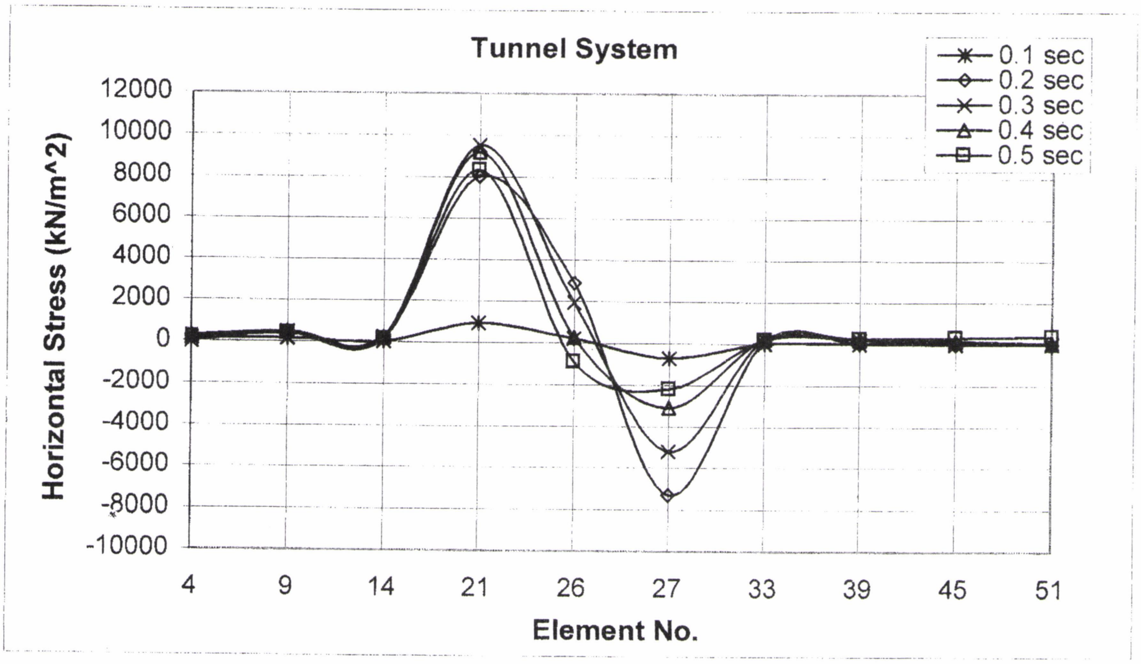


Fig. (10). Bounding Surface Model Stress in a 7m Deep Tunnel System Due to Blast Loading.



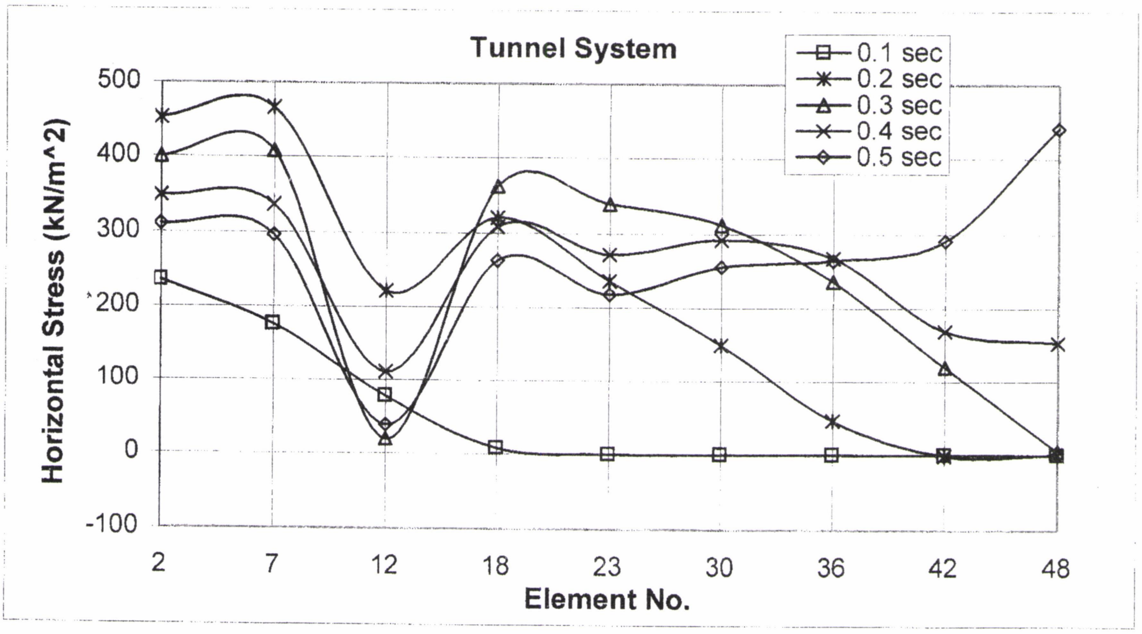
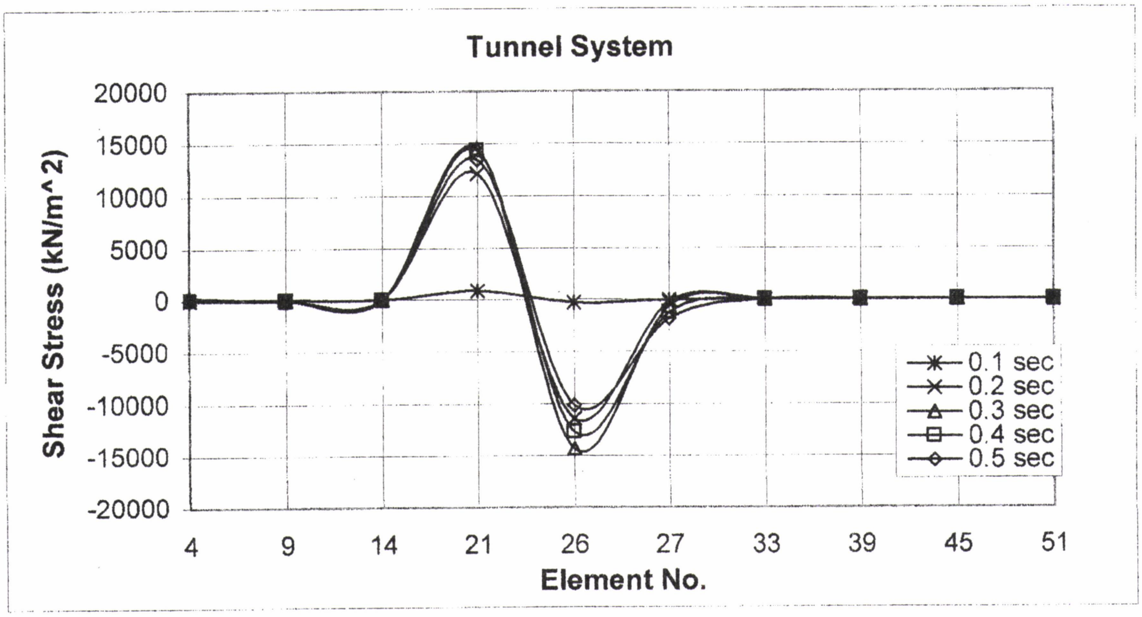


Fig. (11). Bounding Surface System Stresses in a 7m Deep Tunnel System Due to Blast Loading



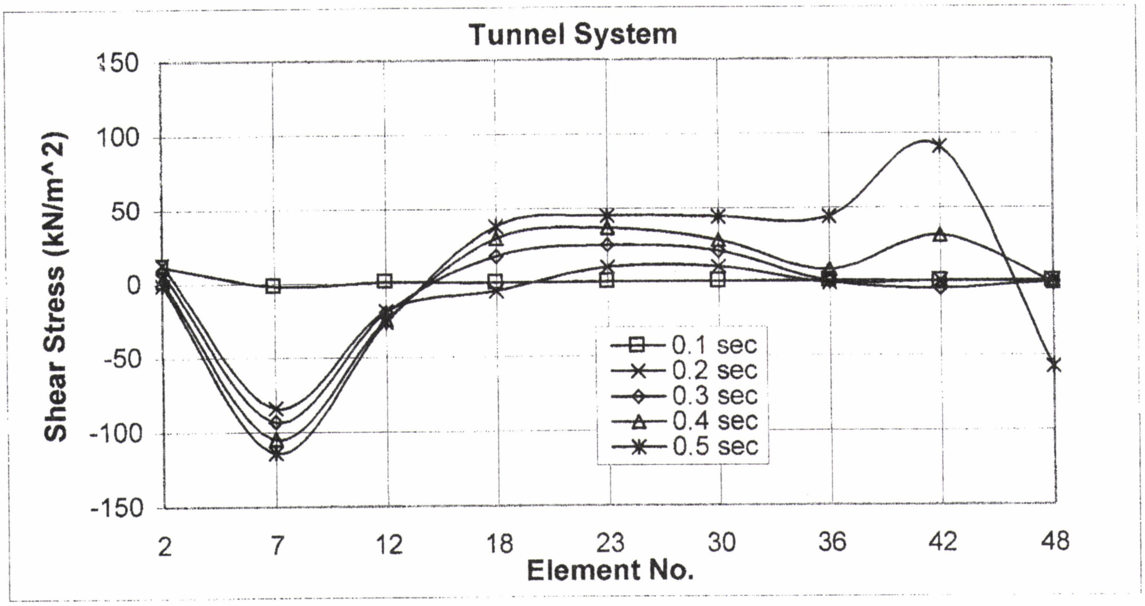
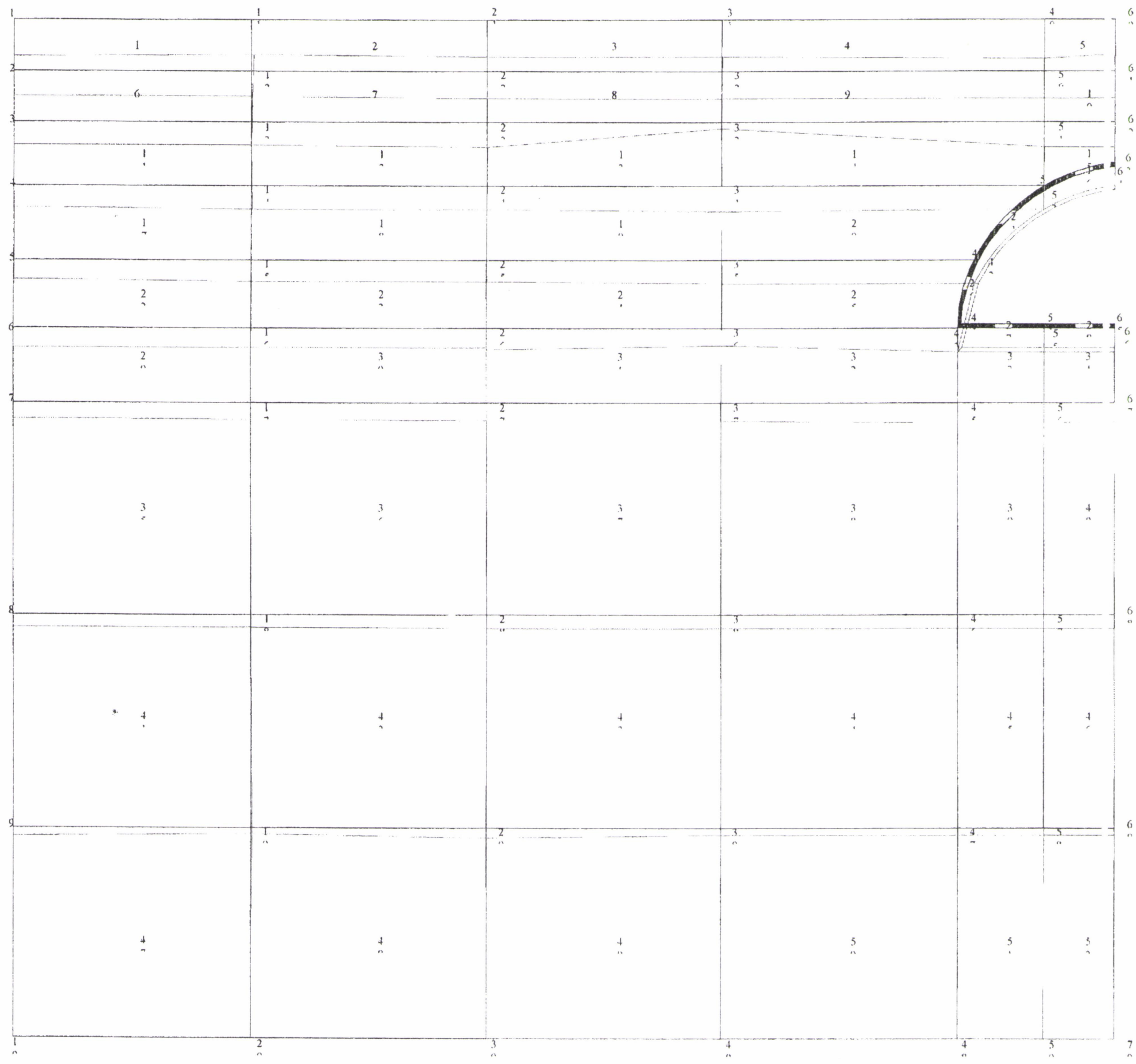


Fig. (12). Bounding Surface Model Stresses in a 7m Deep Tunnel System Due to Blast Load.



D e fo rm ed shape

E le m ents shape before applying blast load

Fig. (13). Bounding Surface Model Final Location of Underground Openning (Tunnel System) Due to Blast Loading.