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Military Technical Colleg
Kobry El-Kobbah,
Cairo, Egypt

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New Model to Calculate Blast Loading on Above and Underground Structures

Hassan M. Farag (MTC)

ABSTRACT

Blast loading is a type of extraordinary dynamic load to which structures or any object may be exposed to. The load resulted on structures or any targets from explosion is a complicated task to do. This paper presents an accurate and so simple model and program “***BLAST***” to predict the blast or shock wave resulted from the explosion that termed “Over Pressure” which comes from conventional and non-conventional weapons (such as Nuclear weapons). The pressure from the mass of air flow at and behind the shock front that termed the "Dynamic Pressure" is also predicted.

The loads on any structure or target from the explosion are combination of overpressure $P_s(t)$ and dynamic pressure $P_d(t)$, this dynamic load on different faces of a structure either above or under the ground is predicted and presented in this paper.

The over pressures resulted from different charges or weapon yields that are calculated in this study are compared to those obtained from “ConWep”.

The load on structures predicted by the present study is also compared to that obtained from “AUTODYN” software. A study is performed to investigate the effect of depth of burial on the load affecting the different faces of the buried structure.

KEYWORDS: Explosions, Nuclear, Overpressure, Buried structures, Dynamic loading.

1. Introduction

Blast loading is a type of extraordinary dynamic load to which structures or any object may be exposed to. The load resulted on structures or any targets from explosion is a complicated task to do.

Explosion is always followed by a blast wave (a pulse of air in which the pressure increases sharply at the front) and is accompanied by blast winds. The destructive effects of a blast wave are generally characterised by the peak overpressure p_{os}. However, in many cases, the drag forces associated with the strong transient winds behind the shock front are responsible for the actual damage. The pressure from this mass of air flow at and behind the shock front is termed the "dynamic pressure". This pressure is a function of the density of the air through which the blast wave passes and the wind velocity behind the shock front and it is responsible for what is called drag loading. These drag forces are a function of the shape and size of the structure and the transient dynamic pressure [1, 2, 3]. The blast or shock wave and the dynamic pressure are responsible for the load resulted on any object or structure exposed to explosion.

2.1 The peak overpressure p_{os}

The peak overpressure, p_{os} which is a function primarily of the weapon yield, the distance from the burst and the height of burst (in psi and kft/kt$^{1/3}$) will be: [1]

$$p_{os}(r,z) = \frac{10.47}{r^{a(z)}} + \frac{b(z)}{r^{c(z)}} + \frac{d(z).e(z)}{1.0 + f(z)r^{g(z)}} + h(x,r,y) \tag{1}$$

Where

$$a(z) = 1.22 - \frac{3.908\,z^2}{1+810.2\,z^5}, \tag{2.a}$$

$$b(z) = 2.321 + \frac{6.195\,z^{18}}{1+1.113\,z^{18}} - \frac{.03831\,z^{17}}{1+.02415\,z^{17}} + \frac{.6692}{1+4164\,z^8}, \tag{2.b}$$

$$c(z) = 4.153 - \frac{1.149\,z^{118}}{1+1.641\,z^{18}} + \frac{1.1}{1+2.771\,z^{2.5}}, \tag{2.c}$$

$$d(z) = -4.166 + \frac{25.76\,z^{1.75}}{1+1.382\,z^{18}} + \frac{8.257\,z}{1+3.219\,z}, \tag{2.d}$$

$$e(z) = 1 - \frac{.004642\,z^{18}}{1+.003886\,z^{18}}, \tag{2.e}$$

$$f(z) = .6096 + \frac{2.879\,z^{9.25}}{1+2.359\,z^{14.5}} - \frac{17.15\,z^2}{1+71.66\,z^3}, \tag{2.f}$$

$$g(z) = 1.83 + \frac{5.361\,z^2}{1+.3139\,z^6}. \tag{2.g}$$

And

$$h(z,r,y) = \frac{-(64.67\,z^5 + .2905)}{1+441.5\,z^5} - \frac{1.389z}{1+49.03\,z^5} + \frac{8.808\,z^{1.5}}{1+154.5\,z^{3.5}} + \frac{0.0014\,r^2}{(1-.158r+0.0486\,r^{1.5}+0.00128\,r^2)(1+2y)} \tag{2.h}$$

$r = \sqrt{x^2 + y^2}$ (kft/kt$^{1/3}$),

Where; x is the scaled ground rang, and y is the scaled height of burst.

2.2 Overpressure time history $P_s(t)$:

Overpressure time history $P_s(t)$ can be get from the expression: [1, 2]

$$p_s(x,y,t) = p_{os}(r,z)(1+a)(b.v+c) \quad psi \quad for\ x \geq xm\ ,\ y \leq 0.38 \tag{3.a}$$

$$p_s(x,y,t) = p_{os}(r,z) * b \quad psi \quad for\ x < xm\ or\ y > 0.38 \tag{3.b}$$

In which, $p_{os}(r,z)$ = peak overpressure, psi as in (1)

$$xm = \frac{170\,y}{1+337\,y^{0.25}} + 0.914\,y^{2.5}, \tag{4.a}$$

$$a = (d-1).\left(1 - \frac{e^{20}}{1+e^{20}}\right), \tag{4.b}$$

$$e = \left|\frac{x - xm}{xe - xm}\right|, \qquad xe = \frac{3.039\,y}{1+6.7\,y}, \tag{4.c}$$

$$b = \left[f.\left(\frac{t_a}{t}\right)^g + (1-f).\left(\frac{t_a}{t}\right)^h\right].\left[1 - \frac{(t-t_a)}{t_o}\right], \tag{4.d}$$

$$f = \left(\frac{0.01477\,t_a^{0.75}}{1+.005836\,t_a} + \frac{7.402*10^{-5}\,t_a^{2.5}}{1+1.429*10^{-8}\,t_a^{4.75}} - 0.216\right).s + 0.7076 - \frac{3.077*10^{-5}\,t_a^3}{1+4.367*10^{-5}\,t_a^3}, \tag{4.e}$$

$$ga = \frac{t - t_a}{dt}, \qquad dt = 475.2\,y.(x - xm)^{1.25}, \tag{4.f}$$

2.3 Time of arrival t_a and positive phase duration t_o:

The time of arrival t_a is given by the following expression:

$$t_a = u \qquad for\ x < xm \tag{4.g}$$

$$t_a = u\frac{xm}{x} + w\left(1 - \frac{xm}{x}\right) \qquad for\ x \geq xm \tag{4.h}$$

$$u = \frac{(0.0543 - 21.8\,r + 386\,r^2 + 2383\,r^3)\,r^8}{[2.99*10^{-14} - 1.91*10^{-10}\,r^2 + 1.032*10^{-6}\,r^4 - 4.43*10^{-6}\,r^6 + (1.028 + 2.087r + 2.69\,r^2)\,r^8]} \tag{4.i}$$

$$w = \frac{(1.086 - 34.605\,r + 486.3\,r^2 + 2383\,r^3)\,r^8}{3.0137*10^{-13} - 1.2128*10^{-9}\,r^2 + 4.128*10^{-6}\,r^4 - 1.116*10^{-5}\,r^6 + (1.632 + 2.629\,r^2)\,r^8} \tag{4.j}$$

And the positive phase duration t_o is given by:

$$t_o = \left(\frac{1640700 + 24629\,t_a + 416.15\,t_a^2}{10880 + 619.76\,t_a + t_a^2}\right).\left[\left(0.4 + \frac{.001204\,t_a^{1.5}}{1+0.001559\,t_a^{1.5}}\right) + \left(0.0426 + \frac{0.5486\,t_a^{0.25}}{1+0.00357\,t_a^{1.5}}\right).s\right] \tag{4.k}$$

$$c = \left[\frac{\left(1.04 - \frac{240.9\,x^2}{1+231.7\,x^4}\right).(ga)^7}{(1+a).\left[1+.923\,(ga)^{8.5}\right]}\right].\left[\frac{2.3*10^{13}\,y^9}{1+2.3*10^{13}\,y^9}\right].\left[1 - \left(\frac{(t-t_a)}{t_o}\right)^8\right], \tag{4.l}$$

$$v = 1 + \left(\frac{3.28*10^{11}\,y^6}{1+1.5*10^{12}\,y^{6.75}}\right).\left(\frac{ga^3}{6.13+ga^3}\right).\left(\frac{1}{1+9.23.e^2}\right), \tag{4.m}$$

$$s = 1 - \frac{1.1*10^{10} y^7}{1+1.1*10^{10} y^7} - \left(\frac{2.441*10^{-8} y^2}{1+9*10^{10} y^7}\right) \cdot \left(\frac{1}{4.41*10^{-11}+x^{10}}\right), \tag{4.n}$$

$$h = 2.753 + \frac{0.05601\, t_a}{1+1.473*10^{-9} t_a^5} + \left(\frac{0.01769\, t_a}{1+3.207*10^{-10} t_a^{4.25}} - \frac{0.03209\, t_a^{1.25}}{1+9.914*10^{-8} t_a^4} - 1.6\right).s \tag{4.o}$$

$$g = 10.0 + \left(77.58 - \frac{64.99\, t_a^{0.125}}{1+0.04348\, t_a^{0.5}}\right).s\ , \tag{4.p}$$

2.4 Dynamic pressure time history $p_d(t)$:

Dynamic pressure time history $p_d(t)$ [3]

$$p_d(t) = p_{ds}(1-\omega)^2.\left[d.e^{(-\delta\omega)} + f.e^{(-\phi\omega)}\right] \tag{5}$$

Which is accurate within ± 2 % for $2 \le p_{os} \le 100{,}000$ psi.

Where

$$p_{ds} = \frac{5}{2}\frac{p_{os}^2}{7p_a + p_{os}}, \qquad for\ p_{os} < 300\ psi \tag{6.a}$$

$$p_{ds} = \frac{5}{2}\frac{p_{os}^2(1+0.0604\lambda+0.0345\lambda^2)}{7p_a + p_{os} - 72.2\lambda^2 + 23.4\lambda^3}, for\ p_{os} > 300\ psi \tag{6.b}$$

Where p_a is the ambient pressure and $\lambda = p_{os}/1000$. This form is accurate within 6 % for $p_{os} \le 200{,}000$ psi.

$$\omega = (t - t_a)/t_d \quad for\ 0 \le \omega \le 1, \tag{6.c}$$

$$t_a = \left(0.004276 + \frac{112.51}{p_{os}^{0.80424}} + \frac{253.9}{p_{os}}\right) W_{Mt^{1/3}}\ \sec, \tag{6.d}$$

$$f = 1 - d,\ \ \delta = 0.38\, p_{os}^{0.8605},\ \ \phi = 5.4\, p_{os}^{0.604}, \tag{6.e}$$

$$d = \frac{0.83\, p_{os}^{0.035}}{1+0.147\left(\frac{p_{os}}{100}\right)^3} + \frac{0.266\left(\frac{p_{os}}{500}\right)^3}{1+6\left(\frac{p_{os}}{500}\right)^{3.5}} \tag{6.f}$$

3. Program BLAST

The above relations were implemented in a program called ***BLAST***, which is also used to calculate the load resulted from the blast on structures above and below ground as will be seen. Although the above expressions were made for weapon yields in ranges of kilotons (Kt) and megatons (Mt), it can be used for small scale yields. The overpressure time histories for different weapon yields compared to that resulted from "***ConWep***" [6, 7], are shown in Fig (1) to Fig (6).

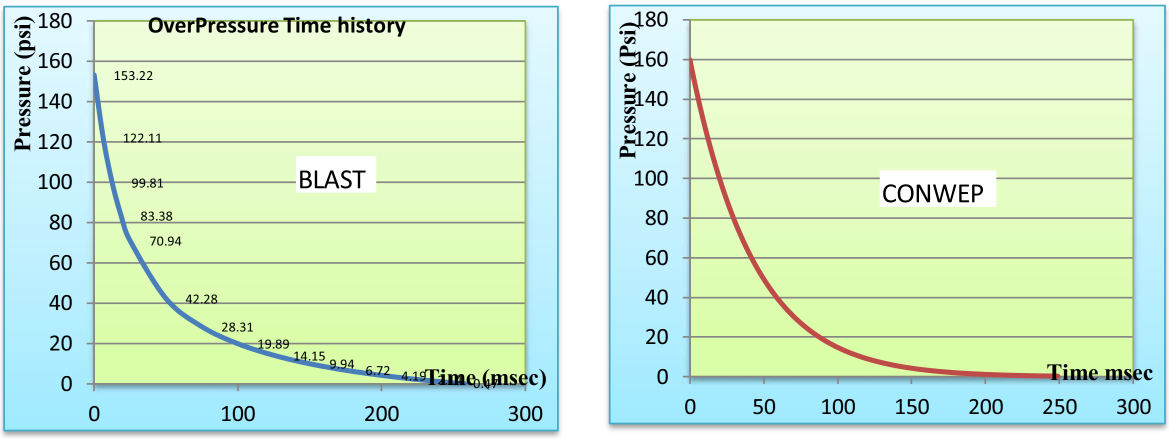

Fig (1) 10 kt at 200 m

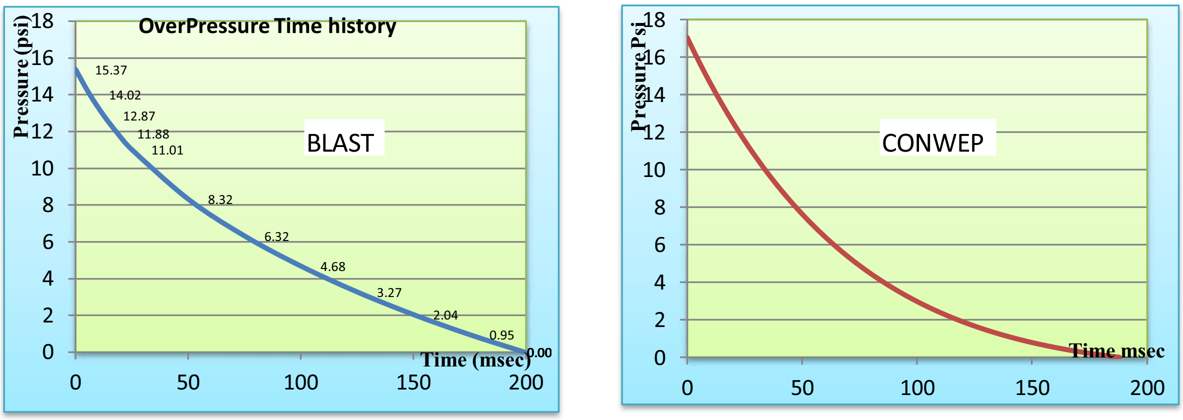

Fig (2) 0.5 kt at 200 m

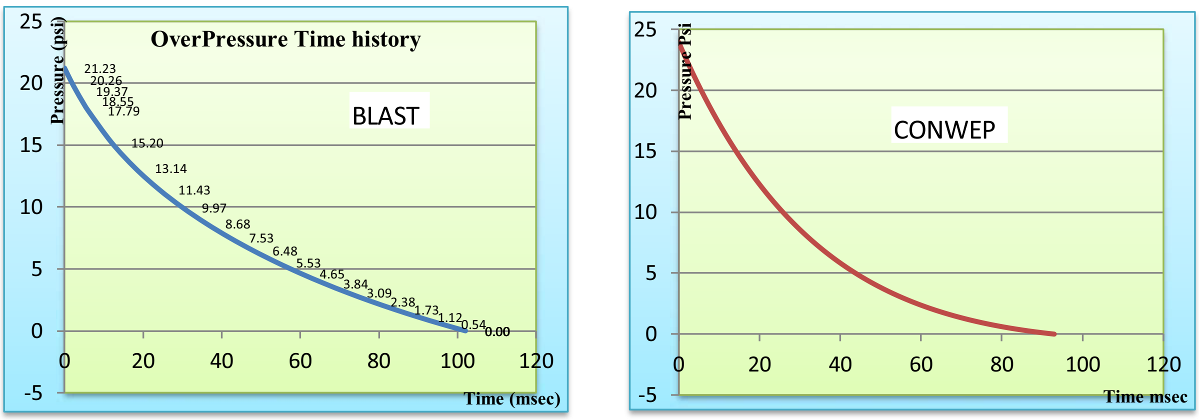

Fig (3) 0.1 kt at 100 m

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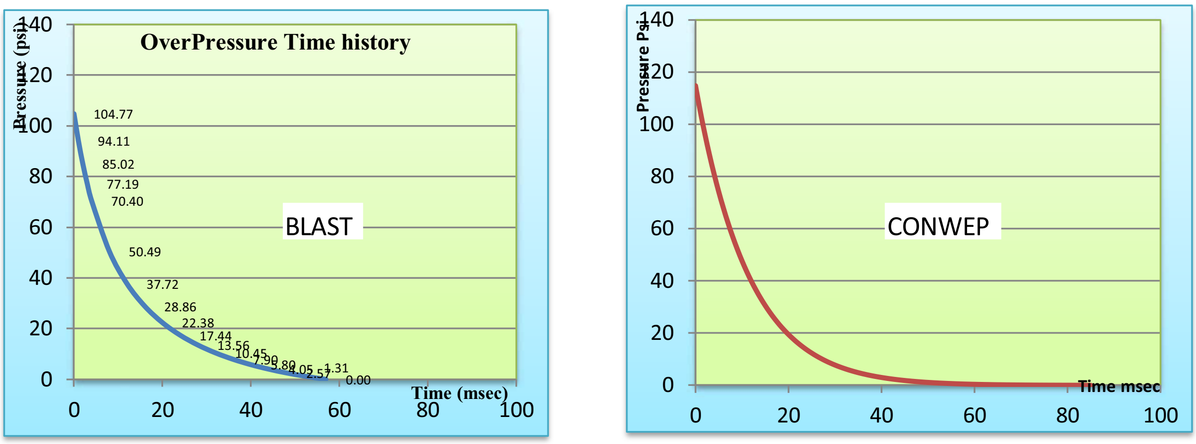


Fig (4) 0.1 kt at 50 m

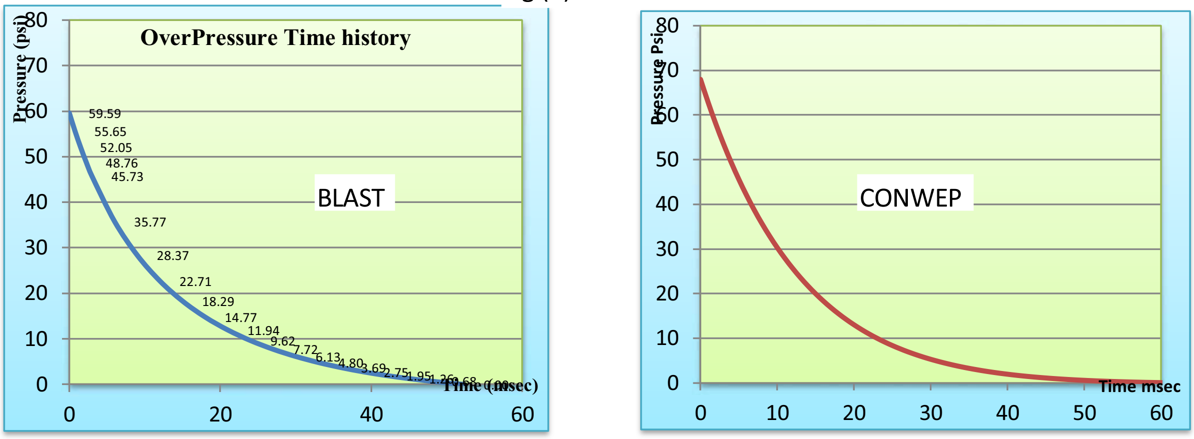


Fig (5) 50000 kg at 50 m

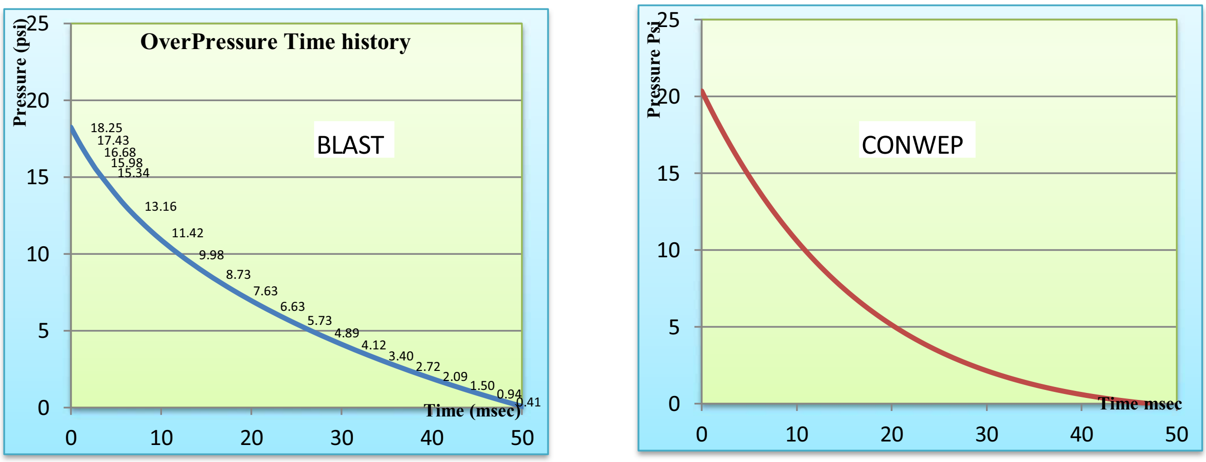


Fig (6) 10000 kg at 50 m

4.1 The blast loading on structures:

The air blast loading on exposed structure surfaces is a function of the free field overpressure (p_{so}) and the dynamic pressure (p_d), the size, the shape and the orientation of the structure. The total loading on a structure can be assumed to consist of three main parts [3, 10]

1) Effect of initial reflected overpressure
2) Effect of general overpressure
3) Drag loading "is related to dynamic pressure by the expression (drag pressure = C_d * P_d)"

Where: C_d is the drag coefficient and P_d .is the dynamic pressure

For front wall $C_d = 1$,

For roof, back and sides $C_d = -0.2$ for overpressure range 50 to 130 psi (34.5 to 89.6 N/cm^2)
= -0.3 for overpressure range 25 to 50 psi (17.2 to 34.5 N/cm^2)
= -0.4 for overpressure range 0 to 25 psi (0 to 17.2 N/cm^2)

The average loading on the front face of the structure P_{front} will consists of the reflected pressure P_r and decreasing linearly up to the clearing time t_c, where the load intensity at time t_c can be calculated as follows:-

$$P_c = P_s\,(t_c) + C_d\,P_d\,(t_c) \tag{7.a}$$

From time t_c to the end of duration of the blast wave (time t_o), the load intensity can be calculated as follows:

$$P(t) = P_s\,(t) + C_d\,P_d\,(t) \tag{7.b}$$

The clearing time (t_c) for a solid flat surface such as the wall of the building can be determinate from the following expression:-

$$t_c = 3S/U_r \tag{7.c}$$

Where S is the least of height (h) or half the length of the structure in the direction of propagation of the wave (L/2) and U_r is the velocity of sound in the region of the reflected overpressure. And it can be calculated from the expression (feet/s) [3]:-

$$U_r = 422\left(\frac{1.0088P_o + 70P_{so} + 720}{102.9 + 6P_{so}}\right)^{1/2} \tag{7.d}$$

Prediction of loads on buried structures is further complicated by the fact that stress wave propagating down ward reflect at structures surfaces that are in the path of the propagation [3].

The pressure acting on the roof of shallow buried rectangular structures (<u>D</u>epth <u>o</u>f <u>B</u>urial "DoB" between 0.2L & 1.5L, L is the clear span of the structure) may be approximated as follows:

$$P(t) = P_{ff}(t)\left(2 - \frac{t}{t_d}\right) \quad \text{for } t \le t_d \tag{8.a}$$

$$P(t) = P_{ff}(t) \quad \text{for } t > t_d \tag{8.b}$$

Where P(t) is the pressure acting on the roof at time t; and P_{ff}(t) is the incident wave pressure in the free field at the location of the structure roof; t_d=12 D/C

Where D is the thickness of the roof and C is the compressional wave velocity of the structural material (2000-2500 m/sec), and t is taken as zero at the time the incident wave strikes the roof. It can be assumed that for a shallow buried structure the vertical free field pressure acting on the soil having the same magnitude as the ground surface overpressure the time t_d is probably in the range **1** to **5** milliseconds

An acceptable approximation for the pressure acting on the base of structure is:

$$P_b(t) = P_{ff}(t), \tag{8.c}$$

In which P_b(t) is the pressure on the base of the structure; P_{ff}(t) is the incident wave pressure in the free-field at base of the structure.

As an acceptable approximation, the pressure acting on the side of a structure can be taken as:

$$P_s(t) = K_o\ P_{ff}(t), \tag{8.d}$$

In which $P_s(t)$ is the uniform lateral pressure on the side of the structure; K_o is the coefficient of lateral earth pressure at rest; and $P_{ff}(t)$ is the incident wave pressure in the free-field at mid-height of the structures sidewall.

4.2 Blast Load using AUTODYN

In AUTODYN, air domain surrounds Reinforced Concrete panel and explosion zone and has boundary condition called FLOW OUT. The flow out permits to translate blast wave to hit the RC panel as in blast field test (i.e. RC panel responds similar to actual practical case). Fig (7) illustrates the boundary conditions of the panel, the air media, and the explosion sphere [8, 9]. In numerical model, air and TNT are simulated by Euler formulation.

The blast load levels are implemented through the application of 10 and 15 kg of TNT explosive at the same stand-off distance of 4 m. The pressure-time histories for both charges are illustrated in Fig (8) [8, 9].

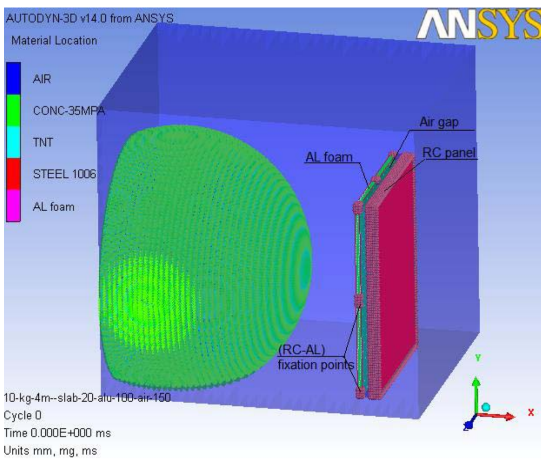


Fig (7) the boundary conditions, air medium and explosion sphere.

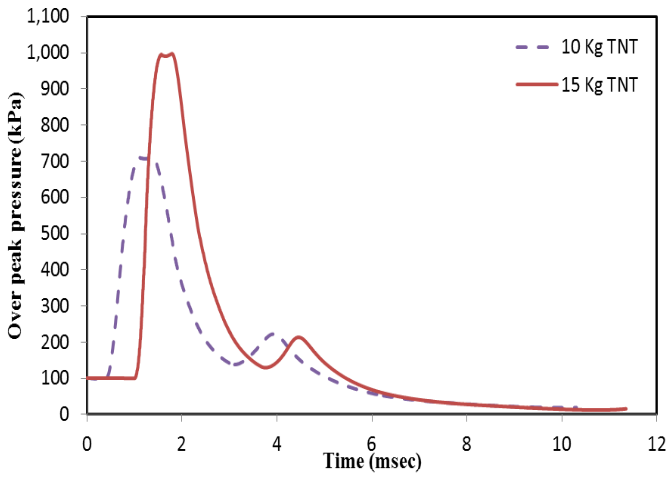


Fig (8) Loads on target from different charges at 4 m

4.3 Output results from Program *BLAST* for 15 kg TNT at 4 m range

P_{so} (peak side on pressure) = 39.4655 psi = 2.72105 bar = 2.7747 kg/cm^2 =272.105 kPa.

P_{do} (peak dynamic pressure) = 27.4182 psi = 1.89042 bar = 1.92769 kg/cm^2 =189.042 kPa.

t_a (time of arrival of the shock wave) = 4.93856 m sec.

t_o (the duration of the shock wave) = 4.12101m sec.

P_r (reflected pressure) = 144.573 psi = 5.65 P_{so} = 996.795 kPa.

U_r (velocity of sound in the region of the reflected over pressure) = 1354.07 ft/sec = 412.722m/sec.

U_o (the shock front velocity) = 2029.5 ft/sec =618.591 m/sec.

t_c (the clearance time) = 0.002908 sec = 2.908 msec.

t_s (the time of the stagnation pressure to take place) = 0.000647 sec = 0. 647 msec.

t_d (the time of the pressure to reach the back face) = 0.001293 sec =1.293 msec.

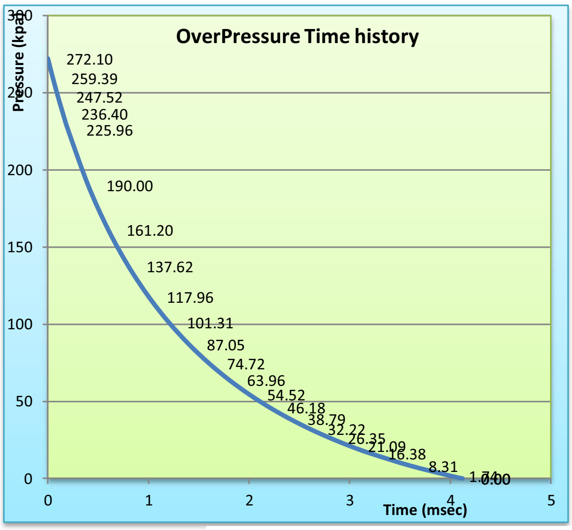
t_b (the built up time) = 0.002587 sec = 2.587 msec.

P_c (the pressure o the front face at the clearance time) = 3.41 psi =23.48057 kPa.

P_a (the average maximum pressure on the roof and sides) =21.1892 psi =146.0943 kPa.

P_{sb} (the over pressure of the blast wave at the time it arrives to back face) = 0.51876psi =3.576741kPa.

$P_{(back)max}$ (the maximum. pressure on the back face) = 0.23618 psi =1.628428 kPa.



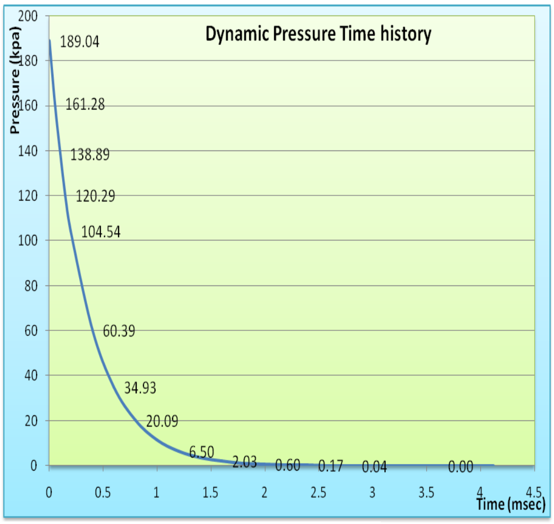


Fig (9) Over-pressure and Dynamic Pressure resulted from 15 kg at 4 m

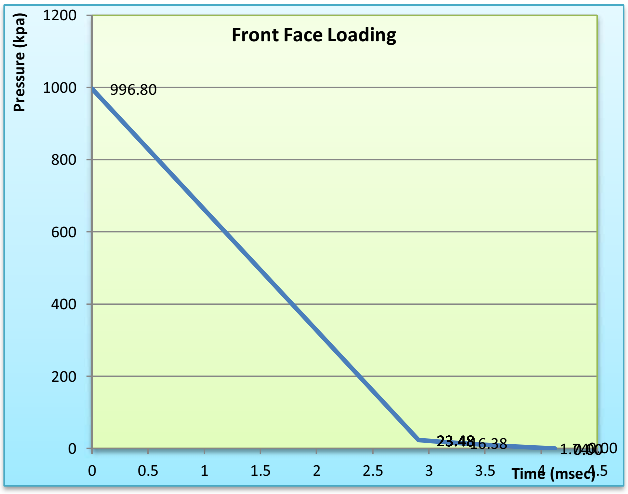


Fig (10) Load on target from 15kg at 4 m

The peak load on front face Fig (10) is 996.8 kPa with duration of 3 msec. which agrees well with that obtained from “AUTODYN” software Fig (8).

5. A case study:

If 200Kt weapon yield explodes at 600 m from the structure with the dimension as shown in Fig (11.a), the over-pressure and the dynamic pressure resulted from the explosion at the place of the structure will be as shown

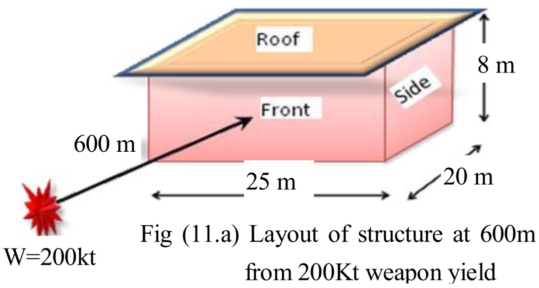


Fig (11.a) Layout of structure at 600m from 200Kt weapon yield

(Fig 11.b). The loads affecting the different sides of the structure will be as shown; if it is above ground (Figs 11.c-11.f) and if it is buried with DoB equal 10 m (Figs 12.a-12.c).

5.1 Sample output from program *“BLAST”*

P_{so} = 118.455 psi = 8.16721bar = 8.32823kg/cm^2 = 816.7 kPa
P_{do} = 158.725 psi = 10.9437 bar = 11.1595kg/cm^2 =1094.37 kPa
t_a = 410.09 m sec
t_o = 707.654 m sec
P_r (psi) = 617.249 = 5.21 P_{so} = 4255.78 kPa
U_r = 1405.6 ft/sec = 428.428 m/sec
U_o = 3140.94 ft/sec = 957.358 m/sec
t_c = 0.056019 sec = 56.0187 msec
t_s = 0.010445 sec = 10.4454 msec
t_d = 0.020891 sec = 20.8908 msec
t_b = 0.074692 sec = 74.6916 msec
P_c = 89.76 psi = 618.844 kpa
P_a = 88.1091 psi = 607.491 kPa
P_{sb} = 54.0968 psi = 372.985 kPa
$P_{(back)max}$ = 25.5908 psi = 176.442 kPa

Underground Structure:

t_d (time for load on roof to decrease to overpressure) = 12 msec.
σ_{ff} (the incident wave pressure in the free field at the location of the roof of structure)=111.364psi =767.829kPa
t_m (the time for the wave takes to reach the mid-height of the structure) = 10.4454 msec.

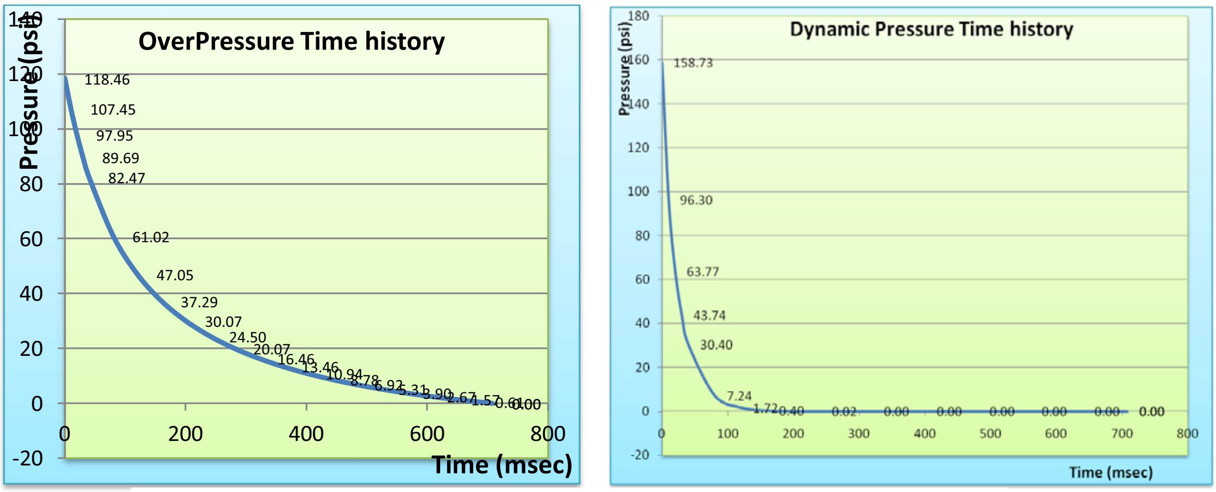


Fig (11.b) Over-pressure and Dynamic Pressure resulted from 200Kt at 600 m

5.2 Loads resulted from the explosion on the Above Ground Structure

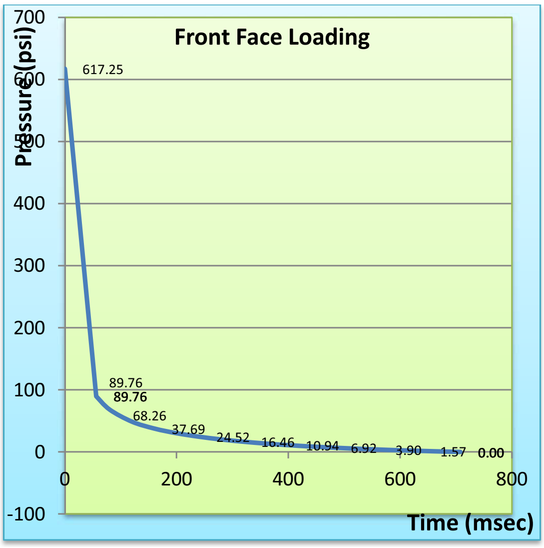


Fig (11.c) Front face loading

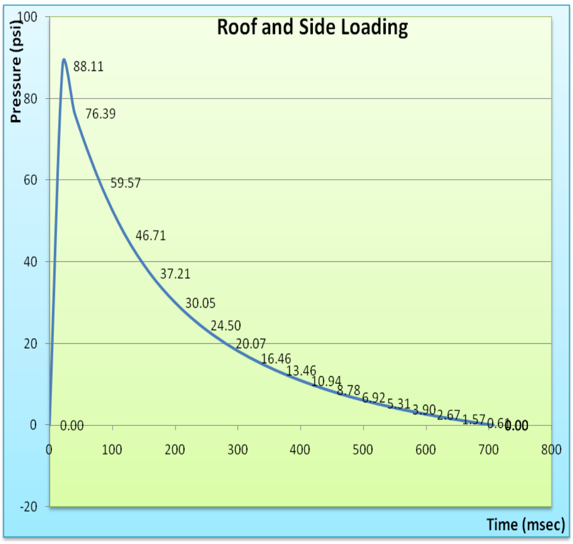
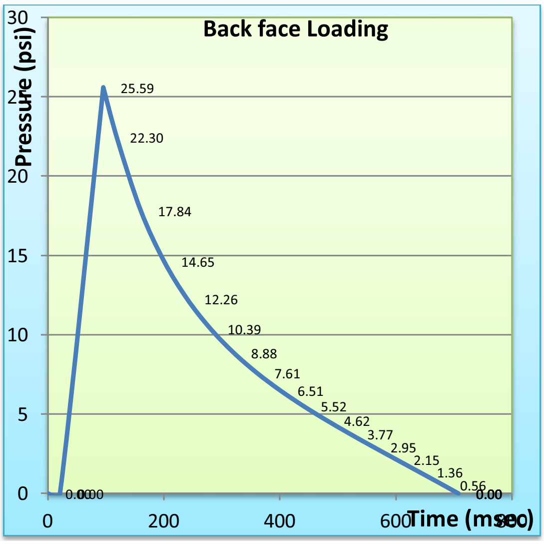


Fig (11.d) Loads on roof and sides



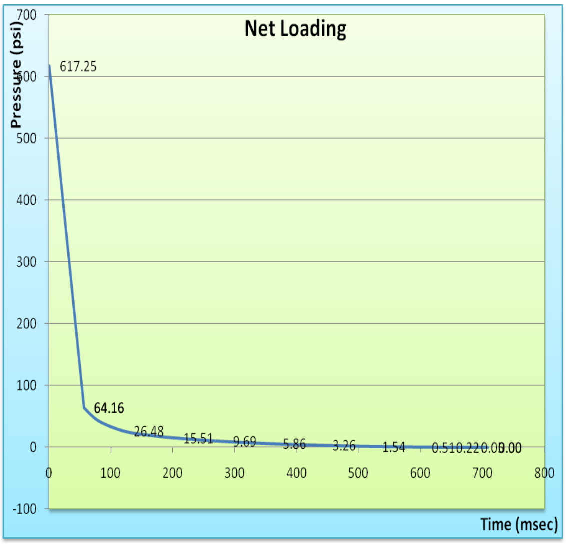


Fig (11.f) Net Loading on Structure

Fig (11.e) Loads on back face

5.3 Loads resulted from the explosion on the Under Ground Structure:

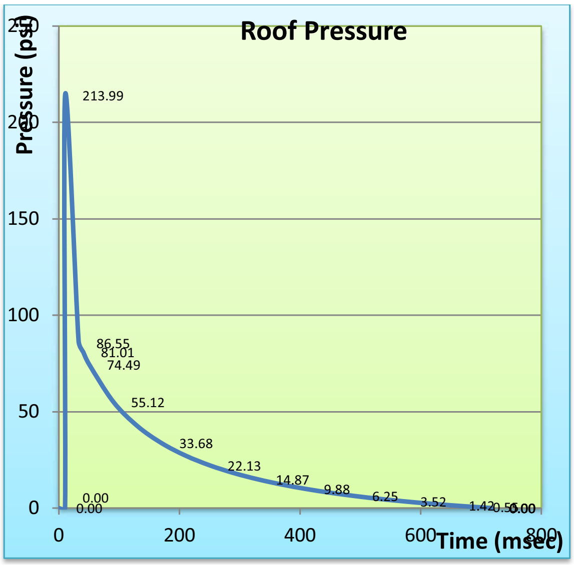


Fig (12.a) Loads on roof of buried structure

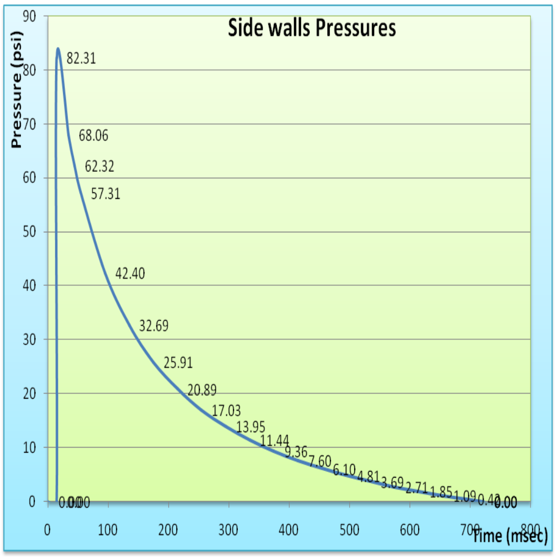


Fig (12.b) Loads on side walls of buried structure

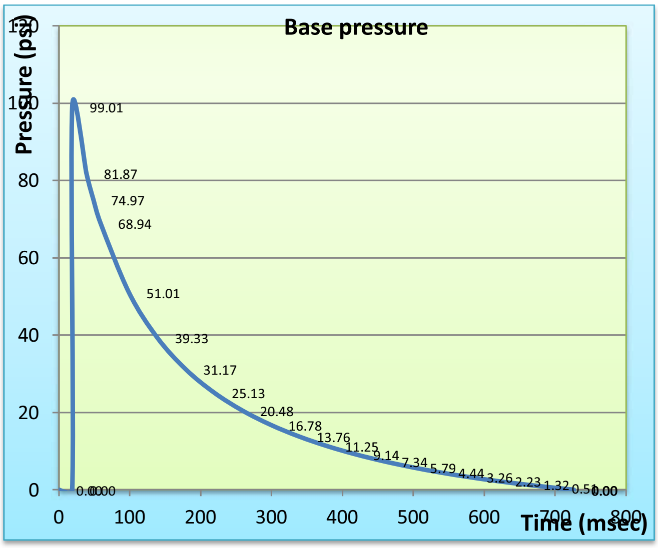


Fig (12.c) Loads on base of buried structure

6. Effect of Depth of Burial (DoB) on Peak loading on a buried Structure:

The effect of burial for the buried structure on the peak loads on roof, sides, and base of the structure were summarized in table (1). A normalized relation is shown in Fig (13). Using curve fitting, equation (9) gives the relation between normalized DoB and normalized peak pressure.

Table (1)

DoB (m)	Normalized DoB=(DoB/L)	Roof Peak Load (psi)	Normalized P_{Roof}/P_{so}	Side Peak Load (psi)	Normalized P_{Side}/P_{so}	Base Peak Load (psi)	Normalized P_{Base}/P_{so}
4	0.2	227.3069	1.91893	87.31631	0.737126	104.90807	0.885636486
6	0.3	222.7284	1.880278	85.59539	0.722598	102.88432	0.86855194
8	0.4	218.2908	1.842816	83.92646	0.708509	100.92054	0.851973661
10	0.5	213.9885	1.806496	82.30745	0.694842	99.014412	0.835882082
12	0.6	209.8161	1.771273	80.73643	0.681579	97.16371	0.82025841
14	0.7	205.7686	1.737104	79.21153	0.668706	95.36631	0.805084716
16	0.8	201.8411	1.703947	77.73097	0.656207	93.620185	0.790343886
18	0.9	198.0288	1.671764	76.29305	0.644068	91.923397	0.77601956
20	1.0	194.3274	1.640517	74.89615	0.632275	90.274094	0.762096104
22	1.1	190.7326	1.610169	73.53872	0.620816	88.670506	0.748558575
24	1.2	187.2404	1.580688	72.21928	0.609677	87.110941	0.735392689
26	1.3	183.8468	1.552039	70.93641	0.598847	85.593781	0.722584787
28	1.4	180.5482	1.524192	69.68875	0.588314	84.117476	0.710121785
30	1.5	177.341	1.497117	68.47503	0.578068	82.680546	0.697991187
32	1.6	174.2219	1.470785	67.293981	0.568097	81.281572	0.686181014
34	1.7	171.1876	1.44517	66.144437	0.558393	79.919196	0.674679802
36	1.8	168.235	1.420244	65.025258	0.548945	78.592119	0.663476586
38	1.9	165.3611	1.395982	63.935357	0.539744	77.299096	0.652560854
40	2.0	162.5631	1.372362	62.873695	0.530781	76.038932	0.641922519

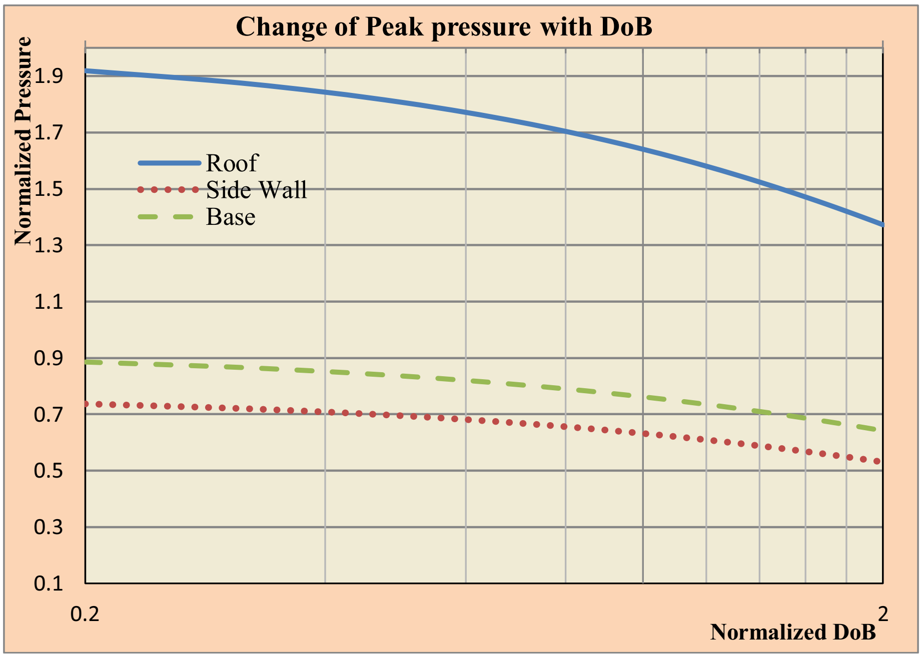


Fig (13) effect of depth of burial on peak loading on roof, side and base of buried structure

For Roof: $P_{peak}/P_{so}=0.0438*(DoB/L)^2 - 0.398*(DoB/L) + 2.0$ (9.a)

For Base: $P_{peak}/P_{so}=0.0188*(DoB/L)^2 - 0.176*(DoB/L) +0.919$ (9.b)

For Side: $P_{peak}/P_{so}=0.0162*(DoB/L)^2 - 0.15*(DoB/L) +0.766$ (9.c)

7. Discussion of Results

This paper presents a program called "**BLAST**" based on a collection of equations from literatures to predict the shock wave from explosion and to calculate the load affecting any structure or target above or under the ground located at a distance from the centre of explosion. The results obtained for different weapon yields at different distances were compared well to those obtained from "ConWep". The load on the structure is also compared to that obtained from "AUTODYN" software. It can be concluded that the results obtained from the program "BLAST" -***which are easy to use and save effort and time***- are compared well to those obtained from sophisticated software. A parametric study to investigate the effect of depth of burial of structure on the load affecting the different faces was carried out. The pressure affecting the roof decreased by (17%) from $1.8065P_{so}$ to $1.497P_{so}$ as the DoB increased (300%) from 0.5L to 1.5L, while for the base the pressure decreased by (16.5%) and for the side it decreased by (16.8%).

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