New Model to Calculate Blast Loading on Above and Underground Structures

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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 $p_{oo}$. 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 \( p_{\text{on}} \)

The peak overpressure, \( p_{\text{on}} \), 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]

\[
p_{\text{on}}(r,z) = 10.47 \cdot \frac{b(z) + d(z)}{1 + f(z)} + h(x,r,y)
\]

Where

\[
a(z) = 1.22 - 3.908 \frac{z^3}{1 + 810.2 z^3},
\]

(2.a)

\[
b(z) = 2.321 + 6.195 \frac{z^{16}}{1 + 1.113 z^{18}} - 0.03831 \frac{z^{17}}{1 + 0.02415 z^{17}} + 0.6692 \frac{z^{17}}{1 + 4164 z},
\]

(2.b)

\[
c(z) = 4.153 - 1.149 \frac{z^{18}}{1 + 1.641 z^{18}} + 1.1 \frac{z^{18}}{1 + 2.771 z^{2.3}},
\]

(2.c)

\[
d(z) = -4.166 + 25.76 \frac{z^{1.75}}{1 + 1.382 z^{1.8}} - 8.257 \frac{z^{1.8}}{1 + 3.219 z},
\]

(2.d)

\[
e(z) = 1 - 0.004642 \frac{z^{18}}{1 + 0.003886 z^{18}},
\]

(2.e)

\[
f(z) = 0.6096 + 2.879 \frac{z^{0.25}}{1 + 2.359 z^{0.35}} - 17.15 \frac{z}{1 + 71.66 z^2},
\]

(2.f)

\[
g(z) = 1.83 + 5.361 \frac{z^2}{1 + 3.139 z^2},
\]

(2.g)

And

\[
h(z,r,y) = \frac{64.67 z^{5} + 2905}{1 + 441.5 z^2} + \frac{1.389 r}{1 + 49.03 z^2} + \frac{8.808 z^{1.5}}{1 + 154.5 z^{1.5}} + \frac{0.0014 r^2}{(1 - 0.158 r + 0.0486 r^{1.3} + 0.00128 r^3)(1 + 2y)}
\]

(2.h)

\[
\tau = \sqrt{x^2 + y^2} \text{ (kft/kt}^{1/3})
\]

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]

\[
p_{s}(x,y,t) = p_{\text{on}}(r,z)(1 + a)(b \cdot v + c) \quad \text{psi for } x \geq xm, \ y \leq 0.38
\]

(3.a)

\[
p_{s}(x,y,t) = p_{\text{on}}(r,z) \cdot b \quad \text{psi for } x < xm \text{ or } y > 0.38
\]

(3.b)
In which, $p_o(r,z) = \text{peak overpressure, psi as in (1)}$

$$x_m = \frac{170 y}{1 + 337 y^{0.25}} + 0.914 y^{2.5},$$

(4.a)

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

(4.b)

$$e = \left|\frac{x - x_m}{x_m - x}\right|, \quad x_e = \frac{3.039 y}{1 + 6.7 y},$$

(4.c)

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

(4.d)

$$f = \left(\frac{0.01477 t_o^{0.75} + 7.492*10^{-5} t_o^{5.25} - 0.216}{1 + 0.00583 t_o^{10^-5} t_o^{25}}\right) + 0.7076 - \frac{3.077*10^{-5} t_o^{3}}{1 + 4.367*10^{-5} t_o^{3}},$$

(4.e)

$$ga = \frac{t - t_o}{dt}, \quad dt = 475.2 y (x - x_m)^{1.25},$$

(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:

$$t_a = u \quad \text{for } x < x_m$$

(4.g)

$$t_a = u \frac{x_m}{x} + w \left(1 - \frac{x_m}{x}\right) \quad \text{for } x \geq x_m$$

(4.h)

$$u = \frac{(0.0543 - 21.8 r + 238 r^2 + 101.5^{1.25}) r^{8}}{[2.99*10^{-14} - 1.91*10^{-10} r^2 + 1.032*10^{-6} r^4 - 4.43*10^{-6} r^6 + (1.028 + 2.087r + 2.69 r^2)r^8]}$$

(4.i)

$$w = \frac{(1.086 - 34.605 r + 486.3 r^2 + 2383 r^3)r^{8}}{3.0317*10^{-15} - 1.2128*10^{-9} r^2 + 4.128*10^{-6} r^4 - 1.116*10^{-5} r^6 + (1.632 + 2.629 r^2)r^8}$$

(4.j)

And the positive phase duration $t_o$ is given by:

$$t_o = \left(\frac{1640700 + 24629 t_o + 416.15 t_o^5}{10880 + 619.76 t_o + t_o^5}\right)^{0.4 + \frac{0.001204 t_o^{1.5}}{1 + 0.00559 t_o^{1.5}}} + \left(\frac{0.0426 + \frac{0.5486 t_o^{0.25}}{1 + 0.00357 t_o^{0.25}}}{t_o}\right) r^{8}$$

(4.k)

$$c = \left[\frac{1.04 - 240.9 x^2}{1 + 231.7 x^2}\right] (ga)^{2.3} \left[\frac{2.3*10^{14} y^9}{1 + 2.3*10^{13} y^9}\right] \left[1 - \left(\frac{t - t_o}{t_o}\right)^{8}\right],$$

(4.l)

$$v = 1 + \left(\frac{3.28*10^{11} y^6}{1 + 1.5*10^{12} y^{0.75}}\right) \left(\frac{ga^2}{6.13 + ga^2}\right) \left(\frac{1}{1 + 9.23 e^2}\right).$$

(4.m)
2.4 Dynamic pressure time history \( p_d(t) \):

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

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

Which is accurate within ± 2 % for \( 2 \leq p_{os} \leq 100,000 \) psi.

Where

\[
p_{ds} = \begin{cases} 5 \frac{p_{os}^2}{p_a + p_{os}}, & \text{for } p_{os} < 300 \text{ psi} \\
\frac{5}{2} \frac{p_{os}^2}{p_a + p_{os}} \left( \frac{1}{p_{os}^{0.0604} + 0.0345} \right)^2, & \text{for } p_{os} > 300 \text{ psi}
\end{cases}
\]

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

\[
\omega = (t - t_a) / t_d, \text{ for } 0 \leq \omega \leq 1,
\]

\[
t_a = \left( 0.004276 + \frac{112.51}{p_{os}^{0.860424}} + 253.9 \right) W_{Mc}^{0.35} \text{ sec}.
\]

\[
f = 1 - d, \ \delta = 0.38 p_{os}^{0.8605}, \ \phi = 5.4 p_{os}^{0.604},
\]

\[
d = \frac{0.83 p_{os}^{0.035}}{1 + 0.147 \left( \frac{p_{os}}{100} \right)^3} + 0.266 \left( \frac{p_{os}}{500} \right)^{3/5}
\]

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
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 \( \text{drag pressure} = C_d \times P_d \)”

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

\( C_d = \begin{cases} 
-0.2 & \text{for overpressure range 50 to 130 psi (34.5 to 89.6 N/cm²)} \\
-0.3 & \text{for overpressure range 25 to 50 psi (17.2 to 34.5 N/cm²)} \\
-0.4 & \text{for overpressure range 0 to 25 psi (0 to 17.2 N/cm²)}
\end{cases} \)

The average loading on the front face of the structure \( P_{front} \) will consist 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:

\[
P_c = P_s(t_c) + C_d P_d(t_c) \quad (7. a)
\]

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

\[
P(t) = P_s(t) + C_d P_d(t) \quad (7. b)
\]

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

\[
t_c = \frac{3S}{U_r} \quad (7. c)
\]

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]:

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

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

The pressure acting on the roof of shallow buried rectangular structures (Depth of Burial “DoB” between 0.2L & 1.5L, \( L \) is the clear span of the structure) may be approximated as follows:

\[
P(t) = P_{ff}(t) \left( 2 - \frac{t}{L_{ff}} \right) \quad \text{for } t \leq t_d \quad (8. a)
\]

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

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; \( t_d = 12 \text{ D/C} \)

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:

\[
P_b(t) = P_{id}(t) \quad (8. c)
\]

In which \( P_b(t) \) is the pressure on the base of the structure; \( P_{id}(t) \) 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:

\[ P_s(t) = K_o P_{fd}(t), \quad (8.d) \]

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 \( P_{fd}(t) \) is the incident wave pressure in the free-field at mid-height of the structure’s 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].

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) = 4.12101 m 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 = 412.722 m/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.
- \( t_t \) (the time of the stagnation pressure to take place) = 0.000647 sec = 0.647 msec.
- \( t_p \) (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.
- \( P_f \) (the pressure on the front face at the clearance time) = 3.41 psi = 23.48057 kPa.
- \( P_r \) (the average maximum pressure on the roof and sides) = 21.1892 psi = 146.0943 kPa.
- \( P_{so} \) (the over pressure of the blast wave at the time it arrives to back face) = 0.51876 psi = 3.576741 kPa.
\( P_{\text{back max}} \) (the maximum pressure on the back face) = 0.23618 psi =1.628428 kPa.

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 in Fig (9). 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).

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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”

\[
\begin{align*}
\text{P}_{so} & = 118.455 \text{ psi} = 8.16721 \text{ bar} = 8.32823 \text{ kg/cm}^2 = 816.7 \text{ kPa} \\
\text{P}_{do} & = 158.725 \text{ psi} = 10.9437 \text{ bar} = 11.1595 \text{ kg/cm}^2 = 1094.37 \text{ kPa} \\
\text{ta} & = 410.09 \text{ m sec} \\
\text{to} & = 707.654 \text{ m sec} \\
\text{P}_{f} (\text{psi}) & = 617.249 = 5.21 \text{ P}_{so} = 4255.78 \text{ kPa} \\
\text{U}_{1} & = 1405.6 \text{ ft/sec} = 428.428 \text{ m/sec} \\
\text{U}_{0} & = 3140.94 \text{ ft/sec} = 957.358 \text{ m/sec} \\
\text{tc} & = 0.056019 \text{ sec} = 56.0187 \text{ msec} \\
\text{ts} & = 0.010445 \text{ sec} = 10.4454 \text{ msec} \\
\text{td} & = 0.020891 \text{ sec} = 20.8908 \text{ msec} \\
\text{tb} & = 0.074692 \text{ sec} = 74.6916 \text{ msec} \\
\text{P}_{c} & = 89.76 \text{ psi} = 618.844 \text{ kPa} \\
\text{P}_{a} & = 88.1091 \text{ psi} = 607.491 \text{ kPa} \\
\text{P}_{ab} & = 54.0968 \text{ psi} = 372.985 \text{ kPa} \\
\text{P}_{(\text{back})\text{max}} & = 25.5908 \text{ psi} = 176.442 \text{ kPa}
\end{align*}
\]

Underground Structure:

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

5.2 Loads resulted from the explosion on the Above Ground Structure

![OverPressure Time history](image1)

![Dynamic Pressure Time history](image2)

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

Fig (11.d) Loads on roof and sides

Fig (11.f) Net Loading on Structure
5.3 Loads resulted from the explosion on the Under Ground Structure:

Fig (11.e) Loads on back face

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 PRoof/Pso | Side Peak Load (psi) | Normalized PSide/Pso | Base Peak Load (psi) | Normalized PBase/Pso |
|---------|-------------------------|----------------------|---------------------|---------------------|---------------------|---------------------|---------------------|
| 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                     | 190.7327             | 1.610169            | 73.53872            | 0.620816            | 88.670506           | 0.748558575           |
| 24      | 1.2                     | 187.2404             | 1.580688            | 72.21928            | 0.609677            | 87.110941           | 0.73392689           |
| 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             | 66.14437            | 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            | 77.290996           | 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**: \( \frac{P_{\text{peak}}}{P_{\text{so}}} = 0.0438*(\text{DoB}/L)^2 - 0.398*(\text{DoB}/L) + 2.0 \)  \hspace{1cm} (9.a)

For **Base**: \( \frac{P_{\text{peak}}}{P_{\text{so}}} = 0.0188*(\text{DoB}/L)^2 - 0.176*(\text{DoB}/L) + 0.919 \)  \hspace{1cm} (9.b)

For **Side**: \( \frac{P_{\text{peak}}}{P_{\text{so}}} = 0.0162*(\text{DoB}/L)^2 - 0.15*(\text{DoB}/L) + 0.766 \)  \hspace{1cm} (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 1.8065\(P_{so}\) to 1.497\(P_{so}\) as the DoB increased (300%) from 0.5\(L\) to 1.5\(L\), while for the base the pressure decreased by (16.5%) and for the side it decreased by (16.8%).

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