

ADDITIONAL STRUCTURAL DAMAGE FROM GROUND SHOCK AS A RESULT OF A BOMBING

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ABSTRACT: The term bombing refers to an uncontrolled demolition (implosion) where a terrorist employs an explosive of a charge weight and detonates it at range and height (air or ground blast) suitable to cause the maximum damage. For a designer trying to design a structure in advance of such a situation happening is extremely difficult thus requiring the consideration of past bombings for the pertinent design parameters. Ground shock is a small earthquake that impacts the structure via energy released from the detonation of the bomb into the ground being converted to wave energy with compression (P) waves, shear (S) waves and the most damaging surface Raleigh (R) waves moving out in all directions from the point of detonation whether it is on or above ground. The common measurement for quantifying ground shock from blast loadings is the peak particle velocity (PPV) as it correlates reasonably well with both building damage and the annoyance levels that people can tolerate under normal circumstances. The Oklahoma City VIED bombing has been used as an example using CONWEP software for a 2200kg VIED detonated at 4.75m from the building. Ground shock results showed that a PPV of 11.5m/s (11500mm/s) was achieved well in excess of guidelines set by AS 2187 and DIN 4150. As well the structure was subjected to radial displacements of 100mm to 350mm adding to the overall damage. Considering the ground shock results along with a reflected overpressure of 51.17MPa it is unsurprising that the building collapsed and many were killed and injured. This is the recommended design overpressure.

Keywords: Ground shock, R waves, PPV, displacement, Charge weight

1. INTRODUCTION

Presently, there is no guidance available to a designer within the Australian environment to design for ground shock from a large blast loading to a commercial or civilian building. Australian Standard AS2187 [1] references the British Standard BS 7385-2 [2] with respect to vibration values that would be suitable in order to restrict cosmetic damage [3] but it in no way covers the unlikely large vibrations (ground shock) from an uncontrolled demolition (the bombing of a structure [4]). The limits normally highlighted are 50mm/s at a frequency of 4Hz and above for reinforced or framed structures buildings and between 15mm/s at 4Hz to 20mm/s at 40Hz for unreinforced or light framed structures. Apart from the points above the other general guidance AS2187.2 gives in relation to higher limits are:

- A frequency-based limit up to 50mm/s to control the threshold of damage.
- An ultimate limit of 100mm/s for control of damage to unoccupied steel or concrete structures.
- A human comfort limit of 5mm/s (long term) and 10mm/s (short term) for sensitive receivers, houses, schools, libraries, theatres etc.

- A human comfort limit of 25mm/s for non-sensitive receivers in industrial and commercial buildings.

As a comparison to the Australian Standard the German Standard DIN 4150 Appendix B [5] provides the following guidelines in Table 1. The guidelines further state that experience has shown that provided the values given in Table 1 are observed damage due to vibration in terms of a reduction in utility value is unlikely to occur. It also states that if the values in the table are exceeded it does not necessarily mean that damage will occur. Should these values be significantly exceeded further investigation is mandatory? Such information is unfortunately virtually useless for any designer trying to design against blast loadings from either a vehicle improvised explosive device (VIED) [6] or an improvised explosive device (IED) [7] particularly as no attack event has yet occurred on Australian. A designer should be in possession of the necessary information to design for ground shock that will result from a detonation of an explosive from either an air burst, surface burst or a buried explosive. An air burst [8] will present a downward propagation of a ground shock [9] and whether it is strong or weak will depend on the charge weight (kg) of the explosive. The surface blast will always be strong and produce surface waves (R) [10] and soil body waves (P and S [11]). For a buried explosive once detonated if the cavity it was held in

is filled it will produce an exceptionally strong ground shock but if the cavity is only partially filled due to coupling it will produce a weaker ground shock. In other words, ground shock is proportional

to the degree of confinement. In the case of near surface detonations such as those just above ground level the ground shock becomes more difficult to predict because of the lack of coupling.

Table 1 Guideline for vibration velocity for structural type

Structural type	Vibration Velocity (v, mm/sec)			
	Foundation			Plane of floor of uppermost full storey
	Less than 10Hz	10-50Hz	50-100Hz	Frequency mixture
Commercial Industrial or Similar Dwellings or Similar Particularly Sensitive	20	20 to 40	40 to 50	40
	5	5 to 15	15 to 20	15
	5	3 to 8	8 to 10	8

2. GROUND SHOCK

2.1 Characterization of Ground Shock

All detonations near or on the ground surface will create the three waves specified in para 1. The isotropic component of the stress pulses causing compression and dilation of the soil in the case of P waves [12] particle velocity is parallel to the direction of propagation and in the case of S waves with the separation resistant component of the stress causing distortion and shearing of the soil the particle velocity is perpendicular to the direction of the propagation of the waves. Near the ground surface particles move in a circular motion in the form of R waves as they have a slower rate of decay with distance from a target. In near surface detonations R waves dominate whilst P and S waves dominate in buried detonations. The propagation velocities produced by a detonation depend primarily on the density and stiffness of the subgrade soil. R and S waves travel at approximately at the same speed as they are concerned with the distortive movement of the subgrade soils:

$$c_R \approx c_S = \sqrt{\frac{G}{\rho}} \tag{1}$$

where G is the shear modulus of the soil (GPa)
 c_R and c_S are velocities if R and S waves (msec)
 ρ is the density of the soil (kg/m³)

Since the propagation of the P waves is concerned with the isotropic compression of soil:

$$c_p = \sqrt{\frac{K}{\rho}} \tag{2}$$

where K is the bulk modulus and is given by

$$\frac{2}{3} G \frac{(1 + \nu)}{(1 - 2\nu)}$$

In seismic terms the velocity is defined as follows:

$$c = \sqrt{\frac{E}{\rho}} \tag{3}$$

where E is the modulus obtained from a uniaxial, unconfined compressive test

Typical ground shock velocities are 200m/s for loose dry sand to 1500m/s and greater for saturated clays. Ground shock wave energy decreases with distance from the detonation point [13] for the following reasons:

- Because of geometric effects such as distance and height of detonation above the ground surface the energy in the transient pulse spreads out over an increasing surface area as the spherical wave front moves away from the detonation point.
- Energy is being lost in the soil as work is being done in plastically deforming the soil subgrade.

A high ground shock velocity implies low hysteresis (lagging effect) and therefore reduced hysteretic reduction with range. For the P and S waves their amplitude is approximately inversely proportional to the range (m) whilst for the R waves amplitude is inversely proportional to the square root of the range (m). P and S waves reduce more rapidly than R waves meaning that in any detonation event the R waves dominate at large ranges (m). For any explosion, the detonation process can be classified as unconfined, partially confined or confined. The case that provides for the greater influence to ground shock is a confined explosion as a simple relationship exists between ground shock, induced air blast and vertical displacement or vibration [14]. The equation defining the relationship is Eq. (4).

$$P = 0.4072V \quad (4)$$

where P is the peak overpressure (Pa)

V is the peak vertical velocity (mm / s)

or alternatively:-

$$dBL = dB(\text{Lin}) P_k$$

Decibels measure the logarithm of the ratio of a variable to a reference level. For sound pressure level, the standard reference level is 20 μ Pa.

2.2 Ground Shock Parameters

In any detonation situation where ground shock is involved, the initial situation parameters such as the charge weight (kg) and type of explosive, the coupling of the explosive, the soils properties (E, ρ , ν , K) and the range (m) to a structure or target are known but these still need to relate to the ground disturbance situation parameters to investigate the overall target response (damage). Additionally, the size of the ground disturbance situation is normally described by two parameters:

- Peak particle displacement (x).
- Peak particle velocity (u).

The soil particle movement via the ground shock produces a loading to the structure of which the following loading parameters apply:

- Peak side on overpressure (p_s).
- Side on specific impulse (i_s).

The magnitude of any ground shock is directly related to the size of the charge weight (kg) and the coupling of the detonation to the soil. Knowing the soil properties and the reduction of the shock waves produced with range will allow for x and u to be calculated at impact on the target. These parameters are directly related to the loading parameters that can then be used to determine the target response and

damage. The relationship between x, u, p_s and i_s is as follows.

$$p_s = \rho c_p u$$

and

$$i_s = \rho c_p x \quad (5)$$

2.3 Ground Shock Predictions

The US Army Corps of Engineers UFC 3-340-02 2008 [15] provides further guidance in relation to predicting ground shock effects with a set of empirical formulas for ground shock induced from air induced blast loadings and from ground (surface) induced blast loadings. The main effort is to predict the outcome of the explosive energy from a blast being imparted to the ground with a portion of the energy transmitted through the ground as direct induced ground shock and then with the remaining portion transmitted through the air as air induced ground shock. At the point of detonation of the explosive the ground shock experienced is the combination of both air induced and direct induced shock waves.

2.3.1 Air Induced Ground Shock [16]

For predicting actual ground shock, a one-dimensional propagation theory has been adopted to quantify maximum displacement (mm), velocity (m/s), and vertical acceleration (m/sec^2) in terms of blast load parameters such as charge weight (kg), range (m) and soil properties. The Equation (7) applies for the maximum vertical velocity at ground level. Regarding the next parameter to design for blast loadings, the maximum vertical displacement is calculated from the Eq. (8).

$$V_v = \frac{P_{so}}{\rho c_p} \quad (6)$$

where V_v is maximum vertical velocity m / s

P_{so} is peak incident overpressure MPa

ρ is mass density of soil kg / m^3

c_p is seismic wave velocity m / s

$$D_v = \frac{i_s}{1000 \rho c_p} \quad (7)$$

where D_v is the maximum vertical displacement mm

i_s is the specific impulse MPa-msec

2.3.2 Direct Ground Shock [17]

In this case the soil conditions need be considered and so UFC 3-340-02 2008 considers three different soil media such as dry soil, saturated soil and rock. Vertical and horizontal motions within these soil media result from the detonation of an explosive at the surface which in turn transmits energy directly into the soil media. The peak vertical displacement (mm) at surface level for rock (D_{rock}) and dry soil (D_{soil}) is given by Eq. 8.

2.4 Combination of Blast Loading and Ground Shock to Structure

When a VIED is detonated the blast immediately moves out towards the structure but at the same time blast waves impact the ground beneath the vehicle thus causing ground shock waves [18] to also move out towards the building but travelling in advance of the blast waves. In other words, in large explosions the total impact on the structure results from the blast wave and ground shock resulting in greater damage to the structure.

2.4.1 Blast Loading

Blast loads are generally extremely intense but of very short duration and measured in milliseconds. So, any structure impacted by a blast load depends on its dynamic characteristics and its ability to satisfactorily respond to the blast load. In the case of structural elements made of steel or concrete they can absorb substantial strain energy and thus undergo much more substantial deformation without failing. Fig.1 is a typical Pressure v's Time graph that defines a blast loading. The peak incident overpressure then decays exponentially to the ambient pressure in time which in fact defines the positive phase. The total area under the curve is the impulse loading measured in MPa-msec and under real conditions both a positive phase and a negative phase (suction) which produces a maximum negative pressure to occur. Time for a blast loading is measured in msec unlike that with earthquake loadings that are of long duration and are measured in sec. For each explosive a peak overpressure exists depending on the explosives. Velocity of Detonation (VOD) and the higher the VOD the greater the capacity of the explosive to cause damage to a structure that it impacts. In order to ascertain the pertinent blast characteristics of the Oklahoma bombing [19], CONWEP has been used to obtain outputs for all blast parameters involved so that they can be considered in conjunction with the ground shock loading to the structure.

2.4.1.1 Incident Pressure (MPa)

Fig.2 shows a peak incident pressure [20] of 5.979 MPa and impulse of 1.669 MPa-msec. This peak pressure is high enough to cause deaths and injury to those caught inside the structure and the collapse of the structure. It is also an indication of the peak pressure transmitted to the ground by the blast which in turn is converted into ground shock. Regarding the US damage and injury thresholds shown in Tables 1 & 2 with a peak overpressure of 5.979MPa many deaths are inevitable. As well Table 2 also clearly shows that collapse of the structure is also inevitable.

2.4.1.2 Reflected Pressure (MPa)

When the incident pressure wave strikes a structure that is not parallel to the direction of the wave's travel it is reflected and reinforced thus producing what is known as reflected pressure. Reflected pressure [20] is always greater than the incident pressure at the same distance from the explosion. The reflected pressure varies with the angle of incidence of the shock wave. When the shock wave impinges on a surface that is perpendicular to the direction it is traveling, the point of impact will experience the maximum reflected pressure and when the reflecting surface is parallel to the blast wave the minimum reflected pressure or incident pressure will be experienced. In addition to the angle of incidence the magnitude of the peak reflected pressure is dependent on the peak incident pressure which is a function of the total explosive charge weight (kg) and range (m) from the detonation. As can be seen in Fig.3 the reflected pressure (51.17 MPa) produced is greater than the incident pressure (5.979 MPa). In the case of the incident pressures they are propelled forward by the blast wave impacting on a structure causing both positive and negative phases but for reflected waves the situation is vastly different except to say that it is much larger than the incident pressure. The rise in pressure is the result of the way in which the blast wave is propagated through the air. Air particles are moved along by the wave as it travels through the air that then collides with a surface. Linear elastically, the particles should be able to bounce back freely leading to both the incident and reflected pressures being equal thus causing the surface to experience a doubling of the acting pressure. However, in a non-linear elastic world as with large shock waves the reflection is hindered by the air particles (obstruct movement) that are moved forward thus leading to much higher reflected pressures occurring. This reflected pressure is the pressure that should be used to design against blast loadings and not incident pressure.

2.4.1.3 Time of Arrival (Toa-msec) and Duration V's Range (m)

For the detonation of 2200kg of ANFO [21] the blast wave time of arrival (Toa) is 1.252msec and the time of duration for the positive phase (Fig.4) of the blast is 2.701msec.

2.4.1.4 Pressure (MPa) v's Range (m)

Whether it is the incident pressure or the reflected pressure the greater the distance from the point of detonation then the lower the pressure and

so the less the damage sustained to individuals or the structure.

2.4.1.5 Impulse (MPa-msec) v's Range (m)

Impulse is a measure of the energy (pressure) from an explosion imparted to a structure over time (msec). Both the negative and positive phases of the pressure-time typical function contribute to impulse. The integrated area under the pressure verse time curve is known as the impulse and represented by the Eq. (9).

$$i = \int P(t)dt$$

where i is impulse (MPa-msec) (9)

P is pressure (MPa)

T is time (msec)

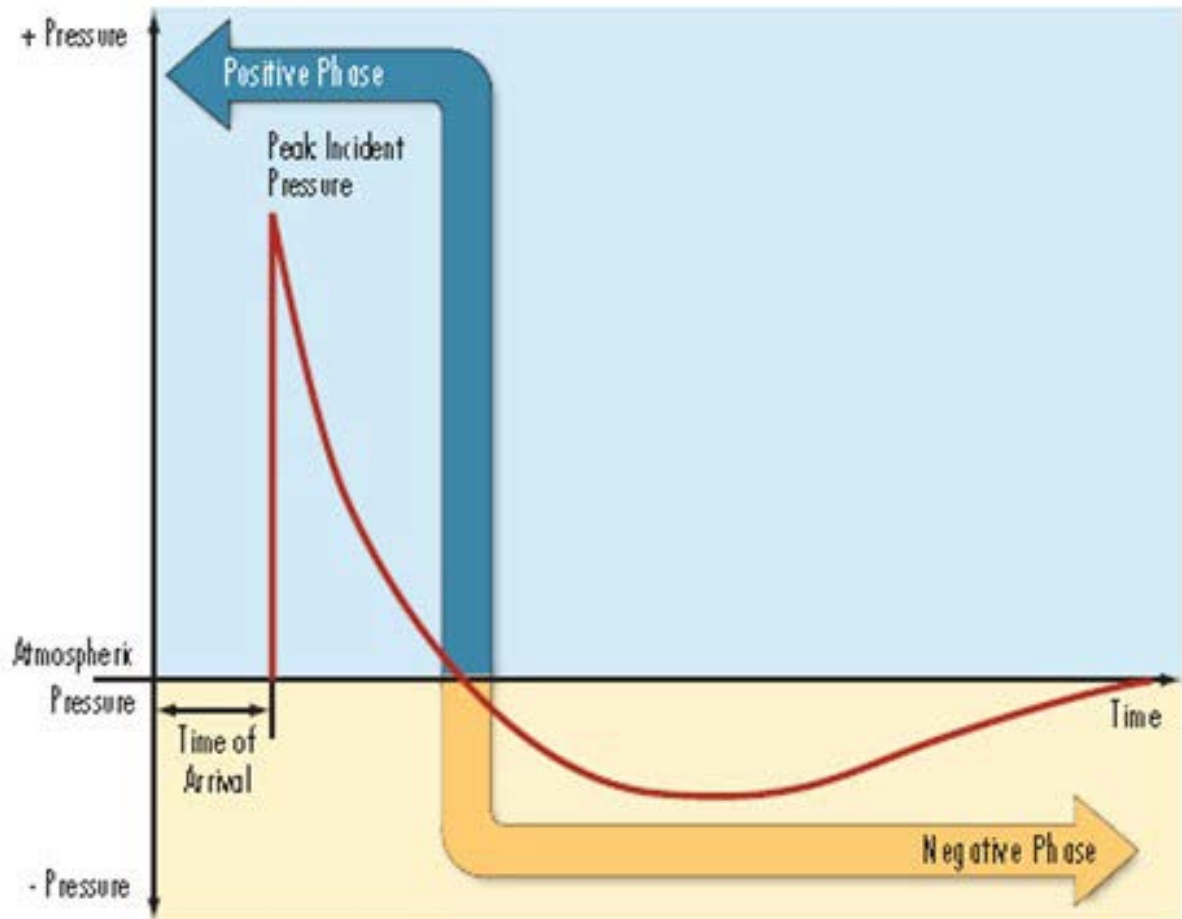


Fig.1 Pressure (MPa) V's Time (msec) [22]

Table 1 Primary injury threshold [22]

CRITICAL EFFECT	LIKELIHOOD OF EFFECT	PEAK OVERPRESSURE (kPa)
Ear Drum Rupture	Threshold	34
	50%	103
Lung Damage	Threshold	207
	50%	552
Lethality	Threshold	689
	50%	896
	100%	1379

Table 2 Damage typical overpressure [22]

DAMAGE	INCIDENT OVERPRESSURE (kPa)
Typical Glass Window Damage	1.03-1.52
Minor Damage to Some Buildings	3.45-7.60
Panels of Sheet Metal Buckled	7.58-12.41
Failure of Concrete Blockwork	12.41-19.99
Collapse of Wood Framed Buildings	OVER 34.47
Serious Damage to Steel Framed Buildings	27.58-48.26
Severe Damage to Reinforced Concrete Structures	41.37-62.05
Probable Total Destruction of Most Buildings	68.95-82.74

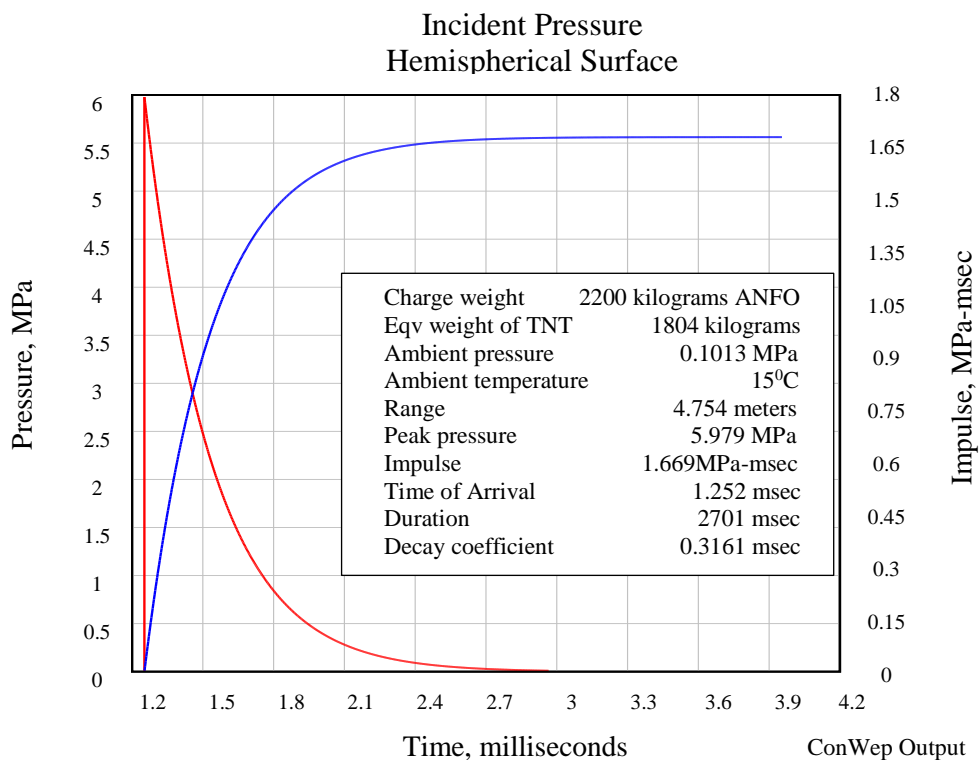


Fig.2 Incident pressure (MPa)

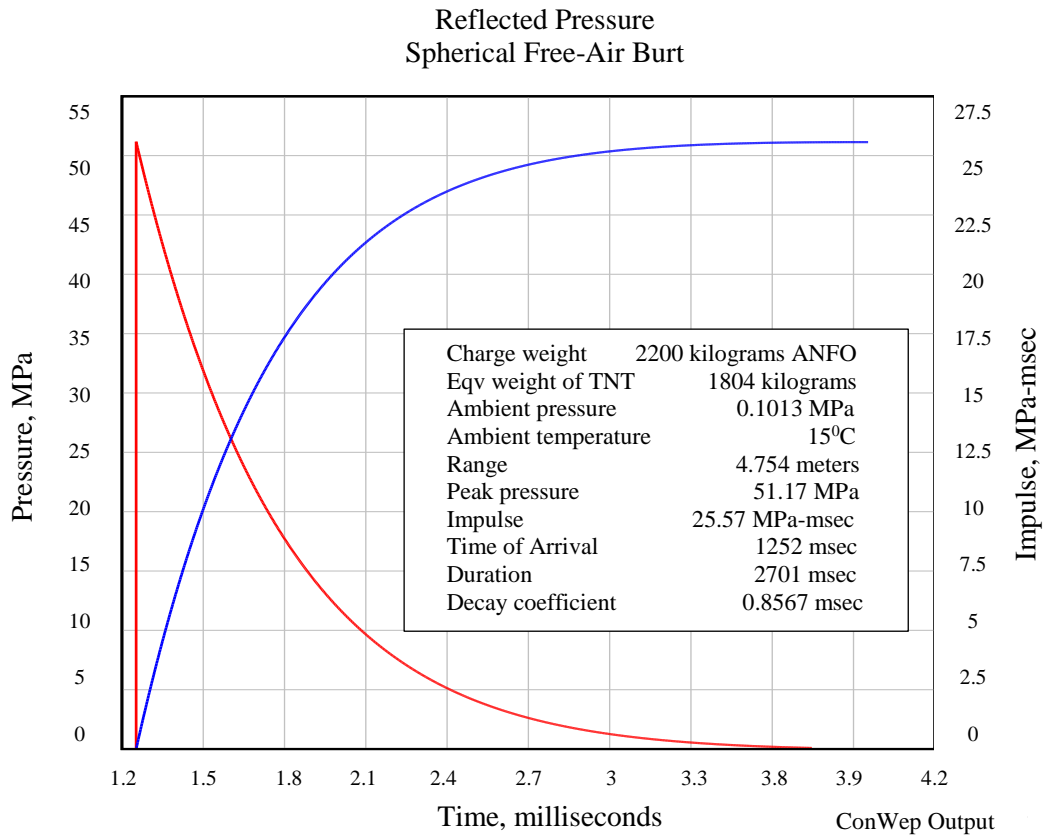


Fig.3 Reflected pressure (MPa)

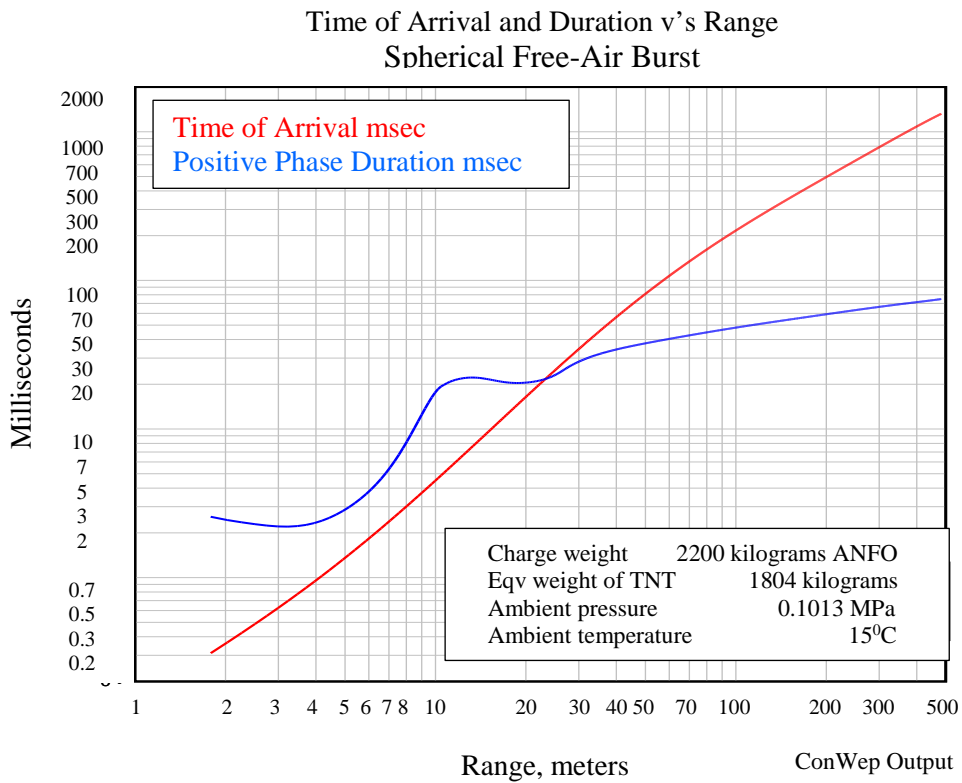


Fig.4 Time of Arrival (Toa-msec) and Duration V's Range (m)

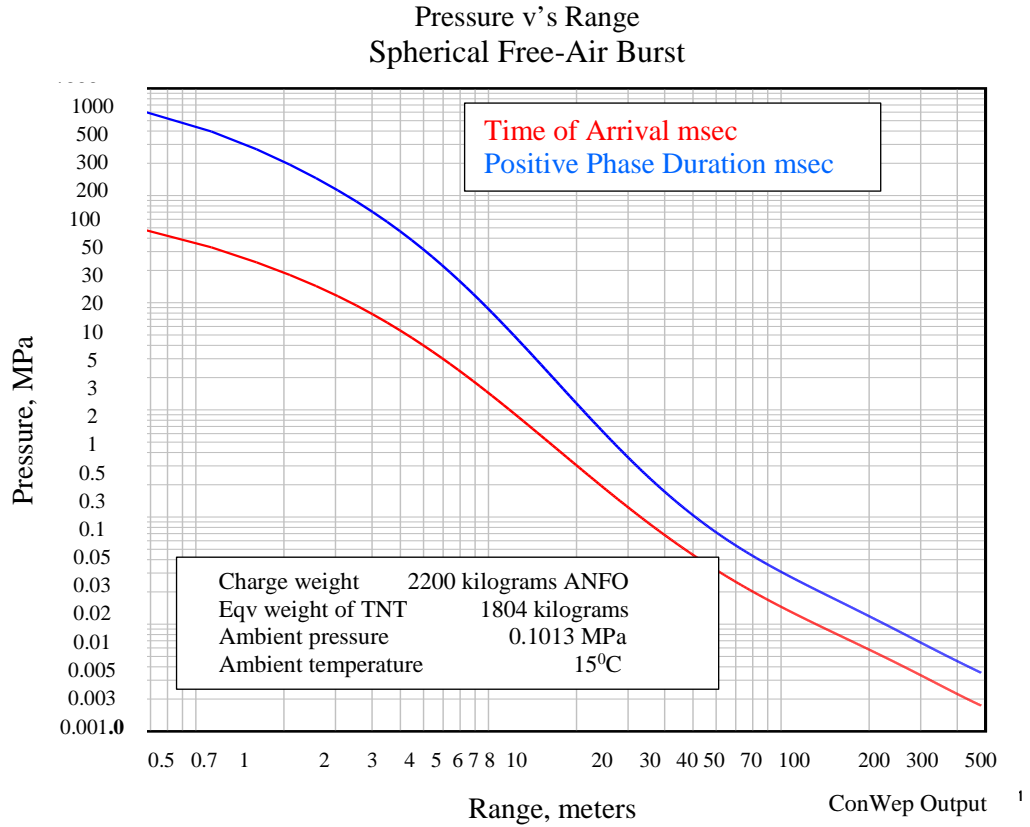


Fig. 5 Pressure (MPa) V's Range (m)

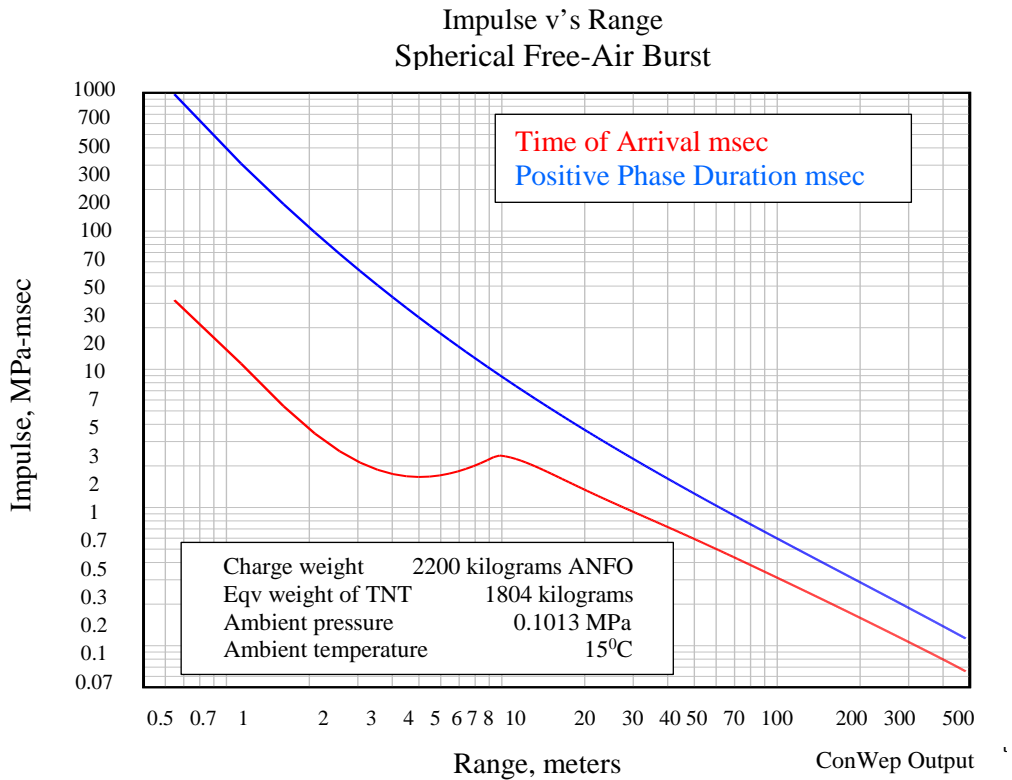


Fig.6 Impulse (MPa-msec) V's Range (m)

2.5 Oklahoma 9 Story Alfred P Murrah Federal Building Truck Explosion 1995

The explosion was a domestic inspired attack in that it was carried out by Americans against Americans and was carried out against a large government occupied building. The blast not only virtually demolished one half of the Alfred P. Murrah building but it also destroyed or damaged 324 buildings within a 16-block radius, destroyed or burned 86 cars and did minor damage to adjacent buildings such as shattering glass and cause cracking in masonry and concrete walls. The damage sustained to the building was certainly considerable as it was designed in the late 60's and built in the early 70's well before bombings became common place worldwide and well before codes were produced stipulating design criteria that had to be adopted in the case of designing against blast loadings. Most of those killed were because of the collapse of the building and not from the actual blast loading. This attack has been closely investigated by other government agencies and many of the structural details that have been adopted to mitigate against structural damage and so save lives has resulted from such an investigation and many recommendations made can now be found in both civilian and military American codes, standards and manuals designing for blast loadings. The Oklahoma bombing incident as well as 9/11 attack on the New York World Trade Centers has led to the increase of the worldwide knowledge base concerning blast loadings.

2.5.1 Explosive Used and Charge Weight (kg)

A 2.5Ton (metric) vehicle improvised device (VIED) was positioned outside of the building with The combined effect of both the blast waves and the ground shock therefore contributed largely to the overall damage to the area of the ground floor glazing as well as concrete structural elements. With the ground shock moving out from the detonation point (see Figures below) at velocity and providing large particle displacements in all directions the other structures close to the Alfred P Murrah building were damaged and it contributed to the damage levels sustained particularly to near masonry and concrete walls. With large explosive charge weights (1000kg plus) ground shock plays a large part in the overall structural damage above ground level but one must never forget the damage sustained to the water, sewerage, storm water and communication assets below ground level.

2200 kg of an explosive mixture (ANFO) inside of prilled ammonium nitrate fertilizer nitromethane fuel and diesel fuel. The velocity of detonation of normal ANFO is 3200 m/s but with the addition of the nitromethane the velocity of detonation (VOD) [23] would no doubt have increased leading to the increase in overall damage to the structure. All products were commercially readily available and easily obtained in nearby stores.

2.5.2 Position of Detonation

The truck was positioned and detonated on the north east corner of the building next to a central column no G20 at the front of the building. The exact standoff distance was measured as 4.75m (15.6ft). Note that the explosive is in the back of the vehicle 1.371m (4.5ft) above ground level. The crater size detailed also alludes to the size of the blast as it produced a crater 2.072m deep and 8.534m wide with the crater in fact being at the exact point from which the ground shock moved out at velocity towards the structure. The subgrade condition over which the ANFO was detonated consists of 0.279m (11inches) of asphalt and 0.177m (7inches) of concrete with "dry sandy clay" beneath.

2.5.3 Structural Damage.

The damage sustained to the structure was massive with the result being that the building collapsed causing many of the deaths of those people caught inside. The explosive was detonated opposite a series of columns that were virtually destroyed. Immediately behind these columns was an expanse of glazing two floors high that the blast waves no doubt shattered along with the ground shock travelling at some 3500m/sec in front of the structure.

2.6 Using CONWEP to Investigate Blast and Ground Shock Outcomes

The CONWEP program [24] produces individual outputs for the following graphed v's time (msec):

- Radial stress (MPa) is a stress in directions co-planar with but perpendicular to the symmetry axis.
- Hoop (circumferential) stress (MPa) is a normal stress in the tangential (azimuth) direction.
- Radial impulse (MPa-msec) is radial stress acting over a timeframe.
- Radial particle velocity (m/s).
- Radial displacement (m).

The program also produces other outputs for the following graphed v's range (m):

- Peak radial stress (MPa).
- Peak hoop stress (MPa).
- Peak radial impulse (MPa).
- Peak radial velocity (m/s).
- Peak radial displacement (m).
- Shock wave time of arrival (Toa-msec).
- Time of arrival of the peak stress (MPa)

2.6.1 CONWEP Output v's Time (msec) Results for Ground shock

2.6.1.1 Radial Stress (MPa)

For a range of 4.75m the blast waves strike the structure some 6msec after the detonation and produce a radial stress of 8MPa which causes, in conjunction with the blast wave incident pressure of 5.597MPa, damage to the structure further out from the structure for a further 225msec plus (Fig.5).

2.6.1.2 Radial Impulse (MPa-msec)

For a range of 4.75m at 6msec a radial impulse of 0.01MPa strikes the structure (Fig 6).

2.6.1.3 Radial Particle Velocity (m/s)

For a range of 4.75m at 6msec the radial particle velocity is 11m/s (11000mm/s) which is a typical value for dry clayey sand and not saturated clayey sand.

2.6.1.4 Radial Displacement (m)

For a range of 4.75m at 6msec the radial displacement is 100mm at the structure.

2.6.2 CONWEP Output V's Range (m) Results for Ground shock

2.6.2.1 Time of Arrival (Toa-msec) & Time of Arrival Peak Stress (Top-MPa)

For a range of 4.75m and an arrival time of 6.5msec the peak pressure arrives 1. msec later at 7.5msec (Fig.7).

2.6.2.2 Peak Radial Stress (MPa)

For a range of 4.75m the peak radial stress is 7 MPa (Fig.8).

2.6.2.3 Peak Hoop Stress (MPa)

For a range of 4.75m the peak hoop stress is 2.5 MPa which is lower than the peak radial stress (Fig.9).

2.6.2.4 Peak Radial Impulse (MPa-msec)

For a range of 4.75m the peak radial impulse is 0.18 MPa (Fig.10).

2.6.2.5 Peak Radial Velocity (m/s)

For a range of 4.75m the peak radial particle velocity is 8.5m/s (Fig.11).

2.6.2.6 Peak Radial Displacement (m)

For a range of 4.75m displacement is 350mm and so causes damage to the structure in addition to the blast load damage (Fig.12)

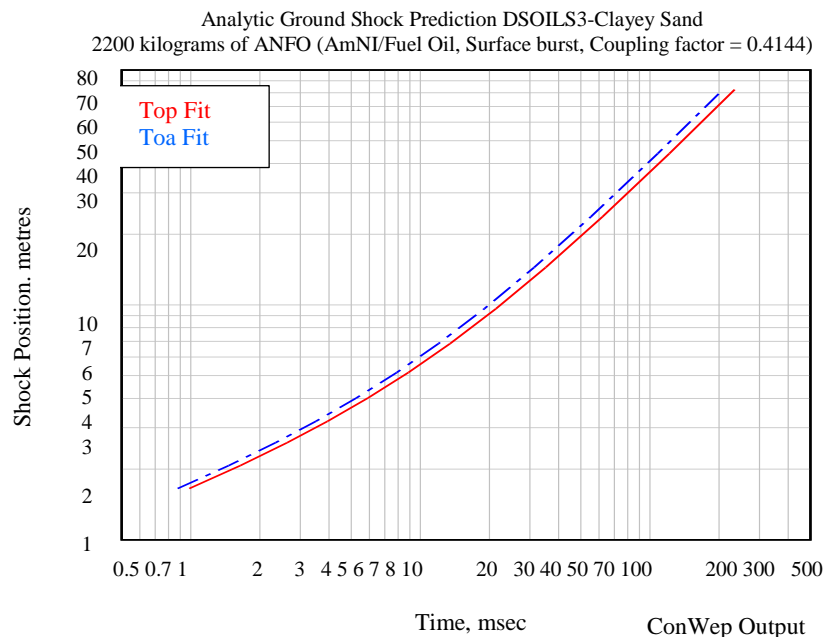


Fig.7 Time of Arrival (Toa-msec) & Time of Peak Stress (MPa)

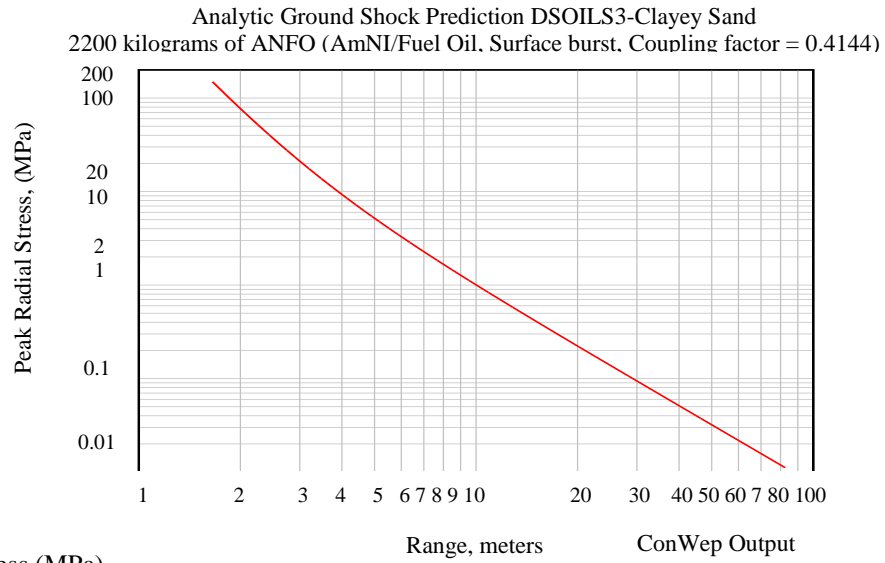


Fig.8 Peak Radial Stress (MPa)

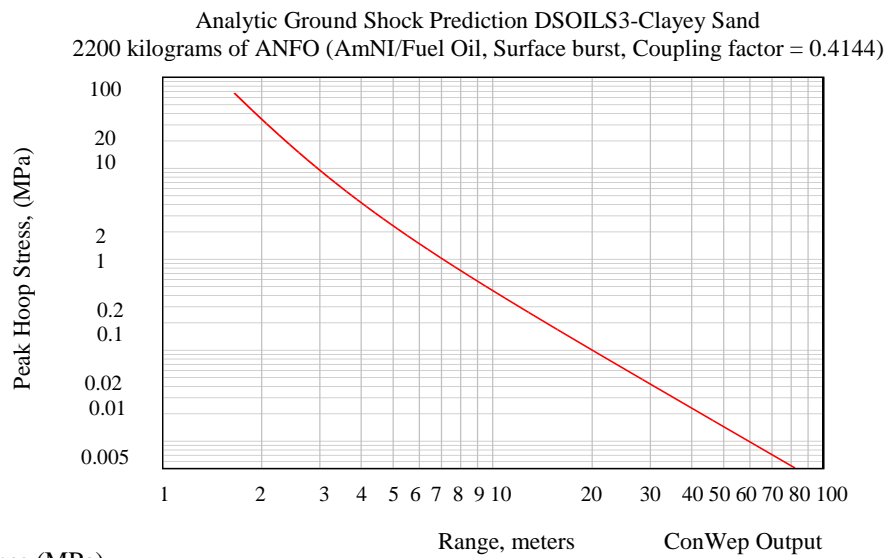


Fig.9 Peak Hoop Stress (MPa)

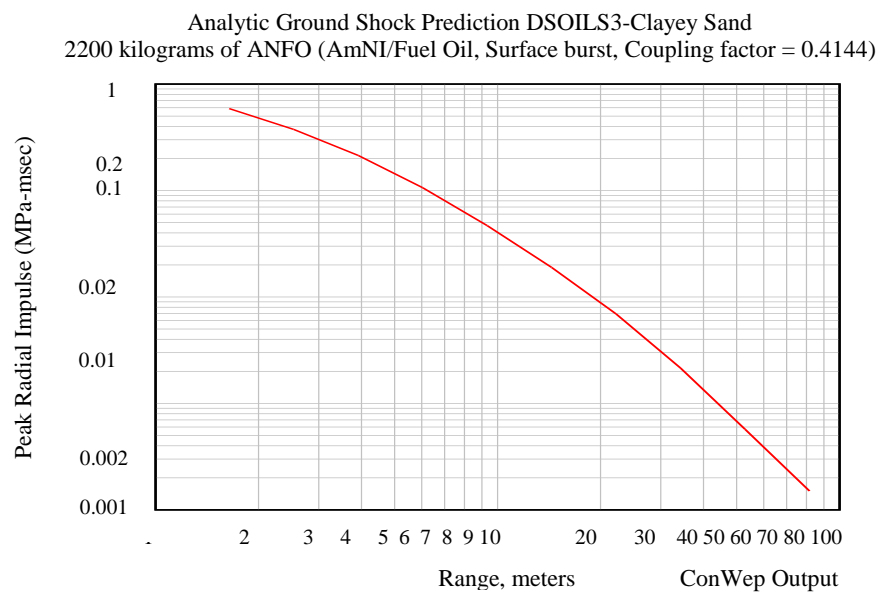


Fig.10 Peak Radial Impulse (MPa-msec)

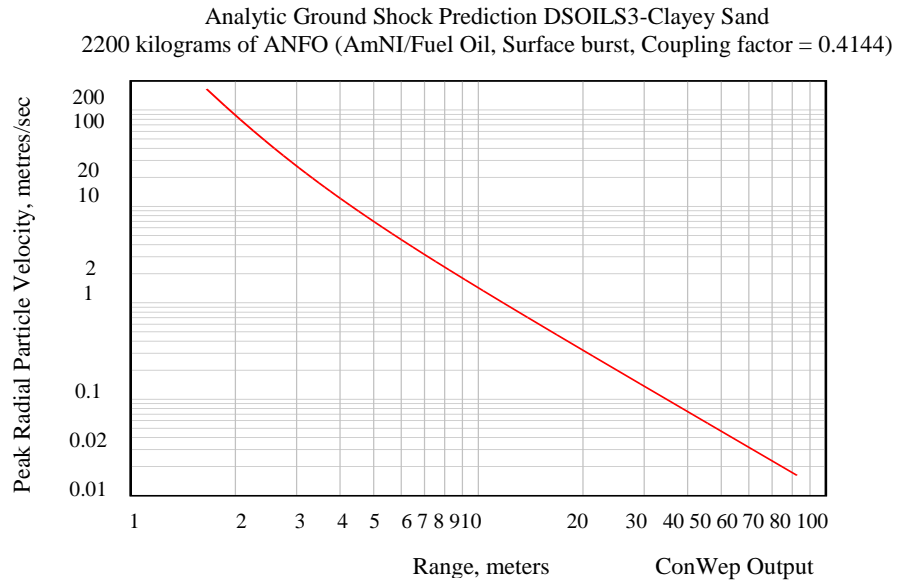


Fig.11 Peak Radial Velocity (m/s)

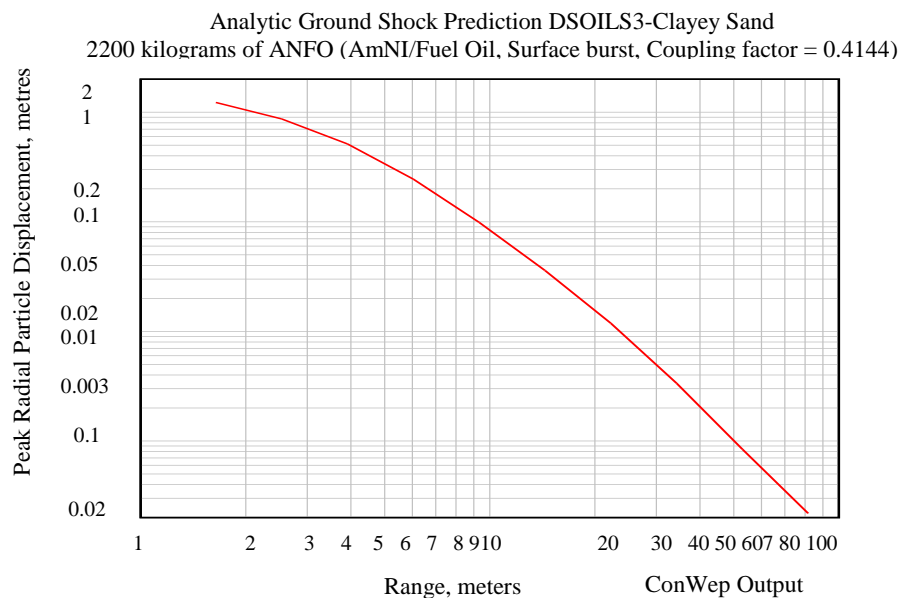


Fig.12 Peak Radial Displacement (m)

3. CONCLUSION

When a structural engineer is designing for an uncontrolled demolition (an IED or VIED attack) the first action the engineer must take is using either experience or current actionable intelligence available specifying the type of explosive and the charge weight (kg) that is going to be used in the design. The main problem as at 2018 is that there have been no major bombings (charge weights more than 10kg) on Australia soil. The closest experience to Australia is with the 2002 Bali

attacks where both some 5kg IED's [25] and one 1000kg VIED [26] were detonated but the question that inevitably arises is to whether to design for a 1000kg blast loading or something much higher as the 2200kg Oklahoma City VIED. If the wrong assumption is made at the start of the design process the flaw in the design will become uncomfortably obvious if a higher blast loading occurs. The problem within the Australian environment is that there is no guidance from anyone as to which assumptions are acceptable considering a likely threat. One would also hope that ground shock would also have been taken into consideration during the design phase it is obvious that a PPV of 11m/s is considerably large enough to play a major

part in the overall structural damage [27] and collapse of any structure along with the 0.18MPa peak radial impulse. The peak radial particle displacement in Fig.12 of 300mm also attests to the significant role ground shock plays. Little can be done to redesign the subgrade over which a structure is to be constructed but it should always be

mandatory to consider ground shock within the design process. Fig.13 details the effects of a blast loading to a structure and all aspects that must be considered in relation to the loading. As can be seen, ground shock particle velocity is an important aspect that must be considered along with all other parameters.

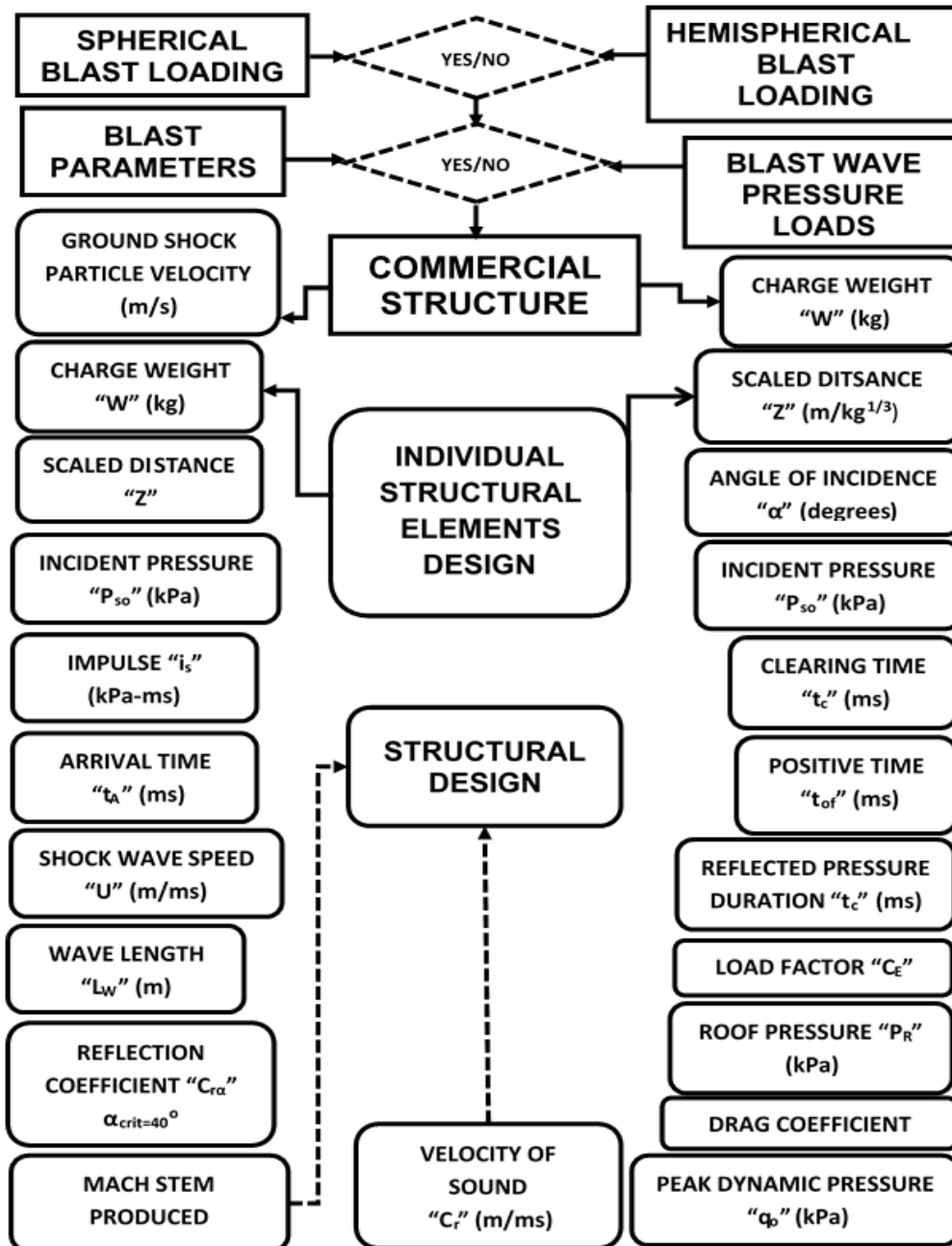


Fig. 13 Blast loading effects design process flowchart

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