COMPARISON OF PRESSURE MEASUREMENT TECHNIQUE FOR FREE-FIELD DOWN SCALED BLAST EXPERIMENTS

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Abstract:

Simulating large blast event using small-scale explosive charges detonation has become a major tool in assessing the effects of terroristic or accidental threats. Scaling laws adapted to modern plastic explosives however still require to be refined to achieve the necessary precision on the blast induced damages determination. This statement was the starting point of the cooperation between the Institute for Radiological Protection and Nuclear Safety (IRSN), a French public institute with industrial and commercial activities, and the French-German Research Institute of Saint Louis (ISL), a bi-national military research institute.

During the past few years, IRSN developed a strong experience on hemispherical blast effect assessment using 42 g Hexomax® charges detonated in contact to a ground surface equipped with different types of pressure sensors (piezo-electric and piezo-resistive). Based on this experience, ISL developed a new outdoor blast-pad located at its own explosive range: 400 g TNT equivalent charges are detonated in a factor 2 up-scaled version of IRSN test configuration. Similar sensors are flush-mounted inside a metallic rail integrated below the concrete pad surface. Blast effects generated by cast-TNT, Hexomax® were recorded at the different IRSN reference scaled-up distances. Peak overpressure, peak positive impulse and arrival time are analyzed and compared for the two different scales, in order to verify Hexomax® scalability between the two configurations, as well as the TNT equivalent factors (in peak overpressure or positive impulse) of Hexomax®. All these measurements are supported by a high speed imaging setup based on Background Oriented Schlieren (BOS) technique.

Keywords: condensed explosives, detonation, shockwave, TNT equivalent, scaling laws.

Nomenclature

Parameter	Unit	Defitinion
d_H	m	Distance from Hexomax® charge
ΔP	Pa	Overpressure
ΔP_H	Pa	Overpressure at distance d_H
$\Delta Pmax$	Pa	Peak overpressure
$\Delta Pmax_H$	Pa	Peak overpressure at distance d_H
$I+$	Pa.s	Maximal positive impulse
$M_{TNT\text{-}ISL}$	kg	ISL TNT charge mass
Po	Pa	Atmospheric pressure
ta	s	Time of arrival
Z, Z_{eq}	$m.kg^{-1/3}$	Scaled distance

1 Introduction

The Institute for Radiological Protection and Nuclear Safety (IRSN) is a French public institute with industrial and commercial activities, placed under the joint authorities of the Ministries of Defense, Environment, Industry, Research, and Health. IRSN is entrusted, among others, to assess and conduct researches in the area of the protection of nuclear facilities and transport of radioactive and fissile materials against accidental and malicious acts. In this context, IRSN establishes projects and studies to improve its knowledge of blast characteristics and weapons effects.

The French-German Research Institute of Saint Louis (ISL) is a bi-national research institute established by the Federal Republic of Germany and the French Republic on the basis of a treaty signed in 1958. The core mission of ISL is: "Research, scientific studies and basic predevelopment in the field of defense and security". Among other tasks, ISL focuses on the physical protection of personnel and assets against the effects of various explosive charges. To improve general survivability, fundamental studies on blast wave propagation and target interaction are continuously being conducted at ISL.

In 2006, IRSN designed and built an experimental set-up to achieve non-destructive shock wave propagation studies on a small scale [1]. This set-up is composed of a modular table, sensors and targets able to perform the detonation of solid explosives up to 64 g of TNT equivalent. It offers the possibility to measure the blast loading in terms of pressure-time curves on reduced scale rigid structures [2].

In this document, we focus on the comparison of blast effects at two different scales in free-field, validating the use of Hexomax® as a candidate high explosive composition for reference down-scaled tests. In addition, TNT charges were manufactured at ISL scale to improve TNT equivalency determination.

2 Experimental configurations

2.1 IRSN test table

The blast table has been principally designed to study shock waves reflection phenomena and interaction with different non-deformable structures. It measures 1.6 x 2.4 meters and features an array of mounting holes that facilitates the placement of modular 0.4 x 0.4 x 0.05 m wooden plates, and pressure transducers (Fig. 1 and 2).

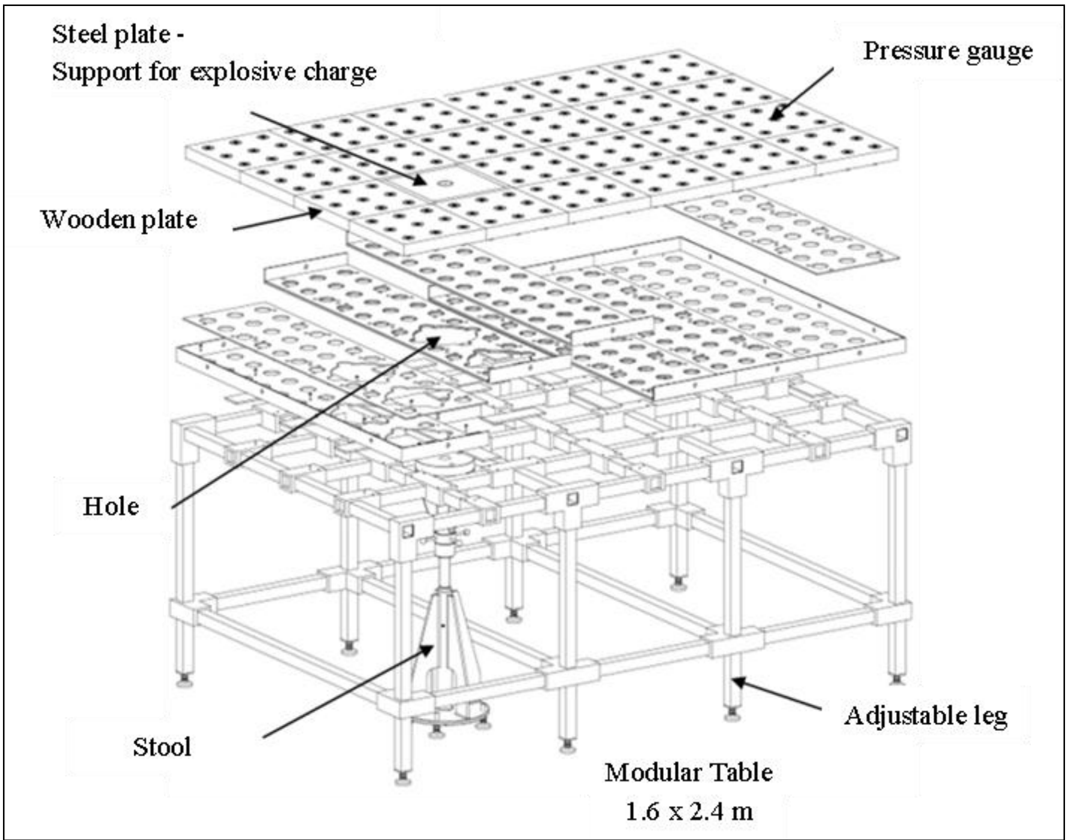


Figure 1. Schematic view of the laboratory scale table

For this campaign, different types of pressure transducers (piezo-electric and piezo-resistive) are mounted on an elastic support inserted in the holes, each

separated by 133 mm, provided for this purpose. Each pressure transducer is calibrated prior to the tests.
Explosive charges are installed and ignited on a dedicated reinforced steel table plate to generate a hemispherical blast wave using a Davey-Bickford SA 4201A detonator.
Experimental campaigns are performed at the ArianeGroup's research center located near Paris (Vert-le-Petit, France). ArianeGroup handles all the experiment pyrotechnics and also provides the data recording system (Nicolet Genesis data acquisition system, sampling rate of 500 kHz). During experiments, the modular table is mounted and placed at the center of a closed bunker, so as to avoid the perturbation from shock reflection on the bunker walls.

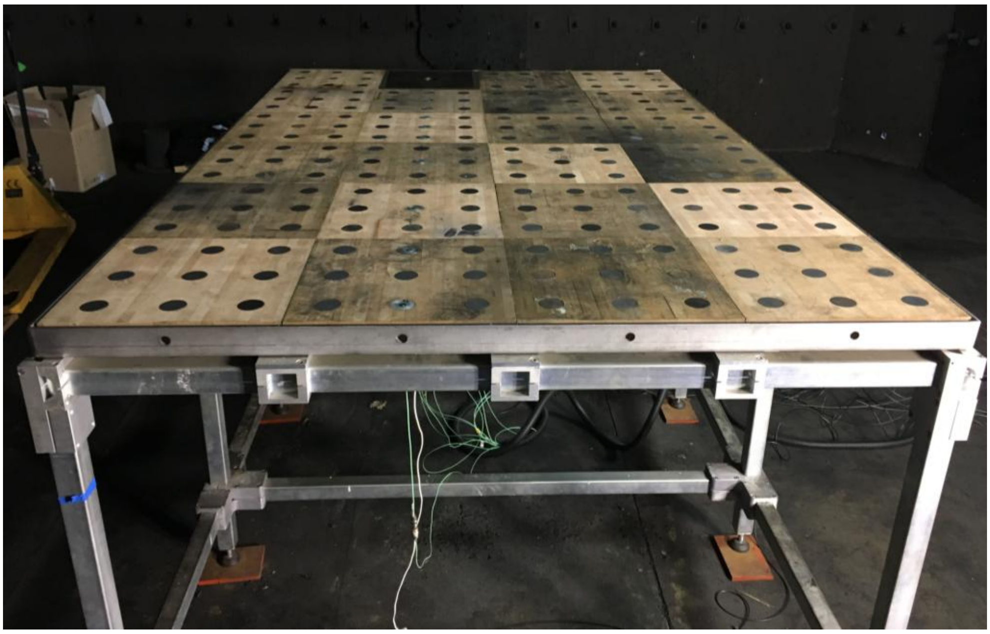


Figure 2. IRSN blast table

2.2 ISL blast pad

ISL developed a dedicated outdoor blast pad located at its own explosive range: 400 g TNT equivalent charges are detonated in a factor 2 up-scaled version of IRSN test configuration. Sensors integration is presented on Figure 3.

Figure 3. ISL blast pad

For this campaign, different types of pressure transducers (piezo-electric and piezo-resistive) are mounted on a polypropylene support inserted in one of the integrated rail ports, each separated by 266 mm. Each pressure transducer is calibrated prior to the tests. All data were recorded using a Transcom system running at 2 MHz.
Explosive charges are installed and ignited by a RP83 detonator on a dedicated reinforced steel ground plate to generate a hemispherical blast wave.

2.3 Pressure sensors positions lists

The authors would like to draw the reader's attention to the fact that all distances presented in the rest of this document correspond to IRSN scale. ISL distances and time have all been downscaled for direct comparison.

Table 1 presents the position of all sensors for both test series (scaled distances *Z* ranging between 0.57 and 4.6 m.kg$^{-1/3}$ for a spherical charge).

Table 1. Explosive tests metrology specifications

	Test reference number					
	ISL configuration			IRSN configuration		
Standard (m) and scaled distances (m.kg$^{-1/3}$)	2118 2122 2117 2121	2138 2141 2139 2142	2160 2161 2162 2163	C8 1-2-3	C8 4-5-6	
0.267/0.57		K		K		Close-range
0.400/0.86			K	K		
0.533/1.15	K			K		
0.667/1.44						
0.800/1.72		K		K		Mid-range
0.933/2.01			K	K-Ref	K-Ref	
1.067/2.30	K			K		
1.200/2.58	P-Ref	P-Ref	P-Ref			
1.333/2.87						
1.467/3.16						
1.600/3.45						
1.733/3.73						
1.867/4.02	K			K		Far-range
2.000/4.31		K				
2.133/4.60			K			

K: Kulite XT190 or HKS375
K-Ref: Kistler 603B
P-Ref: PCB 113B28

2.4 Explosive charges

Inter-scale comparison tests were conducted using hemispherical Hexomax® charges described in Table 2 using respectively 41.6 and 333 g at IRSN and ISL, leading to 50 and 400 g TNT equivalency. Figure 4 shows the four hemispherical explosives charges used at ISL range (Hexomax®, Semtex, C-4, TNT at ISL range).

Figure 4. Left: Hexomax®, Semtex, C-4, TNT at ISL range
Right: Hexomax® at IRSN range

Table 2. Explosive charges characteristics

Configuration	IRSN Hexomax®	ISL Hexomax®	ISL TNT
Mass (g)	41.6	333	336
Diameter (mm)	46.6	94	97
Density (g.cm^{-3})	1.58	1.54	1.63
TNT equivalent Pressure / Impulse	1.2 / 0.9	1.2 / 0.9	1/1
Detonator / Booster TNT equivalent (g) (corresponding mass ratio)	<0.2 / 0 (0.5 %)	<1 / 0 (0.3 %)	<1 / 52.5 g C4 (0.3 %)
Total TNT equivalent (g)	50 / 38	400 / 300	400 / 400
Test reference #	1,2,3,4,5,6	2118, 2122, 2138, 2141, 2160, 2161	2117, 2121, 2139, 2142, 2162, 2163

3 Reproducibility

3.1 IRSN

IRSN reproducibility is assessed using K-Ref sensor (Kistler 603B) present for each test at 0.933 m (Fig. 5). This position fits into the Mid-range distances to the charge. Table 3 summarizes the blast characteristics (peak overpressure, time of arrival and maximal positive impulse) for all tests (Hexomax® charges). We also calculated mean relative deviation (Equation 1) for each blast characteristic. For this study, we analyze the positive phase of the leading wave representing one standard technique for TNT equivalency determination presented in literature [3,4]. We noticed the good reproducibility of all blast characteristics (deviation lower than 5% for the six tests). Secondary shock also proved to be repeatable, except for a slight profile difference for test 5.

$$Deviation = \frac{1}{n \times Average(X_1, X_2..X_n)} \sum_{i=1}^{n} |X_i - Average(X_1, X_2..X_n)| \quad (1)$$

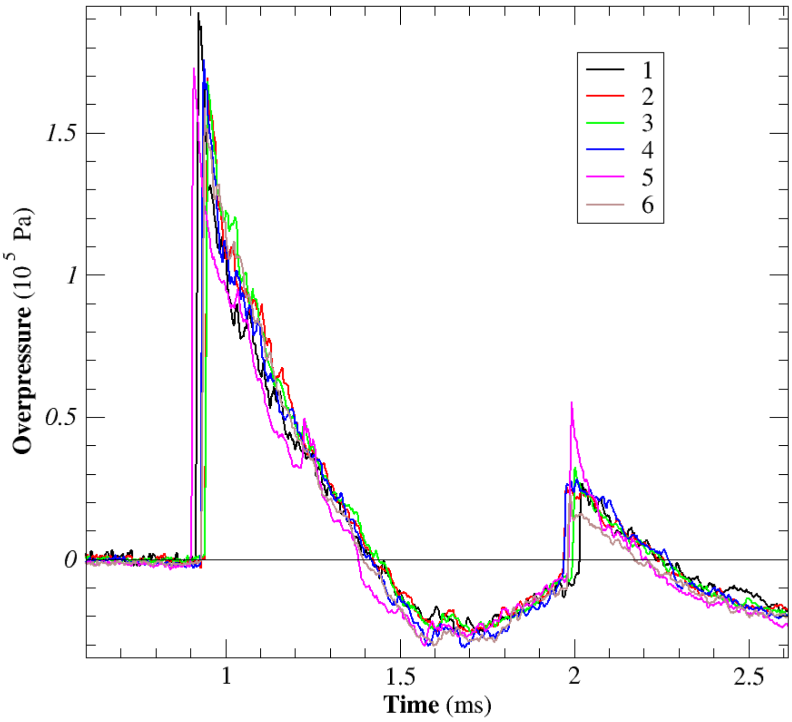


Figure 5. Pressure evolution recorded at 0.933 m (Hexomax® 41.6 g hemispherical charge)

Table 3. Hexomax® charges blast characteristics

Hexomax® (0.933 m)	1	2	3	4	5	6	Average	Deviation
ΔPmax (10^5 Pa)	1.92	1.69	1.68	1.76	1.73	1.59	1.69	4.4 %
ta (ms)	0.915	0.946	0.946	0.930	0.910	0.940	0.932	1.4 %
I+ (bar.ms)	0.305	0.308	0.309	0.294	0.285	0.292	0.295	2.9 %

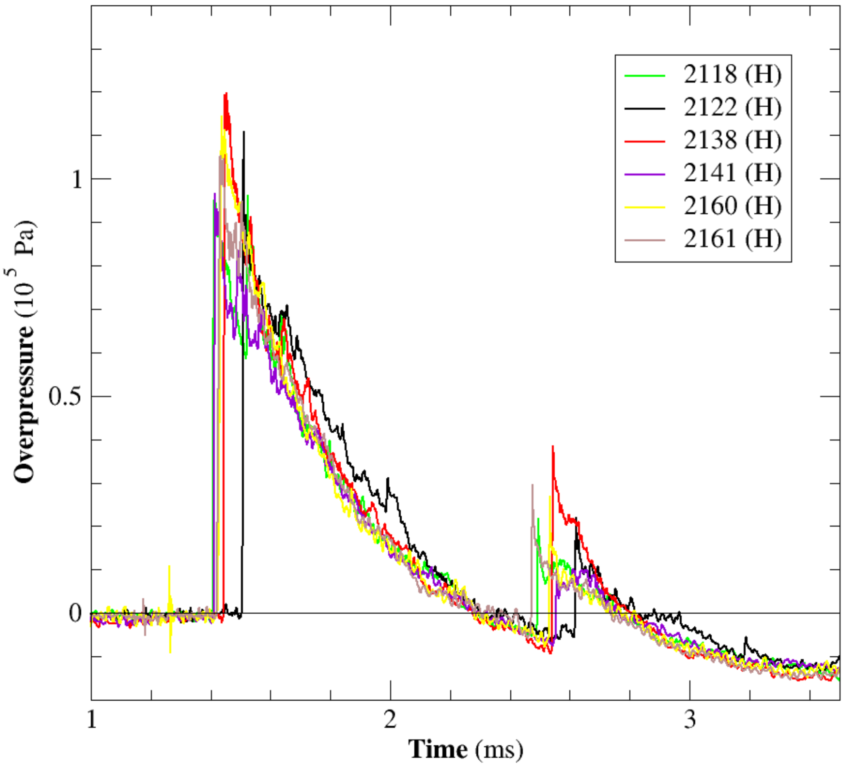
3.2 ISL

ISL reproducibility is assessed using P-Ref sensor (PCB 113B28) present for each test at 1.2 m (Fig. 6). This position also fits into the Mid-range distances to the charge. Table 4 summarizes the extracted blast characteristics (peak overpressure, time of arrival and maximal positive impulse) for all tests (Hexomax® and TNT). We also noticed the good reproducibility of all blast characteristics (deviation lower than 8 % for the six tests). As expected, reproducibility of secondary shock profile was lower than for the small IRSN charges.

Table 4. Hexomax® and TNT charges blast characteristics

TNT (1.2 m)	2117	2121	2139	2142	2162	2163	Average	Deviation
ΔPmax (10^5 Pa)	1.17	1.12	1.11	1.17	1.22	0.99	1.13	5.01 %
ta (ms)	1.455	1.475	1.435	1.46	1.445	1.5	1.46	1.18 %
I+ (bar.ms)	0.311	0.306	0.295	0.3105	0.3085	0.2895	0.30	2.45 %

Hexomax® (1.2 m)	2118	2122	2138	2141	2160	2161	Average	Deviation
ΔPmax (10^5 Pa)	0.95	1.11	1.19	0.96	1.145	1.0543	1.068	7.50 %
ta (ms)	1.405	1.5	1.445	1.41	1.425	1.42	1.434	1.78 %
I+ (bar.ms)	0.307	0.283	0.3015	0.281	0.302	0.2985	0.296	3.05 %



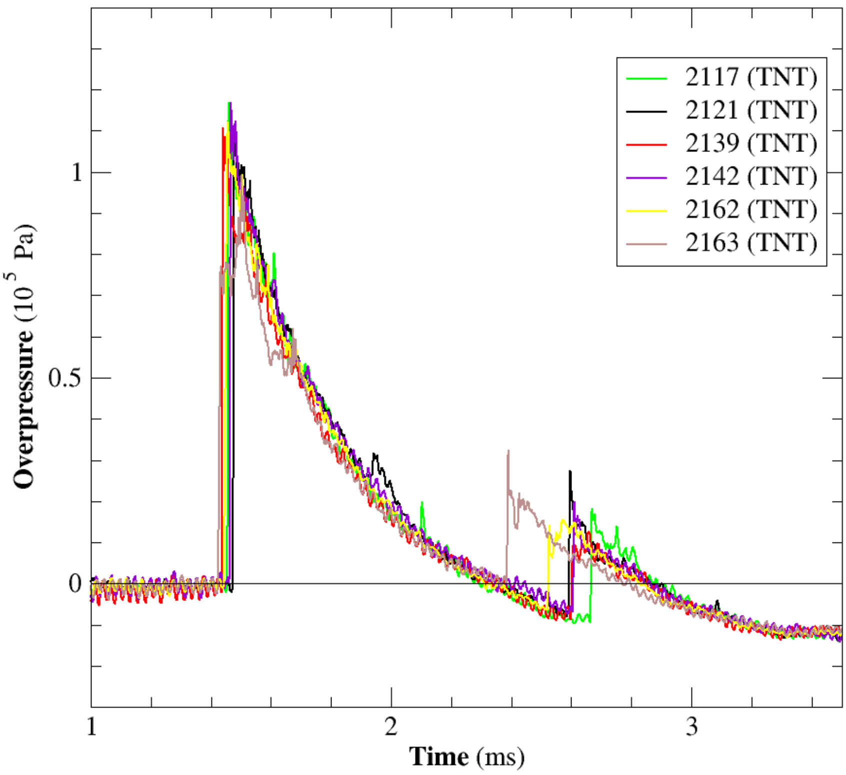


Figure 6. Pressure evolution recorded at 1.2 m
for TNT (top) and Hexomax (bottom)

4 Blast characteristics – Hexomax® Scalability

4.1 Peak overpressure

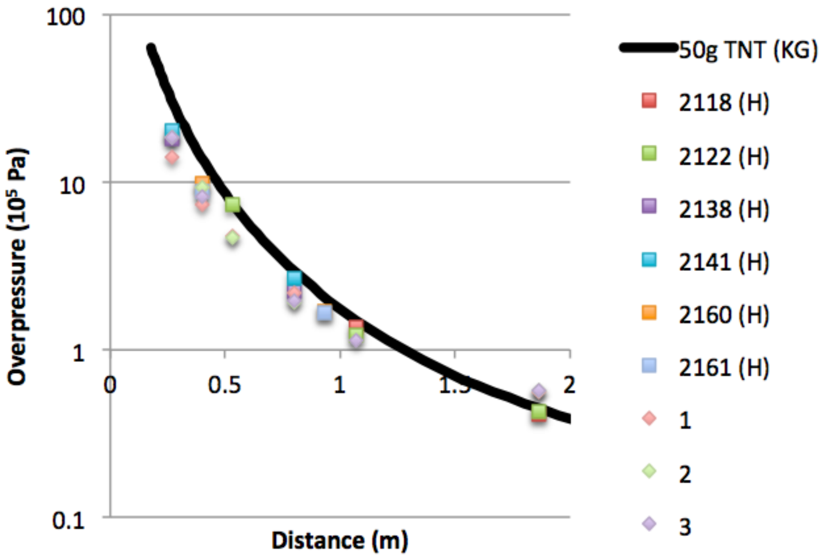


Figure 7. Overpressure versus distance

Figure 7 represents all peak overpressure measured for Hexomax® charges for IRSN and ISL tests. They are compared to the 50 g TNT overpressure evolution calculated with Kinney & Graham equations [3]. Results obtained at both scales are in reasonably good agreement. Experimental dispersion of results between scales ranges from 10 to 20 % in overpressure (cf. Fig. 8), with no significant evolution on the studied range of distances.

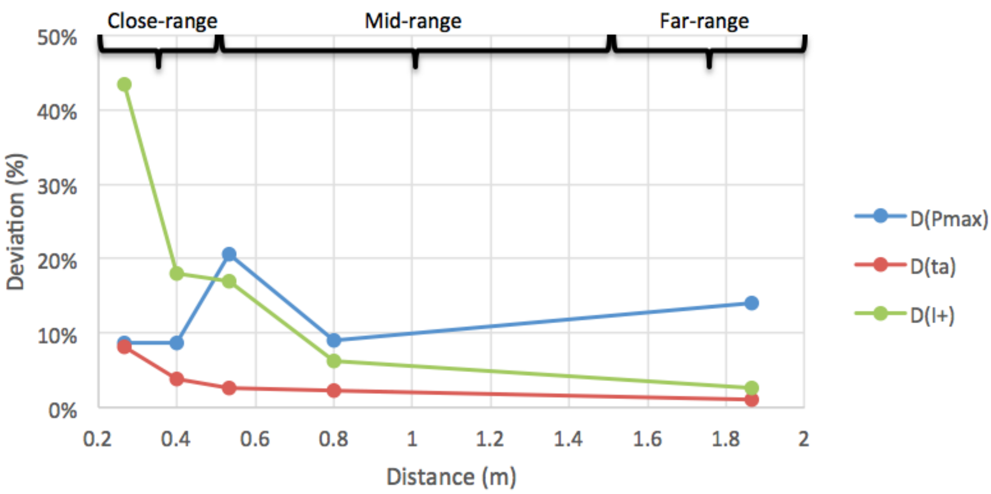


Figure 8. Interscale deviation versus distance

Hexomax® TNT equivalency

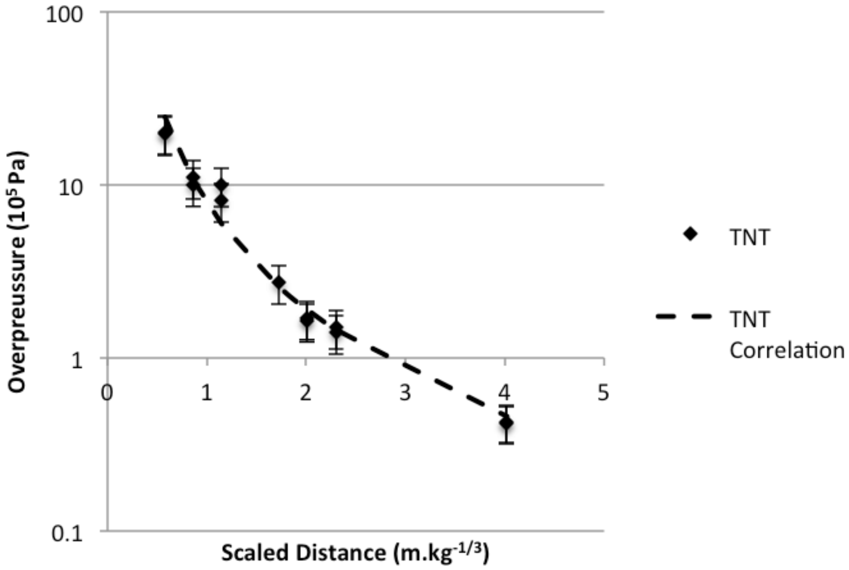


Figure 9. TNT peak overpressure evolution versus scaled distance

Based on overpressure versus scaled distance for the 400 g ($M_{TNT-ISL}$) TNT charges placed on ground (diamonds on Figure 9), the following experimental correlation was determined (dashed line on Figure 9):

$$\frac{\Delta P}{Po} = 7.9147 \times Z^{-2.045} \tag{2}$$

Based on this relation, each overpressure $\Delta Pmax_H$ measured at distance d_H for Hexomax® 41.6 g charge provides a corresponding TNT scaled distance:

$$Z_{eq} = \left(\frac{7.9147}{\frac{\Delta Pmax_H}{Po}}\right)^{\frac{1}{2.045}} \tag{3}$$

Equivalent TNT mass can thus be calculated by:

$$M_{TNTeq} = \left(\frac{d_H}{Z_{eq}}\right)^3 \tag{4}$$

Calculated TNT equivalency versus distance for the two series of Hexomax® tests (IRSN and ISL) is presented on Figure 10. Its values range from less than 1 in close range to 1.5 in far-range. These values can be compared to the Hexomax® manufacturer's provided 1.2 equivalent.

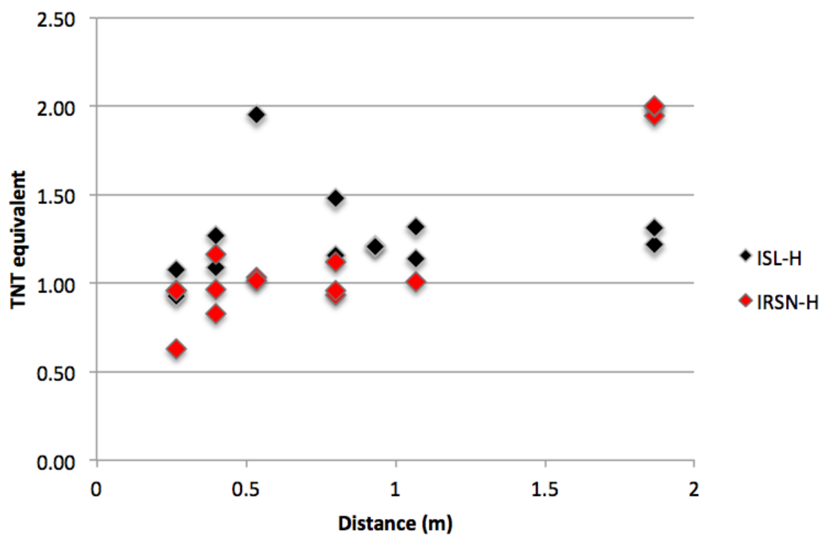


Figure 10. Interscale Hexomax® TNT equivalency versus distance

4.2 Time of arrival

Figure 11 represents the time of arrival distance evolution for all the Hexomax® tests (IRSN and ISL tests represented), in comparison with the 50 g TNT evolution determined using Kinney & Graham equations [3]. Results dispersion (cf. Fig. 8) is significantly lower than for peak overpressure: it progressively decreases from 8% in close range down to 1 % at 1.8 m. Agreement between the two scales is very good for time of arrival.

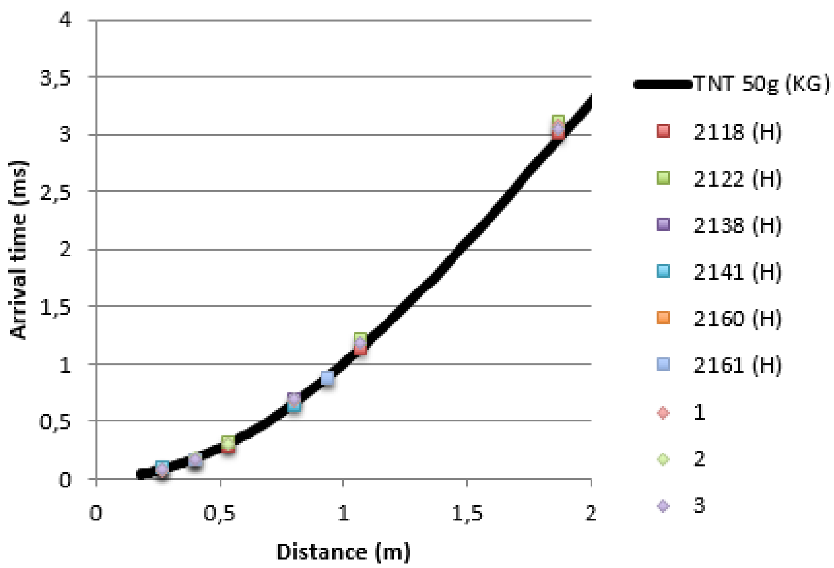


Figure 11. Time of arrival versus distance

4.3 Maximal positive impulse

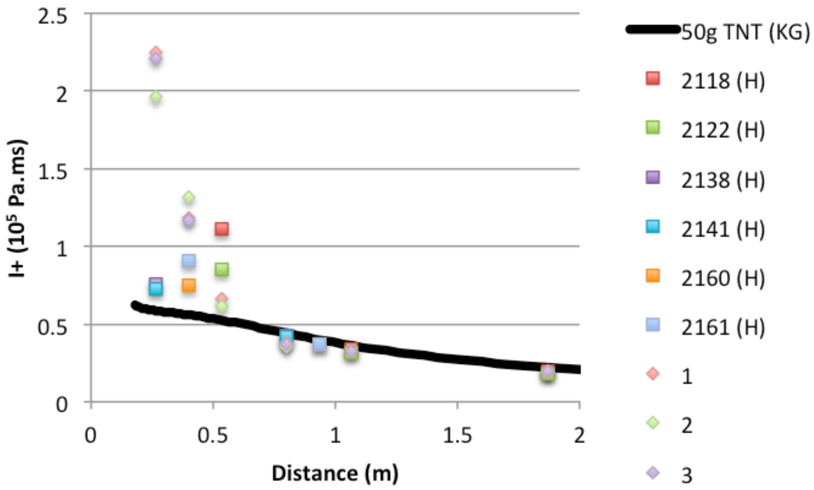


Figure 12. Maximal positive impulse versus distance

Figure 12 finally represents the maximal impulse versus distance for the two series of tests (IRSN and ISL), in comparison with Kinney & Graham 50 g TNT calculation. For distances of 0.8 m and above, both scales are in good agreement (dispersion lower than 7 %, cf. Fig. 8). In close range however, results dispersion reaches 45 %. This could be linked to unstable detonation products generating significant variations in blast propagation in close range (Needham [5]) or sensor thermal drift in the fireball region.

5 High speed visualization

Several ISL blast propagation was recorded at 12 000 i/s using a high-speed Phantom V310 camera equipped with a 135 mm f2 lens. A white wooden board was placed behind the charge to enhance the image contrast (cf. Fig. 3). Vertical black stripes were painted every 20 mm to improve the detection of the shock propagation. The resulting field of view covers 2.5 m x 0.63 m (1024 x 256 pixels).
Figure 13 shows an example of image recorded for the Hexomax® test 2141, at 1.355 µs after charge ignition, corresponding to an approximate 1.6 m propagation distance (at ISL scale). The vertical stripes magnify the density gradient generated by the presence of shockwaves: the main shock and at least one conical shock are visible on the standard image. The conical shock is generated by the flight of a solid piece of material (part of detonator, small metal part, etc.) propagating in front of the leading shock.

Figure 13. Hexomax® blast wave propagation recorded with high speed camera (*t* = 1.355 ms after charge detonation)

Background Oriented Schlieren (*BOS*) was chosen to enhance the recorded high-speed images. The main principle of *BOS* is to visualize the variation of refractive index of air. Different image processing methods are described by Gregoire [6]. The technique applied for this study consists in subtracting the previous image from the current one (all images having been previously grey-scaled). Processed image from Figure 13 is presented on Figure 14. The interaction between the shock front and the sensor position located on the ground surface is difficult to analyze on such high-speed images for different reasons: the tridimensional nature of the multiple shocks, the lack of luminosity, the limited image resolution and acquisition frequency. As a consequence, the irregular pressure decay behind the leading shock, visible on Figure 15, can be explained but the identification of each peak would require a more precise video technique.

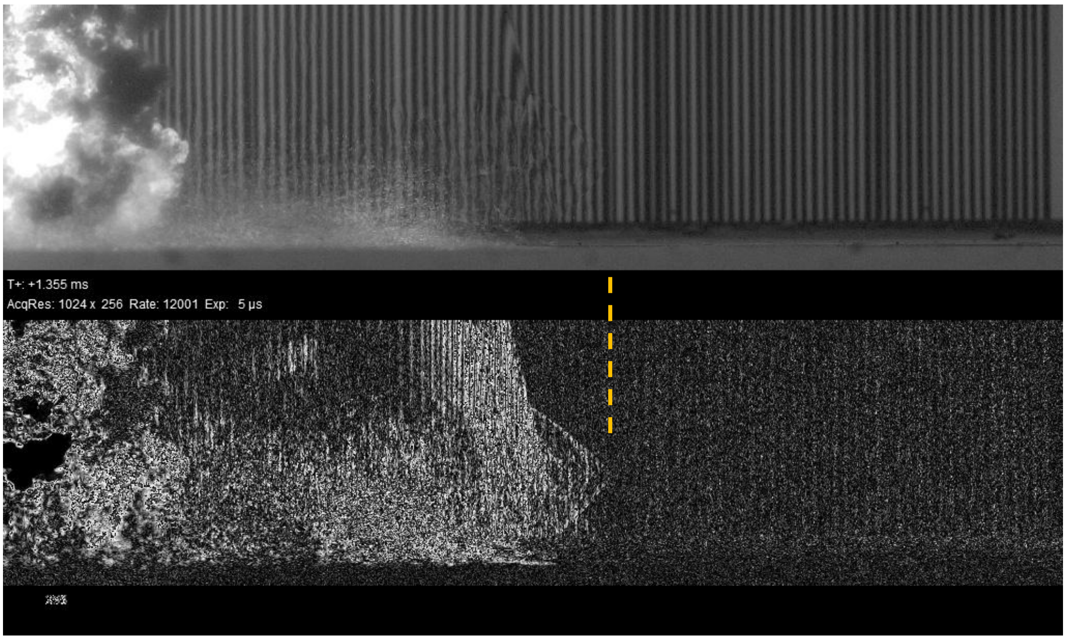


Figure 14. Leading shock and conical shock for the 2141 Hexomax® test (orange line indicating the 1.6 m sensor position at ISL scale distance)

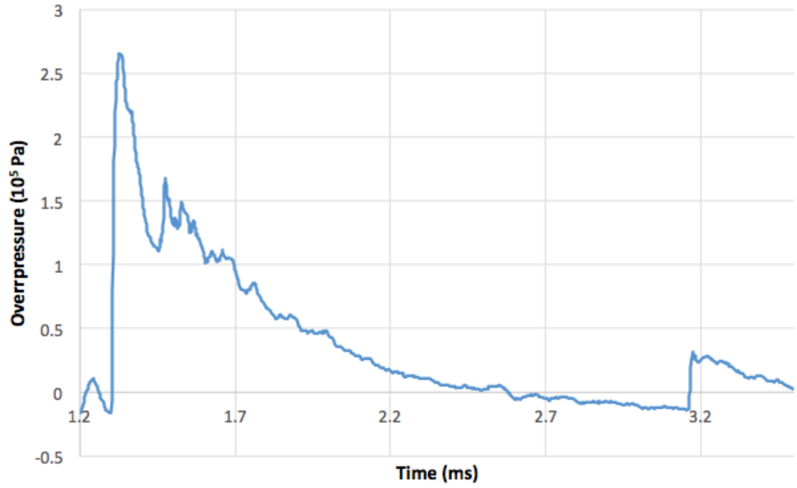


Figure 15. Pressure evolution at 1.6 m (ISL scale distance) for the Hexomax® 2141 test

6 Pressure signal in close range: candidate post-processing technique

Two of the main objectives of this study were to validate Hexomax® scalability and to determine experimentally its TNT overpressure equivalency at two different scales. In our tests, we often record pressure signals that are complex and difficult to process as their profile significantly differs from the classic Friedlander evolution notably by presenting multiple peaks. As a consequence, we propose a candidate technique to extract values of peak overpressure from experimental signals, especially in close-range. We propose the following method:

- to study qualitatively the pressure-time evolutions by sorting them into three main categories,
- to propose an extension of the classic interpolation method [3,7] to signals including a second peak behind the leading shock.

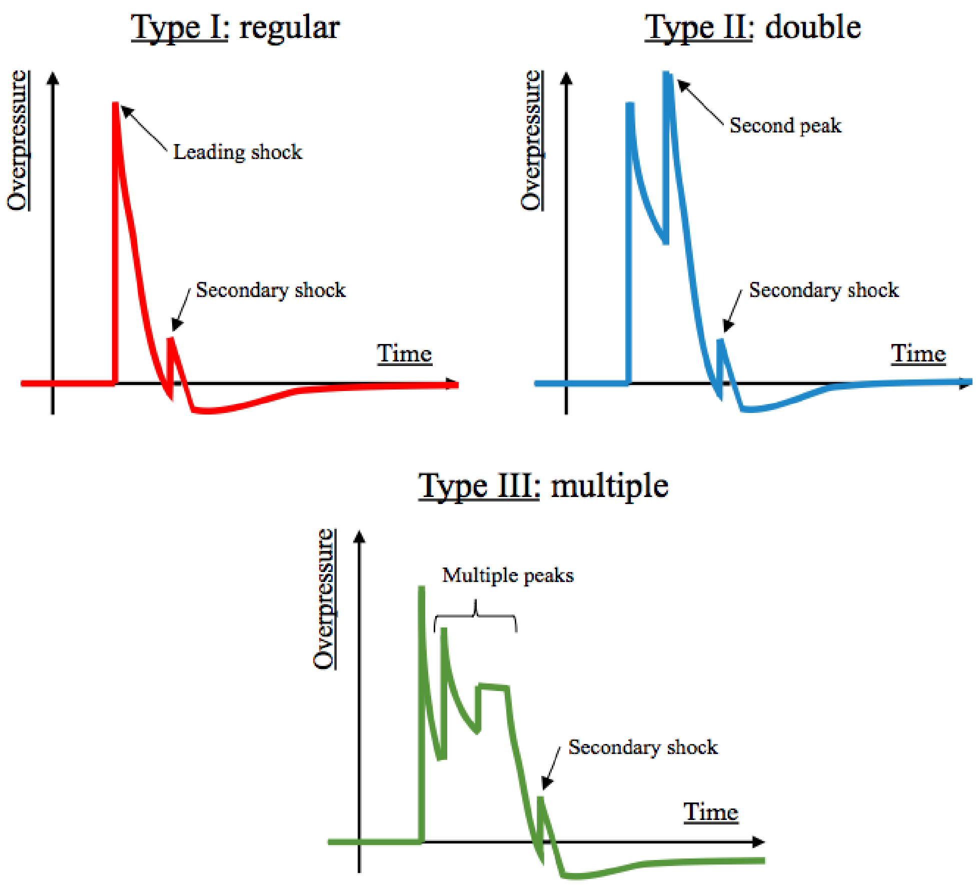


Figure 16. Examples of types of recorded blast wave pressure signals

Among all the overpressure time evolutions recorded for this study, we identified three global types (cf. Fig. 16):

- Type I: regular, single peak overpressure. Time evolution is close to the Friedlander waveform.
- Type II: double peak. A second peak (higher or lower) is propagating close behind the leading shock. Its arrival time is much shorter than the weaker secondary shock propagating due to the re-expanding rarefaction wave formed at the end of the solid phase detonation phase. The second peak may be generated by a conical shock (as seen on figure 14) or by a non-uniform detonation of the explosive charge.
- Type III: multiple peaks (other complex overpressure evolutions).

An example of type I overpressure evolution is presented on figure 17. All previous peak overpressure presented in this document were realized by directly determining the maximal recorded value. This type of signal can however also be processed using the method described in literature [3,7]. This technique proved to be efficient in discarding non-physical artifacts transmitted by pressure sensors.

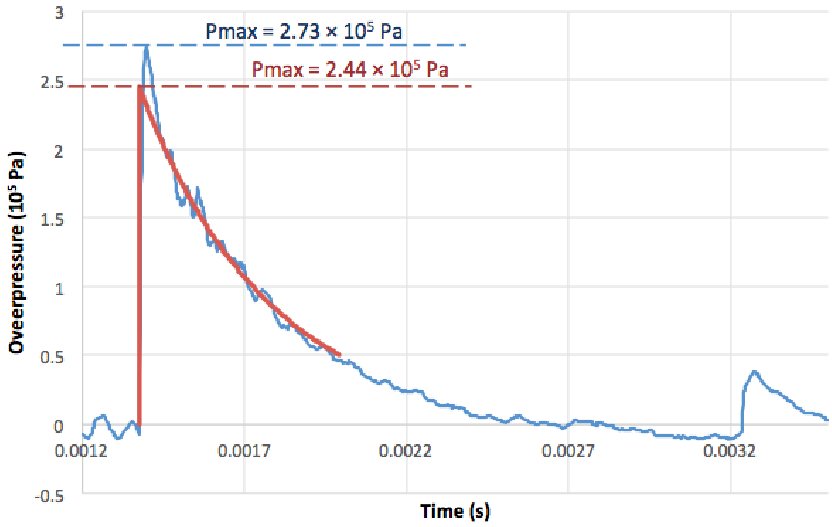


Figure 17. Overpressure versus time evolution for Hexomax® test 2141 at 1.6 m (ISL scale distance)

Peak overpressure is determined by fitting an exponential decay on the first part of the pressure decrease and by evaluating its value at the wave time of arrival. The resulting peak overpressure value (2.44×10^5 Pa) slightly differs from the directly measured value (2.73×10^5 Pa).

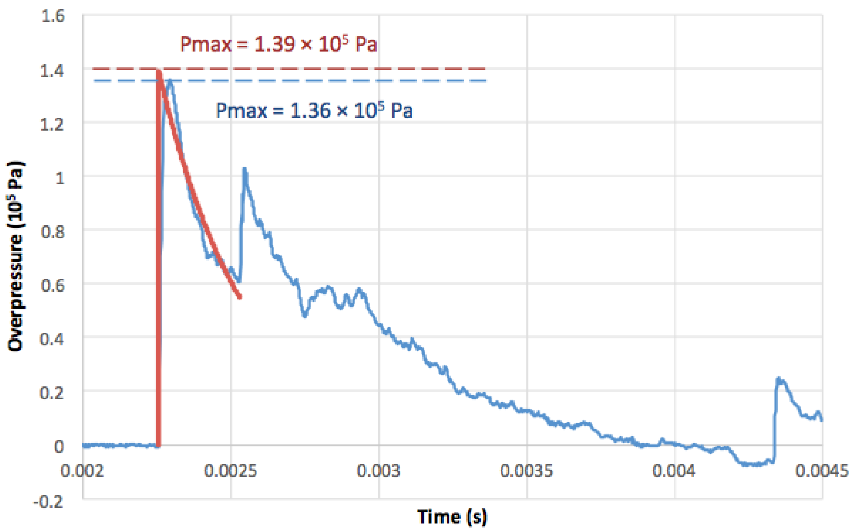


Figure 18. Overpressure versus time evolution for Hexomax® test 2118 at 2.133 m (ISL scale distance).

A similar technique may be applied to a Type II signal, provided we limit the range of the exponential fitting calculation to the first pressure decay (cf. Fig. 18). We can thus determine a peak overpressure for the first blast wave. By doing this,

we however neglect the second peak and potentially the corresponding delayed energy transferred. For safety studies, this underestimation of the explosive yield represents a serious issue.
To address this issue, we propose to evaluate an alternative technique to determine the global output for a Type-II pressure evolution, using numerical simulation.
By simulating the successive detonations of two precisely designed TNT charges with a certain delay, it must be possible to numerically generate a double-peak profile similar to the type II experimental profile presented on Figure 18. First preliminary tests were conducted but only future work will determine if such technique can provide some relevant data.
The complex Type III pressure evolution is not treated in this document, as we are not yet able to propose any relevant post-processing method.

7 Conclusions - Perspectives

Free-field blast waves were successfully generated by high explosives at two different scales: IRSN test table and twice up-scaled ISL blast pad. Blast characteristics (peak overpressure, time of arrival and maximal positive impulse) for Hexomax® charges were measured at both scales. In addition 400 g TNT reference charges were produced and detonated at ISL, providing direct comparison data allowing us to determine the TNT equivalency of Hexomax® in overpressure on the range of studied distances. Best overall repeatability was observed for IRSN test series and Hexomax® scalability between the two configurations proved to be good as long as the first peak overpressure value and arrival time were concerned. Positive impulse could be scaled, except in close range where fireball is probably responsible for data dispersion. High-speed imaging highlighted some details of the interaction between the blast wave and the ground surface at ISL: leading conical shocks generated by projected material interfere with the pressure measurement, in addition to all other phenomena present on the contact surface. Finally we proposed a candidate processing technique of overpressure time history recorded during our experimental campaigns.
Future extension to this study will include other plastic explosives analysis (C-4 and Semtex), spherical blast propagation to evaluate the effect of the ground reflection and TNT equivalency determination based on other blast characteristics (maximal positive impulse, time of arrival, etc.).
The authors wish to thank the ArianeGroup team for their support during the experimental campaign.

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