Defence Research and Development Canada
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Validation of a mine-loading model

The 6kg TNT case

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Technical Report
DRDC Valcartier TR 2013-273
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Canada

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Abstract

The anti-vehicular landmine threat has increased greatly since 2005. It has now become one of the important causes of vehicle losses in combat operations, and a major threat to vehicle occupants in many countries. Experimental and numerical studies of buried charge effects on structure and the measurement of the loading produced by landmines become important topics to study. This type of research is done to support the development of improved vehicle protection to resist blast from landmines and Improvised Explosive Devices (IEDs). Since it is a very challenging task to model explosive detonation, shock wave formation and propagation as well as interaction with structures from the first-principles, a phenomenological approach was investigated. In this study, two non-impulsive pressure models were investigated to model the damage on a plate from a blast landmine. The assumption that the loading generated by the blast is purely impulse is critically investigated and rejected. A new non-impulsive time-distribution pressure model is then proposed. The outputs of the new pressure model were validated using experimental data from 6 kg 2, 4, 6-trinitrotoluene (i.e. TNT) experimental tests.

Résumé

La menace des mines contre les véhicules militaires a augmenté depuis 2005. Elle est devenue une des causes importantes de la perte de ces véhicules et de leurs occupants. Dans le but de faire la conception de systèmes de protection convenables pour ces véhicules, les études expérimentales et numériques des effets de souffle de mines enfouies sur les structures et la mesure de la charge produite par ces mines sont des sujets importants à étudier. Modéliser la détonation d’explosif, la formation de l’onde de choc et sa propagation ainsi que l’interaction avec les structures est un défi très difficile voire même impossible à réaliser si l'on veut utiliser les lois fondamentales. Par conséquent, une approche empirique a été proposée. Dans cette étude, deux modèles non impulsifs, i.e. appliquant une pression en fonction du temps ont été examinés. L’hypothèse que le chargement est purement impulsif est critiquée et rejetée pour être remplacée par un modèle non impulsif qui dépend d’une pression en fonction du temps. Les résultats obtenus avec le nouveau modèle ont été validés avec des tests expérimentaux d’une charge de 6 kg de 2, 4, 6-trinitrotoluene (c.à.d. TNT).

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Executive summary

Validation of a mine-loading model: The 6kg TNT case

Bouamoul, A.; Fillion-Gourdeau, F. and Toussaint, G.; DRDC Valcartier TR 2013-273; Defence R&D Canada – Valcartier; December 2013.

Background: During the past few years, a number of incidents and accidents involving landmines during Canadian Forces (CF) operations have revealed a need to better protect CF Light Armoured Vehicles against anti-vehicular blast landmine threats. The development of protection systems involves a considerable investment in money and time for field trials. Numerical models using the finite element method have proven to be effective in reducing both time and cost factors in this development process. Since it is a very challenging task to model explosive detonation, shock wave formation and propagation as well as interaction with structures from the first- principles, a phenomenological approach seems more suitable. Therefore, two non-impulsive time distribution formulas with different parameters were investigated to generate the initial loadings that can be applied on a target.

Results: Westine's model is one of the impulsive models that are widely used by many laboratories to simulate the initial loading conditions generated from a blast landmine event. The assumption of an impulse loading is that the duration is much shorter than the natural period of the target structure, and so the exact shape of the pressure-time loading is not as important for the calculation of the target's response as its integral over time. This assumption was critically investigated and rejected after comparing the numerical results of two non-impulsive time-distribution formulas with experimental data from a 6 kg 2, 4, 6-trinitrotoluene (i.e. TNT) charge detonated under 25.4-mm and 19.05-mm thick plates.

Significance: A reliable phenomenological model that can be used to simulate the effect of blast landmines on vehicles and their protection system against blast landmines.

Future plans: Future work will include the validation of the empirical model with other types of landmines.

Sommaire

Validation of a mine-loading model: The 6kg TNT case

Bouamoul, A.; Fillion-Goudeau, F. and Toussaint, G. ; DRDC Valcartier TR 2013-273 ; R & D pour la défense Canada – Valcartier; décembre 2013.

Contexte: Au cours des dernières années, le nombre d'incidents et d'accidents impliquant des mines terrestres dans les missions des forces canadiennes a augmenté. Cette triste situation a démontré la nécessité de mieux protéger les véhicules contre ce type de menace. Cependant, le développement des systèmes de protection implique un investissement considérable en temps et argent lors des essais expérimentaux. Les méthodes numériques par éléments finis se sont avérées efficaces pour réduire le temps de développement et les coûts qui y sont associés. Étant donné que modéliser la détonation d'explosif, la formation de l'onde de choc et sa propagation ainsi que l'interaction avec les structures est un défi de la physique très difficile voire même impossible à réaliser si l'on veut utiliser les lois fondamentales, une approche empirique semble plus appropriée. À cet effet, deux modèles non impulsifs sont proposés pour estimer le chargement initial sur une plaque.

Résultats: L'hypothèse que le souffle est impulsif signifie que la durée de l'évènement est courte comparée à la réaction de la structure. Par conséquent, la forme exacte du chargement n'est pas aussi importante dans le calcul de la réponse de la structure. Cette hypothèse est critiquée et rejetée pour être remplacée par un modèle non impulsif. Les résultats du nouveau modèle ont été validés avec des tests expérimentaux d'une charge de 6 kg de TNT détonée sous une plaque d'une épaisseur de 25.4 mm et sous une plaque d'épaisseur 19.05 mm.

Importance: Un modèle empirique fiable qui peut être utilisé pour modéliser l'effet du chargement d'une mine sur les véhicules et leurs protections.

Perspectives: Les travaux futurs comprendront la validation du nouveau modèle pour d'autres types de charge de mines.

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Acknowledgements

The authors would like to thank M. Robert Durocher for planning and conducting the experimental tests as well as providing the experimental data.

1 Introduction

Landmines and anti-vehicular mine blasts are among the most important threats for many military forces [1-7]. For this reason, protection systems have been designed and developed in the last few decades. A series of new ideas and concepts have emerged from this research. These include new ways of protecting and stiffening the hull of the vehicle, suspension systems for the occupants, etc. The testing of these new designs requires a considerable deployment of resources and thus, can be very costly. Hence, a numerical approach becomes a very useful tool for design purposes because it allows more flexibility and an easier implementation than a full-fledged experimental program. The numerical approach, however, suffers from several drawbacks in the mine blast simulations. First, it is a very challenging task to model this phenomenon from first-principles, that is, including the detonation of the explosive, the formation of the shock wave and the blast-soil interaction. The variability in the soil properties and its effect on blast render the task even more problematic because this effect cannot be characterized precisely. Therefore, a phenomenological approach seems more suitable such as the Southwest Research Institute (SwRI) Westine model [8].

Earlier in the 1980s, the US Army contracted the SwRI to develop a computer program that could predict the response of floor plates to a land mine explosion. In the process, SwRI developed a load model from a classical non-dimensional analysis and then performed a series of small-scale experiments to validate the model. The Westine model was used successfully in many applications involving mostly rigid body motion. For example, the effect on the occupants due to the motion of a vehicle subjected to a mine blast has been studied [9-13]. In those applications, the model seems to provide accurate predictions. This is confirmed by examining the experimental results where the total impulse was measured for different soil and different configurations. The Westine model represents the 50^{th} percentile for the total impulse imparted on a plate [13, 14]. The deviation in the results can be related mostly to the soil properties. On the other hand, the same model was used to study the local plate (meshed using shell elements) deformation [9] and over-predicted the deflection by approximately 35-40 %. A correction factor was then introduced to scale down the impulse to get the right deflection, assuming that this discrepancy was due to uncontrolled parameters such as soil properties and imperfect detonation. It is noteworthy here to state that this approach was based, just like the rigid motion studies, on the assumption that the loading on the plate is impulsive, that is, the duration of the loading is much shorter than the typical reaction time of the plate. This seems very plausible given the time of the mine explosion event, on the order of 4-5 ms, and the fact that the plate reaches its highest velocity at approximately 1-2 ms. In this work, this hypothesis is revisited and critically investigated.

The main assumption on which this study is based is that for local deformations and typical material found on a vehicle (RHA plate, between 15 mm and 30 mm); mine loading is not impulsive. Rather, it lasts for a certain time duration, shorter than the time for the whole blast event (around 6 ms, including the structural response). Thus, the loading is applied (on solid elements) as a pressure-time history rather than as an initial velocity (assuming an impulsive loading which is usually applied on shell elements), as was previously done. In this study it is demonstrated that this assumption leads to much more accurate results than the impulsive method.

This report is ordered as follows: in the first section, the experimental set-up is presented, along with certain data acquisition details. The cases studied experimentally include 6 kg explosive mass and two plate thicknesses (25.4 mm and 19.05 mm). Then, the numerical finite element model representative of the experimental set-up is shown. The loading, which is the critical part of this work, is discussed thoroughly. The results of simulations are compared to experimental data and a comparison study between different loadings is conducted.

2 Experimental set-up

The experimental study of buried charge effects on structure and the measurement of the loading produced by buried explosive charge are important topics of research in support of the development of improved vehicle design to resist buried explosive charges such as mines and buried Improvised Explosive Devices (IEDs). A common method to assess the output of buried explosive charge consists in measuring the total impulse transmitted to a given structure. The Army Research Laboratory (ARL) uses the Vertical Impulse Measurement Facility (VIMF) to study effects of buried charge loading on structures [14]. In VIMF, a large-scale piston is used to mount deformable structures at the end of the vertical shaft. This design makes possible the study of the effect of full-scale mines on full-scale structures while measuring the net vertical momentum transfer to the shaft. This is a powerful tool to study the relationship between structural deformation and gross vehicle acceleration.

DRDC has been using several large and small scale facilities in the past to assess buried charge loadings [3, 9]. A similar implementation of a flat plate attachment to a test rig fixed to the ground, used by DRDC, has also been used in Meppen, Germany, to study the response of various flat plate thicknesses to land mine blast. The ONAGER used at DRDC Suffield consisted of a pendulum type device to measure the global impulse of buried mine [15]. One of the main purposes of the ONAGER pendulum was to study the effect of soil conditions on the total momentum transfer to a vehicle. In its study of mine effects on structure, DRDC-Valcartier has been using different test set-ups for characterizing buried charge loadings and assessing material performance. The test set-up used consisted of free flying simple frames, on which material coupons could be installed to monitor both the global (complete set-up) reaction and local (material coupon) reaction. Since this set-up did not provide a direct measurement of the loading on the plate, more recently, DRDC Valcartier has initiated a research program to develop a large scale experimental method to measure the distribution of the specific impulse generated by an explosive charge buried in different soil types and under various conditions and to develop enhanced numerical models for the loading generated by these threats [16].

The simple frame set-up shown in Figure 1 was designed to accommodate material coupon sizes and boundary conditions used by different R&D organizations. The U.S. with their VIMF typically use target size of 1.2 x 1.2 m (48 x 48 inch). European NATO allies, such as Germany at WTD, are typically using 1.5 x 1.5 m (60 x 60 inch) targets. The design of the frame set-up is an iteration of previous set-ups used by DRDC Valcartier and has been made to provide better versatility and control over the target sizes, boundary conditions of the target and better monitoring of the target back face for observing the local deformation and material behavior subjected to buried charge loadings.

Figure 1: Experimental set-up.

The Impulse frame set-up can be described as a “free motion” set-up as the motion of the facility is not controlled by any mechanical guides or restraints and only depends on gravity for deceleration. The decision to use a “free flying” set-up as opposed to a motion controlled set-up was taken for the following reasons:

- Cost of the facility;
- Capability to easily remove or add weight to accommodate different charge sizes;
- Better transportability and mobility and finally;
- No permanent infrastructure required.

The disadvantage of this facility is its sensitivity to unsymmetrical or off-centre loading, which will impart a rotation to the set-up. This may influence the reaction of the frame and requires the monitoring of the four corners of the facility to provide a response from the center of mass of the facility. Also, as no mechanical measurement is made; measurements of the global motion of the set-up rely on high-speed imagery and accelerometers, which require some additional level of analysis. The impulse frame set-up consists of modular metallic frames that can be adjusted to emulate different testing conditions. The base of the facility is a rigid rectangular frame with leg attachments at its four (4) corners. Additional frames can be bolted to the base to adjust the mass of the set-up. The staggered frames are designed to provide maximum camera view over the back face of the target during the event. A vertical structure with reference markers can be installed on the top of the base for better tracking the global motion of the frame with the hi-speed imagery systems. The set-up can be adjusted for simulating different vehicle weight and ground clearances. Details of the set-up specification are provided in Figure 2 while dimensions of the coupon are in Figure 3 for the rigidly clamped edge boundary conditions.

The installation is instrumented to make dynamic measurements of the global reaction of the set-up and local deformation of the target. Dynamic measurements on the facility considered in this study are:

1- Global reaction measurements:
   a. Frame corners displacement vs. time using high-speed imagery;
   b. Frame corners acceleration vs. time using accelerometers;

2- Local reaction measurements of the target:
   a. Displacement vs. time using high-speed imagery;
   b. Displacement vs. time using laser displacement sensor;
   c. Acceleration vs. time using accelerometers mounted on the target.

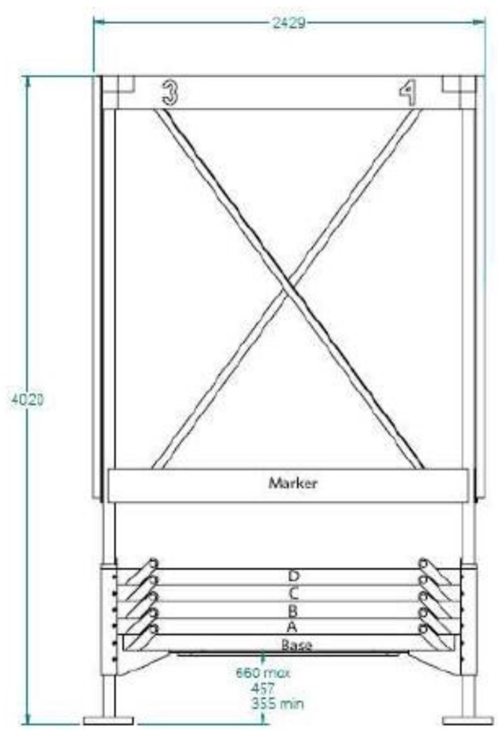

Figure 2: Technical drawing of the experimental set-up.

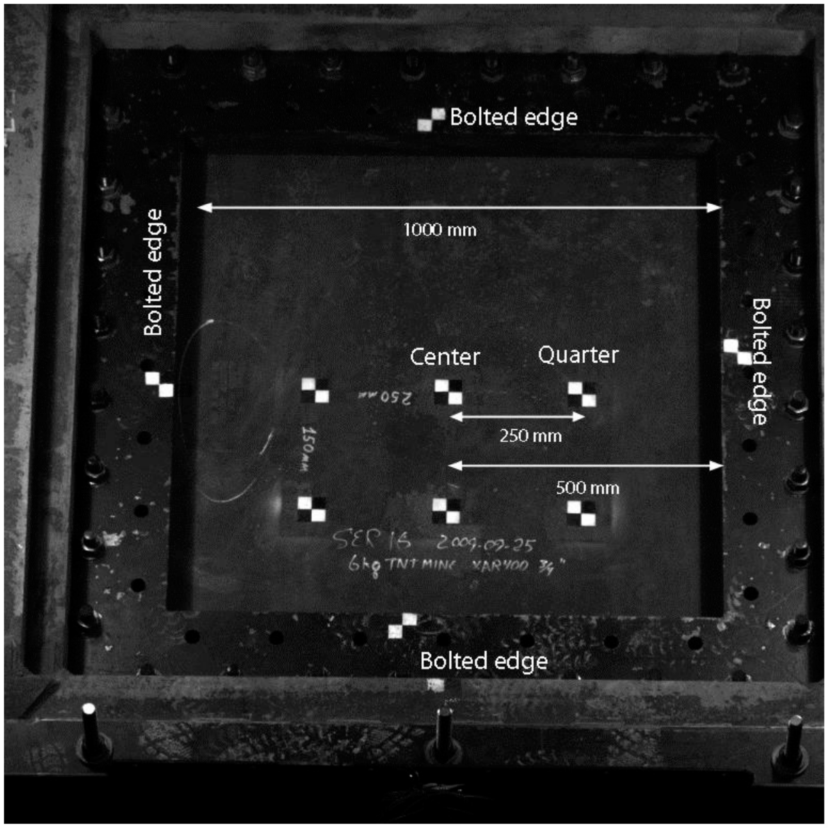

Figure 3: Target dimensions.

3 Numerical model

The simulations were performed with the LS-DYNA finite element hydrocode [17]. This code has very good contact capability, and contains many features such as many material models, element formulations, boundary conditions, etc., making it a very good choice for the simulations performed in this study. Throughout this work, the Lagrangian formulation was used.

3.1 Geometry and mesh

The numerical model of the set-up is shown in Figure 4. The dimensions were taken from the real experimental set-up, shown in Figures 1, 2 and 3. It was made of three parts namely, the support frame, the plate and the bolts. The geometry of the support frame was simplified compared to the real set-up because it was assumed that it did not suffer from any deformations. Thus, only the edge and opening sizes were important for the present analysis.

Non-structural masses were added to the support frame to make sure the whole set-up had the right weight. Only a quarter of the whole problem was simulated taking advantage of the symmetry of the system. Boundary conditions on the symmetry planes were implemented accordingly. The plate thicknesses considered were 25.4 mm (1.00 inch) and 19.05 mm (0.75 inch). The CAD model was meshed using solid elements having an approximate edge size of 7 mm. The frame and the steel plate were made respectively of 84,476 and 76,070 solid elements, whereas the bolts were meshed using 512 and 448 shell elements for the 25.4 mm and 19.05 mm model respectively.

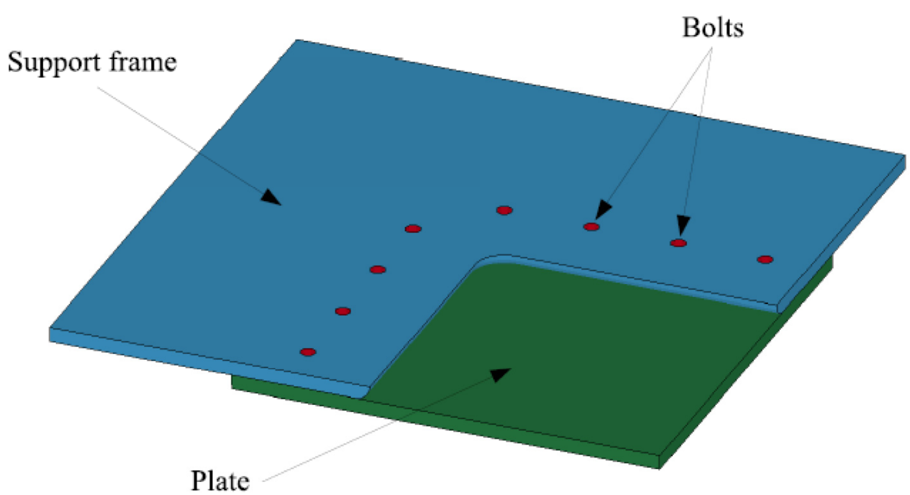

Figure 4: FEM of the plate support (25.4 mm plate thickness).

3.2 Material model

The frame and the bolts were assumed rigid (no deformation) during the mine explosion. Therefore, they were modeled with the *MAT_RIGID material model in LS-DYNA. The density given to these parts was the density of steel, which is shown in Table 1. For the steel plate, the kind of steel used was Algotuf 400F. Because the maximum strain-rate level reached in simulations was approximately 320 s^{-1}, which is relatively low, the strain-rate effects were neglected and a simple elastic-plastic model *MAT_PLASTIC_KINEMATIC was used. The material parameters for this steel are presented in Table 1. Using the steel density given in Table 1, the total mass of the frame set-up was 10,040 kg for the 1st model (25.4-mm plate thickness) and was 10,464 kg for the 2nd model (19.05-mm plate thickness). These values are slightly higher than the ones tested experimentally as shown in Table 4.

No fracture parameter was used since it was known experimentally that the plate would not fail.

Table 1: Material properties for the Algotuf 400F steel used in the FEM.

Material properties	**Units**	**Algotuf 400F steel**
Density (ρ)	kg/m^3	7870.0
Young modulus (E)	MPa	210.0×10^3
Poisson's ratio (υ)	-	0.33
Yield stress (σ_{yield})	MPa	1000.0
Tangent modulus (E_t)	MPa	752.6

4 Numerical model

4.1 Impulsive loading

The impulse produced from a landmine explosion is mainly the result of detonation products and soil ejecta impacting the target at high velocity. The loading generated from the impulse is characterized by a high pressure during a short response time. Assumption of an impulse loading is that the duration is much shorter than the natural period of the target structure, and so the exact shape of the pressure-time loading is not as important for the calculation of the target's response as its integral over time. In previous studies, the Westine model was used [8] along with the impulsive assumption on shell elements.

The Westine model was implemented in the DRDC Mine-Pre pre-processor. Mine-Pre software uses ray-tracing algorithms to apply an initial velocity on each individual node based on the impulse obtained from the Westine model and that are function of the mine mass, TNT equivalent, the depth of burial, and the soil density. This assumes that the loading is impulsive, which means that the time of application of the loading should be much shorter than the typical time response of the plate. In the early part of this work, this approach was used and led to plate deflections much higher (around 40 %) than experimentally measured values. To account for this discrepancy, modifications of the Westine model loading are investigated, mainly, by assuming a non-impulsive loading that has a certain time history over a long period of time (5-6 ms). Two time-distribution formulas with different parameters were investigated in the following section.

4.2 Non-impulsive loading

As discussed previously, it was suggested that the discrepancy between experimental results and simulations was due to the non-impulsive nature of the loading. Rather, it should be applied as a pressure-time history for which the specific impulse is given by the Westine predictions. Remember that the specific impulse (I_s) is given by:

$$I_s = \int_0^{t_A} P(t)dt \qquad (1)$$

Where $P(t)$ is the pressure and t_A is the time of application of the loading. The value of I_s is given by Westine [8] and depends on the depth of burial, standoff distance, explosive mass, type of explosive and the distance from detonation. There is an infinite number of possibilities and combinations of t_A and $P(t)$ that can give the right solution. The goal of this work is to narrow down these possibilities and determine a "working" loading that can be used for design purposes.

It is not possible at the moment to measure experimentally the pressure time history applied on a plate due to the mine blast and ejecta and therefore, the shape of the pressure-time history has to be quite arbitrarily chosen. However, there are a few constraints that allow an educated guess to be made of this shape.

- The time of application t_A should be in the order of a few milliseconds because this is the time that the deformation lasts (around 5-6 ms);
- The limit $lim_{t \to t_A} P(t)$ should be 0;
- The equation should be relatively simple and smooth for numerical implementation.

Two pressure loading profiles *P(t)* are considered in this study. They are given in Eqs 2 and 3. The integral over time of the two equations should give the same impulse (I_s) calculated by Westine.

1- The cosh-Friedlander (cosh-F):

$$P(t,X) = P_{ChF}\left(1 - \frac{t - t_{arr}}{\Delta t}\right) \exp\left(-\alpha \frac{t - t_{arr}}{\Delta t}\right) \frac{1}{Cosh(c\theta)} \quad (2)$$

2- The half-sin Friedlander (Hsin-F):

$$P(t) = P_{HSF} \sin(\pi \frac{t}{\Delta t}) \left(1 - \frac{t}{\Delta t}\right) \exp\left(-\alpha \frac{t}{\Delta t}\right) \quad (3)$$

In the two equations, Δt characterizes the duration of the event, P_{ChF} and P_{HSF} are normalization constants introduced to get a specific impulse from the Westine model. α and c are non-dimensional constants and θ (shown in Fig. 6) is the angle between the vertical of the mine and the location where the loading is calculated.

4.2.1 Cosh-Friedlander model

The cosh-Friedlander equation given in Eq. 2 consists of a Friedlander function $\left(1 - \frac{t-t_{arr}}{\Delta t}\right) \exp\left(-\alpha \frac{t-t_{arr}}{\Delta t}\right)$ multiplied by a second function $\frac{1}{Cosh(c\theta)}$ that represents pressure distribution at a given time (*t*) and location (X) over a target. This model can be described as a dynamic model since the loading is applied progressively on the plate (or target) as the blast arrives to the target (t_{arr}). The time of arrival is calculated using Eq. 4.

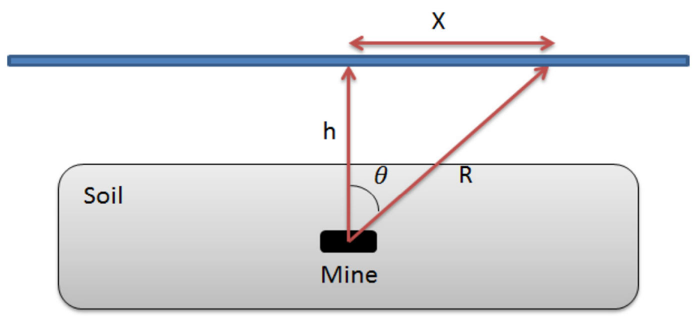

Figure 5: 2D representation of a buried mine.

$$t_{arr} = \frac{V_{blast}}{R} \tag{4}$$

A preliminary analysis was performed with a range of α, c and Δt parameters. Table 2 shows a selected combination of these parameters for which the results are presented in this report.

Table 2: Parameters used in cosh-Friedlander model.

Loading cases	$\boldsymbol{\alpha}$	***c***	$\boldsymbol{\Delta t}$
CoshF1	10	2	2 ms
CoshF2	10	4	2 ms
CoshF3	10	4	4 ms
CoshF4	10	4.9	4 ms
CoshF5	16	4.9	4 ms

4.2.2 Half-sin Friedlander model

The half-sin Friedlander shape given in Eq. 3 consists of a Friedlander function $\left(1 - \frac{t}{\Delta t}\right) \exp\left(-\frac{\alpha t}{\Delta t}\right)$ multiplied by $\sin(\pi \frac{t}{\Delta t})$ that represents pressure distribution at a given time (t) over the total area of the target. This model can be described as a static model since the loading is applied at the same time over the entire plate (target) and do not depends on the time of arrival of the blast.

The values of the parameters for every loading considered in this study are presented in the following Table:

Table 3: Parameter values for the Half-sin-Friedlander model.

Loading cases	α	Δt
HsinF1	0.25	1.00 ms
HsinF2	0.50	1.00 ms
HsinF3	0.25	1.50 ms
HsinF4	0.25	1.75 ms
HsinF5	0.25	2.00 ms
HsinF6	0.25	2.50 ms

5 Results

5.1 Experimental

The following are the data obtained from the experimental tests done for a 6 kg TNT explosive mass on 25.4 mm and 19.05 mm Algotuf 400F steel plate thicknesses. The depth of burial was 10 cm taken from the top of the mine to the ground. The plate was located 0.4 m above the ground. Unfortunately, only one experimental value was available for comparison purposes on 19.05 mm plate and 6 kg.

Table 4: Results for 6 kg explosive mass on the 25.4 mm (1.00 inch) plate thickness.

Test number	***Total mass of the frame set-up, kg***	***Permanent deflection, m***	***Dynamic deflection***		***Maximum velocity,***	
			Centre m	***Quarter m***	***Centre m/s***	***Quarter m/s***
Exp.1	9581	0.088	0.116	0.089	116	91
Exp.2	9882	0.106	0.130	0.102	135	102
Exp.3	9882	0.086	0.121	0.095	123	95

Table 5: Results for 6 kg explosive mass on the 19.05 mm (0.75 inch) plate thickness.

Test number	***Total mass of the frame set-up, kg***	***Permanent deflection, m***	***Dynamic deflection***		***Maximum velocity,***	
			Centre m	***Quarter m***	***Centre m/s***	***Quarter m/s***
Exp.4	9430	0.145	0.164	-	151	-

5.2 Deflection-time history

In the following section, the results of the deflection-time history for the two loading models are presented and compared to the experimental results. This comparison will allow a determination of the most accurate loading.

5.2.1 Cosh-Friedlander model

5.2.1.1 25.4-mm thick plate

Figure 6 and 7 show the plate-centre and quarter deflection vs. time for the 5 scenarios listed in Table 2. It should be noticed that the permanent deflection of the plate depends on the α, c and Δt parameters. A comparison between the center and the quarter permanent deflections shows that the CoshF2 and CoshF5 are similar and they are the scenarios that best match the experimental data.

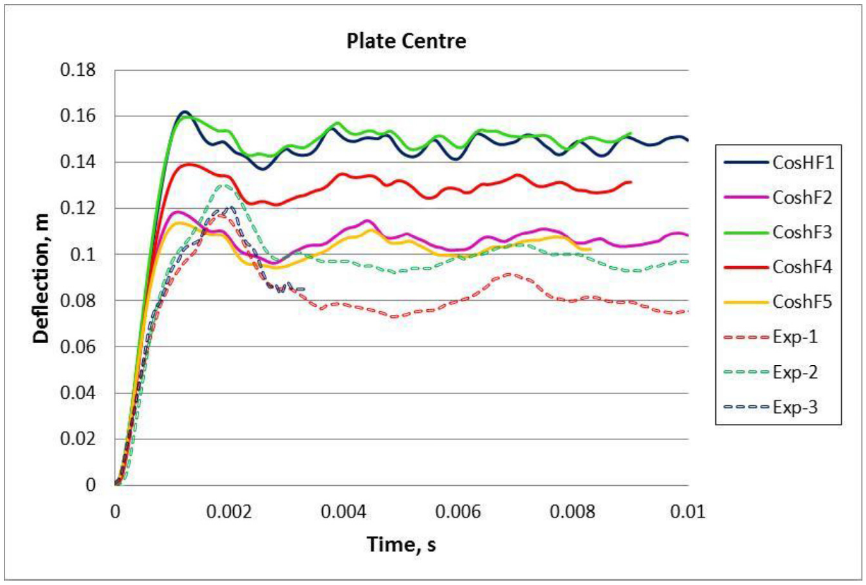

Figure 6: Plate-centre deflection vs. time for Cosh Friedlander model (25.4 mm).

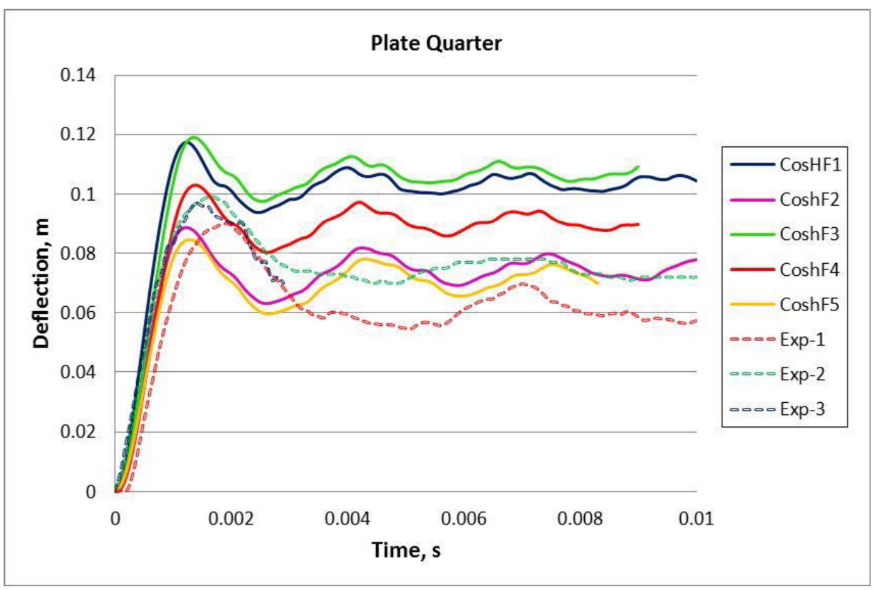

Figure 7: Plate-quarter deflection vs. time for Cosh Friedlander model (25.4 mm).

5.2.1.2 19.05-mm thick plate

Table 6 shows the dynamic and permanent center deflections for the 5 scenarios listed in Table 2. The CoshF2 and CoshF5 cases are the scenarios that best approximate the experimental data. Unfortunately, only one experimental value was available for comparison purposes. The same conclusion was obtained for the 25.4-mm plate case. A ±10% variation in the experimental results is common due the inherent variability of the soil constituents. So, 10% variation in the numerical data is acceptable and is considered to be in accordance with the experimental observations.

Table 6: Plate center dynamic and permanent deflection (19.05 mm)

Test number	***Dynamic deflection, m***	***Relative error, %***	***Permanent deflection, m***	***Relative error, %***
CoshF1	0.216	31.7	0.198	36.6
CoshF2	0.157	-4.3	0.145	0
CoshF3	0.215	31.3	0.207	42.8
CoshF4	0.189	15.2	0.180	24.1
CoshF5	0.152	-7.3	0.141	-2.8
Exp.4	**0.164**	**-**	**0.145**	**-**

*% relative error = (Num - Exp)*100/Exp*

5.2.2 Half-sin Friedlander model

5.2.2.1 25.4-mm thick plate

For the Half-sin Friedlander model, Figure 8 and 9 show plate centre and quarter deflection vs. time for the six scenarios listed in Table 3. A comparison between the experimental and the numerical dynamic and permanent deflections shows that HSinF6 is the closest scenario to the experimental data. The α parameter has no effect on the computed deflection (HSinF1 vs. HSinF2). As the duration of the event (Δt) increases from 1 ms to 2.5 ms, the maximum permanent deflection decreases. This can be explained by the total energy transferred from the buried-mine (a fixed value) to the plate being smeared over a longer period of time, which results in lower pressure values.

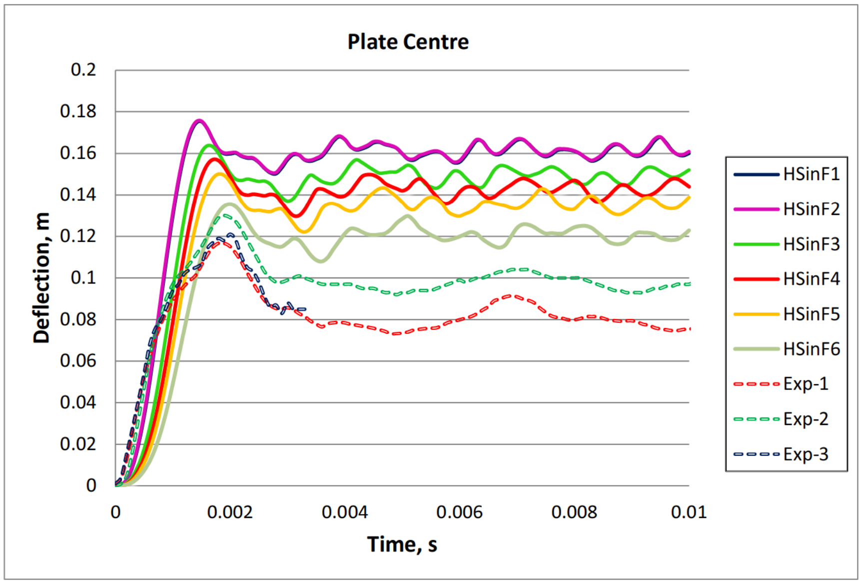

Figure 8: Plate-centre deflection vs. time for Half-sin Friedlander model (25.4 mm).

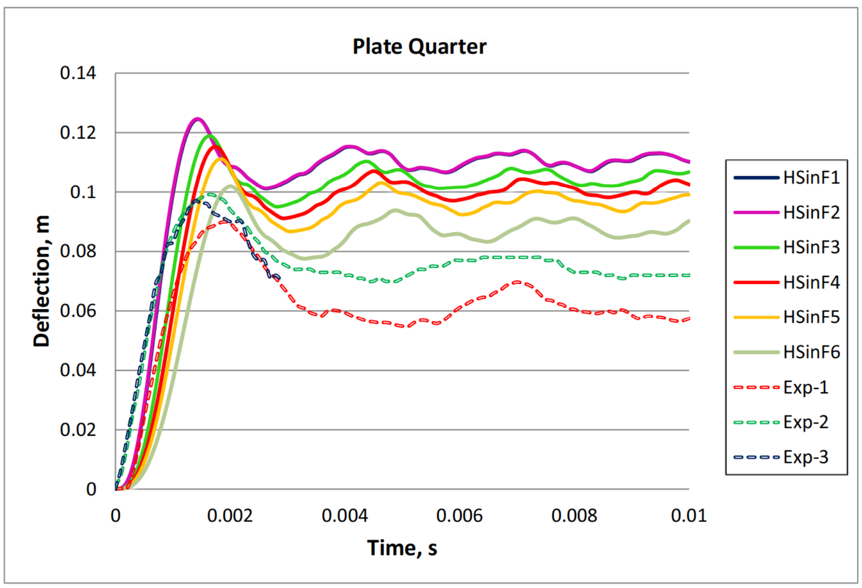

Figure 9: Plate-quarter deflection vs. time for Half-sin Friedlander model (25.4 mm).

5.2.2.2 19.05-mm thick plate

Table 7 shows the dynamic and permanent center deflection for the 5 scenarios listed in Table 3. As for the 25.4-mm case, the scenario that best matches the experimental data is HsinF6 with less than 15% relative error.

Table 7: Plate center dynamic and permanent deflection (19.05 mm)

Test number	***Dynamic deflection, m***	***Relative error, %***	***Permanent deflection, m***	***Relative error, %***
HsinF1	0.228	39.0	0.212	46.2
HsinF2	0.228	39.0	0.212	46.2
HsinF3	0.215	31.1	0.199	37.2
HsinF4	0.208	26.8	0.191	31.7
HsinF5	0.199	21.3	0.183	26.2
HsinF6	0.181	10.4	0.167	15.2
Exp.4	**0.164**	-	**0.145**	-

*% relative error = (Num - Exp)*100/Exp*

5.3 Initial vertical velocity of the set-up

The initial vertical velocities obtained for the two 25.4-mm and 19.05-mm thick plate models as well as for the experimental results are shown in Figure 10 and Figure 11. To calculate the numerical initial velocities of the set-up, a ballistic trajectory was assumed and a second order polynomial curve was fit on the vertical displacement versus time curve. The second order curves represent the displacement as a function of the initial acceleration and initial velocity ($z = a_0 t^2 + V_0 t + z_0$). The first 2 ms were not taken into account when the ballistic trajectory was computed numerically as for the experimental tests. Actually, the first milliseconds of the set-up displacement could not be filmed using high speed video cameras due to the soil ejecta, and therefor were not available to compute the experimental initial velocity.

In Figure 10 and Figure 11, the horizontal lines are the experimental values, whereas the columns are those of the numerical models. Most Cosh-Friedlander cases underestimated the velocity including CoshF2 and CoshF5. These two scenarios were eliminated even if they well approximate the experimental permanent deflections at the center and the quarter locations. The computed Half-Sin Friedlander velocities of all scenarios are in same order of magnitude and within the experimental variation for both 25.4-mm and 19.05-mm thick plate models.

From these comparisons we suggest using the HsinF model with the following parameters (α= 0.25 and Δt = 2.5 ms) corresponding to HSinF6 case to conduct future studies on the effects of mine blast on targets.

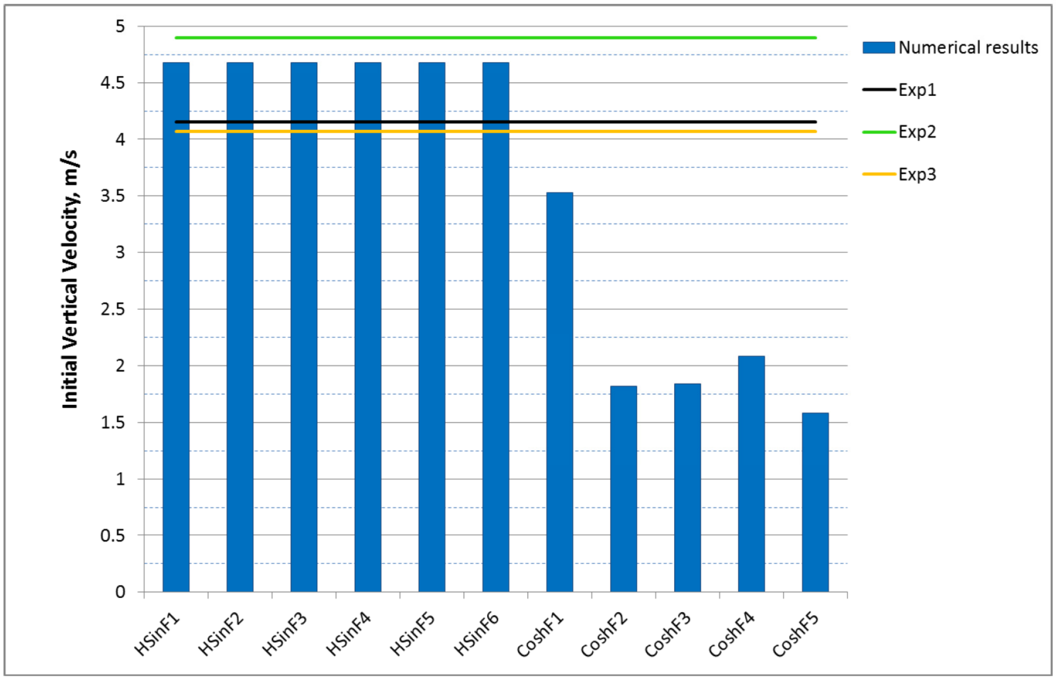

Figure 10: The experimental and numerical maximum velocity at center of mass (25.4 mm).

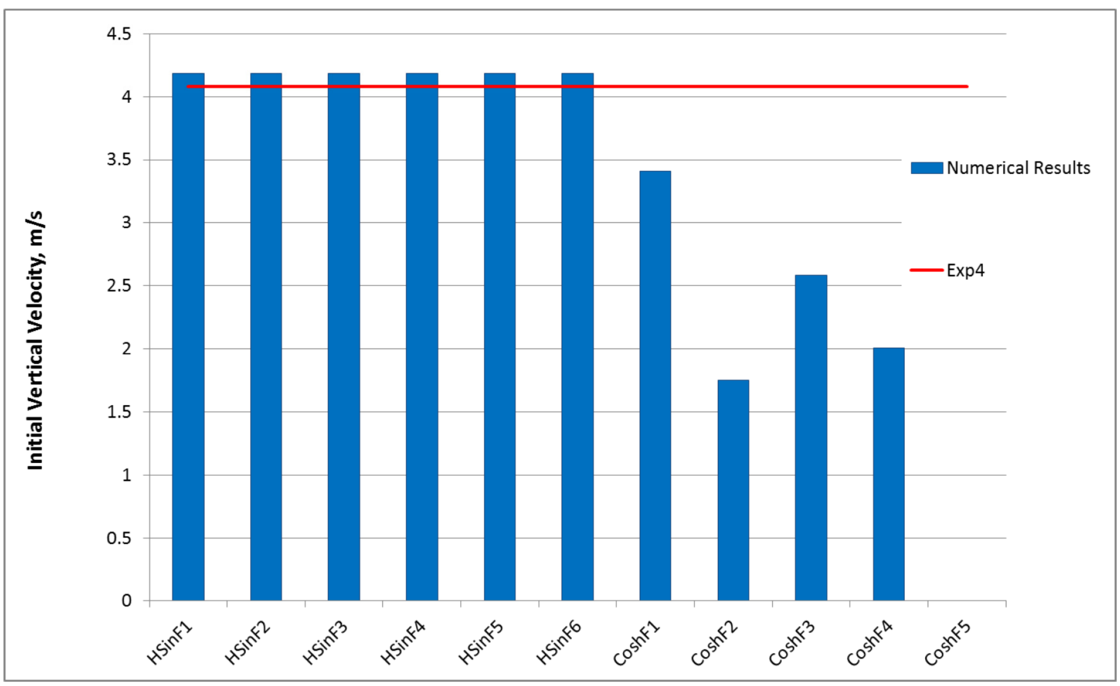

Figure 11: The experimental and numerical maximum velocity at center of mass (19.05 mm).

6 Conclusion

In this study, the assumption that the loading from buried landmines is impulse was critically investigated and two non-impulsive time-distribution formulas with different parameters were investigated to generate the initial loadings that can be applied on a target. The specific impulse of the two pressure-time models was given by the Westine predictions. The final proposed model is a half-sin Friedlander equation that represents pressure distribution at a given time (t) over a target. The parameters of this pressure model were validated using experimental data from a 6 kg TNT charge denoted under a plate of 25.4 mm thickness and under a plate of 19.05 mm thickness. Future work will include the validation of the empirical model with other types of landmines.

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The anti-vehicular landmine threat has increased greatly since 2005. It has now become one of the important causes of vehicle losses in combat operations, and a major threat to vehicle occupants in many countries. Experimental and numerical studies of buried charge effects on structure and the measurement of the loading produced by landmines become important topics to study. This type of research is done to support the development of improved vehicle protection to resist blast from landmines and Improvised Explosive Devices (IEDs). Since it is a very challenging task to model explosive detonation, shock wave formation and propagation as well as interaction with structures from the first-principles, a phenomenological approach was investigated. In this study, two non-impulsive pressure models were investigated to model the damage on a plate from a blast landmine. The assumption that the loading generated by the blast is purely impulse is critically investigated and rejected. A new non-impulsive time-distribution pressure model is then proposed. The outputs of the new pressure model were validated using experimental data from 6 kg 2, 4, 6-trinitrotoluene (i.e. TNT) experimental tests.

La menace des mines contre les véhicules militaires a augmenté depuis 2005. Elle est devenue une des causes importantes de la perte de ces véhicules et de leurs occupants. Dans le but de faire la conception de systèmes de protection convenables pour ces véhicules, les études expérimentales et numériques des effets de souffle de mines enfouies sur les structures et la mesure de la charge produite par ces mines sont des sujets importants à étudier. Modéliser la détonation d’explosif, la formation de l’onde de choc et sa propagation ainsi que l’interaction avec les structures est un défi très difficile voire même impossible à réaliser si l'on veut utiliser les lois fondamentales. Par conséquent, une approche empirique a été proposée. Dans cette étude, deux modèles non impulsifs, i.e. appliquant une pression en fonction du temps ont été examinés. L’hypothèse que le chargement est purement impulsif est critiquée et rejetée pour être remplacée par un modèle non impulsif qui dépend d’une pression en fonction du temps. Les résultats obtenus avec le nouveau modèle ont été validés avec des tests expérimentaux d’une charge de 6 kg de 2, 4, 6-trinitrotoluene (c.à.d. TNT).

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