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Assessment of an experimental method and two loading models used to measure and simulate the effect of buried charges

G. Toussaint
R. Durocher
A. Bouamoul
A. Vallée
B. St-Jean
DRDC Valcartier

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IMPORTANT INFORMATIVE STATEMENTS

Abstract

Numerical simulation and modeling of buried explosives in soil is a challenging task and remains one of the critical gaps for assessing vehicle structural vulnerability to landmines. Defence Research and Development Canada – Valcartier has initiated a research program to focus on this problem. The aim of the project is to generate reliable experimental data to measure the distribution of the specific impulse generated by an explosive charge buried from different soil types and conditions and develop enhanced numerical models for the loading generated by these threats. This paper presents the experimental facility of a buried-charge impulse-gage concept and related finite element models developed for its study. Numerical simulations were performed using the LS-DYNA code to compare two loading methods. The initial data generated experimentally and the results from the FE models are compared with the analytical model predictions. Recommendations for improvement of the experimental facility are made.

Résumé

La simulation et la modélisation numérique des explosifs enfouis dans le sol sont une tâche difficile et demeurent l'une des lacunes principales dans l'évaluation de la vulnérabilité de la structure de véhicule à l'égard des mines terrestres. Recherche et développement pour la défense Canada – Valcartier a entrepris un programme de recherche pour étudier ce problème. Ce projet a pour but de générer des données d'expériences fiables afin de mesurer la distribution de l'impulsion spécifique produite par une charge explosive enfouie dans les différents types et conditions de sols et de concevoir des modèles numériques améliorés pour les charges générées par ces menaces. Le rapport présente le concept d'un dispositif expérimental de jauge de l'impulsion produite par une charge enfouie et des modèles d'éléments finis liés qui ont été élaborés pour cette étude. Des simulations numériques ont été réalisées à l'aide du LS-DYNA code pour comparer les deux méthodes de charge. Les données initiales produites par les expériences et les résultats provenant des modèles d'éléments finis sont comparés avec les prévisions du modèle analytique. Des recommandations d'améliorations au dispositif expérimental sont formulées.

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Authors:
G. Toussaint
R. Durocher
A. Bouamoul
A. Vallée
B. St-Jean

Defence Research and Development Canada – Valcartier
2459 Pie-XI Blvd North, Quebec, Quebec, G3J 1X5, Canada.

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Numerical simulation and modeling of buried explosives in soil is a challenging task and remains one of the critical gaps for assessing vehicle structural vulnerability to landmines. Defence Research and Development Canada – Valcartier has initiated a research program to focus on this problem. The aim of the project is to generate reliable experimental data to measure the distribution of the specific impulse generated by an explosive charge buried from different soil types and conditions and develop enhanced numerical models for the loading generated by these threats. This paper presents the experimental facility of a buried-charge impulse-gage concept and related finite element models developed for its study. Numerical simulations were performed using the LS-DYNA code to compare two loading methods. The initial data generated experimentally and the results from the FE models are compared with the analytical model predictions. Recommendations for improvement of the experimental facility are made.

INTRODUCTION

Numerical simulation and modeling of buried explosives in soil is a challenging task and remains one of the critical gaps for assessing vehicle structural vulnerability to landmines. Since many years, Defence Research and Development Canada (DRDC) – Valcartier is using an experimental set-up consisting in a flat target plate supported by four steel legs on which a mass is added on top and centered over a surrogate mine [1, 2]. Displacement histories and final deformation of the target plate obtained experimentally are used to validate numerical results. Although this set-up provides total impulse and plate response data, it does not allow direct measurement of the loading function generated by the buried mine. DRDC Valcartier has thus initiated a research program to focus on this problem with the aim of developing 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. The

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[1] Defence Research and Development Canada – Valcartier, 2459 Pie-XI Blvd North, Quebec, Quebec, G3J 1X5, Canada.

first step of this project was to design a simple version of a buried charge impulse gage concept to identify structural, geometry and instrumentation set-up requirements to further develop an improved version of the test facility.

This paper presents first a brief description of the Westine's analytical model [3] since both experimental and numerical results are compared and normalized with results from this predictive model. Secondly, the first version of the experimental facility of the buried charge impulse gage concept and preliminary results obtained are presented. Then, to help in the design of this experimental facility, finite element (FE) models were developed and simulations were performed using the LS-DYNA code to compare two approaches simulating the landmine loading: an in-house pressure model [2, 4] and the arbitrary lagrangian eulerian approach in LS-DYNA [5]. Finally, results from the analytical model, the experiments and the FE analyses were compared and are presented. Recommendations are made for future tests.

WESTINE'S ANALYTICAL MODEL

Westine et al. [3] developed an empirical equation to predict the specific impulse imparted to a flat plate placed over a buried land mine. Several authors have presented this empirical equation [6 to 8]. The specific[2] impulse ($i_v(x,y)$) as given in [6] is:

$$i_v(x,y) = 0.1352\left(1+\frac{7\delta}{9z}\right)\left(\frac{\tanh(0.9589\zeta d)}{\zeta d}\right)^{3.25}\sqrt{\frac{\rho E}{z}} \tag{1}$$

$$\zeta = \frac{\delta}{z^{\frac{5}{4}} A^{\frac{3}{8}} \tanh\left(\left(2.2\frac{\delta}{z}\right)^{\frac{3}{2}}\right)} \tag{2}$$

Where z is the stand-off distance of plate P (parallel to the ground) to the center of the mine, E is the energy release in explosive charge, ρ is the density of soil, δ is the burial depth to center of the mine, A is the cross-sectional area of the mine, $d=\sqrt{(x^2+y^2)}$ is the radial distance from the center of the mine and tanh is the hyperbolic tangent.

When using this empirical equation, four criteria depending on δ, z, E, A, d, ρ and the seismic P-wave velocity in the soil must be met [6]. The Westine model was selected as a comparative reference for this study since historical experimental data of total impulse and target plate deformation showed good correlation with this model.

To allow the publication of results in the open literature, both experimental and numerical results are compared with normalized specific impulse predicted by the Westine model [3] for the specific experimental and numerical modeling set-up parameters used, i.e: the type of explosive, the explosive mass, the depth of burial of the charge, the aspect ratio of the charge, the soil density and target stand-off. It was also assumed that the impulse calculated on the exposed surface on a plain plate was the same as the one on a plate with pistons that were flush with the bottom surface.

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[2] i.e. impulse per unit area of the plate at location (x,y).

EXPERIMENT

An experimental program was undertaken to generate preliminary experimental points and provide data and information on which to base the final experimental set-up design that will be developed to conduct more exhaustive test program intended to characterize the loading of buried explosive charges. The experimental set-up consisted of a massive quasi-rigid plate, with a series of holes positioned at specific intervals along the centerline axis of the plate. Simply supported solid pistons were positioned in each hole and were flush with the bottom of the surface of the plate. The specific impulse Is_i (Pa-s) at each piston location was determined using the initial maximum velocity Vo_i (m/s), the mass of each piston M_i (kg) and the exposed area, i.e. the surface of the piston A_i (m^2) and is calculated using Eq. 3.

$$Is_i = \frac{Vo_i M_i}{A_i} \tag{3}$$

For the set-up, different piston masses were used at different offset distances to provide initial velocities of the same order of magnitude to facilitate the tracking of the pistons with a high-speed camera. This provided optimal conditions to track the displacement time of individual piston. A general picture of the experimental set-up is provided in Fig. 1. Typical high-speed imagery tracking results used to calculate the specific and the total impulse of the buried charge loading are presented in Fig. 2. Four (4) tests were done using the same test parameters (explosive mass, depth of burial, soil density, etc.). Each detonation was done at a different location to provide undisturbed soil conditions for each test. Small adjustments to the high speed camera and lightning system settings were done through the tests to improve the quality of the experimental results.

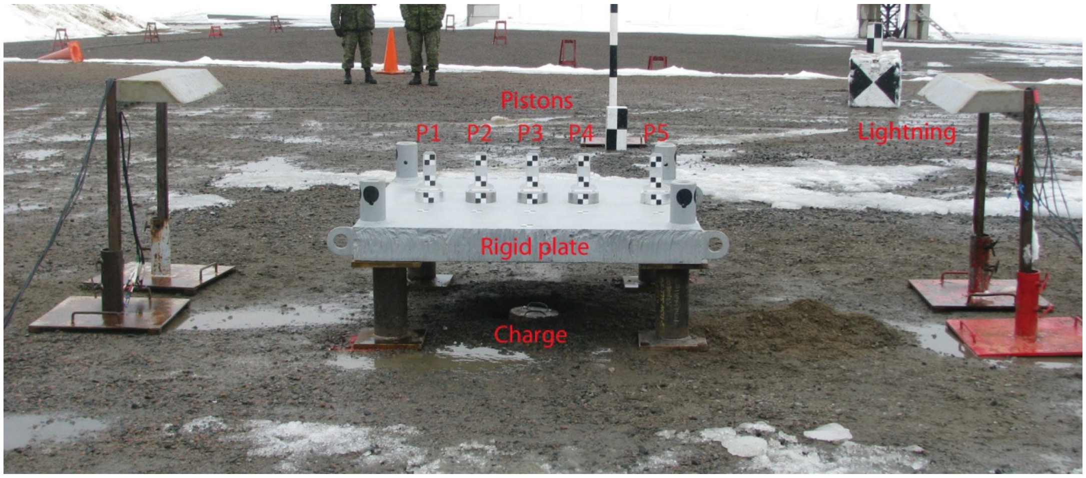

Figure 1. General view of the experimental set-up.

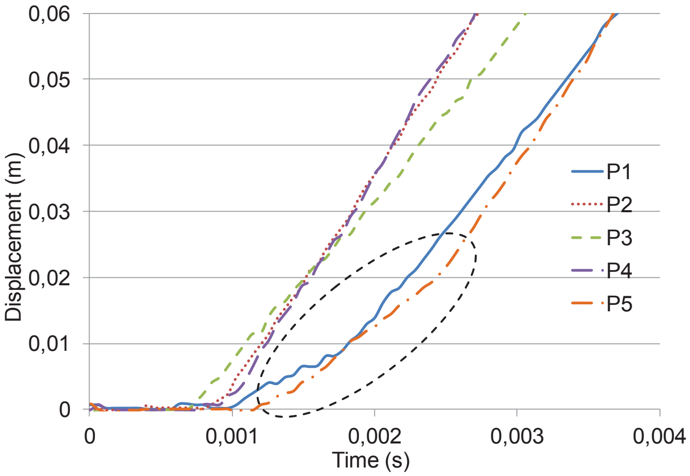

Figure 2. Typical displacement versus time (piston tracking).

The initial velocity of each piston was determined using a linear regression of the steady-state portion of the high-speed imagery tracking results. High speed imagery analysis was done using the ProAnalyst® software [9]. Time zero corresponds to the time of detonation. As shown in Fig. 2, pistons closest to the center (P2, P3 and P4) reached a constant velocity within 0.7 ms and 1.0 ms, whereas pistons farther from the center (P1 and P5) showed discontinuity in there displacement time profile between t=1.5 ms and 2.5 ms. It is believed that this reaction is caused by a combination of a longer time of arrival of the blast/ejecta and an interaction of the piston with the rigid plate response.

The total impulse I_t (N-s) transmitted to the experimental set-up was calculated using the rigid plate initial velocity Vo_p (m/s) and mass M_p (kg) added to the sum of the impulse transmitted to each individual piston and is given in Eq. 4.

$$I_t = Vo_p M_p + \sum_{i=1}^{5} Vo_i M_i \tag{4}$$

The plate initial velocity was calculated by tracking the displacement of its center of mass, assuming a ballistic trajectory, and is shown in Fig. 3. Vo_p was calculated by a second order regression of the displacement versus time curve based on the high speed tracking data.

The normalized experimental results for the specific impulse and total impulse are presented in Fig. 4 and 5. The specific impulse show relatively repeatable results between experiments and total impulses are very consistent. The average experimental results (specific impulse) follow the trend of Westine’s analytical predictions (between 2% and 18 % depending on pistons location) and are generally slightly above, however the experimental results (total impulse) are slightly lower than the Westine’s predictions, which contradict the results obtained with the specific impulse measurements.

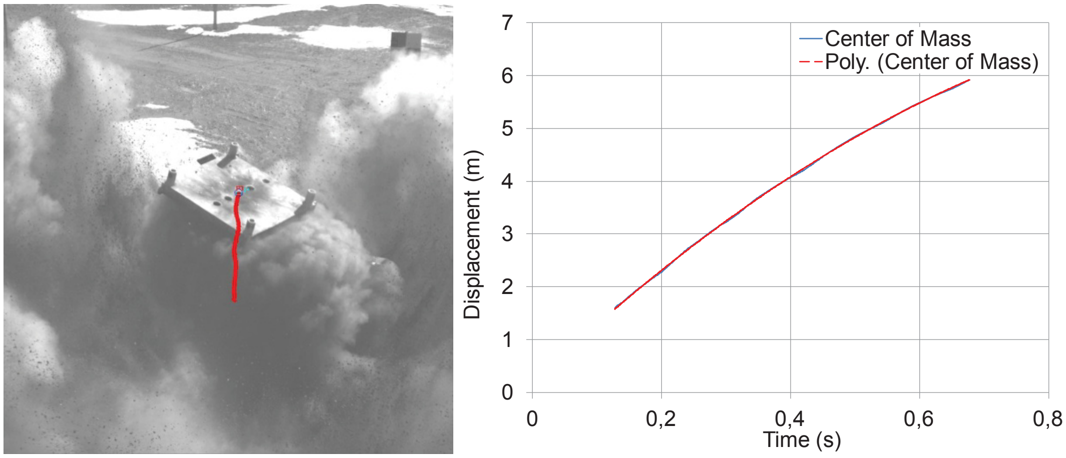

Figure 3. Typical displacement versus time (rigid plate tracking).

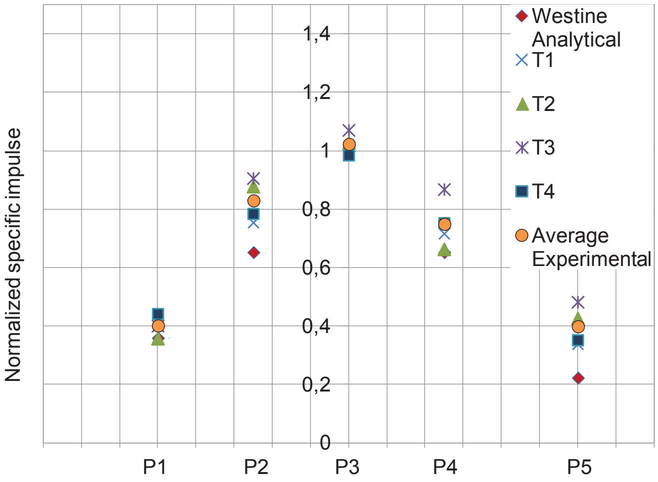

Figure 4. Normalized specific impulse results (for each piston).

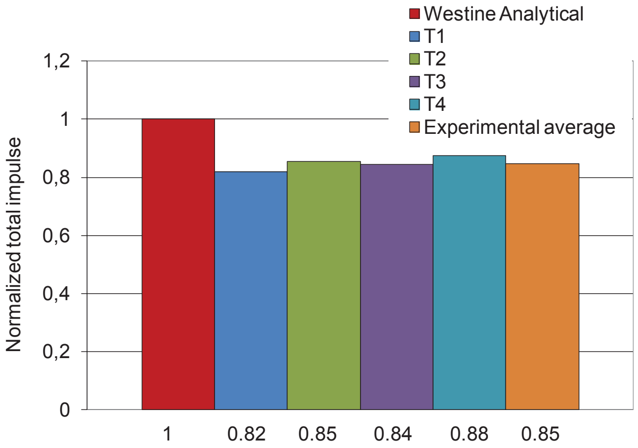

Figure 5. Normalized total impulse results (plate and pistons).

NUMERICAL SIMULATIONS

The finite element (FE) model of the pistons-plate structure, showed in Fig. 6, reproduced the experimental set-up. The geometries and meshes were done using the Femap software [10]. The supports of the plate were not modeled because it was assumed that initially the gravity loading was negligible compared to the blast loading. The rigid plate and the three pistons in the middle were made of steel ASTM A514 [11] whereas the pistons at both ends were made of Aluminum 6061-T6 [12]. The properties are given in Table I. Each piston and plate was meshed respectively with 2320 and 331800 hexahedron elements (cells dimensions of approximately 10 mm). To allow a proper interaction between the plate and pistons a contact was defined.

Two numerical approaches are presented to simulate the loading of a landmine: an in-house pressure model and the LS-DYNA arbitrary lagrangian eulerian (ALE) approach. One advantage of the first model is the shorter time to generate the loading and also the reduced computational time. On the other hand, the ALE model is more physic-based and therefore, has the ability to be used in a variety of conditions (ex. not limited to specific depth-of-burial or stand-off distance and may include shadowing). Both FE analyses were performed using LS-DYNA version 5.1.1 during 40 ms.

Loading method 1: in-house pressure model

Several studies such as [1,2,13], used an in-house software, MinePre, developed at DRDC Valcartier, that transforms the specific impulses given by Westine empirical equation into initial velocities applied to nodes of shell elements, in the direct line of sight from the mine to the structure. Experimental final deformation of the center of plate validated the numerical results. One limitation of this impulse model was its

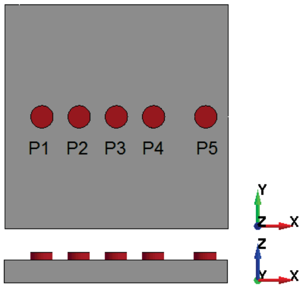

Figure 6. Plate and pistons models.

TABLE I. Plate and pistons properties.

		ASTM A514	6061-T6 [12]
Density (ρ)	kg/m^3	7850.0	2690.0
Elastic Modulus (E)	GPa	205.0	73.08
Poisson’s ratio (ν)		0.29	0.33
Yield stress (σ_y)	MPa	690[3]	335
Tangent modulus (E_T)	MPa	396	645.7
Failure strain (ε_f)		N/R	N/R

[3] From [11].

inability to load a FE structure made of solid elements. Therefore, the pressure-based mine loading model was developed to address this limitation. Donahue et al. [4] showed that the plate deflection was in good agreement with experimental data however, a significant difference was raised between the loading curves of the pressure based model and the computational fluid dynamic approach used.

A series of numerical simulations, using the pistons-plate structure, were performed in order to determine the appropriate pressure-time history to be applied to solid elements. The loading function that was developed provided a representative pressure-time history, not only on the center, but over the entire plate.

An example of pressure contours of the pistons and plate is shown in Fig. 7. Fig. 8 presents the vertical velocity of each piston and plate. During this simulation, the plate was oscillating (i.e. alternating between bending and flexion: which demonstrated that the plate was not totally rigid) and the pistons were tangling while traveling out of the holes. This interaction between plate and pistons is shown in Fig. 8 by an increase in the piston's velocity (except for the piston in the center), proportionally to the distance between the center and the edge of the plate. The velocity obtained for the pistons before the interaction with the plate and the total impulse compare very well with Westine's analytical model predictions.

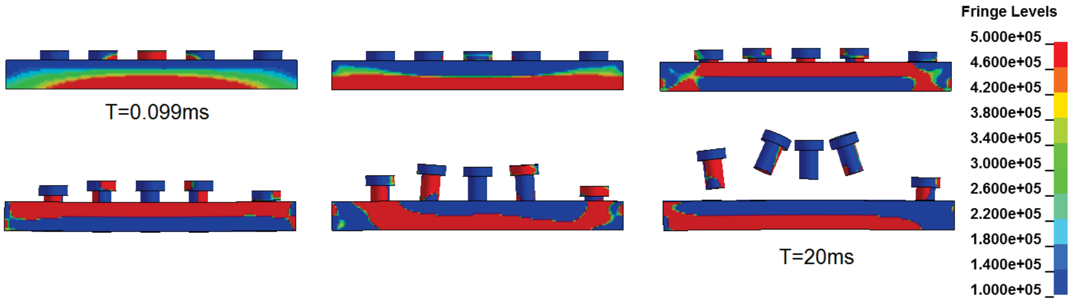

Figure 7. Pressure contours (Model 1) [Pa].

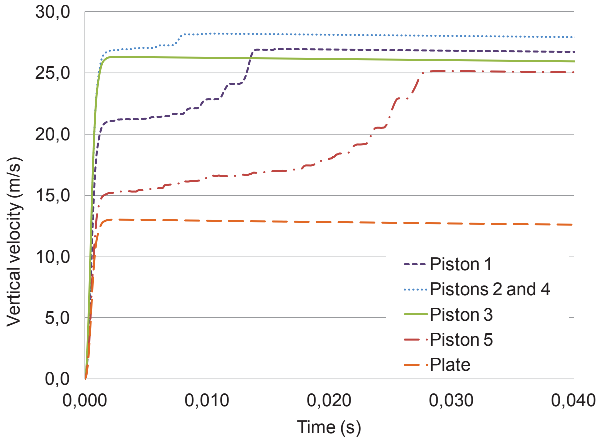

Figure 8. Pistons velocity versus time (Model 1).

Loading method 2: ALE model

An arbitrary lagrangian eulerian (ALE) model, consisting in modeling explicitly the air (gray contour), soil (brown box) and explosive, was developed to simulate the deformation of the solid pistons-plate structure and is shown in Fig. 9.

The air and the soil were modeled with respectively 1,156,000 hexahedron elements. Cells dimensions varied between 12 mm and 25 mm. The air was modeled with the **mat_null* material model using a linear polynomial equation of state. Properties are provided in Table II [2]. The soil was modeled with the **mat_soil_and_foam* model with a density of 2260 kg/m^3. Properties are given in Table III [2]. The landmine was initially modeled with a circular disc shaped using the

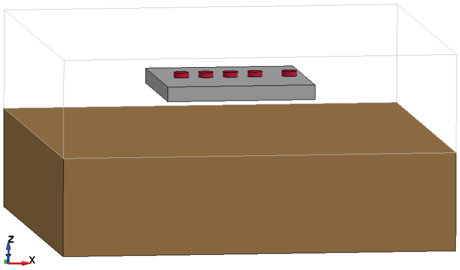

Figure 9. ALE model.

TABLE II. Air properties [2]

	Units	Air
Density (ρ)	kg/m^3	1.293
Pressure cutoff (Pc)	MPa	0.0
Polynomial equation coefficient		
C0, C1, C2, C3 and C6		0.0
Polynomial equation coefficient C4 and C5		0.4
Initial internal energy (E0)	MPa	0.25
Initial relative volume (V0)		1.0

TABLE III. Soil Properties [2]

	Units	Soil
Density (ρ)	kg/m^3	2260
Shear modulus (G)	GPa	40.68
Bulk modulus (K)	GPa	50
A0, A1, A2, PC		0.0, 0.0, 1.19, 0.0
VCR, REF		0.0, 0.0
$\varepsilon_1, \varepsilon_2, \varepsilon_3, \varepsilon_4, \varepsilon_5$		0.0, -0.01861, -0.05616, -0.08934, -0.1276
$\varepsilon_6, \varepsilon_7, \varepsilon_8, \varepsilon_9, \varepsilon_{10}$		-0.1547, -0.2131, -0.2594, -0.2633, -1.0
P_1, P_2, P_3, P_4, P_5	Pa	0.0, 4.58×10^6, 1.5×10^7, 2.92×10^7, 5.92×10^7
$P_6, P_7, P_8, P_9, P_{10}$	Pa	9.81×10^7, 2.894×10^8, 6.507×10^8, 6.95×10^8, 3.753×10^{10}

**initial_volume_fraction_geometry* card and was detonated at time zero. The explosive was modeled using a high explosive burn material combined with the Jones-Wilkins-Lee equation of state. Properties are given in Table IV [14]. The interaction air/soil/explosive with the structure was defined using the **contrained_lagrange-in_solid* card. To simulate ambient conditions outside the meshed domain, a pressure of 101.325 kPa was applied on the outside boundaries of the box; as well, a flow out boundary condition was defined through a **boundary_non_reflecting* card to limit reflection waves to re-enter. Gravity was applied to the model. After 7 ms, the ALE parts were removed and the FE analysis was continued to reach 40 ms.

Fig. 10 presents the pressure contours of the explosive, plate and pistons of model 2 (for clarity, soil and air are not showed). Fig. 11 presents the vertical velocity of each piston and plate. When comparing the results from both loading models, it seems that model 2 generate a more concentric loading (higher velocity of the piston in the center) than FE model 1 while total impulse is approximately half the total impulse of

TABLE IV. Explosive Properties [14]

	Units	**C4**
Density (ρ)	kg/m^3	1601
Detonation velocity (D)	m/s	8193
Chapman-Jouget pressure (P_{CJ})	GPa	28
A, B	GPa	609.77, 12.95
R1, R2		4.5, 1.4
Omega (ω)		0.25
Internal Energy density (E_0)	$GPa–m^3/m^3$	9.0
Initial relative (V_0)		1.0

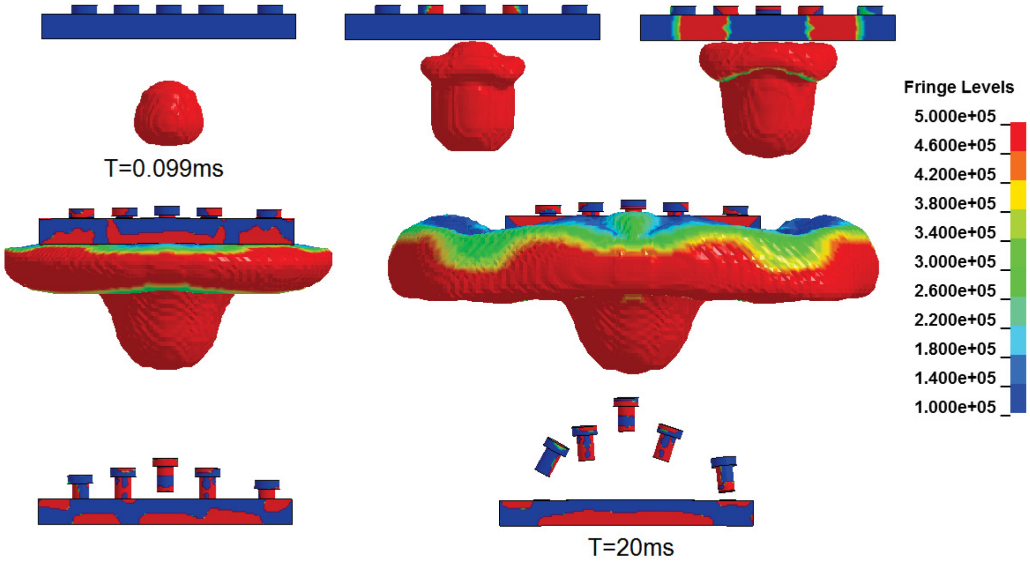

Figure 10. Pressure contours of explosive, plate and pistons (Model 2) [Pa].

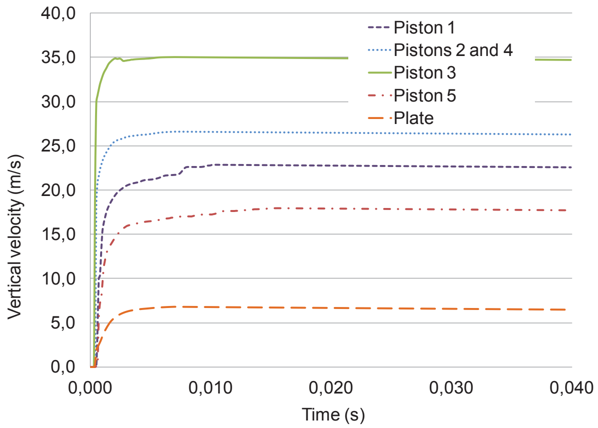

Figure 11. Pistons velocity versus time (Model 2).

model 1. Also, in Fig. 11, the increase in velocity of the pistons (at ~8ms) near the edge is less obvious than for model 1 and could be explained by the fact that the plate reached approximately half the velocity of the first model and thus has transferred a lower impulse to the pistons. The specific impulse of the piston in the center and the total impulse did not agree well with Westine's analytical model predictions.

RESULTS AND DISCUSSION

Fig. 12 presents the normalized impulse for each piston from the experimental data and numerical simulations. The spread in the experimental results is attributed to natural variations of soil parameters, charge detonation variations as well as charge placement. Some variation is also attributed to the interaction between the pistons and the rigid plate. Methods to reduce and eliminate this potential problem are being investigated. In Fig. 12, two set of specific impulses are given for FE Model 1, the first one corresponding to the initial impulse provided to the piston (which is believed to be the true loading transmitted by the charge) and the second set of data corresponding to the impulse reached by the pistons after the plate has transferred some impulse to the pistons through their interaction. This FE model response seems to confirm the experimental observations and could explain, partially, why the experimental data (specific impulses) are higher than the ones predicted by Westine. In general, both FE models predicted similar specific impulse except for the piston in the center where the ALE model reached a value 34% higher.

Fig. 13 presents the normalized total impulse transmitted to the plate and pistons from the experimental data and from the numerical simulations. For both the experiment and model 1, the total impulse results are very consistent but slightly lower than the Westine's analytical model prediction. This is in contradiction with the experimental specific impulse measurements obtained that were higher than Westine's analytical model predictions. Experimentally, the following may explain such results: 1) Specific impulses of pistons at the extremities are amplified by the response and interaction with the rigid plate 2) A portion of the total impulse is not being transferred to the rigid plate due to the masking effect of the four support legs. This masking effect should also be further investigated in the FE models by modeling the support legs and 3) Possible measurement errors.

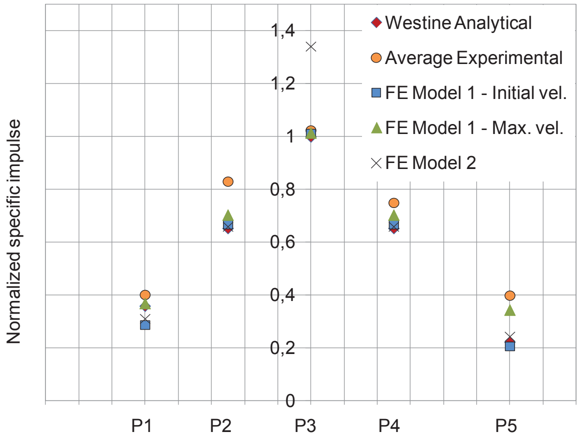

Figure 12. Normalized specific impulse (for each piston).

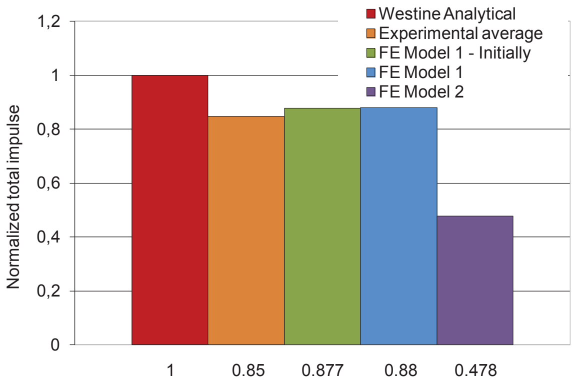

Figure 13. Normalized total impulse (plate and pistons).

For model 2, the specific impulse of the piston in the center and the total impulse did not agreed well with Westine's predictions. The constitutive soil model and the parameters used could be one reason to explain this discrepancy. More work needs to be done in order to develop and implement a constitutive soil model that better represents the soil tested experimentally.

CONCLUSION

DRDC Valcartier has initiated a research program to generate reliable experimental data to measure the distribution of the specific impulse generated by an explosive charge buried in different soil types and under various conditions. This paper presented the initial experimental facility of the buried charge impulse gage concept developed and the initial finite element (FE) models developed to help in the design and improvement of this experimental facility. Numerical simulations were performed using LS-DYNA code, to compare two loading methods: an in-house pressure model and ALE model. The results obtained experimentally and numerically were compared and normalized on Westine's analytical model predictions.

Experiments showed higher specific impulse and slightly lower total impulse than Westine's analytical predictions. Overall, the in-house pressure model (FE model 1) provided a loading function on the plate (specific and total impulse) that agreed well with Westine's model predictions and with experimental observations. However, for the ALE model (FE Model 2), more work is required to develop and parameterized a constitutive soil model that will be more suitable for the soil being tested.

Finally, this study has identified and confirmed sources of error in the experimental methods and provided good indications for improving the experimental set-up and interpreting the experimental data. The following modifications are being implemented to the test facility and considered in the FE model: 1) Installation of reinforcement ribs to rigidify the rigid plate and reduce risk of plate/pistons interaction 2) Design of flash/blast ejecta suppressor to provide clearer images and longer tracking distances for the pistons 3) Introduction of piston isolator to reduce the impulse transmitted by the rigid plate response to the pistons 4) Review of the piston geometry 5) Modification of rigid plate support legs to eliminate their masking effects.

Additional test are being planned in early 2013 to assess the effects of these modifications and generate additional experimental data. These new results will be used to assess FE model 1 and help in the development of a new constitutive soil model for FE model 2.

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Assessment of an experimental method and two loading models used to measure and simulate the effect of buried charges

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Toussaint, G.; Durocher, R.; Bouamoul, A.; Vallee, A. St-Jean, B.

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Numerical simulation and modeling of buried explosives in soil is a challenging task and remains one of the critical gaps for assessing vehicle structural vulnerability to landmines. Defence Research and Development Canada – Valcartier has initiated a research program to focus on this problem. The aim of the project is to generate reliable experimental data to measure the distribution of the specific impulse generated by an explosive charge buried from different soil types and conditions and develop enhanced numerical models for the loading generated by these threats. This paper presents the experimental facility of a buried-charge impulse-gage concept and related finite element models developed for its study. Numerical simulations were performed using the LS-DYNA code to compare two loading methods. The initial data generated experimentally and the results from the FE models are compared with the analytical model predictions. Recommendations for improvement of the experimental facility are made.

La simulation et la modélisation numérique des explosifs enfouis dans le sol sont une tâche difficile et demeurent l'une des lacunes principales dans l'évaluation de la vulnérabilité de la structure de véhicule à l'égard des mines terrestres. Recherche et développement pour la défense Canada – Valcartier a entrepris un programme de recherche pour étudier ce problème. Ce projet a pour but de générer des données d'expériences fiables afin de mesurer la distribution de l'impulsion spécifique produite par une charge explosive enfouie dans les différents types et conditions de sols et de concevoir des modèles numériques améliorés pour les charges générées par ces menaces. Le rapport présente le concept d'un dispositif expérimental de jauge de l'impulsion produite par une charge enfouie et des modèles d'éléments finis liés qui ont été élaborés pour cette étude. Des simulations numériques ont été réalisées à l'aide du LS-DYNA code pour comparer les deux méthodes de charge. Les données initiales produites par les expériences et les résultats provenant des modèles d'éléments finis sont comparés avec les prévisions du modèle analytique. Des recommandations d'améliorations au dispositif expérimental sont formulées.

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buried explosives; numerical modelling

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