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CRATERS PRODUCED BY EXPLOSIVE LOADS CARRIED ON VEHICLES

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Abstract. In case of terrorist attacks or other intentional actions using explosives, it is extremely important the information that can be obtained from the crater generated by the blast waves. For example, the focus of the explosion and the mass of the explosive used in the attack can be deduced examining the location and dimensions of the crater. However, studies about craters produced by explosions on or above ground level, which would be the case when the explosive charge is carried on a vehicle, are rarely found in the open technical literature.

In previous papers from the authors, numerical studies related to crater produced by explosive loads located on, above or below the soil surface, the influence of the variability of the soil properties and the influence of rigid and flexible pavement on the crater dimensions, were presented. In those papers, only the explosive load without any obstacle was considered in the model.

In this paper, the effect of the consideration of the vehicle in the global model is analyzed and discussed. Different parts of the numerical model, as well as the analysis procedure, were validated with experimental observations of the crater diameters and the actual response of a concrete plate.

1 INTRODUCTION

Blasting loads have come to be forefront of attention in recent years due to a number of accidental and intentional events that affected important structures all over the world, clearly indicating that this issue is important for purposes of structural design and reliability analysis. In consequence, extensive research activities in the field of blast loads have taken place in the last few decades (Ambrosini et al. 2002).

Dynamic loads due to explosions result in strain rates of the order of 10^{-1} to 10^{3} s^{-1} which imply short time dynamic behaviour of the materials involved, characterised mainly by a great overstrength and increased stiffness, in comparison with normal, static properties. In the case of soils, the response and the mechanism of crater formation are particularly complex due to the usual anisotropy and non linear nature of the material, and to the variability of mechanical properties and coexistence of the three phases: solid, liquid and gaseous. Generally, simplifying assumptions must be made in order to solve specific problems. Until now, most practical problems have been solved through empirical approaches. Years of industrial and military experience have been condensed in charts or equations (Baker et al. 1983, Smith and Hetherington 1994). These are useful tools, for example, to establish the explosive weight to yield a perforation of certain dimensions or to estimate the type and amount of explosive used in a terrorist attack, from the damage registered. Most research is related to underground explosions and only a few papers are concerned with explosions at ground level. Studies about craters produced by explosions above ground level, which would be the case when the explosive charge is situated in a vehicle, are rarely found in the open technical literature. Some reports are classified and access is limited to government agencies.

Most of the information about explosively formed craters found in the literature is based on experimental data. Numerical studies were scarce until recently.

However, with the rapid development of computer hardware over the last years, it has become possible to make detailed numerical simulations of explosive events in personal computers, significantly increasing the availability of these methods. New developments in integrated computer hydrocodes complete the tools necessary to carry out the numerical analysis successfully. Nevertheless, it is important to be aware that both these models and analysis procedures still need experimental validation.

In previous papers (Ambrosini et al. 2004, 2006, 2007, 2009 and Luccioni et al. 2006, 2007, 2009. 2010), numerical studies related to craters produced by explosive loads located on, above or below the soil surface, the influence of the variability of the soil properties and the influence of rigid and flexible pavement on the crater dimensions, were presented. In those papers, only the explosive load without any obstacle was considered in the model.

In many cases, the explosive load is carried out in a malevolent vehicle. In this paper, the effect of the consideration of the vehicle in the global model is analyzed and discussed and preliminary guidance of its effect is indicated.

2 DESCRIPTION OF THE PROBLEM AND EXISTING RESULTS

A crater produced by an explosive charge situated on or above the ground level is schematized in Figure 1. The crater dimensions defined by Kinney and Graham (1985) are used in this paper (Figure 1): D is the apparent crater diameter, D_r is the actual crater diameter and H_2 is the apparent depth of the crater. The depth of the crater created by an explosion ordinarily is about one quarter of the diameter of the crater, but this ratio depends on the type of soil involved. The diameter of the crater produced by an explosion also depends on the relative location of the explosive charge to the ground level. Thus, explosions above surface level may not create any crater at all (Kinney and Graham 1985).

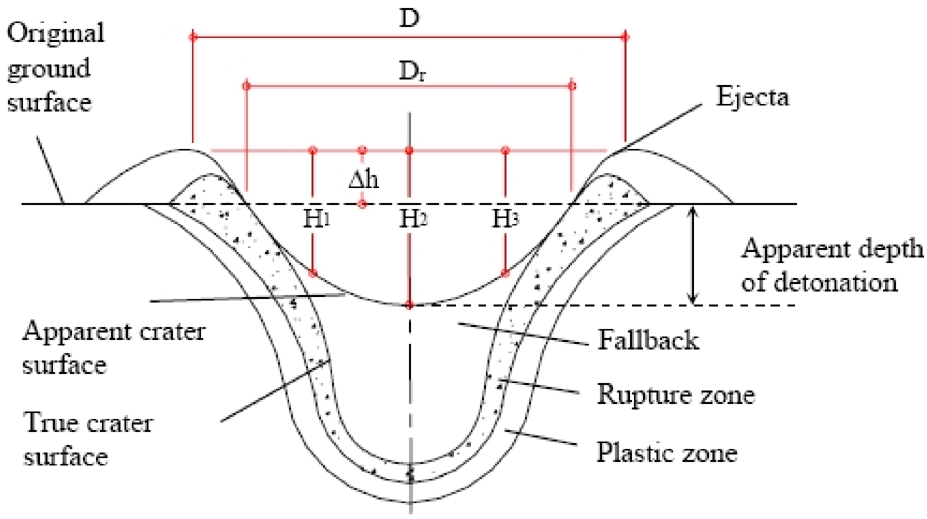


Figure 1: Definitions of the crater dimensions

Tests of crater formation are appropriate tools to study the blast phenomena, the behaviour and destructive power of different explosives and the response of soils and rocks under this type of load (Persson et al. 1994). The mechanism of crater formation is complex and it is related to the dynamic physical properties of air, soil and soil-air interface. Even very carefully performed cratering tests give deviations in the dimensions measured of the order of 10% , while differences of as much as 30% to 40% are common (Bull et al. 1998)

A cavity is always formed when a confined explosion is produced in a mass of soil. If the explosion is close to the surface, a crater is formed and a complex interaction between gravity effects, soil strength and transient load conditions takes place. The most important variables in defining the crater shape and size are the mass W of the explosive and the depth of the detonation beneath the air/soil interface d. When $d<0$, the explosive is detonated over the air/soil interface, $d = 0$ when the detonation occurs in the air/soil interface and $d>0$ when the explosive is detonated beneath the soil surface. For $d > 0$, the crater mechanism is altered by gravitational effects. When the depth of the detonation increases, larger amounts of subsoil must be expelled by the explosion. Thus, the crater radius and the depth of the crater increase when d increases, until a certain limit value, from which they rapidly decrease (Bull et al. 1998).

Studies concerned with the characteristics of craters caused by explosions usually resort to dimensional analysis and statistics. The scaling law establishes that any linear dimension "L" of the crater can be expressed as a constant multiplied by W^{α} divided by the distance of the charge from the ground, where W represents the equivalent TNT mass of explosive and α is a coefficient that is dependent on whether the gravitational effects can be neglected or not. When the gravitational effects can be neglected the cubic root law is applicable (α = 0.33) and in the other cases the functional dependence can be quite complex.

Baker et al. 1983 present a dimensional study to model the crater formation phenomenon in the case of underground explosions. Six parameters are chosen to define the problem: the explosive mass *W*, the depth of the explosive charge *d*, the apparent crater radius *R*, the soil density ρ, and two strength parameters to define the soil properties: one with the dimensions of stress σ, related to soil strength, and the other with the dimensions of a force divided by a cubic length (Nm^{-3}) *K*, that takes into account gravitational effects.

After a dimensional analysis and many empirical observations, the following functional relation may be obtained (Baker et al. 1983).

$$\frac{R}{d} = f\left(\frac{W^{7/24}}{\sigma^{1/6} K^{1/8} d}\right) \tag{1}$$

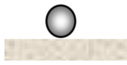
If $\frac{R}{d}$ (scaled radius of the crater) is plotted as a function of $W^{7/24}/d$ (Baker et al.[7]), it can be seen that this relation is close to experimental results and can be approximately simplified by two straight lines, one with a moderate slope for $W^{7/24}/d > 0.3$ and one steeper for $W^{7/24}/d < 0.3$. For $W^{7/24}/d < 0.3$, the scaled radius of the crater is sensitive to small changes in the independent parameter and, due to this fact, the independent parameter or the scaled radius may exhibit great variability. Experimental conditions are better controlled for $W^{7/24}/d > 0.3$.

The preceding paragraphs refer to underground explosions. There is less information about explosions at ground level. Statistical studies of about 200 accidental above-ground explosions of relative large magnitude are presented by Kinney and Graham (1985). The results exhibit a variation coefficient in the crater diameter of about 30%. From these results, the following empirical equation for the crater diameter was proposed.

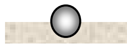
$$D\,[m] = 0.8W[Kg]^{1/3} \tag{2}$$

In connection with the morphological and structural types of the craters, Melosh (1989) determine four different basic types: (a) bowl-shaped, (b) flat-floored with central uplift, (c) flat floored with a peak ring and (d) flat floored with >2 asymmetric rings (multiring basins). One of the factors that determine the shape is the height of burst. On the other hand, numerical and independent research results presented by Iturrioz et al. (2001) preliminary confirm the formation of the same shapes of craters. Additionally, there are important contributions in the literature related to cratering studies, but many of them are about predicting *rock* damage, ex. Yang et al. (1996), Liu and Katsabanis (1997) and Wu et al. (2004) and others are related with *buried* explosions, ex. Wang and Lu (2003) and Zhou et al. (2003). In the best knowledge of the authors there are not results in the open literature about craters in pavements produced by elevated loads and studies about the influence of the vehicle on the dimensions of the crater.

On the other hand, Ambrosini and Luccioni (2006) proposed the following equations for the prediction of crater dimensions for spherical explosive charges situated on the ground (case a) and with the energy release center at ground level (case b) respectively. These equations represent the linear approximation of numerical result by minimum least-fit squares. The variation of ± 5% accounts for the differences between soil properties that could be found in different sites.

Case (a) 

$$D[m] = 0.51W[Kg]^{1/3} \pm 5\% \quad (3)$$

Case (b) 

$$D[m] = 0.65W[Kg]^{1/3} \pm 5\% \quad (4)$$

In a previous paper, Ambrosini et al. (2002) presented the results of a series of tests performed with different amounts of explosive at short distances above and below ground level, as well as on the soil surface. These results were used in this paper to calibrate the soil parameters of the numerical model as well as to validate the analysis procedure. The description of the tests as well as the numerical-experimental comparison and the model calibration was presented by Ambrosini and Luccioni (2007). Moreover, for the case of charges elevated 50 and 100cm above the soil, the main findings were also presented on Ambrosini and Luccioni (2007).

3 MALEVOLENT VEHICLE

The use of vehicle bombs to attack city centers has been a feature of campaigns by terrorist organizations around the world. A bomb explosion within or immediately nearby a building can cause catastrophic damage on the building's external and internal structural frames, collapsing of walls, blowing out of large expanses of windows, and shutting down of critical life-safety systems (Ngo et al. 2007).

The threat for a conventional bomb is defined by two equally important elements, the bomb size, or charge weight *W*, and the standoff distance *R* between the blast source and the target. For example, the blast occurred at the basement of World Trade Centre in 1993 had the charge weight of 816.5 kg TNT. The Oklahoma bomb in 1995 had a charge weight of 1814 kg TNT at a stand off of 4.5m. As terrorist attacks may range from the small letter bomb to the gigantic truck bomb as experienced in Oklahoma City, the mechanics of a conventional explosion and their effects on a target must be addressed (Ngo et al. 2007).

For design purposes, large-scale truck bombs typically contain 10.000 pounds or more of TNT equivalent, depending on the size and capacity of the vehicle used to deliver the weapon. Vehicle bombs that utilize vans down to small sedans typically contains 4.000 to 500 pounds of TNT equivalent, respectively. A briefcase bomb is approximately 50 pounds, and a pipe bomb is generally en the range of 5 pounds of TNT equivalent. (FEMA 426, 2003)

Figure 2 shows an example of a range-to-effect chart that indicates the distance or stand-off to which a given size bomb will produce a given effect. This type of chart can be used to display the blast response of a building component or window at different levels of protection. It can also be used to consolidate all building response information to assess needed actions if the threat weapon-yield changes (FEMA 426, 2003).

In this paper, a medium range of explosive load was used and, for this reason, vehicles type vans were selected. As examples, Citroen C25 and Renault Traffic are presented in Figure 3. The sizes adopted were based on the last model (Figure 4).

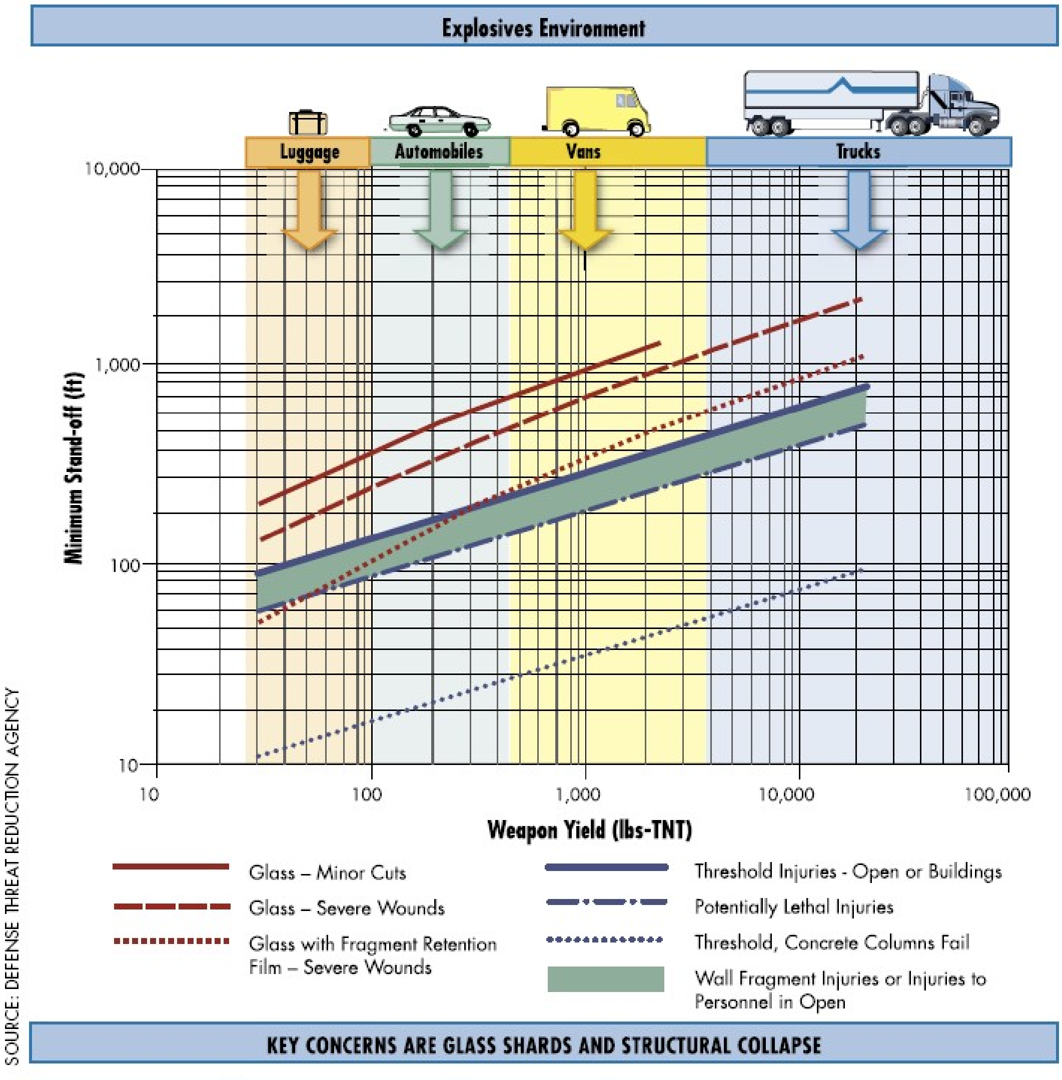


Figure 2: Explosives environments – blast range to effects (FEMA 426, 2003).

(a) (b)

Figure 3: Van-type vehicles that could be used as malevolent vehicle. (a) Citroen C25. (b) Renault Traffic

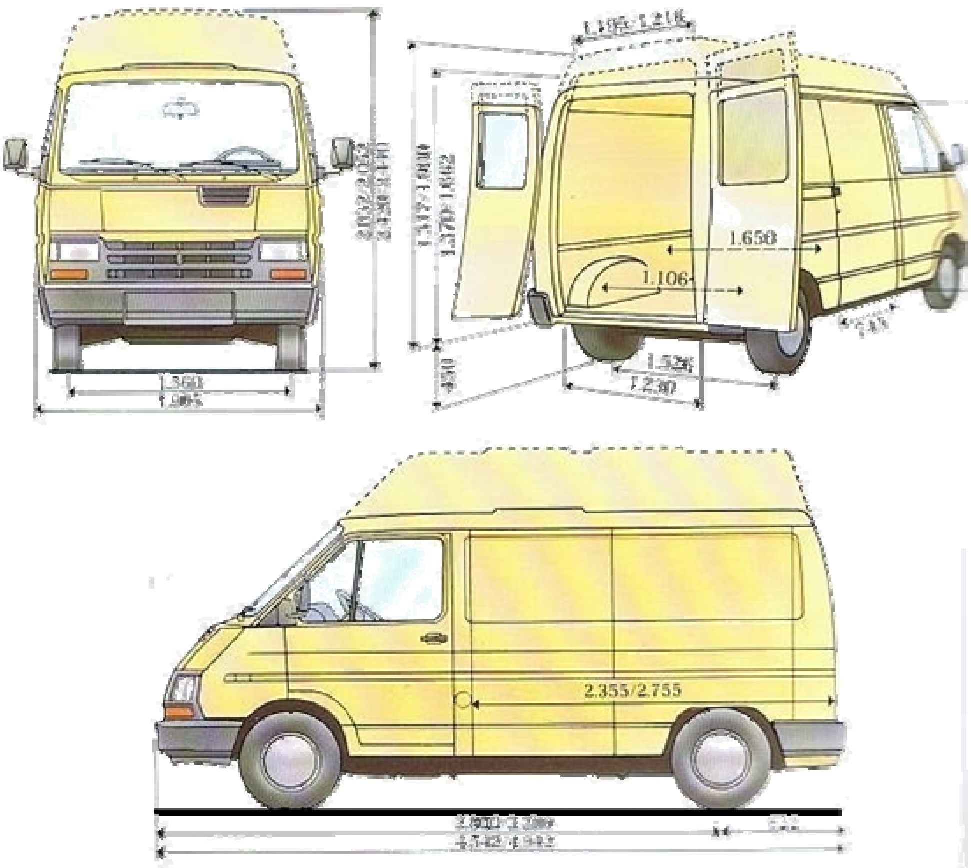


Figure 4: Sizes adopted to model the malevolent vehicle

4 NUMERICAL MODEL

4.1 Introduction and numerical tool

Computer codes normally referred as “hydrocodes” encompass several different numerical techniques in order to solve a wide variety of non-linear problems in solid, fluid and gas dynamics. The phenomena to be studied with such a program can be characterized as highly time dependent with both geometric non-linearities (e.g. large strains and deformations) and material non-linearities (e.g. plasticity, failure, strain-hardening and softening, multiphase equations of state). Different numerical tools are used in some papers in order to solve similar problems of crater determination. For example ABAQUS (Yang et al. 1996), AUTODYN (Wu et al. 2004, Wang and Lu 2003), SALE2D (Baratoux and Melosh 2003, Nolan et al. 2001) and CTH (Pierazzo and Melosh 1999).

In this paper, the software AUTODYN-3D (2009), which is a “hydrocode” that uses finite difference, finite volume, and finite element techniques to solve a wide variety of non-linear problems in solid, fluid and gas dynamics, is used. The phenomena to be studied with such a program can be characterized as highly time dependent with both geometric non-linearities (e.g. large strains and deformations) and material non-linearities (e.g. plasticity, failure, strain-hardening and softening, multiphase equations of state).

The various numerical processors available in AUTODYN generally use a coupled finite difference/finite volume approach similar to that described by Cowler and Hancock (1979). This scheme allows alternative numerical processors to be selectively used to model different components/regimes of a problem. Individual structured meshes operated on by these different numerical processors can be coupled together in space and time to efficiently compute structural, fluid, or gas dynamics problems including coupled problems (e.g. fluid-structure, gas-structure, structure-structure, etc.).

AUTODYN includes the following numerical processors: Lagrange, Euler, ALE, Shell, Euler-Godunov, Euler-FCT and SPH. All the above processors use explicit time integration. The first-order Euler approach scheme is based on the method developed by Hancock (1976).

4.2 Materials models

a) Air: The ideal gas equation of state was used for the air. This is one of the simplest forms of equation of state for gases. In an ideal gas, the internal energy is a function of the temperature alone and if the gas is polytropic the internal energy is simply proportional to temperature. It follows that the equation of state for a gas, which has uniform initial conditions, may be written as,

$$p = (\gamma - 1)\rho e \tag{5}$$

in which p is the hydrostatic pressure, ρ is the density and e is the specific internal energy. γ is the adiabatic exponent**,** it is a constant (equal to $1 + R/c_v$) where constant R may be taken to be the universal gas constant R_0 divided by the effective molecular weight of the particular gas and c_v is the specific heat at constant volume.

b) TNT: High explosives are chemical substances which, when subject to suitable stimuli, react chemically very rapidly (in order of microseconds) releasing energy. In the hydrodynamic theory of detonation, this very rapid time interval is shrunk to zero and a detonation wave is assumed to be a discontinuity which propagates through the unreacted material instantaneously liberating energy and transforming the explosive into detonating products. The normal Rankine-Hugoniot relations, expressing the conservation of mass, momentum and energy across the discontinuity may be used to relate the hydrodynamic variables across the reaction zone. The only difference between the Rankine-Hugoniot equations for a shock wave in a chemically inert material and those for a detonation wave is the inclusion of a chemical energy term in the energy conservation equation.

Since the 1939-45 war, when there was naturally extensive study of the behaviour of high explosives, there has been a continuous attempt to understand the detonation process and the performance of the detonation products, leading to considerable improvements in the equation of state of the products. The most comprehensive form of equation of state developed over this period, the “Jones - Wilkins - Lee” (JWL) equation of state, is used in this paper.

$$p = C_1\left(1 - \frac{\omega}{r_1 v}\right)e^{-r_1 v} + C_2\left(1 - \frac{\omega}{r_2 v}\right)e^{-r_2 v} + \frac{\omega e}{v} \tag{6}$$

Where $v = 1/\rho$ is the specific volume, C_1, r_1, C_2, r_2 and ω (adiabatic constant) are constants and their values have been determined from dynamic experiments and are available in the literature for many common explosives.

It can be shown that at large expansion ratios the first and second terms on the right hand side of Equation (4) become negligible and hence the behaviour of the explosive tends towards that of an ideal gas. Therefore, at large expansion ratios, where the explosive has expanded by a factor of approximately 10 from its original volume, it is valid to switch the equation of state for a high explosive from JWL to ideal gas. In such a case the adiabatic exponent for the ideal gas, γ, is related to the adiabatic constant of the explosive, ω, by the relation $\gamma=\omega+1$. The reference density for the explosive can then be modified and the material compression will be reset. Potential numerical difficulties are therefore avoided.

An explosion may be initiated by various methods. However, whether an explosive is dropped, thermally irradiated or shocked, either mechanically or from a shock from an initiator (of more sensitive explosive), initiation of an explosive always goes through a stage in which a shock wave is an important feature. Lee-Tarver equation of state (Lee and Tarver 1980) was used to model both the detonation and expansion of TNT in conjunction with JWL EOS to model the unreacted explosive.

c) Soil: A shock equation of state combined with an elastoplastic strength model based on Mohr Coulomb criterion and a hydro tensile limit were used for the soil.

A Mie-Gruneisen form of equation of state based on the shock Hugoniot was used. The Rankine-Hugoniot equations for the shock jump conditions can be regarded as defining a relation between any pair of the variables ρ, p, e, u_p(material velocity behind the shock) and U (shock velocity). In many dynamic experiments it has been found that for most solids and many liquids over a wide range of pressure there is an empirical linear relationship between u_p and U.

$$U = c_o + s u_p \tag{7}$$

in which c_0 is the initial sound speed and s a dimensionless parameter.

This is the case even up to shock velocities around twice the initial sound speed c_0 and shock pressures of order 100 GPa. In this case the equation of state is:

$$p = p_H + \Gamma\rho(e - e_H) \ with \quad p_H = \frac{\rho_o c_o{}^2 \mu(1+\mu)}{[1-(s-1)\mu]^2} \ ; \ \ e_H = \frac{1}{2}\frac{p_H}{\rho_o}\frac{\mu}{1+\mu} \ ; \quad \mu = \frac{\rho}{\rho_o} - 1 \tag{8}$$

where p is the hydrostatic pressure, ρ_0 is the initial density, e is the specific internal energy and Γ is the Gruneisen Gamma parameter and it is assumed that $\Gamma\rho = \Gamma_0\rho_o = const$

An elastoplastic model with Mohr Coulomb yield criterion was used for the strength effects. This model is an attempt to reproduce the behaviour of dry soil where the cohesion and compaction result in an increasing resistance to shear up to a limiting value of yield strength as the loading increases. This is modelled by a piecewise linear variation of yield stress with pressure. In tension (negative values of p) soils have little tensile strength and this is modelled by dropping the curve for $Y(p)$ rapidly to zero as p goes negative to give a realistic value for the limiting tensile strength.

A non associated flow rule (Prandtl-Reuss type) that avoids the problem of shear induced dilatancy in soils was used. A constant HTL was specified as failure criterion.

All the material properties of air, TNT and soil used for the models are presented in Ambrosini et al. (2003).

d) Steel (Vehicle): A constitutive model based on a linear equation of state combined with a Johnson Cook strength model originally presented for common steel in AUTODYN was adapted for this case, incorporating the failure considering the principal tensile failure stress and the erosion algorithm. The material properties are given in Table 1.

Table 1: Material properties for steel (vehicle)

EOS: Linear Strength: Johnson Cook
Reference density 7.83000E+00 (g/cm3)
Bulk Modulus 1.59000E+08 (kPa)
Shear Modulus 8.18000E+07 (kPa)
Yield Stress 7.92000E+05 (kPa)
Hardening Constant 5.10000E+05 (kPa)
Hardening Exponent 2.60000E-01
Strain Rate Constant 1.40000E-02
Principal Tensile Failure Stress 4.00000E+05 (kPa)
Max. Princ. Stress Difference / 2 2.00000E+05 (kPa)
Erosion Geometric Strain
Erosion Strain 7.50000E-01

4.3 Numerical meshes

In this paper, an Euler Godunov processor is used to model the air and the explosive charge as well as for the soil, meanwhile a Shell processor is used to model the vehicle. In all studied cases, a 3D model was used with planar symmetry in *x* and *y* axes (a quarter of the model is considered). The cases analyzed are presented in Table 2.

Table 2: Cases analyzed

Case	Weight of the explosive (Kg TNT)	Malevolent vehicle	Height above ground (cm)	Dimensions of the load (cm)
1	800	CITROEN C25	80	90 x 125 x 44
2	2000	RENAULT TRAFFIC	80	120 x 120 x 85

The numerical models for the cases listed in Table 2 are presented in Figures 5 to 8. In both cases, the thicknesses of the plates of the vehicle are: 2mm for the floor and 1mm for the remaining plates. Moreover, in both cases, the load is arranged in the middle of the back box of the vehicle. The detonation point is located on the upper face of the explosive.

The four vertices of the vehicles are considered fixed in order to take into account the support on the tires of them.

The first instants after the blast for are presented on Figure 9 in order to show as the vehicle is disintegrated.

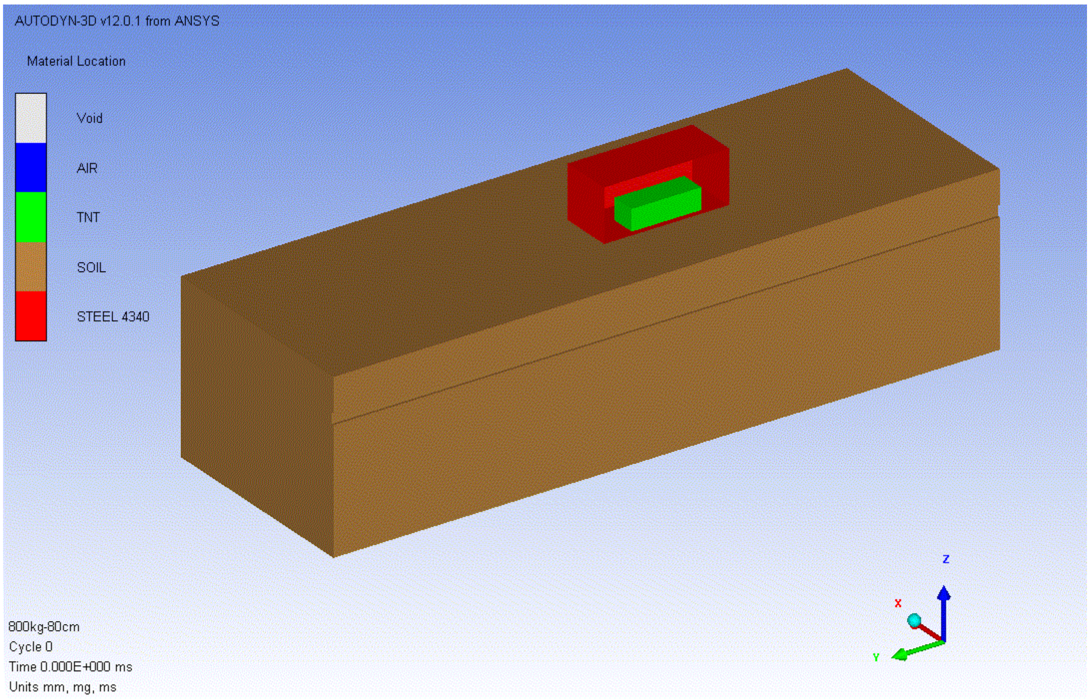


Figure 5: Numerical model for case 1 (Half). 800 kg of TNT. Planar symmetry about *xz* and *yz* planes. Mesh: x = 4.00m (8.00m); y = 4.00m (8.00m); z = 3.00m (soil) 3.24m (air)

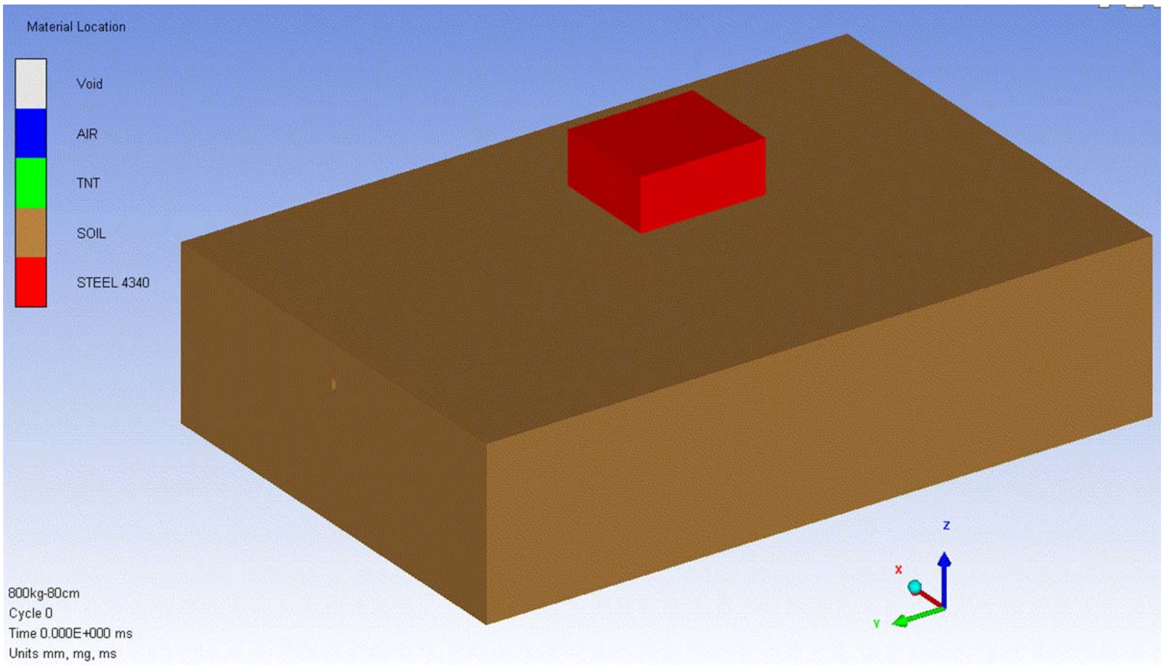


Figure 6: Numerical model for case 1 (Full). 800 kg of TNT.

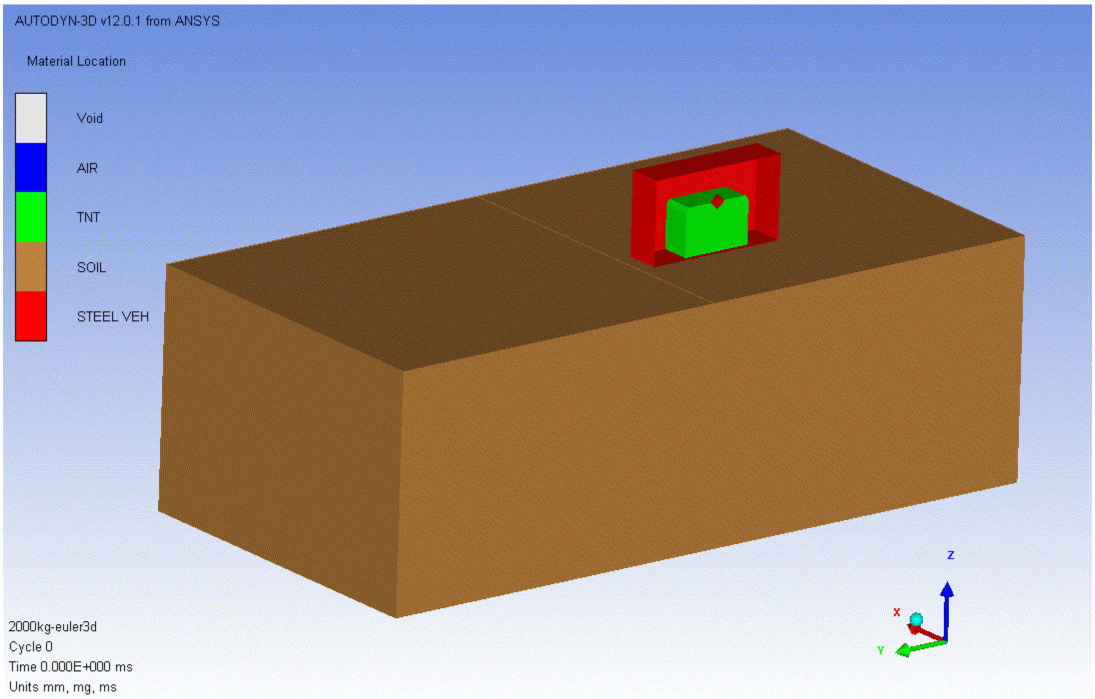


Figure 7: Numerical model for case 2. 2000 kg of TNT. Planar symmetry about *xz* and *yz* planes. Mesh: x = 6.00m (12.00m); y = 6.00m (12.00m); z = 4.00m (soil) 4.15m (air)

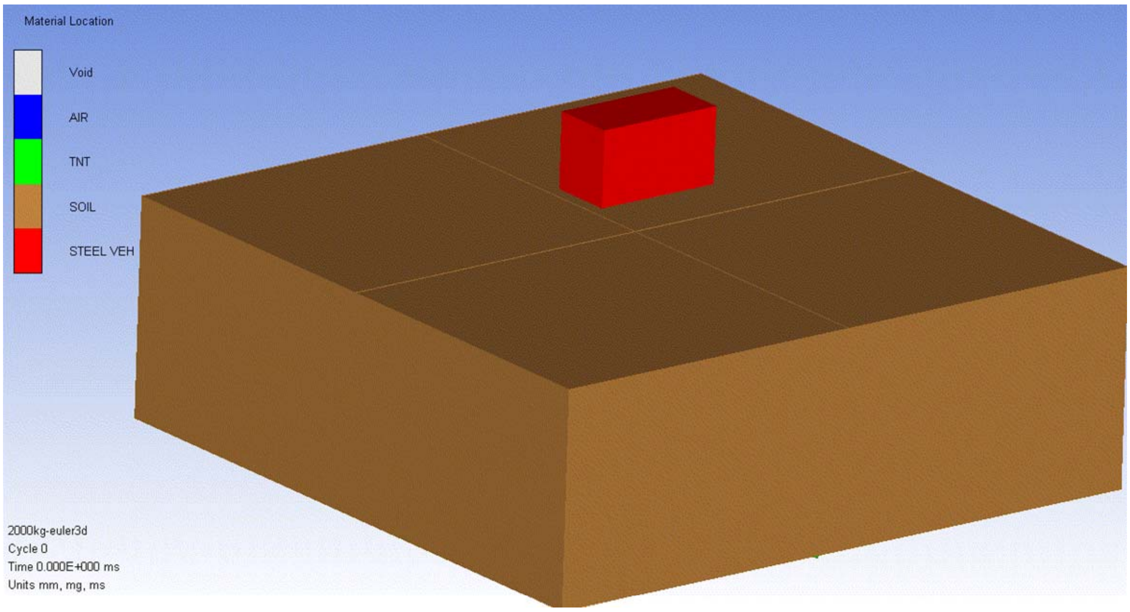


Figure 8: Numerical model for case 2 (Full). 2000 kg of TNT.

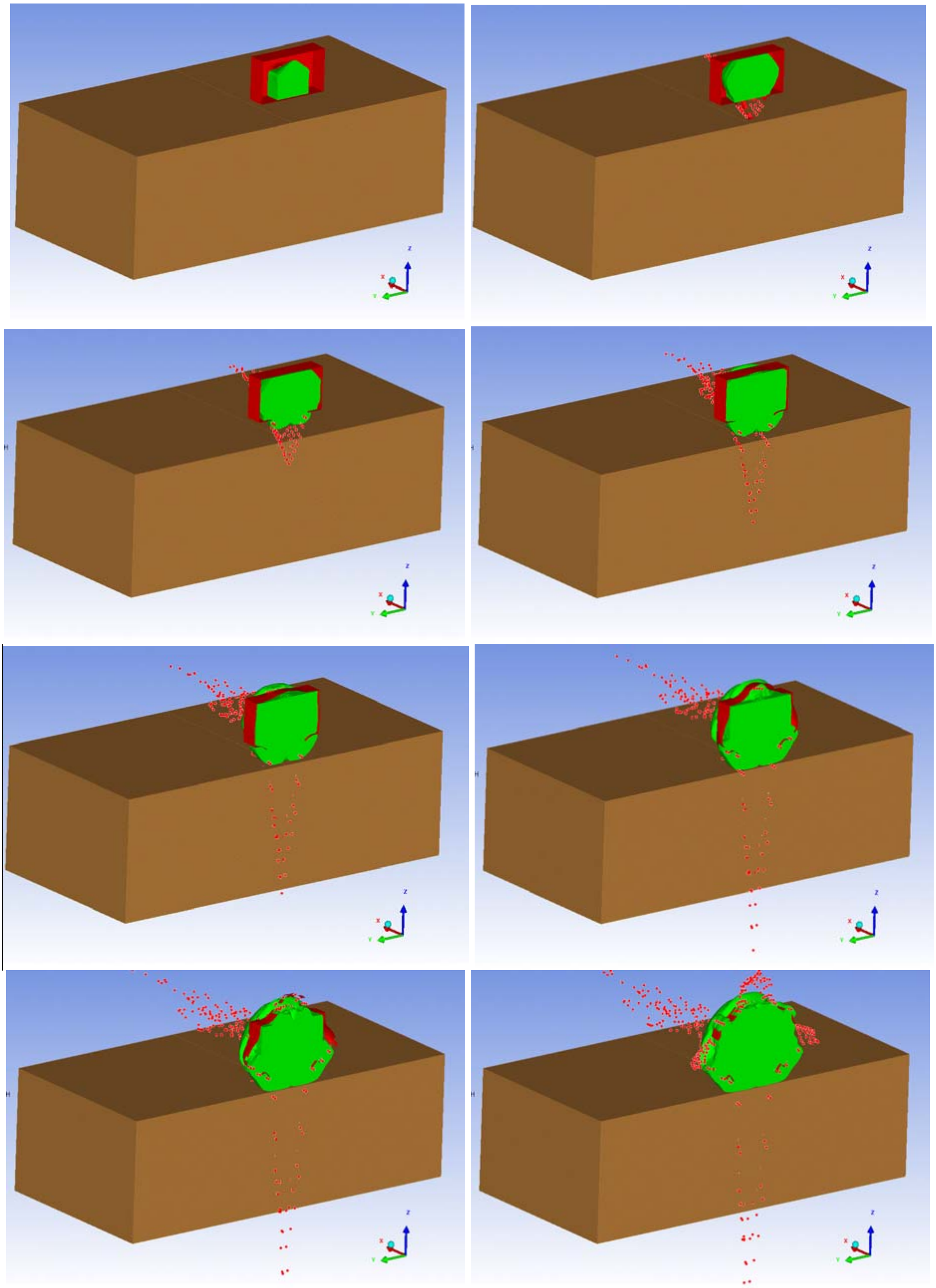


Figure 9: Case 2. 2000 kg of TNT. Expansion of TNT and disintegration of the vehicle

4.4 Boundary transmit

In order to fulfil the radiation condition, a transmitting boundary was defined for air as well as soil subgrids external limits. The Transmit Boundary condition allows a stress wave to continue “through” the physical boundary of the subgrid without reflection. The size of the numerical mesh can be reduced by use of this boundary condition. The transmit boundary is only active for flow out of a grid. The transmit boundary is calculated as follows:

Let the normal velocity at the boundary be U_n, where U_n is positive for outflow. Then the boundary pressure (P) is computed as follows:

For $U_n > 0$:

$$P = P_{ref} + (U_n - U_{ref})I \tag{9}$$

For $U_n < 0$:

$$P = P_{ref} \tag{10}$$

in which P_{ref} and U_{ref} are the pressure and velocity of reference respectively (material model properties) and I is the material impedance (density*soundspeed). If the impedance at the boundary is undefined, it is taken from values in adjacent cells.

5 RESULTS AND DISCUSSION

The process of crater formation and crater dimension for the cases listed in Table 2 was analyzed with the procedure described above. On the other hand, the same cases but without vehicle were numerically studied following the procedure described in Ambrosini and Luccioni (2009).

5.1 Final crater

The final crater obtained in the analysis is presented in Figures 10 and 11. In all cases, in order to facilitate the visualization, as the air as the TNT, are not showed.

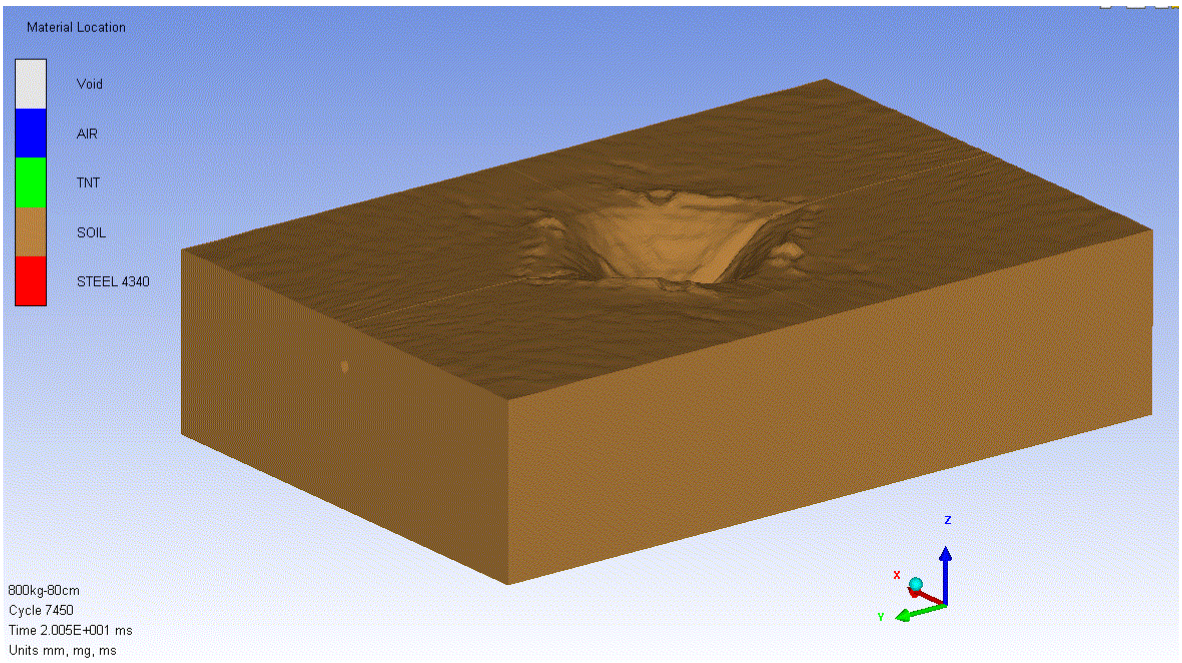


Figure 10: Final crater. Case 1. 800 kg TNT

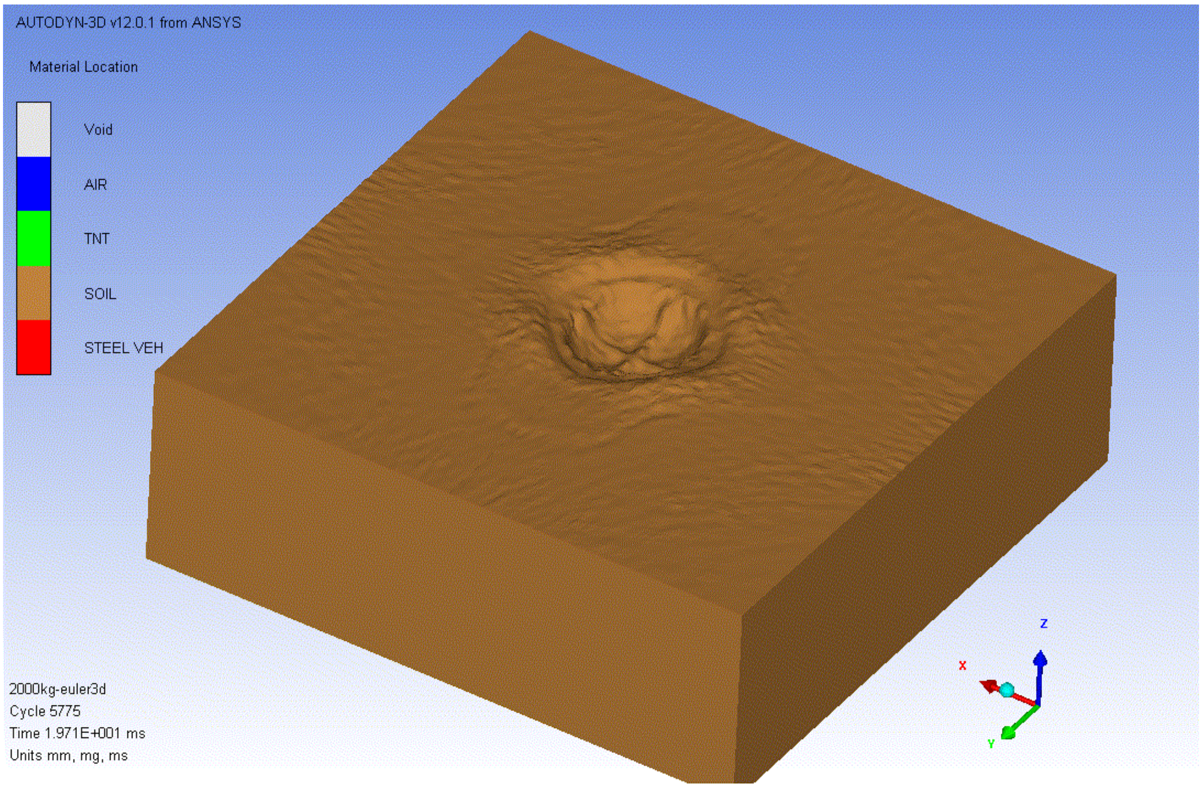


Figure 11: Final crater. Case 2. 2000 kg TNT

5.2 Numerical results

The crater dimensions for all cases listed in Table 2 are presented in Table 3. It must be pointed out that, in most cases, it is difficult to "measure" the final crater in the same way that in actual cases some differences could appear between two independent measurements.

Table 3: Numerical results obtained. Dimensions of the crater.

Case	**Weight of explosive (Kg TNT)**	**D_x (m)**	**Diff. (%)**	**D_y (m)**	**Diff. (%)**
1 With vehicle	800	3.58	6.8	3.45	18.4
1 Without vehicle	800	3.84		4.23	
2 With vehicle	2000	4.09	7.9	4.09	11.5
2 Without vehicle	2000	4.44		4.62	

It may be observed that the vehicle affect the final dimensions of the crater. It must be pointed out that, as it was demonstrated by Ambrosini et al. (2004), the elastic properties of the soil do not affect significantly the diameter of the crater. However, a variation of ± 5% could be obtained in particular cases.

6 CONCLUSIONS

A numerical study about the influence of a vehicle on the dimensions of craters created by exploding charges ranging from 800 kg to 2000 kg of TNT is presented in this paper. The charge consists of different ordnances stacked in different configurations inside the vehicle.

Based on the obtained results, the following conclusions could be drawn:

- In the direction of the width of the vehicle, the malevolent vehicle reduces with regard to the plain soil, in average, 7% the horizontal dimension of the crater.
- In the direction of the length of the vehicle, the malevolent vehicle reduces with regard to the plain soil, in average, 15% the horizontal dimension of the crater.
- The malevolent vehicle has influence on the final shape of the crater. The vehicle leads to a crater with similar dimensions in both directions although the shape of the crater be rectangular.

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