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Craters produced by underground explosions

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ABSTRACT

Extensive research activities in the field of blast loads have taken place in the last few decades. There are many experimental results related to underground explosions. The mechanism of crater formation is complex and it is related to the dynamic physical properties of air, soil and air/soil interface. Studies concerned with the characteristics of craters caused by explosions usually resort to dimensional analysis and statistics. Some empirical equations proposed for the evaluation of crater dimensions can be found in the literature. Nevertheless, they were obtained for particular type of soils, shapes of explosives, ranges of explosive mass and depth of explosive and they present considerable variability.

The main objective of this paper is to prove the accuracy of numerical simulation of craters produced by underground explosions. For this purpose, the numerical analysis of crater formation due to underground explosions is performed with a hydrocode. Several numerical approaches are carried out using different models and processors for the soil. Moreover, different alternatives for the constitutive model of the soil are used.

Comparison with experimental results is performed in order to validate the numerical approach and prove its ability to model the crater formation. Many simulations of the same physical model lead to the same crater dimensions and a good agreement between the test results and the predicted crater measures is achieved.

1. Introduction

Tests of crater formation are appropriate tools to study the blast phenomena, the behavior and destructive power of different explosives and the response of soils and rocks under this type of load (Persson et al. [1]). The mechanism of crater formation is complex and it is related to the dynamic physical properties of air, soil and air/soil interface. Even very carefully performed cratering tests give deviations in the dimensions measured of about 10%, while differences of as much as 30–40% are common (Bull and Woodford [2]).

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, a complex interaction taking place between gravity effects, soil strength and transient load conditions. 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 and Woodford [2]).

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 depending on if the gravitational effects can be neglected or not. In the first case the cubic root law is applicable ($\alpha = 0.33$) and in the other cases the functional dependence can be quite complex.

Baker et al. [3] 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

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properties: one with the dimensions of a stress σ, related to soil strength, and the other, K, with the dimensions of a force divided by a cubic length (Nm^{-3}) that takes into account gravitational effects.

After a dimensional analysis and many empirical observations, the following functional relation may be obtained [3]

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

If $\frac{R}{d}$ (scaled radius of the crater) is plotted as a function of $W^{7/24}/d$, 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 $W^{7/24} < 0.3$, the scaled radius of the crater is sensible 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 $W^{7/24} > 0.3$.

It can be deduced that the specific weight ρg is the best measure for K and that ρc^2 is the best measure for σ, where c is the seismic velocity in the soil. If experimental results for different types of soils are plotted in a $\frac{R}{d}$ versus $\frac{W^{7/24}}{\rho^{7/24}c^{1/3}g^{1/8}d}$ graph, it may be clearly seen that there is very little variability in the results.

The numerical evaluation of the dimensions of craters produced by underground cylindrical TNT loads is presented in this paper. Although there are many experimental results and empirical equations for the size of craters produced by underground explosions, the main objective of this paper is to check the ability of numerical tools to reproduce experimental values in order to use these tools for more complex problems such as the evaluation of damage produced on vehicles or objects situated on the ground by underground explosions.

The analysis is performed with a hydrocode (AUTODYN v6.1 [4]). Many alternative models for the same problem are first run in order to check the variability of the results. Then the dimensions of the craters for different TNT masses and depths are obtained and compared with experimental values. The crater dimensions defined by Kinney and Graham [5] are used in this work (Fig. 1). D is the apparent crater diameter measured from the loose soil mounts around the crater, D_r is the actual crater diameter and H_2 is the apparent depth of the crater.

2. Problem description

2.1. Introduction

First a typical problem is chosen in order to study the variability obtained in craters dimensions when different processors, different mesh sizes and slightly different physical models are used. Once these aspects have been checked, the mass and depth of the explosive are varied, maintaining all the other properties, and the resulting craters dimensions are compared with experimental and empirical values.

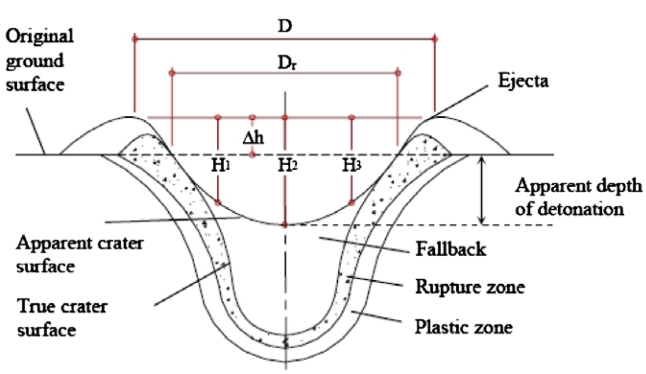

Fig. 1. Definitions of the crater dimensions.

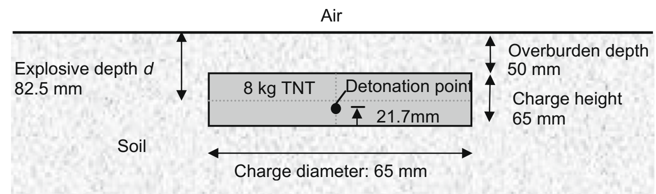

Fig. 2. Typical problem set-up.

2.2. Explosive

In order to carry out a comparable analysis, the mass of the explosive is defined by TNT masses. The corresponding masses for other explosives can be obtained through the concept of TNT equivalence (Formby and Wharton [6]).

A mass of 8 kg of TNT is defined for the typical problem and then the mass is varied from 0.26 to 8 kg of TNT.

A cylindrical explosive load like that represented in Fig. 2 is considered for all the problems. The dimensions of the TNT load for the typical problem are also indicated in Fig. 2. For the other problems the TNT mass is varied preserving the shape and the aspect ratio of the explosive load.

The explosive charge includes a Pentolite booster with a hole for the detonator at one third of the height from the lower face of the TNT cylindrical charge.

2.3. Soil

All the results are obtained for a ferricrete, gravelly sand soil with the properties presented in Table 1 for two different depths. The plasticity index of soil, that is, the difference between the plastic and the liquid limit, indicates the size of the range over which the material acts as a plastic – capable of being deformed under stress, but maintaining its form when unstressed.

2.4. Location

For the typical problem the cylindrical charge is buried with top surface 50 mm below the soil level. The charge is covered up to the ground level with loose soil (no strength). The set-up is graphically displayed in Fig. 2.

Problems varying the depth of the explosive load were also studied.

The detonation point is considered to be placed in the center of the lower face of the explosive load as indicated in Fig. 2. Nevertheless, the variation of results for other positions of the detonation point is also studied.

3. Numerical models

3.1. Introduction

Computer codes normally referred as "hydrocodes" encompass several different numerical techniques in order to solve a wide

Table 1
Soil properties.

Depth (mm)	Dry density (g/cm^3)	Plasticity index
150	1.987	4
300	2.071	5