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Evaluation of soil and fluid structure interaction in blast modelling of the flying plate test

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ABSTRACT

The influence of the soil properties on the structural integrity of impacted structures is important in light of the increased use of improvised explosive devices (IED's) and buried explosives. The study deduces material parameters for the Federal Highway Authority (FHWA) soil model in LS-DYNA and comparisons are made with the ConWep and two commonly used soil models. The softening behaviour of semi-cohesive prairie soils due to pore pressure development and the reduction of the cohesion angle are highlighted. The flying plate test is used for validation with very good agreement found, capturing the plate's kinematic and structural responses.

1. Introduction

In light of the increased use of improvised explosive devices (IEDs) against combat and tactical vehicles, analysis of the survivability and the dynamic responses of these platforms has become a pressing issue. The typical impulse loads associated with an air blast are further complicated when the blast occurs within a soil substrate. The additional complexity arises by virtue of the additional soil medium which is in itself comprised of solid, fluid and gaseous phases. In the thermodynamic sense the explosive reaction transforms the chemical energy into thermal and kinetic energy, with the large and rapid increase in entropy doing 'work' on the system. This work can be the propagation of discontinuities, shock waves through the air, liquefaction and cratering of the soil, structural damage to surrounding objects or injuries to nearby persons. An accurate rheological model is thus needed to best capture the prevailing physical aspects of the blast event. Earlier studies [1,34] investigated the use of a hydrocode for the analysis of both ballistic and blast events; primarily Lagrangian based analysis of kinetic energy impactors and ALE (Arbitrary Lagrangian Eulerian) analysis of blast events. The current study presents a further iteration of the blast analysis initiated in that study through the implementation of a modified Mohr–Coulomb soil model, FHWA, in lieu of the test steel pot used as per the NATO standard [2].

A high explosive detonation in air causes a strong shock to propagate freely into the surrounding medium/atmosphere. This blast wave is inherently a discontinuous condition where pressure, density, temperatures and fluid velocity increase. The Friedlander [4,5] formulation is generally used to describe the shock pressure:

$$P_s(t) = P_{so}\left(1 - \frac{t - t_a}{t_0}\right) \cdot e^{\left(-B\frac{t-t_a}{t_0}\right)} \quad (1)$$

where P_{so} is Peak incident pressure, t_0 is the positive phase duration, t_a is the arrival time and B is the decay coefficient.

The Friedlander formulation generally fails to accurately represent the static overpressure for distances less than 10 charge radii. As such its application for detonic blast regimes is limited. The widely used ConWep blast model, based on the work of Kingery and Bulmash [4] and the blast resistance design manual TM5-855-1 or UFC 3-340-02 [5,10], is also employed in the current study for comparison. The implementation of the ConWep blast model in LS-DYNA [6] was done by Randers–Pehrson and Bannister [7] as hemispherical or spherical type blasts. Previous studies [1] have shown the ConWep model to fail in accounting for charge shape, shadowing, soil composition or confinement effects. The model also largely fails, without mass scaling, to accurately predict both peak pressures and impulse for near field blast regimes.

Thus the authors elected to evaluate the fluid structure using the ALE method and address the effects of buried charge on the

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deformation of the soil and the structure with reference to the field tests of Weckert and Anderson [3]. The experimental test is of a 590 kg square steel plates placed atop four 400 mm long wooden posts with a 6 kg TNT surrogate landmine centrally buried 50 mm below the surface. The maximum plate height reached, the plastic deformation, and the crater size are reported in Weckert and Anderson [3] as a measure of explosive effects. The detonation of the explosive, stress propagation in the soil, the soil–structure interaction and the material response of a steel plate are all computed numerically herein for the same analysis. Additionally the material parameters for prairie type soil were deduced for the soil test bed along with a mesh and soil model sensitivity study. Comprehensive work by Remenniko [57,58] highlights the use of ALE methods for blast analysis with the studies by Souli et al. [8] and Chafi et al. [9] demonstrating specific implementation for air blast.

In contrast to air blasts, soils cannot generally be characterised in the same fashion, rather three distinct phases are generally recognised [12]: (i) the soil in close proximity to the charge is crushed by the initial enveloping shock wave. This rapid process is independent of the strength properties of the soil. (ii) Outside this initial rupture zone the second zone typically exhibits irreversible plastic deformation that directly correlates to crushing and pore collapse, thus rapidly increasing the density of the soil and further concentrating the blast products upwards. (iii) The last significant response of the soil is in a third zone which is elastically loaded by the shock wave with the process being largely reversible. Fig. 1 shows the graphical representation of the three zones as per Bangash [11].

As the explosive products expand the cratering of the soil medium forces these gases to expand upwards towards the surface. The soil cap at this point is ejected in a hemispherical fashion; the size of the soil cap correlates to the depth of the charge from the surface. The compressive waves travelling through the soil towards the surface are partially transmitted into the air as a shock wave but largely reflected back into the soil as tensile waves. This precipitates from the large impedance difference between the soil and the air. The soil is ejected in an inverse cone shape forming an annulus of ejecta surrounding the detonation products. Generally the angle of the soil ejecta is between 60° and 90° [12] depending on the depth of burial and the moisture content of the soil. It is during this phase that the soil impacts neighbouring structures causing localised material deformation and possible breach of these structures.

For the analysis of blasts in soils there are generally two camps of thought: the continuum soil models [13,17,18,36,37] and the discrete particle models where inter-granular interactions are treated explicitly [12,38]. The study herein centres on the continuum treatment of the soil, air and the blast products with a focus on prairie soil, based on the experimental work of Fišerová [18], who employed ALE modelling using LS-DYNA and AUTODYN. Other comparable work to the current study was done by Pickering et al. [37] who looked at buried charges in sand and employed ALE modelling in AUTODYN. Their studies also highlight the increased impulse delivered by buried charges as opposed to a surface laid or free air blasts.

A detailed experimental study of buried charges by Anderson et al. [36] showed correlation between increasing moisture content and the increasing momentum of the test plate. Hlady [16] also presented extensive experimental results of buried charge experiments looking at depth of burial and moisture content effects. Soil modelling carried out by Neuberger et al. [35] centred mainly on the effects of charge scaling rather than soil properties. They employed the standard form of the Mohr–Coulomb soil model and noted the need to calibrate their model to achieve good agreement with their experimental studies. Further work by Wang et al. [56] identified the role of the excess pore pressure ratio in the failure and liquefactions of soils under explosion loading, while the work by Ambrosisni et al. [59] provides an experimental and modelling study of buried charges using a 2D Eulerian model based on the Mohr Coulomb criterion and hydro tensile limit.

Eulerian descriptions of the computational domain are based on fixed grid points and cells that occupy the spatial domain. Their positions and volume are invariant in time, thus allowing material flow across each element boundaries. The ALE formulation introduces a third domain [20], an arbitrary displacement of the reference domain. This method has the added complexity and benefit of computing the moving boundaries, free surfaces and large deformations using an advection step [8,13]. The inherent strength of the ALE formulation is the ability to model events where large element distortions would otherwise give erroneous results. The errors in the Lagrangian formulations generally precipitate out of: (i) highly distorted elements degrading accuracy and (ii) severe reduction of the time step as explicit FE codes uses the Courant–Friedrich–Levy condition.

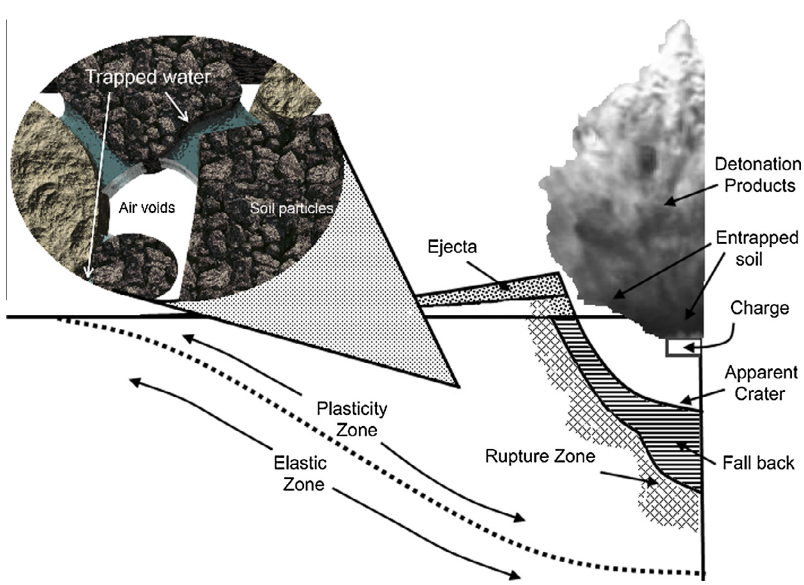

Fig. 1. Soil response to detonation events, adapted from [11].