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GENERAL OVERVIEW OF CAPABILITIY IN THE SIMULATION OF SHAPED CHARGES PENETRATING SOIL/CONCRETE TARGETS

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The defeat of a wide range of hard targets (e.g. bridges, bunkers etc.) is becoming an increasingly important military requirement. These targets can comprise many layers of geological materials and are generally large scale. This precludes the development of efficient systems using full-scale trials on cost grounds. Therefore an alternative approach is required which fully integrates the simulations and relatively small-scale precise experiments. Careful attention to target constituents, construction and analysis of the borehole profile has allowed a systematic comparison between the hydrocodes and the experimental results. This has allowed the construction of more sophisticated models to describe geological materials in the hydrocode and has enabled them to be evaluated more effectively. This has shown that more work is required on the crack growth aspects of the model. The general agreement obtained between the hydrocode and the experiments has given rise to a capability to assess full-scale systems.

INTRODUCTION

The defeat of a wide range of hard targets is becoming an increasingly important requirement, since these targets usually comprise significant aspects of the infra-structure of the opposing forces. Whilst present systems are capable of producing useful lethality levels in the target, they were largely designed using full-scale trials. In the present fiscal environment this approach is simply not feasible and there are defined requirements to signficantly reduce the size whilst increasing the efficiency of the munition.

Therefore an alternative approach is required which demands a full integration of simulations and precise relatively small-scale experiments. For this approach to succeed great care is required in controlling the constituents used to construct the targets and their method of fabrication as these can all greatly affect the target response [1]. In addition some effort is required to carefully extract the maximum information concerning the borehole formation; this is particularly difficult for sands and soils.

This paper describes the general methodology in the development of an assessment capability for a variety of shaped charge designs to defeat concrete employing an integration of hydrocode modelling and experiments. The paper also gives some examples of the general capability and discusses areas that require further study.

EXPERIMENTAL PROGRAMME

The main aim of the experimental programme was to provide precise data to compare with numerical simulations and to systematically study the effect of controlled target variations on the borehole formation. This requires accurate target construction, precise charges and precise measurements of the subsequent borehole.

Target Control

A key part of the experimental programme was the close control placed on the construction of the targets. The practicality of achieving this is not trivial when one is considering large concrete and soil targets.

The methodology adopted in this programme started with the careful weighing of the concrete constituents before mixing and then ensuring a thorough mixing of the aggregates so that they are uniformly distributed. The targets were also cured for a minimum of 28 days to ensure they were consistent with civil and military engineering specifications. Indeed we have a close liaison with civil engineering consultants who advise on target manufacture and the level of reinforcement embedded within them. From the same mix as the target a representative cube of material is manufactured which is continuously tested to monitor its density and compressive strength during and after curing. This ensures consistency of the target.

For the soil and sand targets the methodology was essentially the same except the target was constructed in well controlled layers to facilitate its dismantling when investigating the borehole. No curing is required. In addition more samples were taken for testing to measure the density, compaction and compressive strength.

Experimental Trials

The experiments performed have consisted of firing precisely engineered shaped charges and EFPs [2] against semi-infinite concrete, sand and soil targets, multi-layer soil/sand and concrete targets and concrete panels. The semi-infinite targets were designed to investigate the borehole formation. The multi-layer targets were designed to investigate the relative proportions of the jet energies deposited into the soil and the concrete as well as the final borehole formation. In addition these targets were designed to investigate the front and rear surface spall in the middle concrete layer. The panel targets were designed to determine which part of the jet interacted with the target over a range of stand-offs and to evaluate the front and rear surface spall. Each shaped charge design was fired in air to determine the jet break-up characteristics. In general two charges were fired against each target to ensure reproducibility.

Experimental Data Analysis

The borehole profile and the degree of compaction around the borehole were accurately measured. In addition the degree of spallation and cracking was recorded. Some of the targets also had thin metal foils positioned within them to determine the penetration/time history of the projectiles. In the case of the panel targets flash-radiographs were taken of the emerging jets which were used to determine how much of the jet was consumed in penetrating the target.

The borehole analyses of the soil and sand targets were obtained by careful excavation of the targets after the trial. This revealed the borehole profile which can then be measured in a straightforward fashion. An example of a typical borehole in sand is shown in Fig. 1.

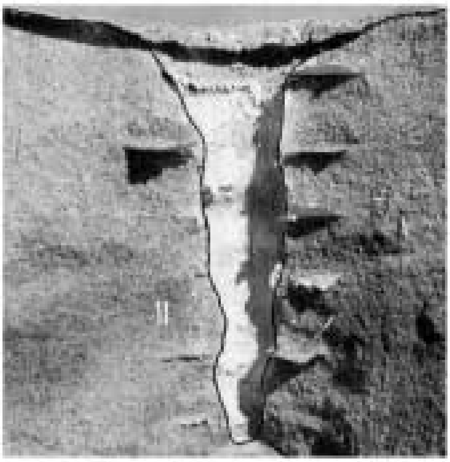

Figure 1 – Experimental borehole for shaped charge in sand.

NUMERICAL SIMULATIONS

The carefully determined output from the experimental trials was employed to validate the numerical simulations. This determined the robustness of the simulation techniques and also the equation of state and constitutive models for the geological materials. In particular the detailed comparison indicated areas which require further investigation and development.

Numerical Methodology

The simulation tool used for this study was the cAst Eulerian hydrocode which is capable of multi-material 1D, 2D and 3D analyses. cAst includes the capability to simulate a range of materials including gases, explosives, metals, soil, sand, concrete. It provides a platform to run very large problems in a useful timescale, cost effectively. cAst is also capable of linking to analytic and higher order OA models. The hydrocode runs were performed on a 32 processor ORIGIN 2000 computer and were performed in 2D axisymmetric geometry using a mesh size such that the shaped charge jet formation was adequately resolved. This is an important consideration because if the mesh is too coarse the borehole profile and depth will be in significant error. The general run times for the semi-infinite penetration simulations were about 100 hours, though this depended on the nature of the charge design. Although this seems excessive, it should be remembered that the stand-off of the jet from the target was significant and the penetration depth into sand, for example, was well in excess of 1m. Furthermore, the simulation had to be run to several milliseconds to ensure that the penetration process had completed. This was further complicated by the jet break-up within the target. The contribution to the final hole profile by each jet particle therefore had to be determined.

Geological Model

The geological model incorporates a porous compaction equation of state which features an initial small elastic region followed by a gradual compaction up to a lock-up point. The behaviour then follows the equivalent quartz solid hugoniot including the well documented solid/solid phase transition. The material unloads along a different paths dependent upon the level of compaction. The equation of state surface is illustrated schematically in Fig. 2. It shows the regions explored by various projectiles.

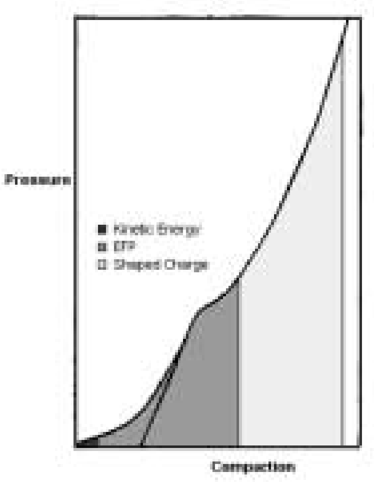

Figure 2 – Equation of state surface for concrete showing different impact regimes.

The constitutive model is based on a modified Johnson-Holmquist law [3] which describes the yield strength as a tabular function of pressure for both the undamaged and the fully damaged material. The transition from the undamaged to the damaged state is calculated by means of a damage criterion based on the level of compaction in the material. This allows the material to damage in both tension and compression and in addition the model incorporates a spall model which is also a function of damage. This reflects the expected degradation of the spall strength with damage. The model has been incorporated into the hydrocode in a generic fashion and can therefore be used for concrete, soil and sand.

Simulation Results Compared with Experiments – Concrete

In general the results for the semi-infinite concrete simulations were in excellent agreement with the experiment, both in terms of the penetration depth and the general borehole shape, as illustrated in Fig. 3. However, some of the finer details such as the damage zone around the borehole were more difficult to ascertain. Another aspect that is not readily picked up in the simulation is the front and rear surface cratering. The reason for this is that the failure model is based on tension, whereas the surface cratering involves other failure mechanisms. Alternative failure models are being investigated with this in mind. In general the results for the concrete targets are fairly consistent and provide a good basis for comparison with the simulations. The simulations indicated that the main differences in borehole dimensions were usually attributed to slightly different densities and compressive strengths within the concrete.

Figure 3 – Comparison of hydrocode simulation and experiment (solid line).

One of the main difficulties in obtaining good agreement between experiment and simulation is related to jet particulation within the target. This is a major issue since the prediction of jet break-up in free field for these jets is far from adequate. Research into improved material and fracture models is underway to address this issue [4]. Clearly the problem is compounded by the jet breaking up within the target, since it is not known if the break-up observed in free field is modified by the presence of the target.

In an attempt to shed some light on the importance of jet break-up within the target some experimental trials were performed on finite panels with flashradiography behind the panel to examine the emerging jet. This identified the portions of the jet actually performing the penetration of the target and determined whether the break-up was significantly different to that in freefield. The overwhelming result is that the jet break-up is very different, indicating significant influence on the jet break-up by the target. Given the inability of the hydrocode to predict this accurately it is perhaps surprisng that such good agreement is obtained with the general borehole profile. The reasons for this will be discussed later.

Simulation Results Compared with Experiments – Sand

The data for the sand equation of state was obtained from Reinhart [5]. This data illustrated a large variation depending on the porosity and moisture content. The simulations used a fitted equation of state to this data and a simple strength model based on the GREAC cell (i.e. a quasi-static confined compression test). One of the main problems is that there is little dynamic equation of state data for UK sands or soils. This is currently being addressed within another research programme. The comparison between the hydrocode and the experimental hole profile is shown in Fig. 4. This model is currently being evaluated on the multi-layer sand and concrete targets.

Figure 4 – Comparison of hydrocode with experiment (solid line) for shaped charge in sand.

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DISCUSSION

In general the agreement between the hydrocode and the experiment for semi-infinite penetration into concrete or sand is very good in terms of the borehole depth and shape. This is curious, since studies have indicated that the jet is significantly particulated within the target and the hydrocode predictions of jet break-up are generally inadequate. The reason for this good agreement is that for these designs of shaped charges, the number of jet particles is relatively small and the particles are relatively large. Thus the hydrocode is probably not significantly in error in predicting the main particle lengths and thus their contribution to the penetration within the target. Hence the overall momentum, energy and impulse delivered to the target is effectively captured.

Of greater concern is the inability of the constitutive and fracture model to capture the surface cratering. The fracture model is based on a simple spall strength as a function of damage, whereas the surface cratering probably requires a shear component to the fracture behaviour. It reflects the crudity of the understanding of the damaging and failure mechanisms within the concrete. Alternative descriptions for the damage of concrete are being investigated, which attempt to link the micromechanics to the macroscopic behaviour of the concrete [6].

Another important issue in this area is the great lack of a dynamic equation of state and constitutive model data for sand and soil. This is compounded by the large variation of properties with porosity and moisture and the general variability of these materials, even in well controlled range targets.

CONCLUSIONS

1. cAst Euler has been demonstrated to have a predictive capability in the simulation of shaped charges against concrete and sand targets in terms of borehole depth and shape over a range of scales and stand-offs.
2. More research is needed to predict the surface and rear cratering often observed with shaped charge jets.
3. The general damage and dynamic fracture behaviour of concrete is not well understood in these scenarios.
4. The importance of a full integration of precise experiments coupled with second generation hydrocode modelling has been demonstrated as a key requirment for significant progress in a research programme.

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