Article:
Warren, J., Kerr, S., Tyas, A. et al. (2013) Briefing: UK Ministry of Defence Force Protection Engineering Programme. Proceedings of the ICE - Engineering and Computational Mechanics, 166 (EM3). 119 - 123 . ISSN: 1755-0777

https://doi.org/10.1680/eacm.13.00014

Engineering and Computational Mechanics
Volume 166 Issue EM3

Briefing: UK Ministry of Defence Force Protection Engineering Programme
Warren, Kerr, Tyas *et al.*

ice | proceedings

Proceedings of the Institution of Civil Engineers
Engineering and Computational Mechanics 166 September 2013 Issue EM3
Pages 119–123 http://dx.doi.org/10.1680/eacm.13.00014
Paper 1300014
Received 22/05/2013 Accepted 10/06/2013
Keywords: dynamics/mathematical modelling

ice
Institution of Civil Engineers
publishing

Briefing: UK Ministry of Defence Force Protection Engineering Programme

Jim Warren PhD
Managing Director, Blastech Ltd, Sheffield, UK

Stephen Kerr
Principal Scientist, Defence Science and Technology Laboratory, Porton Down, UK

Andrew Tyas PhD
Senior Lecturer, Department of Civil and Structural Engineering, University of Sheffield, Sheffield, UK

Samuel Clarke PhD
Lecturer, Department of Civil and Structural Engineering, University of Sheffield, Sheffield, UK

Mihail Petkovski PhD
Lecturer, Department of Civil and Structural Engineering, University of Sheffield, Sheffield, UK

Andrew Jardine PhD, Royal Society University Fellow
Cavendish Laboratory, University of Cambridge, Cambridge, UK

Philip Church
Qinetiq Fellow, Numerical Simulations, QinetiQ, Fort Halstead, UK

Peter Gould PhD
Senior Scientist, Numerical Simulations, QinetiQ, Filton, UK

Angus Williams PhD
Force Protection Engineering Technical Leader, QinetiQ, Farnborough, UK

The Defence Science and Technology Laboratory sponsored, QinetiQ-led Force Protection Engineering Research Programme has two main strands, applied and underpinning research. The underpinning strand is led by Blastech Ltd. One focus of this research is into the response of geomaterials to threat loading. The programme on locally won fill is split into four main characterisation strands: high-stress (GPa) static pressure–volume; medium-rate pressure–volume (split Hopkinson bar); high-rate (flyer plate) pressure–volume; and unifying modelling research at the University of Sheffield, which has focused on developing a high-quality dataset for locally won fill in low and medium strain rates. With the test apparatus at Sheffield well-controlled tests can be conducted at both high strain rate and pseudo-static rates up to stress levels of 1 GPa. The University of Cambridge has focused on using one-dimensional shock experiments to examine high-rate pressure–volume relationships. Both establishments are examining the effect of moisture content and starting density on emergent rate effects. Blastech Ltd has been undertaking carefully controlled fragment impact experiments, within the dataspace developed by the Universities of Sheffield and Cambridge. The data from experiments are unified by the QinetiQ-led modelling team, to predict material behaviour and to derive a scalable locally won fill model for use in any situation.

1. Introduction

For many years, a significant proportion of work conducted under the Ministry of Defence (MoD) Force Protection Engineering (FPE) Research Programme produced information and data on protective materials and structures that could be used by military fortifications designers. Traditionally, materials of interest have included locally won natural fill materials, steel, concrete and timber, with key military drivers being low logistic burden and ease of construction as well as effective protection. However, during recent operations in the Middle East (Op TELIC in Iraq, and Op HERRICK in Afghanistan), a significant amount of effort focused specifically on the development of protective measures and equipment for personnel in operational bases, primarily against the threats from indirect fire rocket and mortar attacks, rocket-propelled grenades and small arms fire (Figure 1). Effective designs were produced through a combination of traditional design, numerical simulation and experimental trialling, including dynamic mortar and rocket firings.

Figure 1. Lightweight sangar developed under the research programme

However, the value of longer term enabling or underpinning research has long been recognised by the MoD and the QinetiQ-led consortium conducting the FPE research programme. The change of emphasis away from highly applied work towards underpinning research is deemed necessary to develop enhanced capability to better meet unknown future challenges of military operations. The raison d'être of the underpinning programme is thus to provide an enhanced level of fundamental understanding of the physical performance of protective materials used in FPE, as well as protective structures both in normal service conditions and under physical attack.

In consultation with the programme sponsor, the Defence Science and Technology Laboratory, the following measures were formulated.

- Define the current level of understanding of the behaviour of materials relevant to FPE and, where understanding is insufficient, conduct research to develop enhanced understanding.
- Understand the response of improvised or semi-permanent protective structures undergoing blast and/or ballistic attack, and how engineering decisions may affect long-term survivability, serviceability and logistic burden for such structures.

This immediately flows down into the basic work areas for the underpinning section of the programme.

- Materials characterisation. In order to be best placed to exploit protective materials, it is necessary to have a detailed understanding of the physics of the behaviour of those materials. Although such detailed understanding is either known or being investigated elsewhere for concretes, steels and composites, one area where many gaps in behavioural understanding still remain is for soils, under extreme loads. To this end, it was decided to characterise one particular readily-available sand in some detail, before seeking to establish the extent to which the results could be extrapolated to predict the performance of other cohesionless fill materials, and the extent to which the behaviour could be extended to other materials (clays, silts, etc.).
- Structural considerations. These are very much of interest to the FPE programme, because protective systems need to be supported in some way, either as an integral part of the systems to be protected or as independent structures. In the future, the range of equipment that may need protection is likely to increase, and the range of threats will change. Without having an in-depth understanding of the full range of structures that will need protection, and the weights of protective materials required to defeat potential threats, it was felt that a generic approach considering a range of span lengths or wall heights for a range of potential protective weights will provide a very broad understanding of the 'state of the art'. By establishing this broad picture, specific applications may be effectively addressed. To this end, this work strand has been broken down into the following areas
  - foundations
  - protective walls
  - overhead protective structures.
- Modelling techniques. Modelling techniques and computational tools are continuously being developed and improved across the full spectrum of applications. In this area of the underpinning programme a study has been conducted to evaluate new computational tools to determine whether they may, with or without additional work, satisfactorily model the behaviour of masonry walls to the dynamic effects of blast loadings.

2. Case study: geomaterials undergoing extreme loadings

Although there are several active streams of fundamental materials and structures research in the FPE programme, this briefing will focus on the work being undertaken on cohesionless soil as a protective medium. Locally sourced material is frequently used as a protective material in field protective systems, yet many of the mechanisms of its action in defeating blast and ballistic threats are not fully understood. This means that there is scope for performance optimisation in these materials.

Work on the effects of threat loading on soil has been undertaken at the University of Sheffield, University of Cambridge, QinetiQ Fort Halstead and Blastech Ltd. The work centres on understanding how the soil parameters affect the penetration of high-velocity fragments into the soil continuum. The Universities of Sheffield and Cambridge have been undertaking studies on defining and validating material models for use in modelling of soils under high-intensity dynamic loading. The fundamental research questions to be addressed are how do mechanical properties (e.g. bulk modulus, failure surface) vary with

- changes in geotechnical conditions
- changes in confinement pressure
- changes in loading rate.

These studies have undertaken shock loading and unloading experiments in one-dimensional (1D) space at very high rates (Figure 2). The equation of state (EOS) of a material at high rates is developed by subjecting it to a fully developed shock from Flyer plate experiments conducted at Cambridge University. By applying conservation of mass, momentum and energy and through the Hugoniot jump conditions, the principal Hugoniot curve of the material of interest's EOS may be derived. The University of Cambridge has developed techniques for measuring the unloading phase of this event, and has also developed the first soil shock unloading data at high strain rate in the published literature.

Medium rate pressure–volume split Hopkinson pressure bar (SHPB) experiments have been undertaken at the University of Sheffield (Figure 3). The SHPB test rig consists of two long, steel bars held in linear bearings with the specimen placed between them. The specimen is loaded rapidly by inducing a stress pulse down the input bar, which interacts with the specimen, partially

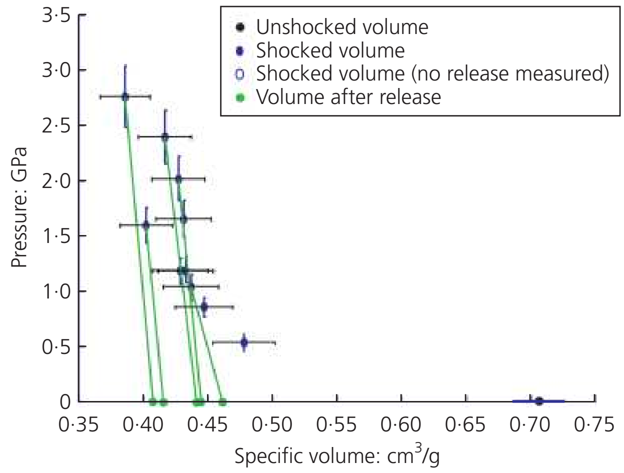

Figure 2. Sand shock unloading data

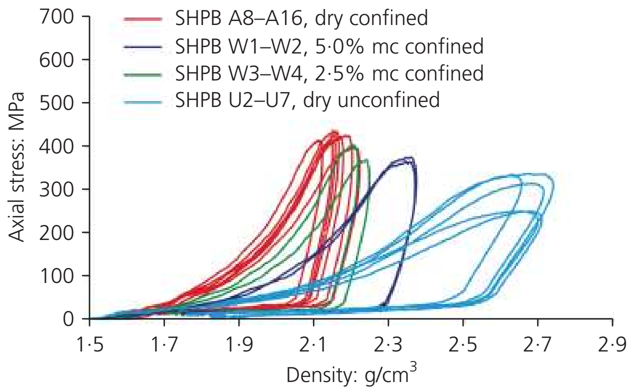

Figure 3. Sand split Hopkinson bar data, mc = moisture content

reflects along the first bar and partially transmits into the second bar. In conventional SHPB work, the transient stress and strain experienced by the specimen are determined from analysis of the incident, reflected and transmitted pulses, recorded by strain gauges set on the perimeters of the bars.

The presence or absence of a steel confining ring around the soil specimen allows for different lateral confining conditions to be generated, from effectively full 1D strain conditions with the ring in place, to nominally unconfined conditions with the steel ring replaced by a frangible thin plastic annulus. This latter condition gives an insight into the purpose of the SHPB tests. Even in nominally unconfined conditions, the rate of axial loading is so great that the lateral inertia of the specimen generates a state of lateral confinement. The resulting inertial confining stress varies both temporally and spatially along the radius of the specimen and is extremely difficult to quantify experimentally. The SHPB test is therefore not necessarily determining fundamental material properties, but rather properties that are dependent on the length scales of the sample. Consequently, in the FPE work, the SHPB tests are being conducted in order to develop validation data for finite-element (FE) modelling approaches that take fundamental properties from the shock loading and static material tests (see below) with assumptions for the material rate sensitivity. The SHPB test is to be modelled explicitly and the measure of the veracity of the material model used in the FE analysis will be how well the reflected and transmitted stress pulses in the pressure bars are predicted compared to those recorded in experimental work.

Low-rate triaxial tests have been undertaken using the Mac2T apparatus at the University of Sheffield. The Mac2T rig allows specimens to be tested in compression at high stresses while controlling the x-, y- and z-directions independently, with either load or displacement boundary conditions. This technique was used to carry out triaxial tests in order to find the peak normal stress (PNS) surface of dry FPE sand. In this case the sand was actively loaded on the x-axis with the y- and z-axes stationary as in the 1D tests; then the x-axis load was maintained while backing off the y- and z-axis platens to find the PNS surface (Figure 4). While it would be expected that during this unloading process the sand would flow around the revealed gap in the platens, in this case the sand extruded laterally, without moving into this void and maintained contact with the platens. This is the first time this behaviour has been observed in the literature.

QinetiQ Fort Halstead leads the modelling effort in this section of the programme. The modelling group are developing a theoretical Porter–Gould EOS method using quantitative structure property modelling (Porter and Gould, 2003). This method predicts the 1D shock Hugoniot (Figure 5) for a range of geological materials from granite through concrete to dry sand from their density and

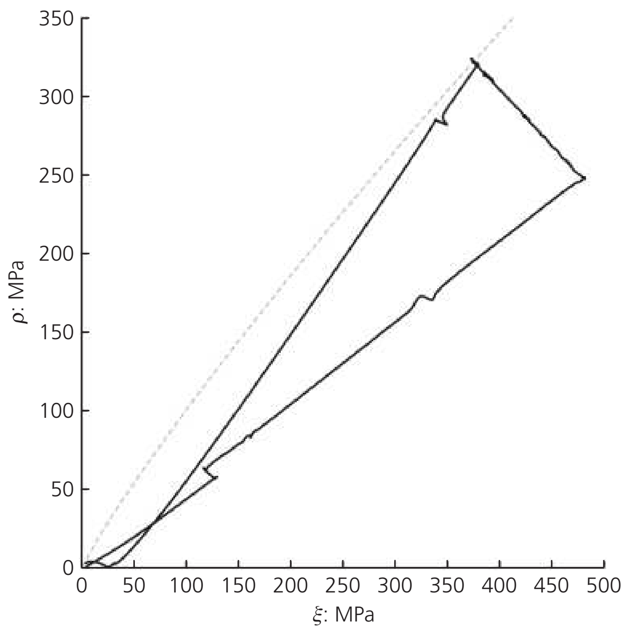

Figure 4. Mac2T PNS attempt data, ρ = deviatoric stress, ξ = hydrostatic stress

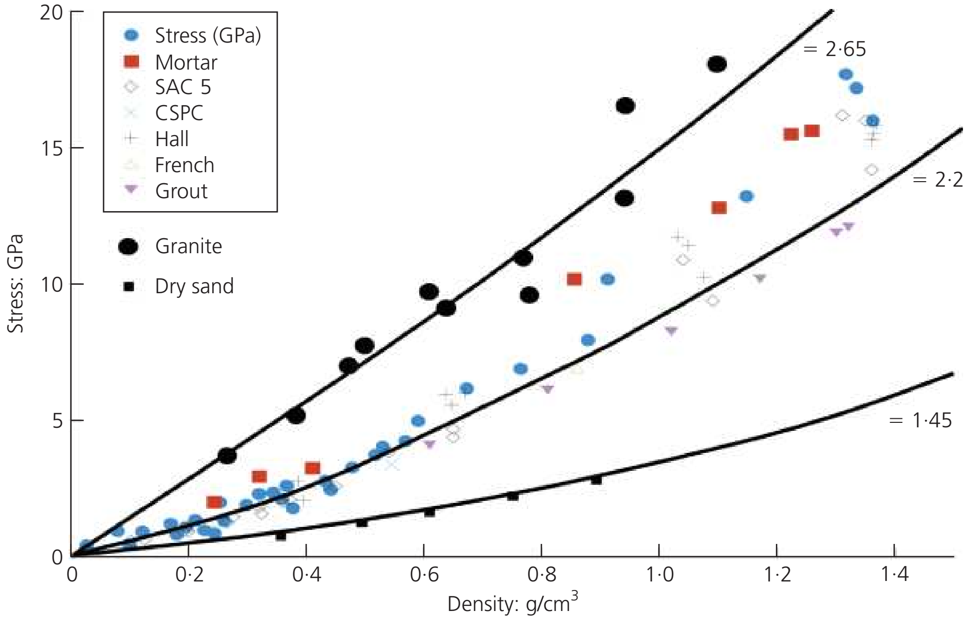

Figure 5. Porter–Gould EOS for various geomaterials

for moist sand from a method of mixtures. This is different from other methods, which are essentially fitted to the Hugoniot data, allows generation of an EOS for a silicaceous material to be a matter of a few hours work, and reserves experimental effort for independent validation. The constitutive model, based on a Johnson–Holmquist model, is currently populated based on gauged reactive confinement cell (GREAC, basically a hollow tube with radial strain sensors, such that as axial stress is applied to a sample inside the tube, the actual confinement condition is accurately known) tests and the Mac2T experiments. QinetiQ is also developing theoretical methods based on polymer physics to describe the complex constitutive behaviour, particularly of moist sands, to reflect the general features of the response of granular materials such that any sand or soil could be described with minimal characterisation overhead.

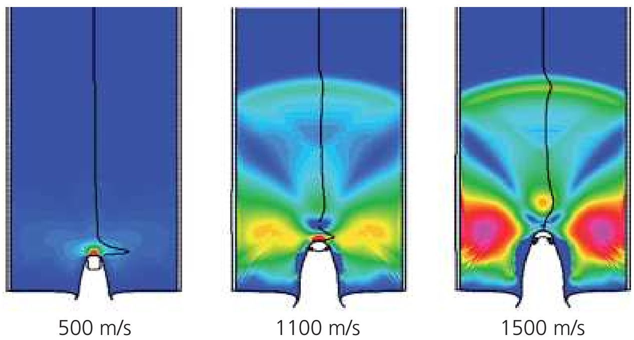

Figure 6. Grim 2D simulations of fragment impact on sand targets

This EOS and constitutive model was applied in Grim Eulerian two-dimensional (2D) simulations (Figure 6) of fragment impact experiments undertaken at Blastech Ltd, and SHPB experiments undertaken at the University of Sheffield, in order to assess whether the model is capturing the physics involved and to direct further research so as to understand the mechanisms fully. Eulerian hydrocodes are numerical models where the mesh is static, with the material being modelled moving through it, with conservation of mass, momentum and energy being balanced in each cell at each time-step. The Rankine–Hugoniot equations are solved to track the passage of shocks through the mesh. The EOS and constitutive models of the materials being modelled govern exactly how the material responds. In the context of the events being modelled, the Eulerian formulation is critical as it allows for large and rapid deformation without the attendant Lagrangian (mesh moves with material) mesh instability in these cases.

The predictions from the fragment impact simulations lie within the error expected in the fragment simulating projectile (FSP) impact experiments. Although encouraging, this does highlight the fact that while it is possible to very accurately control the samples for target purposes (i.e. to $\pm 0{\cdot}1$ g/cm^3), there is still significant scatter in the data. The modelling suggests this scatter is probably due to either yaw or shot placement on the target affecting the timing of the reflected waves from the confinement interacting with the FSP. Further FSP work undertaken at Blastech suggests that the principal parameter was shot placement and further simulations are currently being conducted.

The agreement with the SHPB data is also encouraging, although some more subtle features of the transmitted strain gauge trace are not reproduced. It is at present unclear as to how sensitive these features are to parameters in the material model. The existing model appears sufficient for dry sand in that there is no strain rate dependency. However, the preliminary analysis indicates that there is a clear strain rate dependency for the wet sand, although these effects may also be explained by a pressure dependency effect. Thus, these effects need to be quantified experimentally in more detail to give additional guidance as to how the material model should evolve.

The data gathered from Mac2T experiments are being integrated into the QinetiQ material model, along with unloading data gathered from the Cavendish flyer plate 1D shock experiments. This will allow either sensitivity and scaling studies to be undertaken to allow the model to be used as a predictive tool for multi-theatre use, or model modification to capture the physical processes with greater fidelity.

REFERENCES

Porter D and Gould PJ (2003) Multiscale modelling for equations of state. *Journal de Physique* **IV(110)**: 809–814.