Modelling Split-Hopkinson pressure bar tests on quartz sand

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ABSTRACT. FE modelling of a confined split Hopkinson pressure bar (SHPB) test on dry quartz sand was carried out using LS-DYNA in order to assess whether Material Model 5 could replicate experimental results, which would enable a more detailed investigation of the stress state in SHPB specimen. Quasi-static test data was used to select the material model input, and the model SHPB was set up to replicate the experimental conditions. The results show that Material Model 5 replicates the volumetric response provided as input data, but fails to predict the shear response observed in the quasi-static experiments. This was found to be due to the model treating the shear modulus as a constant rather than it increasing with strain, a feature which makes the Material Model 5 unsuitable for modelling SHPB tests on sand.

KEYWORDS. LS-DYNA; Sand; One-dimensional compression; Strain rate.

INTRODUCTION

This research forms part of the Dstl-sponsored and QinetiQ-led Force Protection Engineering (FPE) research programme, which investigates protective materials and structures that can be used by military fortifications designers [1]. The underpinning research element of this programme aims to enhance the understanding of how materials used in FPE perform under a wide range of loading conditions. In order to make accurate predictions of the response of soils to blast and impact events, it is vital to have an understanding of the soil behaviour at very high pressures, and over a wide range of strain rates and ground conditions.

In previous work, the effect of strain rate on the behaviour of dry and partially-saturated sand was investigated at high stresses, seeking to clarify the existence of a strain-rate dependence [2]. Quasi-static one-dimensional compression tests on a fine quartz sand were carried out to axial stresses of 800MPa using the mac^{2T} multi-axial test rig at The University of Sheffield, alongside dynamic tests to 400MPa using a split Hopkinson pressure bar. Specimens were laterally confined using a steel loading box or steel ring to ensure one-dimensional test conditions, and lateral stresses were recorded to allow the three-dimensional stress state of the specimens to be analysed. Between strain rates of 10^{-3} s^{-1} and 10^{3} s^{-1} it was found that constrained modulus increased with strain rate, but little change in bulk modulus occurred: while the axial stress increased with strain rate, the radial stress measured at the specimen surface decreased. This was attributed to radial inertia within the specimen during the high-strain-rate split-Hopkinson pressure bar (SHPB) tests, which would indicate that the increase in stiffness was a structural effect rather than a strain-rate dependence in the sand. It is desirable to quantify this inertial effect, but this requires knowledge of the evolving stress state within the specimen during the SHPB test, which is very difficult to achieve experimentally. In this paper the Finite Element (FE) code LS-DYNA is used to simulate a SHPB test on dry sand to investigate whether a simple soil material model can sufficiently model the soil behaviour to make analysis of the inertial effects possible.

FINITE-ELEMENT MODELLING OF SOILS

Modelling soils using FE methods usually involves treating the soil as a continuum with uniform bulk properties. In the last decade there has been a great increase in the use of Discrete Element Modelling (DEM), as originally proposed by Cundall and Strack [3], which considers the movement and behaviour of individual particles in the soil, and explicitly models the contacts between the particles [4]. These properties give DEM the potential to be used to research fundamental soil behaviour, but a detailed understanding of the inter-particle friction and particle fracture is also required to obtain accurate results, and computational limitations currently restrict its use to modelling small numbers of particles.

Since particles are not modelled explicitly in a continuum model, it relies on the material model to capture the important bulk properties, which can usually be attained using standard geotechnical tests. LS-DYNA has a number of built-in material models which can be used to model the behaviour of soil, varying from the simple definition of a compressibility curve and yield surface to more complex models incorporating pore water effects, strain softening and hardening and strain-rate effects [5]. Most studies in the open literature which involve soil modelling are related to buried explosive events [6-8], but LS-DYNA has also been used to model aircraft and spacecraft crashworthiness [9] and to assess DEM models of soil systems [10]. Most of these studies are not directly comparable, but it can be seen that models with a rigorously-defined soil material model are more likely to accurately predict the soil response, while models with less evidence of characterisation can be made to match a final deflection or a peak pressure, for example, but cannot accurately predict the response over the whole time or volume of interest.

To ensure that the sand material model used in this study is based on experimental results of soil behaviour, data from high-pressure quasi-static tests on the dry sand will be used to select the parameters used in an LS-DYNA material model. The material model will be used in a simulation of a SHPB test on the sand, and the predicted response compared with the experimental data. If the model and experimental data matches well, the model data can be investigated further with some confidence. If it does not, the model cannot be simply adapted to fit, instead another model will be selected which more closely captures the behaviour of the sand.

Variable	Description
`ro`	Initial density. [kg/m^3]
`g`	Elastic shear modulus. [Pa]
`bulk`	Bulk modulus, used to define the unloading response. [Pa]
`pc`	Tensile pressure cut off (< 0). [Pa]
`eps1-eps10`	Volumetric strain values corresponding to pressures p1–p10. Volumetric strain is given by the natural logarithm of relative volume. Negative in compression.
`p1-p10`	Pressure values corresponding to volumetric strains eps1–eps10. Positive in compression. [Pa]
`a1, a2, a3`	Constants used to create a quadratic fit yield function in J_2–P space.
`vcr`	Volumetric crushing option (boolean): 0: unloading dependent on unloading bulk modulus; 1: loading and unloading defined by the pressure-strain curve.

Table 1: LS-DYNA Material Model 5 variables, in current model units.

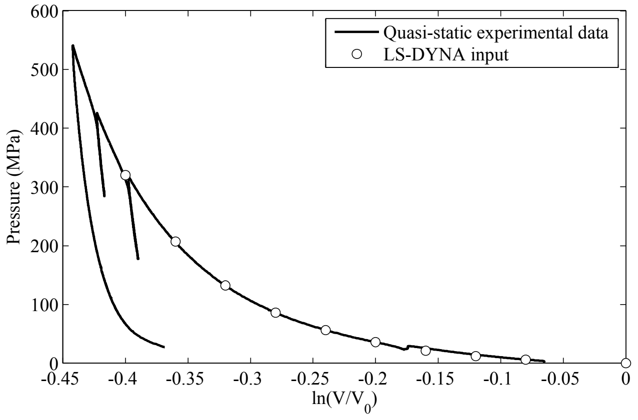

Figure 1: Sand pressure–volumetric strain relationship used in LS-DYNA, derived from experimental quasi-static data.

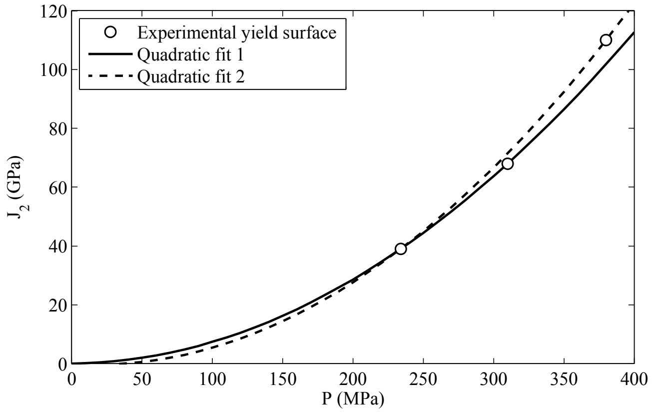

Figure 2: Shear strength relationship used in LS-DYNA, derived from triaxial tests on dry sand.

MATERIAL MODEL 5

LS-DYNA's Material Model 5 (`*MAT_SOIL_AND_FOAM`) is a simple pressure-dependent model designed for foams and soils which are confined within a structure [5]. Definition of the material requires the variables in Tab. 1, comprising of a compressibility curve, a shear strength function, shear and bulk moduli and a tensile cut-off. Material Model 5 has been used to successfully simulate contingency landings of the Orion capsule onto sand [9], and so it is worthwhile considering it before moving on to more complex models.

Compressibility

The variables `rho`, `p1`–`p10` and `eps1`–`eps10` define the compressibility of the soil, and were determined using the pressure–volumetric strain relationship from quasi-static one-dimensional compression tests on the dry sand. The sand was prepared at a dry density `rho` = 1500 kg/m^3 and loaded to a pressure of 550 MPa using the mac^{2T} test rig [2]. Ten pressure and volumetric strain pairs can be provided to the model, and these were chosen to describe the experimental curve to the maximum pressures experienced in the SHPB test, as shown in Fig. 1. The unloading bulk modulus `bulk` and the elastic shear modulus `g` can also be obtained from the one-dimensional compression tests, where the bulk modulus is the slope of the pressure-volumetric strain curve during unloading, and the elastic shear modulus can be calculated using the relationship

$$G=\frac{M(1-2\nu)}{2(1-\nu)} \qquad (1)$$

where G is the shear modulus, M is the constrained modulus and ν is Poisson's ratio. Tests performed on dry FPE Sand provided values for the bulk and shear moduli of 22GPa and 13MPa respectively, using a Poisson's ratio of 0.3.

Shear strength

The variables `a0`, `a1` and `a2` are coefficients in the deviatoric perfectly-plastic function φ, which is defined as

$$\varphi=J_2-\left(a_0+a_1P+a_2P^2\right) \qquad (2)$$

where J_2 is the second deviatoric invariant and P is pressure. This function can be fitted to experimental triaxial data by plotting a strength envelope in J_2–P space, as shown in Fig. 2. In these high-pressure triaxial tests the sand was loaded one-dimensionally in the mac^{2T} rig, and then the lateral stresses were reduced to move the stress state towards the yield surface. Two possible quadratic fits are shown for the data, which use three known points on the yield surface and the origin, as the sand is cohesionless. 'Quadratic 1' was chosen to represent the surface, as it best represents the stress range in the SHPB tests, leading to the coefficients `a0` = 0, `a1` = 4.51 and `a2` = 0.693.

The tensile cutoff `pc` is required to be non-zero, so while the sand is cohesionless it is provided with a very small tensile strength `pc` = 0.001 Pa.

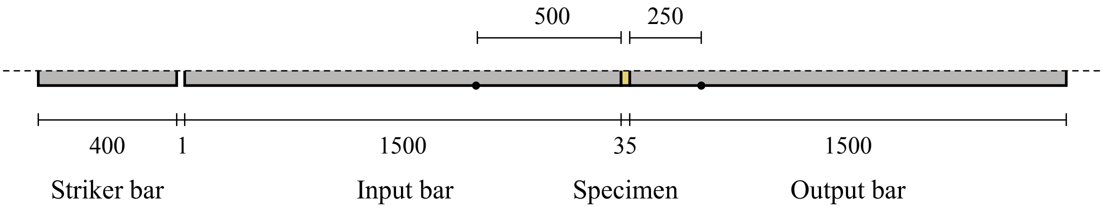

Figure 3: LS-DYNA model geometry and locations of strain gauge recordings.

SHPB MODEL

An axisymmetric FE model was set up to replicate the geometry of the SHPB test, as shown in Fig. 3. The stainless steel striker, incident and transmitter bars all have a diameter of 25 mm, a density of 7850 kg/m^3, a Young's modulus of 168 GPa and Poisson's ratio 0.29, and are modelled using the material model `*MAT_ELASTIC`. The strain gauge readings from the physical experiment were used to assess the performance of the model, and so their positions are also noted on Fig. 3. The striker bar was given an initial velocity of 22.4 m/s to match the incident pulses experienced in the physical tests, and the sand specimen set up with an initial length of 35 mm. In the physical test the sand specimen is confined laterally by a steel ring, and so this is approximated here by restricting the nodes on the surface of the sand specimen from displacing laterally.

PERFORMANCE OF THE MODEL

The output of the model is first presented in terms of the axial stress–density behaviour of the sand specimen, as this is the main output of the physical tests. As shown in Fig. 4, the modelled sand has a much lower stiffness than both the quasi-static and dynamic specimens, indicating that it does not represent the sand behaviour well. The compressibility of the modelled sand (Fig. 5) shows that, while the input curve is followed closely, the maximum pressure in the sand exceeds the defined range, so that the compressibility is extrapolated linearly. The pressures generated in the model (400 MPa) far exceed the experimentally measured pressures (< 250 MPa), which suggests that the material is behaving in a fluid-like manner, with insufficient resistance to shear forces. This is confirmed by Fig. 6, which shows that the modelled sand deviates from the experimental response at low mean stresses and generates very little shear resistance, despite being far from the yield surface. Further investigation reveals that the shear modulus defined in the model does not increase as the soil compacts, as is expected, but remains constant throughout the test, as shown in Fig. 7. This causes the unrealistic shear behaviour observed in the modelled sand, and the associated error increases as the soil becomes compressed and the bulk modulus increases. As a result Material Model 5 is clearly not suitable for modelling a SHPB test on soil, and an alternative will have to be found which models the variation of shear modulus.

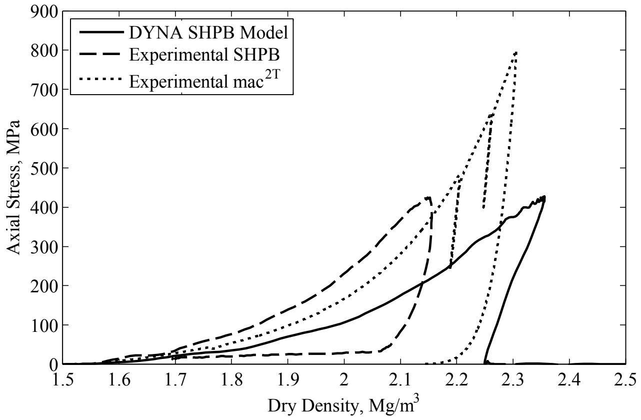

Figure 4: Axial stress–density response of LS-DYNA specimen compared to experimental data.

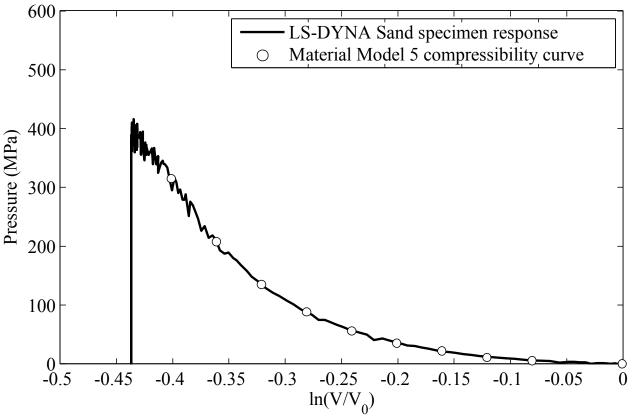

Figure 5: Sand pressure–volumetric strain relationship as modelled by LS DYNA.

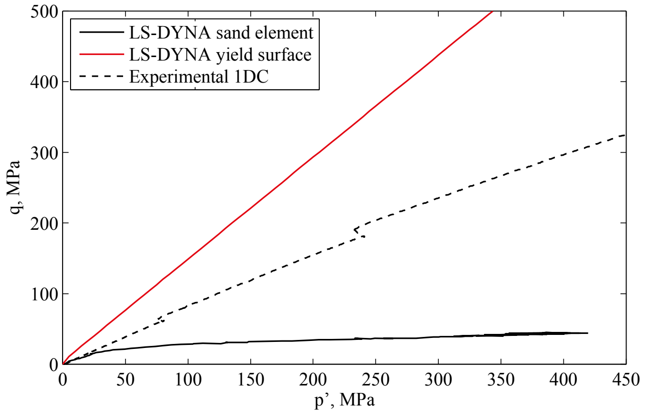

Figure 6: The shear response of the LS-DYNA specimen compared to experimental data and the model yield surface.

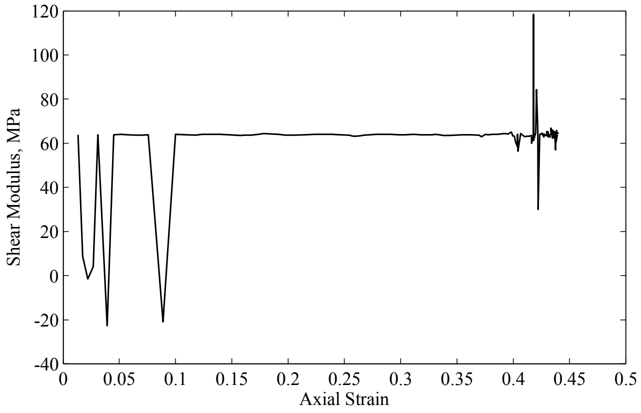

Figure 7: Variation of shear modulus with axial strain.

CONCLUSIONS

Finite Element modelling of a SHPB test on fine quartz sand was carried out using LS-DYNA in order to assess whether Material Model 5 could replicate the results from experimental tests, which would enable a more detailed investigation of the stress state in the sand specimen. Quasi-static test data was used to select the input data for the material model, and the model SHPB was set up to replicate the experimental conditions. The results show that Material Model 5 replicates the volumetric response provided as input data, but fails to predict the shear response observed in the quasi-static experiments. This was found to be due to the model treating the shear modulus as a constant rather than it increasing with strain, a feature which makes the Material Model 5 unsuitable for modelling SHPB tests on sand.

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