Experiments and simulation of split Hopkinson Bar tests on sand

P D Church[1], P J Gould[1], A D Wood[1] and A Tyas[2]

[1]QinetiQ, Fort Halstead, Sevenoaks, Kent, TN14 7BP, UK
[2]Sheffield University, Sheffield

pdchurch@qinetiq.com, pjgould@qinetiq.com, adwood@qinetiq.com, a.tyas@sheffield.ac.uk

Abstract. Static triaxial cell data and Split Hopkinson Bar data has been generated for well controlled dry and wet sand under confined and unconfined conditions. This has demonstrated that the dry sand is rate independent in its behaviour, whereas the wet sand exhibits a strain rate dependency in its behaviour. Simulations have been performed with the Lagrangian hydrocode DYNA using a Porter-Gould equation of state (EOS) and Johnson-Holmquist type constitutive model. Comparison with the raw strain gauge data is qualitatively reasonable, although some of the details of the trace are not reproduced. Sensitivity studies have also been performed, which has demonstrated some deficiencies in the constitutive model, relating to wave-speed and definition of moduli in a granular material. This has given some insights into how the constitutive model should be improved and which future experimental tests will be required.

1. Introduction

QinetiQ has a long standing interest in the characterisation of sands and soils particularly under blast and impact loading. The response of this type of material is described using an equation of state (EOS) and constitutive model. Generally the EOS is fitted to shock Hugoniot data and the compaction behaviour is described using a P-α type model [1, 2]. These models also attempt to describe the effect of moisture on the material, which is critical to their response. All these approaches are largely empirical and hence require a large database on the materials being investigated.

QinetiQ has developed an approach based on Quantitative Structure Property Modelling (QSPM) deriving physically based EOS directly, from knowledge of the constituents of the material [3]. For geological materials this is based on an implicit assumption that many geological materials are a derivative of different crystal forms of silica (i.e. crystobalite, coesite, α-quartz, and stishovite). This method has been demonstrated to predict the shock Hugoniots for a range of geological materials from dry sand to granite, including concrete.

The constitutive model used for these materials is based on the Johnson-Holmquist type model [4], which is a semi-empirical approach to describing the pressure hardening of the material and usually features a simple tensile failure model. This model requires a significant amount of material data to describe the effect of moisture content, which are obtained from static triaxial compression tests. A key issue is the validation of these material models under high strain rate loading. A standard test for achieving this is the Split Hopkinson Pressure Bar (SHPB). This paper describes the application of these models to high strain rate SHPB experiments.

Journal of Physics: Conference Series **500** (2014) 112018 doi:10.1088/1742-6596/500/11/112018

2. Experiments

The quasi-static compression tests are based on the Multi-Axial Compression (MAC2T) triaxial testing rig developed at the University of Sheffield [5]. The rig is unique in the World in that it performs true triaxial tests on geological materials, using three, independent loading actuators, capable of >1GPa loading, as shown in figure 1. 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. To retain the samples in these tests, the 50mm sand specimen is contained in a bespoke "loading cube", allowing load to be applied actively on one axis (smallest face in figure 1), with the load required to prevent displacement of the cube faces on the other two axes being generated passively by using displacement control to prevent the movement of these faces (larger faces in figure 1). The testing cube is fabricated from plates of heat-treated EN30B steel with a yield strength >1,030MPa, with the faces of the six separate elements of the cube machined to a tolerance of <5microns. The four passive faces of the cubes are connected using small coach screws on spring washers to hold these faces of the cube in place pre-loading, but allow movement of the faces if required during loading with negligible resistance. This allows the load to be applied actively on one axis, with the load required to prevent displacement of the cube faces on the other two axes being generated passively by using displacement control to prevent the movement of these faces. One great advantage of this test is that it is possible to perform a truly hydrostatic compression test and thus this data does not need to be inferred and this work is progressing. This means that the true compaction behaviour of the material can be determined for the first time.

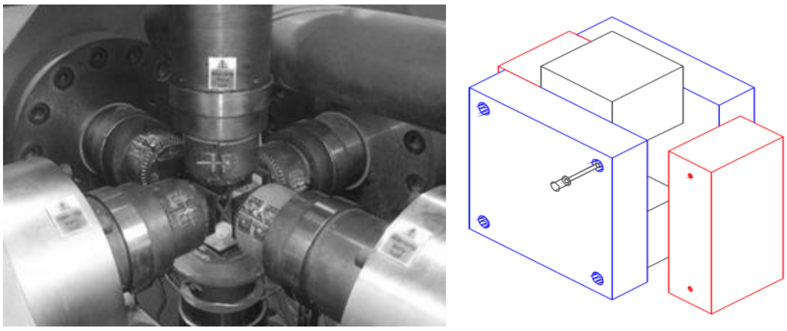

Figure 1. MAC2T triaxial rig for sand and novel platen design for loading cube.

For medium strain rates a standard SHPB apparatus is used [6] and the specimens are tested in the confined and unconfined conditions as shown in figure 2, with confinement provided by the presence of an EN24T steel strain-gauged annulus. It should be noted that in the unconfined condition the specimen is actually slightly confined using paper to maintain its geometry.

Preparation of the sample was as follows. With the output bar held vertically in a purpose-made jig, the gauged ring was placed on the end of the bar to the required position. A thin (<0.01mm thickness, >0.01g mass) aluminium foil disk was placed on the face of the output bar inside the gauged ring. The sand sample was prepared to the required moisture content and a pre-weighed amount was carefully poured into the ring. A second foil disk was placed on top of the soil sample and the soil was leveled to achieve a sample length of ~5mm. The second foil disk was then secured to the confining ring using a very small amount of cyano-acrylate adhesive, thereby confining the sample. The output bar was then carefully placed horizontally in a set of linear bearings, and the sample in the gauged confining ring offered up to the co-axial incident bar. A key point is that the measurement of the specimen length, which is critical in SHPB analysis, cannot be made directly. Instead, measurement of the sample length is achieved by scoring marks on both the input and output Hopkinson Bars, and using a vernier microscope to calculate the lengths between the marks and the ends of the bars, and the pair of marks after insertion of the test sample. Using this method the density can be controlled to an accuracy of ±0.01g/cc. At present this method has been used for dry sand and sand with 5% moisture content and work is continuing to refine the preparation technique for higher moisture contents, although this is not trivial.

In the SHPB tests, a 400mm long, 25mm diameter stainless steel striker bar was loaded into a 27mm diameter gas gun and fired at a 1500mm long 25mm diameter stainless steel incident bar, giving rise to an incident pressure pulse. The soil samples were confined using a 25mm inner diameter, 35mm outer diameter EN24T steel confining ring, with 2.8mm wide 1mm thick locating flanges to facilitate positioning of the ring on the pressure bars, and prevent loss of retained soil.

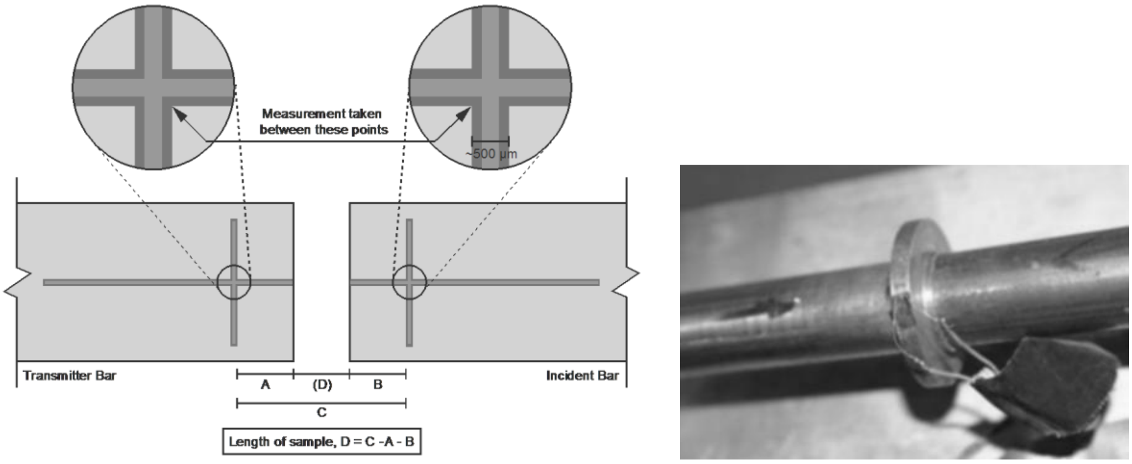

Figure 2. SHPB set-up for confined test.

An interesting result is that for the dry sand the behaviour appears to be largely strain rate independent, whereas there is a strain rate dependency for moist sand, which is consistent with other similar studies [7-9], as demonstrated in figure 3.

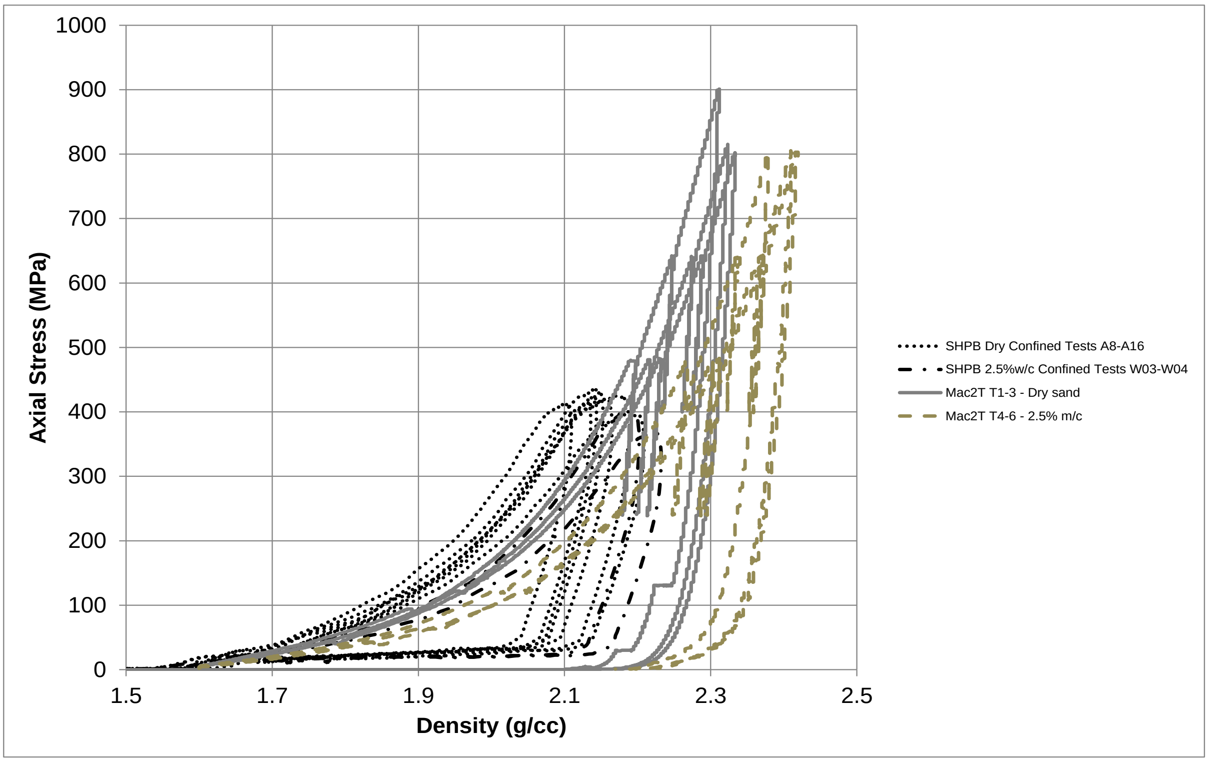

Figure 3. Comparison of results for MAC2T and SHPB for dry and moist sand.

The main reason for this is that the moisture will migrate through the material depending on the rate of loading, whereas the granular friction between individual grains is not a strong function of loading rate. However, there comes a point where the rate of loading is too high for the moisture to be able to migrate, as in a shock wave, where the material response is dominated much more by the EOS than the constitutive model. A key question is whether this behaviour is truly rate dependent or due to other effects that are not well represented in the model. The purpose of the simulations was to provide some insight into this issue.

3. Simulations

The EOS was based on the Porter-Gould approach described above and the constitutive model was fitted to the QS data for both the dry and moist sand. There was no strain rate dependency in the model and the simulations were used to determine how well the models predicted the high strain rate data from the SHPB tests.

The simulations were performed using the Lagrangian hydrocode DYNA3D and were only performed on the confined tests. A key lesson learnt for comparing the simulations with the experiments is that it is critical to compare with the input, reflected and output pulses within the bars, rather than relying on the classical one-wave or three-wave analysis. The reason for this is that two of the fundamental assumptions in the SHPB analysis are that the specimen is in stress equilibrium and there is no volume change within the sample during the test. The issue is that the nature of the material model being used will actually determine whether the sample is in equilibrium in the simulation. This approach can become a circular argument and lead to erroneous conclusions on the validity of the model. Another important consideration is the mesh resolution required to adequately resolve the waves and the specimen behavior. A mesh resolution study was performed and a mesh size of 1mm was selected to be a good compromise between run time and accuracy. This resolution was sufficient to resolve the Pochhammer-Chree oscillations due to the elastic waves propagating along the bar material.

The comparisons between the simulation and experiment are shown for the reflected and output pulses in figure 4.

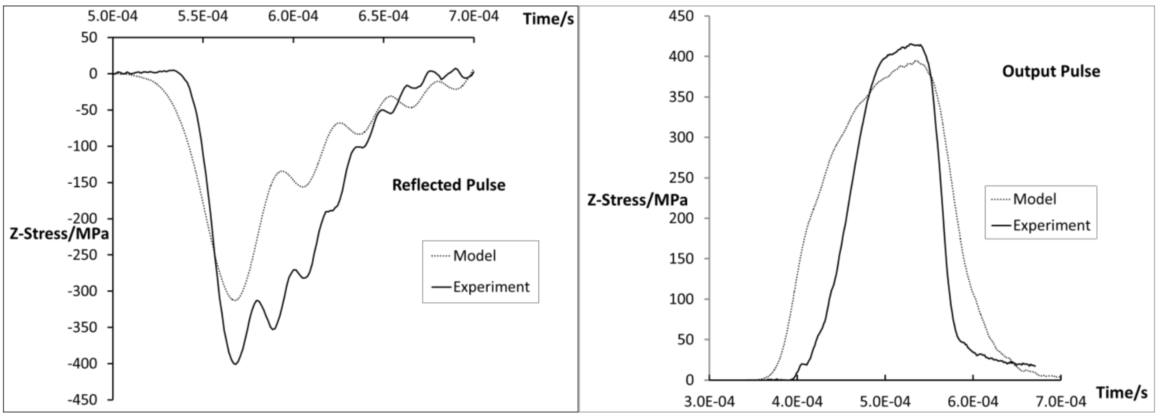

Figure 4. Comparison with reflected and output pulses.

Qualitatively the comparison is reasonable between the model and experiment for general shape, but it is clear that some of the details are not reproduced. In particular the output pulse length is too large indicating that the wave speed is not correct and this is not due to dispersive effects since the model predicts the Pochhammer-Chree oscillations in the input pulse. The sample in the simulation absorbs more energy than in reality from the input pulse and then transmits that to the output bar. Also the initial responses seen in the reflected waves contain detail about differences in response for the continuum representation of a granular material. A sensitivity study was performed investigating the effect of moisture content and initial density of the sand on the output traces as shown in figure 5, below.

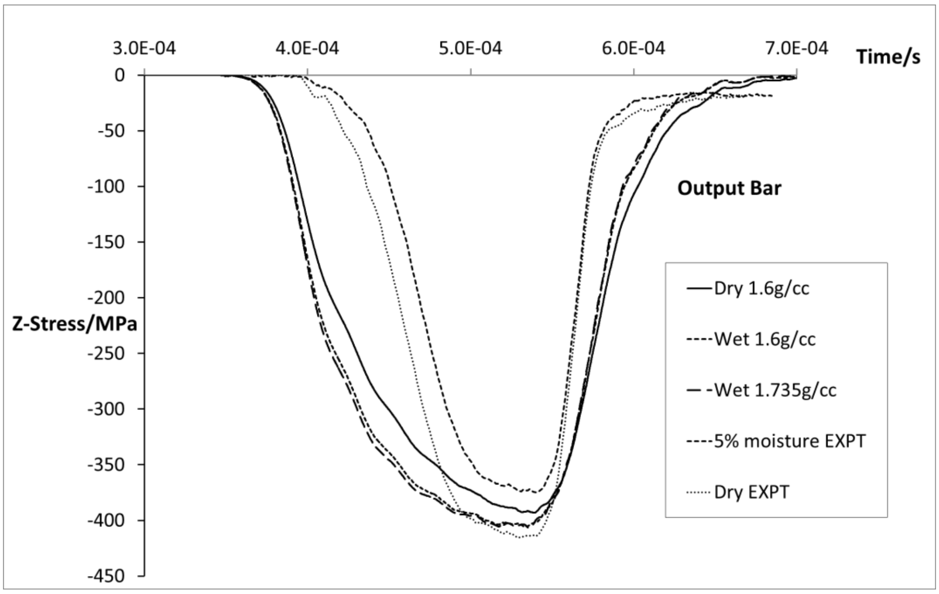

Figure 5. Effect of moisture content.

This actually shows that the output pulse is not that sensitive to the moisture content in the experiment between dry sand and sand with 5% moisture content. However, it does demonstrate the sensitivity of the result to the initial density in the model, which is exhibited in both the pulse length and wave-speed and supports the assertion that the initial density needs to be measured very accurately. Given that the wave-speed in the model is driven by the modulus it raises the question as to how one actually defines the shear modulus of a granular material such as sand. This is quite difficult since measurements using ultrasonic methods for the wave speed in the sand would be a mixture of the wave-speed in the silica grains which is very large compared to the air gaps in between the grains. However, another definition of the modulus is the slope between the stress and strain, which can give a very low value due to the general compaction behavior of sand. At present these two measurements give anomalously different results which vary by an order of magnitude. This causes great difficulty for the simulations since the model forms used in the hydrocodes actually need defined moduli in a continuum, in order to calculate the wave speeds in the sand. Thus one is immediately hampered by an artificial construct in the hydrocode; that is the need to separate the hydrostatic and deviatoric components. This is further exacerbated by the fact that the hydrocode is invariably written for a metal response featuring Von Mises plasticity yield surfaces, for example, whereas the material response in these material is much more driven by the modulus and pressure-dependent shear interactions between sand grains.

There is also the question of how this is related to the microstructural changes in the sand, such as grain fracturing for example. Local microstructural rearrangements are probably responsible for the difference in wave structures as the waves cross interfaces. At present the existing and commonly used models are not capable of resolving these effects. The future work is intending to derive more physically based constitutive models using the MAC2T triaxial test data such that these effects can be related directly to the microstructural mechanisms. All this means that it is not necessarily straightforward to determine whether the effects observed are rate dependent as all the mechanisms are closely interrelated. From an experimental point of view it is difficult to separate the rate-dependence of shear effects from pressure-dependence given that most easily achievable high rate experiments also involve high pressures. In this scheme the SHPB data would only be used to validate the model and would not be part of the derivation process.

This integral approach is driving the experimental program and particularly the need to perform truly hydrostatic measurements in the sand so that some of these components can be isolated properly. Indeed a key challenge with understanding the behaviour of granular materials is to separate the key deformation mechanisms to allow the construction of a physically based constitutive model and to determine from a physical basis which effects are truly fundamental to the material response and which are second order effects, in predicting the ballistic penetration and blast loading behaviour, for example.

At present the models described do predict the ballistic penetration data quite well and certainly within the experimental spread. However as stated these models rely on having the test data to fit them. One of the key advantages of the Porter Gould approach is that it potentially allows a rapid assessment of a weapon system in a granular material such as soil for which there is very little experimental data. This is important when one is trying to de-risk a new ballistic or weapon concept and determine where the effort should be focused in terms of maximizing the effect in the granular material.

4. Conclusions

This paper has outlined a robust testing technique for sand based on triaxial testing such that the stress system can be properly controlled. Also, robust methods for reliable SHPB testing has been described and shown that measurement of the specimen initial length is vital to provide reliable data. Differences in experimental data for wet and dry sand are reflected in different wave-speeds and moduli. Existing models are not capable of resolving these effects and this has raised issues as to how the modulus is defined for a granular material. This information is also important for understanding the microstructural changes in the sand. All this has profound implications for the hydrocode models which makes implicit assumptions concerning elastic moduli and the yield surface behaviour. This approach is driving the need to separate the material response mechanisms and hence for new experiments on these materials such as a true hydrostatic compression tests.

References

[1] Hermann W 1968 *J. Appl. Phys.* **40** 6 2490-99.
[2] Grady D 2003 *AIP Conf. Proc.* **706** 205-8
[3] Church P, Porter D, Cullis I, Townsley R, Fishpool D and Taylor E 2006 *Proc. 1st. Int. Conf. Impact Cratering in the Solar System* (Njordwick, Holland)
[4] Johnson G and Holmquist T 1985 *High Pressure Science and Tech.* **2** 981-4
[5] Petkovski M 2013 *Journal of Engineering Mechanics-ASCE* **139** (5) 612-28
[6] Bragov A M, Lomunov A K, Sergeichev I V, Tsembelis K and Proud W G 2008 *Int. J. Imp. Eng.* **35** 967–76
[7] Proud W, Chapman D, Williamson D, Tsembelis K, Addiss J, Bragov A, Lomunov A, Porter D, Cogar J and Borg J 2007 *AIP Conf. Proc.* **995** 1403-8
[8] Abdel-Malek S, Meyer L and Herzig N 2012 *J. Phys.* IV **26** 1018-23
[9] Bragov A M, Lomunov A K, Sergeichev I V, Proud W, Tsembelis K and Church P 2005 *Tech. Phys. Lett.* **31** 530-1