Proceedings Paper:

Clarke, S.D., Rigby, S.E., Tyas, A. et al. (5 more authors) (2016) Reflected pressures from explosives buried in idealised cohesive soils. In: Proceedings of the 24th Military Aspects of Blast and Shock. 24th Military Aspects of Blast and Shock, 19-23 Sep 2016, Halifax, Nova Scotia, Canada. MABS .

REFLECTED PRESSURES FROM EXPLOSIVES BURIED IN IDEALISED COHESIVE SOILS

S. D. Clarke[1], S. E. Rigby[1], A. Tyas[1,2], S. D. Fay [1,2], J. J. Reay[2], J. A. Warren[1,2], M. Gant[3], I. Elgy[3]

[1]*Department of Civil & Structural Engineering, University of Sheffield, Mappin Street, Sheffield, S1 3JD, UK;*
[2]*Blastech Ltd., The BioIncubator, 40 Leavygreave Road, Sheffield, S3 7RD, UK;*
[3]*Defence Science and Technology Laboratory (Dstl), Porton Down, Salisbury, Wiltshire, SP4 0JQ, UK.*

ABSTRACT

Recent work has concentrated on the characterisation of the temporal and spatial impulse distribution of blast form buried charges. A new soil container preparation methodology has been created to allow for the generation of highly repeatable, tightly controlled clay beds which will allow clays of different undrained strengths to be generated. Tests using these well controlled beds has allowed for an improved understanding into which geotechnical parameters govern the impulse delivered by a buried charge. Namely in the current programme of work this is an investigation into the 'undrained strength' of a cohesive material as an indicator of potential impulse output.

Initial results are compared against previously published work on cohesionless soils (sands) to try to establish the full range of loading which can be generated by a buried charge.

INTRODUCTION

Our knowledge of the effect soil has on the output of buried charges has rapidly expanded over the past decade. We now understand that moisture content and density play an important role in the generated output from a buried charge. Over the past 6 years the Sheffield Blast and Impact Dynamics group have been developing and refining techniques to further our understanding of the behaviour of sands and gravels in blast events [1-3]. The aim of the research contained within this paper was to extend this knowledge to develop understanding of the effect of the geotechnical conditions on the blast generated by a buried explosive in cohesive soils (clays). The ultimate goal of this is to eventually develop a framework which looks at the grain sizes present within any given soil and is able from this to predict the impulse (and distribution) from a buried explosive for a range of moisture contents.

To date there have been no tests carried out on clays where the geotechnical parameters have been scientifically controlled. Previous research has shown that for sands and gravels the saturation has an important role on the generated impulse [4-7]. The current paper aims to provide new insight into how the moisture content / air voids affects soils where the spaces between the soil particles are orders of magnitude smaller than in sands and gravels. The premise here is that soils with a greater percentage of fine particles, and hence lower permeability will give higher confinement to the blast and hence develop a greater impulse than in consummate tests with coarse grained soils [8].

The tests utilize a slurry made from Kaolin (a clay mineral), which is then consolidated under a hydraulic ram to achieve set moisture contents. Due to the relatively long time scales required to generate uniform large scale clay samples, testing of this nature has never been performed before, with some tests consolidating for as long as three months.

The secondary, complementary aim of the testing conducted is to test the hypothesis that impulse is inversely proportional soil shear strength [9]. Whilst shear strength may be an indicator of impulse from coarse soils, there is currently no evidence to show that this same link is true for fine grained cohesive soils where the behaviour is essentially always governed by the soil's permeability.

This paper details the results from tests using a new consolidation apparatus to generate soils of differing water contents and hence also different densities and undrained shear strengths. In each tests the reflected pressures are measured by an array of Hopkinson pressure bars (HPBs) as described below.

APPARATUS

The University of Sheffield operates an explosive testing facility in Buxton, Derbyshire, UK. It is at this location that the testing has been conducted. The experimental apparatus has been described repeatedly in previous publications so only the most salient features will be repeated here; full details can be found in Ref. [3]. The apparatus enables pressure-time histories to be measured at specific locations on a rigid plane above a buried charge. In the current tests, a 100 mm thick steel plate is attached to the underside of two massive reinforced concrete 'goalpost' frames. 10.5 mm diameter holes are drilled through the plate in two perpendicular arrays at 25 mm centre-to-centre spacing. Holes are drilled out to ±100 mm from the central hole, which is common to both arrays. 3.25 m long, 10 mm diameter steel HPBs are inserted through the target plate such that their faces sit flush with the loaded face of the plate. Pairs of semiconductor strain gauges are mounted onto the perimeter of the HPBs, 250 mm from the loaded faces, in a Wheatstone bridge circuit to cancel out any bending effects in the bars. The strain-time history from the gauges is therefore used to measure the reflected pressure-time history acting at specific points on the target plate.

The explosives were encased in a 3 mm thick PVC container, with the cap removed to increase the repeatability of the tests [3]. Hence, the explosives were buried to a depth of 28 mm (25 mm to the top of the charge had the cap not been removed). The stand-off was increased to 140 mm to prevent excessive pressures from yielding the bars. The soil container measured 500 mm diameter and 375 mm height. The experimental apparatus is shown in Figure 1b.

SOIL CONDITIONS

Nine tests were conducted in total. The consolidation apparatus (Figure 1a) allows three samples to be prepared in parallel (with the aim of providing identical conditions). One of the advantages of using Kaolin is that it has been heavily utilised in the Geotechnical engineering community and so its behaviour is well documented. Previous researchers have formulated a link between the consolidation pressure and the undrained strength of the final sample [10]. The consolidation pressure also affects the density of the final sample and as in all the tests the clay was saturated, the water content also varies. Table 1 shows the target conditions for the three test series (with three tests in each series).

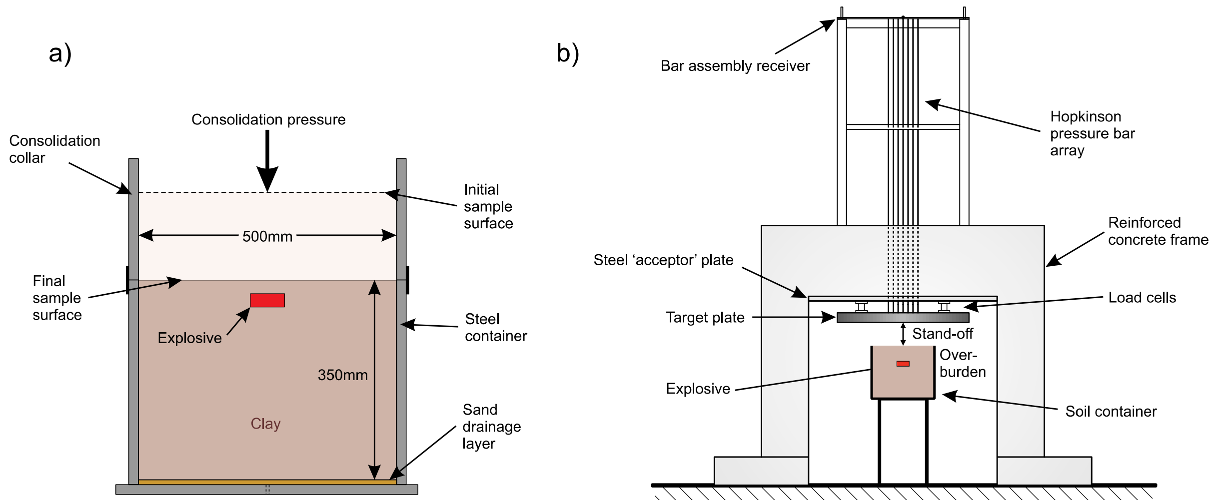

Figure 1: a) Schematic of consolidation apparatus, b) schematic of testing apparatus

Table 1: The designed test series

Test series	Consolidation pressure (kPa)	Undrained strength (kPa)	Moisture content (%)	Density (Mg/m^3)
A (1-3)	72.9	24.0	55.9	1.75
B (4-6)	139.4	45.8	51.2	1.87
C (7-9)	207.5	68.2	48.3	1.95

The method of mixing the kaolin from a 100 % moisture content slurry (1 kg of water : 1 kg of kaolin) is simplified by rounding the mixes for each test series to the nearest kilogram to aid preparation on site. This is the reason why the values in Table 1 are not simply scaled factors of each other, as they are a product of the mixing process. The mixes involved 57, 60 and 62 kg of kaolin for series a-c respectively. The kaolin used was Speswhite China Clay, which is a highly refined kaolin of ultrafine particle size. 76-83 % of the kaolin is finer than 2 microns with 99.5% being finer than 10 microns. Due to the mixing and consolidation process it is not possible to generate samples that are not fully saturated.

EXAMPLE RESULTS

In all test presented in this paper, the data were recorded at 14-bit resolution with a sample rate of 1.56 MHz. The recording software was triggered via a voltage drop in a breakwire channel, with a new breakwire wrapped around the detonator for each test. The timebase of the pressure signals was shifted by 50 μs to correct for the delay between the pressure acting on the face of the HPB and being recorded at the strain gauge location.

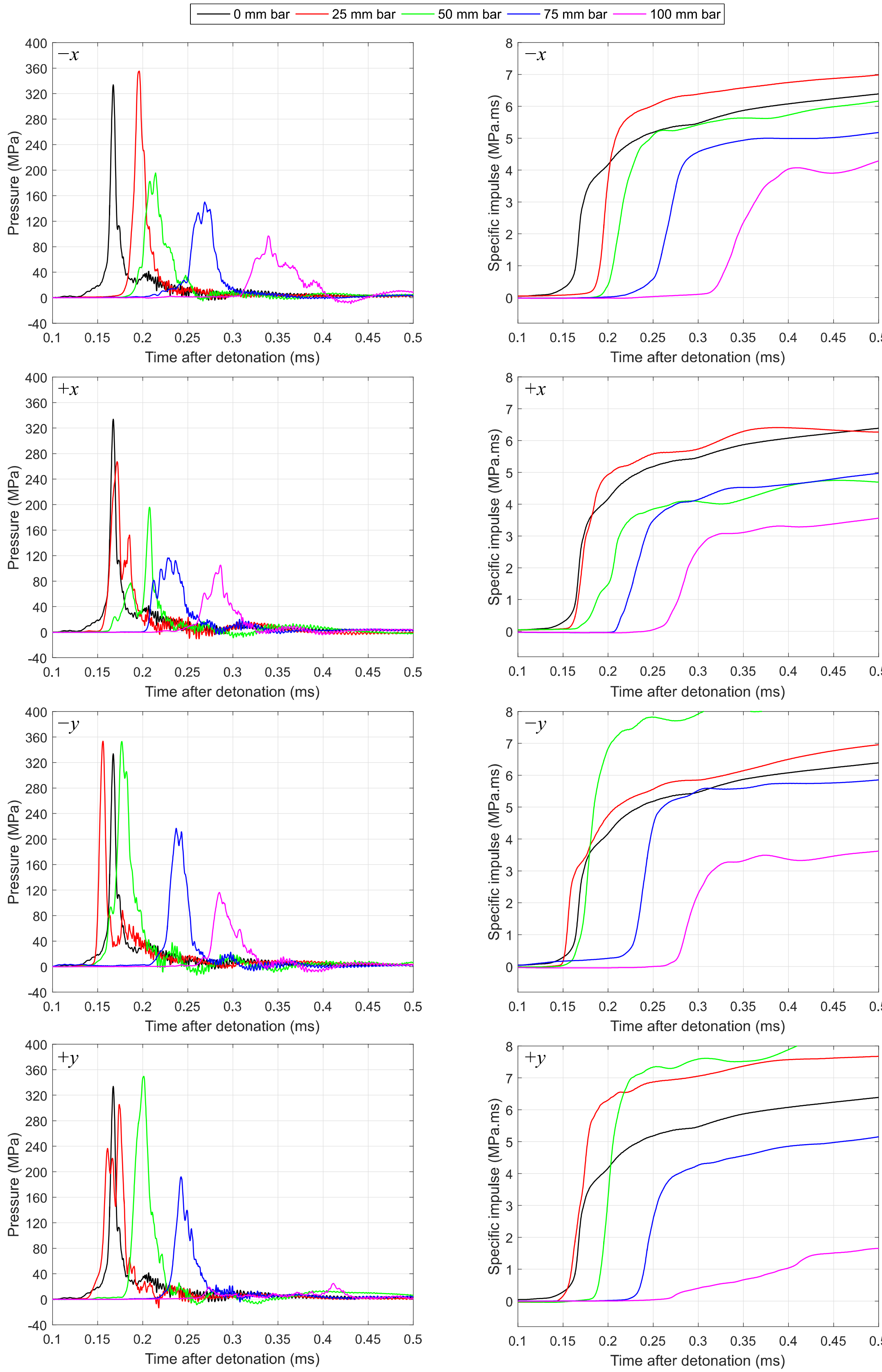

Figure 2: Example pressure-time and impulse-time histories for all 4 arrays, from a single test (a2)

Figure 2 shows the pressure and specific impulse histories from a single test with the explosive buried to a depth of 28 mm. The specific impulse was determined from cumulative integration of the recorded pressure histories. Each subplot shows signals from the bars located between 0 and 100 mm from the plate centre, in each of the $-x$, $+x$, $-y$ and $+y$ arrays respectively. The central 0 mm bar is common to all 4 arrays and hence is repeated in each subplot.

The peak pressure and peak specific impulse for the 75–100 mm bars show a marked decay when compared with the 0-50 mm region in which *generally* there is quite similar maximum peak pressure. The 0-50 mm bars appear similar in magnitude and form (some of the 50 mm traces are notable exceptions). As these five bars all lie within the projected area of the charge, it is likely that this is a feature of the charge geometry and that the central area of the target is confined by the expanding soil annulus. Figure 3 shows the test setup pre- and post-test. It should be noted that Figure 3b is not from a high speed video, but actually shows the static state of the clay material after the test. Here any areas of venting of the detonation products can clearly be seen. The clay 'wall' seen in this image is likely due to the interaction of the shock wave with the steel boundary and lies outside the instrumented region of the plate.

Figure 3: a) pre-test arrangement showing level surface of clay bed,
b) post-test showing solidified flow of material across the target plate.

The pressure histories shown in Figure 2 are indicative of the loading mechanism caused by the impact and lateral spreading of a highly pressurised fluid annulus, hypothesised by Grujicic [11], in fact Figure 3b actually shows the remains of this annulus. As the expanding soil annulus propagates across the loaded face, the form of the imparted pressure becomes lower in magnitude and longer in duration, and at any instant in time there appears to only be a small area of the target being loaded, with the pressure traces returning to zero shortly after arrival, and passing, of the soil annulus. Qualitatively, there appears to be a good degree of bar-to-bar repeatability for both pressure and impulse.

COMPILED RESULTS AND DISCUSSION

For each series the tests the results for each bar location have been averaged so that the effect of the undrained strength can be seen. Peak reflected pressure, peak specific impulse and time to peak pressure are presented in Figure 4.

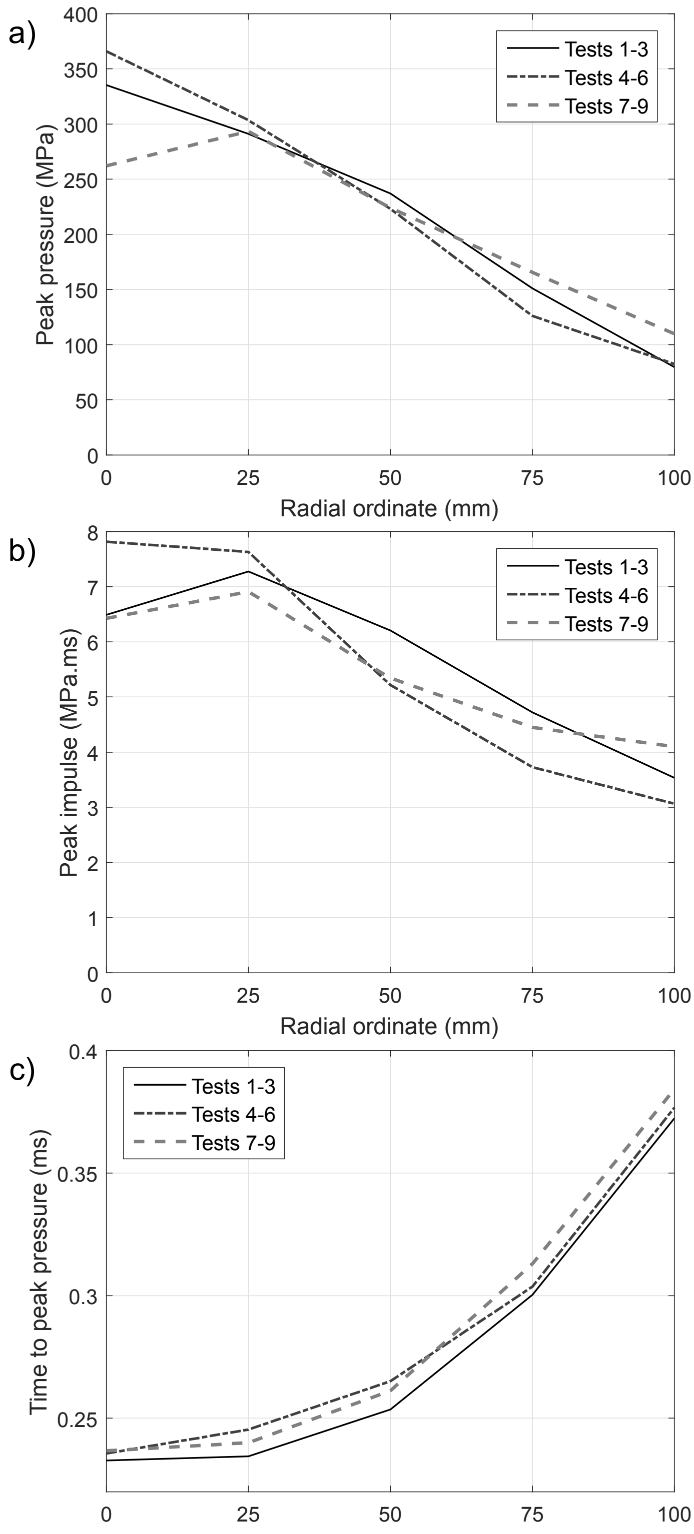

Figure 4: Compiled average a) peak reflected pressure, b) peak specific impulse, and c) time to peak pressure for each of the clay series.

The distribution of mean peak pressure distribution shows a rapid decay from with the peak pressure varying from ~ 325 MPa for the central bar to approximately 100 MPa at 100 mm from the centre. This is very similar to the Leighton Buzzard tests shown by Rigby et al. [8]. The peak specific impulse ranges from ~7 MPa.ms above the charge to ~4 MPa.ms at the 100 mm bar.

The critical observation of the results presented is the *lack* of variation between the three test series. There are no notable differences between any of the series plots in Figure 4. This shows that while soil shear strength may be an indicator of impulse from charges buried in cohesionless soils, it is certainly not the case for undrained shear strength in cohesive soils.

The effects of moisture content and density in the current test series are also designed to cancel each other out, as moisture content increases (+16%), so the density decreases (-11%). This would mean that any trends observed would only be attributable to the undrained strength rather than other geotechnical parameters. This gives a higher confidence in the fact that strength is a secondary factor in governing the output from a buried charge with moisture content and density being more important.

SUMMARY AND CONCLUSIONS

Three test series have been conducted in total on explosives buried in a Clay soil. Samples were generated using a hydraulic press to allow creation of ideal clay bed, whose geotechnical parameters are easily determinable. Between each series the undrained strength which the samples attained was varied in a linear manner allowing the investigation of undrained shear strength as a 1^{st} order predictor in the output of buried charges.

In each test, reflected pressure was measured at 17 locations within the central 200 mm diameter region of a rigid target plate using Hopkinson pressure bars, allowing the spatial and temporal distribution of loading to be recorded. The individual pressure traces show a high degree of similarity with tests done on other saturated soils.

The collated data for each test series shows clearly that the influence of undrained strength on the generated peak pressure, peak specific impulse and time to peak pressure is minimal, albeit for cohesive soils. Numerical models for soils based around such parameters should first focus on the effects of moisture content and density when predicting the output from buried charges, rather than focussing on second order factors.

ACKNOWLEDGEMENTS

This work was funded by EPSRC grant EP/L011441/1: Understanding the Role of Soil in Subsurface Explosive Events and forms part of the Dstl-funded *Characterisation of Blast Loading* project.

REFERENCES

[1] S. D. Clarke, S. D. Fay, J. A. Warren, A. Tyas, S. E. Rigby, J. J. Reay, R. Livesey, and I. Elgy. Geotechnical causes for variations in output measured from shallow buried charges. *International Journal of Impact Engineering*, **86**:274–283, 2015.

[2] S. E. Rigby, S. D. Fay, S. D. Clarke, A. Tyas, J. J. Reay, J. A. Warren, M. Gant, and I. Elgy. Measuring spatial pressure distribution from explosives buried in dry Leighton Buzzard sand. *International Journal of Impact Engineering*, **96**:89–104, 2016.

[3] S. D. Clarke, S. D. Fay, J. A. Warren, A. Tyas, S. E. Rigby, and I. Elgy. A large scale experimental approach to the measurement of spatially and temporally localised loading from the detonation of shallow-buried explosives. *Measurement Science and Technology*, **26**:015001, 2015.

[4] S. D. Clarke, S. E. Rigby, S. D. Fay, A. Tyas, J. J. Reay, J. A. Warren, M. Gant, R. Livesey, and I. Elgy. 'bubble-type' vs 'shock-type' loading from buried explosives. In: *Proceedings of the 16th International Symposium on Interaction of the Effects of Munitions with Structures (ISIEMS16)*, Florida, USA, 2015.

[5] D. M. Fox, X, Huang, D. Jung, W. L. Fourney, U. Leiste, and J. S. Lee. The response of small scale rigid targets to shallow buried explosive detonations. *International Journal of Impact Engineering*, 38(11):882–891, 2011.

[6] J. Q. Ehrgott, R. G. Rhett, S. A. Akers and D. D. Rickman. Design and fabrication of an impulse measurement device to quantify the blast environment from a near-surface detonation in soil. *Experimental Techniques*, 35(3):51–62, 2011.

[7] D. M. Fox, S. A. Akers, U. H. Leiste, W. L. Fourney, J. E. Windham, J. S. Lee, J. Q. Ehrgott, and L. C. Taylor. The effects of air filled voids and water content on the momentum transferred from a shallow buried explosive to a rigid target. *International Journal of Impact Engineering*, 69(0):182–193, 2014.

[8] S. E. Rigby, S. D. Fay, A. Tyas, S. D. Clarke, J. J. Reay, J. A. Warren, M. Gant, and I. Elgy. Localised variations in reflected pressure from explosives buried in uniform and well-graded soils In: *Proceedings of the 24th International Symposium on Military Aspects of Blast and Shock (MABS24)*, Halifax, Canada, 2016.

[9] D. Fiserova. Numerical analyses of buried mine explosions with emphasis on effect of soil properties on loading.

[10] PhD thesis - Cranfield University, 2006.

[11] J. H. Atkinson, D. Richardson, and P. J. Robinson. Compression and extension of k0 normally consolidated kaolin clay. Journal of Geotechnical Engineering, 113(12):1468–1482, 1987.

[12] M. Grujicic and B. Pandurangan. A combined multi-material Euler/Lagrange computational analysis of blast loading resulting from detonation of buried landmines. *Multidiscipline Modeling in Materials and Structures*, **4**(2):105–124, 2008.