Impulse transfer during sand impact with a solid block

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A vertical pendulum apparatus has been used to experimentally investigate the impulse and pressure applied by the impact of wet synthetic sand upon the flat surface of a back supported solid aluminum test block. The transferred impulse and maximum pressure applied to the sample were both found to decrease with increasing standoff distance between the bottom of the sand layer and the impact face of the solid block. A particle based simulation method was used to model the sand’s acceleration by the explosive and its impact with the test structure. This method was found to successfully predict both the impulse and pressure transferred during the tests. Analysis of the experimentally validated simulations indicates that the momentum transmitted to the test structure is approximately equal to the free field momentum of the incoming sand, consistent with the idea that the sand stagnates against a planar surface upon impact. The decrease in transferred impulse with increasing standoff distance arises from a small reduction in sand particle velocity due to momentum transfer to air particles, and an increase in lateral spreading of the sand particles as the standoff distance increased. This spreading results in a smaller fraction of the sand particles impacting the (finite) area of the test sample impact face.

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1. Introduction

The pressure applied to the surface of an elastic half-space by the reflection of acoustic pulses propagated through water is twice that of the incident disturbance because the reflected and incident amplitudes are equal and in-phase at the surface [1]. Conservation of momentum then dictates the impulse transferred to the half-space is twice that of the incident pulse. Analogous amplifications of the impulse and pressure accompany the reflection of high intensity shock fronts with engineering structures, causing sometimes large permanent deformations and fracture. In this case, the nonlinear behavior of the fluid in which the shock is propagated can lead to even higher reflection coefficients, especially in air [2] and even in water if the pressures close to the source of the disturbance are sufficiently high. As a result, the investigation of materials and structures with improved resistance to impulsive loads applied by the impingement of shocks propagated through air [3–6] and water [2,7–9] has attracted considerable interest.

Foundational work by G. I. Taylor [10] during World War II showed that the shock reflection from a thin, air-backed movable plate was substantially reduced for water propagated pulses because plate motion resulted in the development of a tensile reflected pulse, which cannot be supported in shallow water, leading to its cavitation. This fluid structure interaction (FSI) at the surface of low inertia plates substantially reduced the pressure and impulse applied to a light (thin) movable plate. Several studies have subsequently confirmed this prediction [3,11], and led to an interest in the use of sandwich panels with thin faces supported by a compliant core to mitigate shock loads [12–14]. Controlled experiments conducted in the laboratory with air [15] and water shock tubes [16,17] have enabled the conditions needed to induce strong FSI effects to be experimentally studied. Other studies with explosive charges have been used to impulsively load instrumented targets to record the transmitted pressure and impulse [18,19]. Numerous analytic and numerical simulation studies have also explored cavitation at the fluid–structure interface, and investigated structural designs that exploit the underwater FSI phenomenon [11,20–22]. Analogous studies have also investigated mitigation of air shock loading where the beneficial FSI with thin plates is more difficult to exploit [23–25].

While the response of structures to nearby air and underwater explosions is now quite well understood, the design of structures to resist the impulsive loads resulting from shallow buried explosions in soil is much less well developed. In particular, it is not clear if the FSI effect observed in underwater shock loading scenarios exists during the impulsive loading of a structure by soil. This is partly a consequence of the difficulty of conducting controlled experiments where the loading of a structure can be understood [6,26,27]. As
several groups have indicated, it is also compounded by the complexity of the analytical and numerical analysis required to (i) understand the mechanisms by which the detonation of a buried explosive accelerates soil, and (ii) predict the loads applied by this soil upon impact with a nearby structure [27–29]. Together, they have delayed a comprehensive characterization of the soil–structure interaction, and hampered the development of mitigation concepts.

Experimental work by Bergeron et al. [30] has provided important basic insight into the phenomena activated during the detonation of a small explosive charge buried within dry sand. They used high speed photography and pulse X-ray methods to characterize the sand plume. These observations led Deshpande et al. [31] to identify three temporal regimes associated with the detonation of a buried explosive. Initially, immediately following detonation, a compressive shock pulse travels through the soil [29,30,32]. Once the shock reaches the soil/air interface, the pulse is reflected, and sign converted to a tensile shock within the soil as a result of the large acoustic impedance difference between soil and air. The tensile pulse then results in spallation of the surface soil. The second regime coincides with expansion of the high pressure gaseous detonation products which push the soil; especially in the direction of least resistance which is normal to the soil surface for a shallow buried explosive. This causes the soil to acquire a velocity and momentum that are complicated functions of the soil density, composition, and the depth of burial, the mass, type, shape and manner of detonation of the explosive, and various properties of the foundation upon which the explosive is supported (soil type, degree of compaction and moisture content). This leads to the third regime of soil propagation: in our case, toward a target where it is arrested or undergoes reflection. If simply arrested at a surface oriented perpendicular to the direction of propagation, the soil would transfer its incident momentum to the structure, and if it were strongly reflected back towards the source, substantial impulse amplification would arise from momentum conservation considerations.

A variety of numerical modeling approaches have been used to analyze the velocity and density distributions, and thus momentum distribution, within a soil plume ejected by a buried explosion, and to investigate the ensuing soil–structure interaction during impact with a target [33,34]. These numerical schemes include coupled Lagrangian–Eulerian techniques implemented in commercial codes such as LS-DYNA [27,29] and ANSYS AUTODYN [28], as well as gridless Lagrangian approaches such as Smooth Particle Hydrodynamics (SPH) [35]. The Euler–Lagrange based methods require the use of a soil constitutive model that approximates the response of the soil during its initial compressive shock loading, during spallation, propagation through air, and upon impact with a structure. Either an empirical three-phase model [33]; a modified form of the Drucker Prager [36] approach, or a porous-material compaction model [37] have been widely used for this with varying levels of success. Deshpande et al. [31] recently proposed a micromechanical based approach to better model both wet and dry soil. While this approach held promise for analyzing the shock compaction process in a densely packed soil (where the particle–particle contacts were semi-permanent), implementations within LS-DYNA failed to properly analyze the ejection of low density sand from the surface. Furthermore, this model, like all other soil constitutive models, required calibration for each soil type and moisture level combination [38], since each have strong effects upon ejecta momentum. However, such calibrations also compensate for other effects such as non-modeled physics, inaccuracies of the numerical implementation scheme or the many other, often uncontrolled factors (such as the soil type below the explosive charge) that influence the characteristics of ejecta from buried tests.

To side-step many of the practical problems with soil impact experiments, Park et al. [39] recently reported a laboratory method for creating cylindrical sand slugs whose axial velocity (in the 50–100 m s\(^{-1}\) range) could be well characterized by high speed video techniques. They used a piston to push water saturated, moist, or dry sand columns through cylindrical tubes, which resulted in the ejection of sand slugs with an axial velocity gradient. By impacting sand slugs with axial velocities up to ~100 m s\(^{-1}\) against an instrumented Hopkinson pressure bar, they measured the pressure exerted by the sand, showing it to be well approximated by the sand stagnation pressure, \(p_{sv}\) where \(p\) is the instantaneous incident sand density and \(v\) its axial velocity just prior to impact with the flat end of the bar. They also discovered that the impulse transmitted to the bar was almost identical to that of the incident sand, consistent with a weak reflection of sand from the bar surface. These experiments then provided a data set that could be used to evaluate numerical simulation schemes.

Pingle et al. [40] and Liu et al. [41] proposed a discrete particle method to simulate the impact of a sand column aggregate. In this approach a particle contact law defined inter-particle contact forces. The behavior of a sand aggregate during its propagation could then be simulated using a molecular dynamics method, and interface with a finite elements package to analyze the impact of a structure impacted by a sand column. This simulation methodology successfully predicted the experiments of Park [39], and confirmed that the impulse transferred to a rigid, back supported solid plate by a sand slug impacting a rigid plate at zero obliquity was no more than 10% higher than that of the incident impulse.

Recently, an analogous coupled discrete particle–finite element based approach [42], has been combined with particle-based models of explosive events to simulate the interactions between high pressure explosive detonation products, sand, and air particles. This simulation has been interfaced to a robust finite element analysis method incorporating node splitting and element deletion to address crack growth, and used to investigate the effect of soil impact upon the deformation and failure of structures. The method is based on a Lagrangian formulation for the structure, but uses the particle based approach for the soil to avoid the errors often associated with arbitrary Lagrangian–Eulerian (ALE) methods and the computational expense of Eulerian approaches [43]. A second advantage is that the corpuscular method allows a simple treatment of the discrete particle interactions with the finite element modeled structure, which is difficult to represent with ALE or Eulerian methods. The method has been implemented commercially as the IMPETUS Afea Solver [44], and experimentally validated with dry and fully water saturated, spherically symmetric synthetic sand shells that were explosively accelerated by spherical charges against edge-clamped metal plates [45].

The aim of the work described here is to experimentally investigate the pressure and momentum transferred to a relatively rigid, back-supported aluminum block by a model buried explosive event. Hopkinson pressure bars were attached to the rear of the aluminum block so that the transmitted pressure resulting from sand impact could be measured, and its time integral (the impulse) determined. In a second series of experiments, the bars and apparatus that support them were clamped together and allowed to rise following impact of the aluminum block by the ejecta, thereby enabling the apparatus to act as a vertical pendulum, and the impulse transferred by the event to be independently measured. The results are then used, in conjunction with discrete particle based simulations to investigate the nature of the soil-structure interaction for this test geometry. It is shown that the simulation methodology predicts the impulse and pressure applied to the rigid structure, and the effects of varying the distance between the explosive charge and the test structure. It also reveals
new insight into the subtle, but significant interactions of sand particles with an elastically deforming test structure.

2. Test methodology

The impulse and pressure transferred to a back-supported solid aluminum block following impact by explosively accelerated wet synthetic sand was measured in a vertical impulse test apparatus constructed for the study at a test site operated by NEWTEC Services Group, Inc. (Edgefield, SC, USA). A detailed description of the experimental approach including an analysis of measurement error has been provide by Holloman [46].

2.1. Test geometry and procedures

The test sample, Fig. 1, consisted of a solid Al6061-T6 block with a square, 203.2 mm by 203.2 mm impact face and thickness of 82.6 mm, welded to a 4.76 mm thick square plate of the same alloy. Since the back plate supported only compressive loads, it was designed to be relatively thin. It contained a hole pattern to enable bolting to a vertical impulse test apparatus shown in Fig. 2. The pendulum was constructed from four Al6061-T6 vertical rods that were each 2 m in length and 5.08 cm in diameter, and also served as Hopkinson pressure bars. The large diameter was chosen to reduce the likelihood of plastic deformation at the impacted end of the bars. A variable mass weight could be bolted to the top of the pendulum to control the pendulum mass, and thus jump height during subsequent testing. The lower end of the four aluminum bars were connected with counter-sunk screws to a 2.54 cm thick A514 grade B lid was bolted to the sand box during the tests. The standoff distance between the top of the Datasheet® explosive and five detonators to accelerate a planar, 50 mm thick layer of wet (Type I) synthetic sand consisting of approximately 150–200 μm diameter amorphous silica particles (grade GL-0201Silica Glass Spheres, Mo-Sci Corporation). A layer of polystyrene foam was used to support five, millisecond delay, electric detonators (Dyno Nobel Electric Super SP/MS). A polyurethane foam pad with a hole pattern drilled to match the location of the detonators in the polystyrene layer was used to support a 300 g, 25.4 cm by 25.4 cm, by 3 mm thick Datasheet®. These five holes were each filled with 10 g of C4 plastic explosive to boost the detonation event. The polystyrene and polyurethane foams both had a density of approximately 33 kg/m³, and were used since they quickly disintegrate to effectively form an air cavity below the charge, and thereby reduced sensitivity of the tests to the properties of the foundation upon which the tests were conducted.

The steel box had a 25.4 mm thick steel top with a 203.2 mm by 203.2 mm square opening at its center through which the explosively accelerated sand was directed towards the test sample. The aperture was designed to be the same size as the bottom surface of the test block so only the bottom surface of the sample was directly impacted by the sand; the soil bed largely remained trapped inside the steel box or was expelled though circular side vents on the steel box, Fig. 2. The standoff distance between the top of the Datasheet® and the lower surface of the sample was systematically varied between 14 and 40 cm to modify the density and impulse of the sand column that impacted the test sample. The standoff distance was varied by adjusting the level of the test charge in the steel box while maintaining the lower surface of the test sample 8 mm above the opening of the steel plate covering the top of the box.

The set-up of a test began by adjusting the level of the Type II soil bed within the steel box. The test charge assembly was then centrally positioned on the sand bed, and a 50 mm high, 254 mm by 254 mm hollow aluminum guide box was placed on top of the Datasheet® to create a cavity. The Type II soil bed was then built up around the external sides of the aluminum guide with a steep angle to the soil bed below. The 5 cm deep aluminum mold cavity was then filled with 5.6 kg of a water saturated mixture of the silica

\[1 \text{ Datasheet is composed of 63% pentaerythritol tetranitrate (PETN), 8% nitrocellulose, and 29% acetyl tributyl citrate (ATBC) as an organic plasticizer (for simplicity it was modeled 100% PETN in subsequent simulations).}\]
micro-spheres (4.4 kg of the silica microspheres and 1.2 kg of water), and the aluminum guide removed. Finally, the A514B steel lid with its 203.2 mm by 203.2 mm central aperture, was attached to the top of the steel box, Fig. 2. The time between pouring the water saturated sand and initiating detonation of the charge was typically 30 min. Laboratory experiments to simulate the water drainage that occurred during this period indicated that approximately 20% (220 g) of the water drained from the Type I sand into the surrounding Type II sand during this 30 min period.

### 2.2. Sand velocity measurement

In order to characterize the sand front shape and its speed in the direction of the test sample, the pendulum and sand box cover plate were temporarily removed to enable the explosively accelerated silica micro-sphere overburden to be observed with a high speed Vision Research Phantom V12 video camera. Fig. 4 shows a time sequence of images collected during the first 426 ms following detonation. Detonation of the test charge configuration resulted in a relatively planar sand front, but with several higher speed sand spikes, Fig. 4(f), that extended beyond the primary sand front. Fig. 4(d) shows that at 284 μs after detonation, the left side of the sand front had a slightly higher velocity than the right, which may have resulted from detonator firing delay, and would result in non-uniform loading of some samples. The average sand front speed for test charges consisting of 300 g Detasheet plus an additional 50 g of C4 inserts with a 50 mm thick wet sand overburden, was approximately 300 m/s; just below the sound speed of air at the test site.

### 2.3. Vertical pendulum test mode

A photograph of the vertical pendulum with a solid test sample attached is shown in Fig. 5(a). The total weight of the pendulum consisting of the four Hopkinson bars (43.7 kg), the bottom 2.54 cm thick aluminum plate (6.064 kg), the solid cylindrical aluminum plate (12.6 kg), the solid aluminum block (11.65 kg), and attachment hardware (3.8 kg) was 77.8 kg. Trial tests indicated that reducing the pendulum’s height limit, steel weights each weighing 7.2 kg were added to the aluminum plate at the top of the Hopkinson bars, Figs. 2 and 5. Table 1 lists the mass of the pendulum, sample, and the counter-weights for each test.

During a test, impulse was transferred to the pendulum causing a time dependent rise in its height, \( h(t) \) which could be measured using a Vision Research Phantom V12 video camera. The images shown in Fig. 5 are still frames from the high speed camera for a test conducted at a standoff distance of 19 cm at (a) the moment of detonation, \( t = 0 \) ms and (b) at \( t = 472 \) ms when the pendulum had reached its peak jump height.

The impulse per unit area \( I \), transferred to a rigid plate of area \( A \) positioned at the lower end of a pendulum due to the application of a force, \( F(t) \), for time \( t_1 \) to \( t_2 \) is:

\[
I = \frac{1}{A} \int_{t_1}^{t_2} F(t) dt.
\]
This impulse imparts a velocity $v_2$ to the initially stationary pendulum of mass $m_p$ such that.

$$I = m_p v_2$$  \hspace{1cm} (2)

The height $h_{\text{max}}$ to which the vertical pendulum rises is related to $v_2$ by energy conservation via the relation.

$$\frac{1}{2} m_p v_2^2 = m_p g h_{\text{max}}$$  \hspace{1cm} (3)

where $g$ is the gravitational constant (9.81 m/s$^2$) and therefore the impulse transmitted to the pendulum through the test structure is

$$I = m_p \sqrt{2gh_{\text{max}}}$$  \hspace{1cm} (4)

Fig. 4. Sequence of high speed camera images following the detonation at $t = 0$ $\mu$s of a 300 g Detasheet buried below a 5 cm thick layer of wet silica glass micro-spheres. The lid of the containment structure has been removed to visualize the sand front. The measured sand front speed in the vertical direction was 300 m/s.

Fig. 5. Images from a high speed camera showing the pendulum jump in height, $h(t)$, for a 19 cm standoff test. a) Time $t = 0$ ms corresponds to the time of detonation and b) $t = 472$ ms corresponds to the time at which the pendulum reached its peak height.
The vertical impulse test apparatus shown in Fig. 2 was also used to measure the transmitted pressure. The four 2 m long pendulum arms were replaced with dimensionally identical Hopkinson bars that each had two strain gauges (manufacture by Vishay Precision Group) attached diametrically to the bar surface, 50.8 cm from the lower end of each bar. A protective layer of epoxy was applied to the surface of the bar where the strain gauges were attached to avoid detachments of the sensors during high intensity loading. The top of the bars were bolted to the test apparatus frame to eliminate bar sliding. The strain gauges attached to each bar formed a full Wheatstone bridge circuit, and the output voltage signal was amplified using a series of operational amplifiers. Each pair of sensors on a bar were connected to separate input channels of an analogue to digital converter which allowed four separate output voltage signals for the four bars to be recorded. Recording was initiated by a trigger signal coincident with the electrical pulse used to initiate charge detonation, and continued for a period of 4 ms.

The voltage-time waveforms recorded for a sand impact test with the solid aluminum block was used to determine the pressure applied by the back of the specimen to each bar. The pressure-time waveform for each bar was deduced from the axial strain of the bar, \( \varepsilon \), which could be determined from the voltage-time waveform using a relationship between the output and input voltages of the full Wheatstone bridge given by:

\[
\frac{V_o}{V_i} = \frac{GF^*\varepsilon(1 + \nu)}{2 + GF^*\varepsilon(1 - \nu)}
\]

where the gauge factor \( GF = 2.15 \), Poisson’s ratio \( \nu = 0.33 \), the input voltage \( V_i = 10 \) V, and the sensor output voltage, \( V_o \), is the output from each amplifying circuit. The stress at the sensor location on each bar was then calculated using Hooke’s law:

\[
\sigma_i = E\varepsilon_i
\]

where \( \sigma_i \) is the stress, \( \varepsilon_i \) the axial strain in the \( i \)-th bar, and \( E = 70 \text{ GPa} \) is Young’s modulus of the aluminum bar. The force applied to each bar, \( F_i \), was given by:

\[
F_i = \sigma_i A_b
\]

where \( A_b \) is the cylindrical cross-sectional area for each of the four bars. The pressure applied to the test structure was assumed to be given by:

\[
P = \frac{F_{\text{Total}}}{A_{\text{Sample}}}
\]

where \( F_{\text{Total}} \) is the sum of the four forces supported by the bars and \( A_{\text{Sample}} = 0.04 \text{ m}^2 \) is the test sample area impacted by sand.

Integration of the pressure-time curve was also performed to deduce the impulse-time relationship until elastic wave reflections from the upper end of the bars interfered with the signal. The time before the first reflection arrives can be deduced from the measured longitudinal elastic wave speed of Al6061-T6 which was 5350 m s\(^{-1}\). Since the strain gauges were placed 50.8 cm from the impacted end of the 2 m long bars, the first (sign reversed) reflection from the distal end of the bar arrived 558 \( \mu \text{s} \) after the direct signal.

3. Experimental results

We begin by experimentally examining the sand loading against the solid aluminum block and measure the impulse and pressure that are transferred. Simulations using the IMPETUS Afea Solver approach are subsequently used to resolve the sand interaction with the solid structure, which could not be observed visually because of sand flow around the test structure. We then use the experimentally verified simulation methodology to investigate the sand—structure interaction for the model event.

![Fig. 6.](image)

a) Dependence of impulse transmitted to a solid aluminum block upon the standoff distance. The transmitted impulse was determined from the jump height of the vertical pendulum. Impulse was also measured from the integration of the pressure-time curves in part b) for 0.558 ms from the initial rise in impulse. b) Dependence of pressure transmitted to the distal side of the solid aluminum block upon standoff distance.
3.1. Vertical pendulum impulse measurements

The impulse transmitted by sand to the solid aluminum block was first deduced from the pendulum mass and jump height data summarized in Table 1 using Equation (4). This impulse is shown (solid squares) as a function of standoff distance in Fig. 6(a). The impulse was observed to decrease from approximately 14 kPa s for a standoff distance of 14 cm, to approximately 8 kPa s at a standoff distance of 40 cm. The error bars shown with the data were estimated from the uncertainty in pendulum height measurement during the exposure time of a high speed video image and estimates of the parallax error. The impulse decreased linearly with standoff distance at a rate of \(-0.20 \text{ kPa s cm}^{-1}\).

3.2. Hopkinson bar pressure measurements

The pressure-time signals measured with the Hopkinson bar test arrangement are shown in Fig. 7 (solid black lines) for each standoff distance. Time \(t = 0\), corresponded to detonation of the test charge. All the pressure-time signals exhibited an initial sharp rise in pressure, terminating with a small pressure spike that decreased in strength with increasing standoff distance. Following the initial pressure peak, a period of slowly declining pressure was observed. Its slope decreased with standoff distance, and at the largest standoff distance, the slope of this region was almost zero (a plateau), Fig. 7(d). This region was followed by an abrupt drop in pressure corresponding to the arrival of the first reflected signal at the sensor location, and was then followed by the second reflection, and eventually elastic reverberations of the Hopkinson bars. At the closest standoff distance of 14 cm, the initial peak pressure was 28.2 MPa. This fell with increase in standoff distance to 9.3 MPa at a standoff distance of 40 cm. The peak pressures for each standoff distance are summarized in Table 2, and plotted against standoff distance in Fig. 6(b).

The pressure-time curves shown in Fig. 7 were integrated to calculate the impulse-time curves shown in Fig. 8 (solid black lines). The time at which the first distal reflection (558 \(\mu s\) after the direct arrival) and the second reflection (748 \(\mu s\) after the first arrival) reached the sensor locations on the Hopkinson bars are shown for each standoff distance. It can be seen that the impulse deduced from the pressure waveform decreased in the time interval between the first and second reflected arrivals due to sign conversion of the first reflected signal. The impulse began to rise again after the second reflected signal passed through the sensor locations. Since the reflection coefficients and bar attenuation processes are not well understood, the impulse obtained by integrating the pressure waveform for 558 \(\mu s\) after the first direct arrival was measured, and this is summarized in Table 2. It was approximately 3 kPa s less than the impulse determined in the pendulum mode, Fig. 6(a), indicating the time over which momentum was transferred exceeded the integration time.

The impulse obtained by continued integration of the pressure waveform for 4 ms after detonation is shown also on Fig. 8. It is interesting to note that the impulse deduced in this way eventually approached the impulse obtained with the vertical pendulum, Fig. 6(a), even though multiple bar reflections occurred. Integration of the pressure data acquired up to the arrival of the first bar reflection, Fig. 6(a), captured a substantial fraction, but not all of the full impulse from the sand impact. It is finally noted that the initial slope of impulse time response gives the impulse rate \(I\). Using the data from Fig. 8 it is found that \(I = 21.5\) MPa at a 14 cm standoff distance, falling to 8.1 MPa at a 40 cm standoff distance; consistent with the average pressures.
measured during the first 558 μs of loading with the instrumented Hopkinson bars, Fig. 7.

4. Numerical simulations

The commercial IMPETUS Afea Solver [44] was used to simulate the experiments conducted with the vertical impulse test apparatus. The geometry of the modeled problem is shown in Fig. 9. The approach is based on a discrete particle (or corpuscular) method first described by Olovsson et al. [42] and Borvik et al. [43] The key features of the model, and the validity of its predictions for spherically symmetric C4 charges surrounded by dry and water saturated synthetic sand have been discussed by Borvik et al. [45] and were successfully used to analyze the deflection and fracture of aluminum extrusions during impulsive loading by spherically symmetric, sand encased charges [47].

4.1. Modeling of high explosive (PETN) and air particles

The IMPETUS Afea Solver represents explosive detonation products, and air by rigid, spherical particles that represent many (~10^{18}) actual molecules. These particles transfer momentum by particle–particle collisions defined by contact laws between the particles. The contact interactions of high explosive reaction and air particles are assumed to be elastic and accordingly follow Maxwell’s molecular kinetic theory of gases [48]. Since at high densities, the co-volume effect can cause very large pressures to be predicted, the model incorporated co-volume effects when the particle fill fraction, b was large. Since the particle parameters for the plastic explosive Detasheet C used here have not been measured, we have used those for the same mass of PETN which is its majority constituent (63%). This is presumed to have led to an overestimate of the explosive energy created by the detonation. However, it was perhaps offset to some extent by the explosive energy of the five primary explosives used to initiate the experiments as well as various other factors.

The Maxwell–Boltzmann velocity distribution applied to the discrete particle model for the PETN high explosive used here was determined by selecting the PETN high explosive option in the IMPETUS Afea Solver code. This defined the PETN initial density, \rho_0 = 1765 kg/m^3, its initial internal energy, E_0 = 10.2 GJ/m^3, the ratio of heat capacities at constant pressure and volume, \gamma = C_p/C_v = 1.4, the initial solid-fill fraction of the particles, b = 0.35, and the detonation velocity, V_D = 8350m/s. This option was applied to the region occupied by the 300 g, 254 mm by 254 mm, by 3 mm thick Detasheet®. The code does not allow use of a second high explosive type, and since the parameters for C4 explosive are similar to those of PETN [45], the 50 g, C4 booster charges was approximated by an additional 0.5 mm thick layer of PETN placed at the lower surface of the charge. The particles remained stationary in the model until the explosive was initiated at the center of the bottom surface of the charge. The resulting PETN distribution of velocities was then applied to the region of high explosive particles that had been traversed by a detonation wave that propagated through the explosive at speed

<table>
<thead>
<tr>
<th>Standoff distance (cm)</th>
<th>Initial peak pressure (MPa)</th>
<th>Transferred impulse at 558 μs, I_t (kPa·s)</th>
<th>\frac{dI}{dt} – I (MPa)</th>
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<tr>
<td>14</td>
<td>28.2</td>
<td>10.8</td>
<td>21.5</td>
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<td>25.3</td>
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<tr>
<td>40</td>
<td>9.3</td>
<td>4.6</td>
<td>8.1</td>
</tr>
</tbody>
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Fig. 8. Measured and wet sand simulated impulse-time waveforms obtained by integration of the pressure-time waveforms for the solid block at standoff distances of a) 14 cm, b) 19 cm, c) 24 cm, and d) 40 cm.
The air was modeled as an ideal gas with a Maxwell–Boltzmann distribution of velocities and random initial directions. The velocities were governed by selection of an air pressure of 100 kPa (one atmosphere) with a density of 1.3 kg/m³, an initial internal energy of 253 kJ/m³, and a ratio of specific heats $\gamma = 1.4$.

4.2. Sand model

The sand was also modeled by representative particles, but unlike the high explosive gases and air particles that were modeled as elastic collisions, the wet sand particles were modeled using a penalty based contact formulation that is described by Borvik et al. [45]. During real sand particle impacts, energy can be dissipated by sliding friction at contacts between particles, by conversion of translational energy to particle rotation, by phase change and by particle fracture. The model approach used in the IMPETUS Afea Solver does not treat particle rotation since it substantially increased the computational cost of the calculations, and fracture and other dissipative processes within the particles were also not explicitly addressed. However, the procedure used by Borvik et al. [45] to tune the model parameters to match soil properties is presumed to have accounted for these effects. To address dissipation, the same penalty contact stiffness, $k$ for linear springs was used for both the normal and tangential components of a contact, Fig. 10. In the IMPETUS Afea code, the penalty stiffness is dependent upon the scaled size of the unit cell, $L$, and that of the initial un-scaled unit cell $L_0 = 1$ m. The penalty contact stiffness is defined by $k = (L/L_0)k_0$, where $k_0$ is the particle–particle contact stiffness for the un-scaled unit cell. A linear dashpot with damping constant, $c$, that was proportional to a damping factor, $\xi$, acted in parallel with the normal contact spring while the tangential spring was limited by a Coulomb friction coefficient, $\mu$. Recent observations by Deshpande et al. [31] have indicated that the interparticle separation in dry sand quickly increases following detonation, but water saturated sand particles do not immediately form a loose spray when accelerated by a detonating charge. Wet sand remained clumped with semi-permanent contacts. This has led earlier studies [45,47] to conclude that the damping coefficient, $\xi$, is important in water saturated soils while the friction coefficient, $\mu$, is more significant in dry sand.

The Type I sand used here consisted of the same silica microspheres (with a diameter of 150–200 μm and an amorphous silica density of 2700 kg/m³) analyzed by Borvik et al. [45]. The sand fill fraction for this synthetic sand was 60%, and the initial density was therefore 1620 kg/m³. In the study by Borvik et al. [45] the remaining volume was either filled with water (water saturated sand), resulting in an increased initial sand density of 2020 kg/m³ or was left unfilled for dry sand. The actual water was not modeled in the system; instead, the particle packing, friction coefficient, contact stiffness, and damping were adjusted so that simulations agreed with the experiments. The IMPETUS Afea Solver enables a user to specify dry or wet sand which in turn specifies default contact model parameters proposed by Borvik.
et al. [45] Selection of dry sand defines $\rho = 1620 \text{ kg/m}^3$, $k_0 = 0.4 \text{ GN/m}$, $\xi = 0$, and $\mu = 0.1$ while selection of wet sand specifies $\rho = 2020 \text{ kg/m}^3$, $k_0 = 4.0 \text{ GN/m}$, $\mu = 0.0$, and $\xi = 0.005$. The code also enables the user to specify other values of these parameters.

To investigate the effect of the Type I sand water content, the default wet sand option was used which selected $\rho = 2020 \text{ kg/m}^3$, $k_0 = 4.0 \text{ GN/m}$, and $\xi = 0.005$. The numerical results for this saturated sand case are shown as the dotted blue curve in Fig. 7(a). Since water saturated sand has little free volume for compaction before pressure builds, this sand model resulted in a significantly higher peak pressure than was observed experimentally. The other limiting case assigned the default parameters for the dry sand model to the Type I sand, and is shown as the green dotted curve in Fig. 7(a). It resulted in peak pressures below those observed experimentally. Since drainage of the originally water saturated sand occurred during set-up of the experiment, the estimated water saturation was 80%, and therefore the sand model density, $\rho = 1940 \text{ kg/m}^3$, which lies between that of wet and dry sand. After several trials, it was found that the contact stiffness and damping coefficient parameters that gave best agreement with experimental pressure data also lay between those of the dry and water saturated sand, and so for all the subsequent simulations $k_0 = 0.76 \text{ GN/m}$, $\mu = 0.0$, and $\xi = 0.005$.

A convergence study was also conducted to determine the optimum number of discrete particles. From this study convergence was reached with $2,000,000$ discrete particles. The particles were distributed by the IMPETUS Afea Solver as $45,595$ air particles, $1,941,610$ soil particles, and $12,795$ high energy explosive reaction product particles based on prior work by Borvik et al. [45]. It is noted that the iterative process used for selecting the wet sand parameters and number of discrete particles effectively calibrates the model, and therefore off-sets some of the inaccuracy associated with the simplified representation of the explosive charge and the manner of its detonation.

To characterize the ejecta from a simulated event, twenty spherical virtual “monitors” each with a $0.508 \text{ cm}$ radius were located at a distance of $2.5 \text{ cm}$ from the location of the lower surface of the solid block at equal lateral distances between each other, Fig. 11(a). These measured the discrete particle velocity and density within the monitors at $4 \mu \text{s}$ time step intervals. Since the pressure applied by sand whose motion is arrested at a rigid surface was shown in the introduction to be well approximated by the hydrodynamic pressure ($\rho v^2$) the monitors were used to estimate the sand density, $\rho$, and its upward velocity component, $v$. The sand density was calculated by summing the mass of all sand particles that passed through a monitor in each measured $4 \mu \text{s}$ time interval and dividing by the spherical monitor volume, $(V)$:

$$\rho = \sum \frac{m_i}{V}$$  

(9)

where $m_i$ is the mass of the $i$-th particle. The sand particle velocity was calculated from the total momentum of each particle measured at each simulated time step interval divided by the total mass within the monitor during the same simulated time step:

$$v = \frac{\sum m_i v_i}{\sum m_i}$$  

(10)

where $v_i$ is the vector velocity of the $i$-th particle.

The hydrodynamic pressure ($P_h$) applied by the sand particles, could be calculated from the numerically measured values for sand density and velocity within the spherical monitors using:

$$P_h = \rho v^2$$  

(11)

Fig. 11. A sand particle propagation sequence for simulations without a solid block sample attached to the test structure. The standoff distance was 14 cm. The burgundy particles correspond to the explosive gases while the brown particles correspond to sand. Air particles are not shown. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
By integrating the hydrodynamic pressure, the impulse-time relation for sand particles could also be calculated. The total pressure exerted by the particles on the sample front face 2.5 cm above the monitors could also be directly obtained during a simulation. The contact pressure responses are slightly delayed because of the extra distance traveled by the particles from the monitor location to the sample impact surface. The contact impulse was an output file created by the IMPETUS Afea post processor that automatically calculated the momentum transferred between sand particles and the solid blocks front face.

4.3. FE modeling

**Geometry:** The test geometry shown in Fig. 9(a) including the solid test sample modeled to its true dimensions by combining the test charge particle model with the finite element package in the IMPETUS Afea Solver. The solid block was modeled with a thin front face that was merged with the remaining sample thickness, defined in Fig. 2, to calculate the force between the merged sections. The four Hopkinson bars were modeled as multiple merged cylindrical parts with the dimensions defined in Fig. 2. The first short cylindrical part extended 2.54 cm and the second cylindrical part extended 48.3 cm from the base of the bars, to the location where the force was experimentally measured. Another 2.54 cm cylindrical section covered the length of the region where strain gauges were used for the force measurements while a fourth cylindrical section ensured the full 2 m length of the bars was modeled. The top of the Hopkinson bars were merged with a cylindrical top plate with an artificial material viscosity to introduce dampening to the bars oscillatory response. The support structures, four tie downs, and concrete foundation were modeled as rigid structures with a fixed boundary condition. This approximation had negligible effect upon the results, but significantly reduced the computational time. The steel box was modeled using the same dimensions as the test geometry. Top panel oscillations near the square aperture were particularly important to characterize since they affected the gap between the bottom of the sample and the upper surface of the top panel through which partially arrested sand particles escaped the test structure. A514 B steel material properties were therefore applied to the entire steel box. The pressure in the Hopkinson bars was calculated at their sensor locations from the force-time response between the merged short cylindrical model section in each bar and its adjoining base section. These four force signals were summed and divided by the solid sample area. The vertical pendulum mode impulse was calculated from a post-processor output function that measured momentum transferred between discrete sand particles and the finite element model of the sample.

The FE model was constructed from 7104 cubic and 19,608 linear hexahedra elements with 246,216 nodes. The Hopkinson bars and all connecting parts were modeled with a coarse mesh since material failure was not observed experimentally. The solid test block was modeled with a finer mesh since some local deformation (thought to be associated with sand fingers) was observed experimentally. The solid block was constructed from 16,944 8-node 3rd-order linear hexahedra elements. A mesh sensitivity study was performed to confirm solution convergence with this level of discretization.

4.3.1. Materials

All the aluminum parts were fabricated from Al6061-T6 and modeled as an isotropic material with a von Mises flow stress defined by a form of the Johnson–Cook constitutive model:

\[
\sigma_y = (A + B(\varepsilon_{eff})^n) \left(1 + C \ln\left(\frac{\varepsilon_{eff}}{\varepsilon_0}\right)\right) \left(1 - \left(\frac{T - T_0}{T_m - T_0}\right)^m\right)
\]

where \(\varepsilon_{eff}\) is the equivalent plastic strain and \(A, B, n, C,\) and \(m\) are material constants. The first term on the right hand side of Eq. (12) governs the strain hardening and the constant \(A\) represents the initial yield strength, and \(B\) and \(n\) are both hardening parameters. The second term on the right hand side of Eq. (12) governs strain rate hardening and the constant \(C\) is the strain rate hardening parameter, and \(\varepsilon_0\) is a user defined reference strain rate parameter. The last term of Eq. (12) controls thermal softening of the material. Al6061-T6 material parameters were obtained from a study by Wadley et al. [46] The A514 grade B steel was modeled in a similar manner using material properties from Johnson et al. [49] The coefficients used in conjunction with Eq. (12) to model both materials are provided in Table 3. Fracture/failure of the Al was not observed in any of the experiments and hence failure was not included in the numerical model.

To account for the two foam layers below the high explosive, Fig. 3, the foam was explicitly included using a simple model for crushable foam built into the IMPETUS Afea code. The model is limited to isotropic elastic behavior under impact loading conditions with an assumed constant Young’s modulus, \(E = 0.9\) MPa. A geometric strain failure criteria was introduced that required the foam to lose its shear strength and erode once the failure strain, \(\varepsilon_{fail} = 0.1\) was reached. Since both the polystyrene and polyurethane foams disintegrated quickly, and have similarly low densities (both measured at approximately 33 kg/m³), only one generic layer of foam was modeled, with a thickness equal to the sum of the two layers used in the tests. Fig. 9 summarizes the test charge model geometry including the sand particles, high explosive particles, and foam for the specimen that was back-supported by four Hopkinson bars.

5. Simulation results and discussion

5.1. Pressure waveforms

The simulated pressure waveform using the wet sand model with an 80% water saturation is shown as the red dotted curve in Fig. 7(a). It can be observed that the simulated and measured waveforms prior to arrival of the first reflected signal were in remarkably good agreement at the short standoff distance. As the standoff distance increased, the simulated pressure signal began to rise above the quiescent background earlier than was observed in the experiments. The time gap between the simulated and measured pressure jump increased with standoff distance. However, apart from this shift in timing, the rest of the simulated pressure waveform was in good agreement with the experimental data. Beyond the first reflected arrival (shown on each waveform in Fig. 7), the agreement between simulated and measured pressure response deteriorated, especially as bar reverberation began to dominate the response. This is thought to have been a consequence of an inadequate representation of the boundary conditions at the top and bottom of the bars, and of the dissipation mechanisms within the bars.

To investigate the phenomena governing the simulated pressure responses, Fig. 11 shows the location of explosive and sand particles at various times after simulated detonation for the 14 cm standoff distance case. The test sample has been removed from the simulation to more clearly reveal the unimpeded motion of the particles though the aperture of the top lid of the sand...
containment box. The location of virtual monitors that were used to measure particle density and velocity are also shown in Fig. 11(a). Highly time resolved observations of the initial stages of the event (Fig. A1 of the appendix) indicated that after detonation of the explosive, a compressive shock front propagated through the 5.08 cm thick wet sand layer and was reflected at the sand-air interface with sign conversion to a tension wave. This reflection occurred 50 μs after detonation, and was accompanied by ejection (spallation) of surface sand particles normal to the sand surface. Simultaneously, the pressure of the explosive reaction products began to push the wet Type I sand layer upwards. As the Type I sand slab moved upwards, it also began to laterally spread. Fig. 11(a) shows the particle locations later; at t = 0.12 ms after detonation. Multiple collisions between the explosive reaction product and Type I sand particles resulted in motion of the sand particles in the upward direction. The velocity of sand particles at the leading edge of the sand front was higher than that at the tail, leading to stretching of the sand in the direction of upward propagation. Some widening in the transverse direction also occurred, Fig. 11(b). The fast sand particles that were spilled from the surface by shock reflection can be observed passing through the monitor location in Fig. 11(b), while those associated with the denser sand slab passed through the monitors later, Fig. 11(c). The majority of the upward moving Type I sand passed through the aperture of the top plate on the test sample attached to the apparatus. It can be observed in Fig. 11(e) that it had begun to impact the bottom surface of the test block other than simulated pressure, Fig. 7(d). The higher velocity of this fast sand resulted from additional momentum supplied to surface sand particles by recoil of the compressive sand during (sign converting) shock reflection at the sand surface.

To further investigate these phenomena, the sand particle velocity and density were determined at the sand monitor locations, and are shown as a function of time in Figs. 15 and 16(a) and (b) for standoff distances of 14 and 40 cm respectively. Sand velocities and densities are shown for simulations both with and without a standoff distance. In both cases the leading edge sand had the same initial velocity (1690 ms $^{-1}$) as the test sample with a sand velocity close to that observed by pressure measurements, Fig. 7(a) are consistent with sand arriving at the test samples with a sand velocity of about 500 ms $^{-1}$ while that for the 40 cm case, Fig. 16(a), was lower. In both cases the leading edge sand had the same initial velocity (1690 ms $^{-1}$) as it left the sand slab surface. Detailed examination of the simulation results indicated that the sand’s deceleration with distance of propagation was a consequence of momentum transfer from sand to air particles.

The origin of the early simulated pressure signal arrival in Fig. 7 can be most clearly resolved by examining simulations for the largest standoff distance test shown in Fig. 13 (no test sample present) and Fig. 14. At 0.4 ms after detonation, Fig. 13(a), some Type I sand had advanced a significant distance upwards creating a diffuse leading edge and an axially stretched sand column. At 0.64 ms this leading edge sand had passed through the aperture of the sand containment box lid, and through the location of the monitors, Fig. 13(b), Fig. 14(b) shows that it had begun to impact the bottom surface of the test block at time t = 0.64 ms, which also corresponded to the start of the rise of the simulated pressure, Fig. 7(d). The higher velocity of this fast sand resulted from additional momentum supplied to surface sand particles by recoil of the compressive sand during (sign converting) shock reflection at the sand surface.

The most significant effect of a longer standoff distance was to allow additional time for the spalled sand to separate from the axially stretching and laterally spreading Type I wet sand slab. The higher velocity of the spalled sand, Fig. 14(b), resulted in sand-sample impact occurring well before the arrival of the axial stretched main sand slab, Fig. 14(c and d). This fast spalled sand impact was the origin of the early simulated pressure signal arrival which became more prominent with increasing standoff distance. However, increasing the standoff distance also provided additional time for the sand slab stretching, and time for particles to escape through the gap between the side of the test sample and the cover plate of the apparatus, Fig. 14(c) to (h). The additional time also permitted more lateral stretching of the sand column, and resulted in an increased fraction of Type I sand particles impacting the lower surface of the cover plate.

To further investigate these phenomena, the sand particle velocity and density were determined at the sand monitor locations, and are shown as a function of time in Figs. 15 and 16(a) and (b) for standoff distances of 14 and 40 cm respectively. Sand velocities and densities are shown for simulations both with and without a test sample attached to the apparatus. It can be observed in Fig. 15(a) that the fast (spalled) sand in the 14 cm standoff simulation had a monitor location velocity of about 500 ms $^{-1}$ while that for the 40 cm case, Fig. 16(a), was lower. In both cases the leading edge sand had the same initial velocity (1690 ms $^{-1}$) as it left the sand slab surface. Detailed examination of the simulation results indicated that the sand’s deceleration with distance of propagation was a consequence of momentum transfer from sand to air particles.

However, two experimental observations suggest that the sand-air deceleration mechanism was underestimated by the simulation methodology. First, high speed video observation of the sand fronts, Fig. 4, show that the sand front velocity was 300 ms $^{-1}$, about 100–200 ms $^{-1}$ slower than that predicted for the spalled sand at the simulated sand front. Secondly, the Hopkinson pressure bar pressure measurements, Fig. 7(a) are consistent with sand arriving at the test samples with a sand velocity close to that observed by the high speed video camera. It is possible that a substantial air drag acted on the fast (supersonic) spalled sand particles and was not accounted for in the simulations. It is also important to note

<table>
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<tr>
<th>Material</th>
<th>Elastic constant and density</th>
<th>Yield stress and strain hardening</th>
<th>Strain rate hardening</th>
<th>Temperature softening and adiabatic heating</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>E (GPa) v ρ (kg m$^{-3}$)</td>
<td>A (MPa) B (MPa) n</td>
<td>$t_0$ (s$^{-1}$) C</td>
<td>T$_0$ (K) T$_m$ (K) m</td>
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<tr>
<td>AA6061</td>
<td>70.0 0.3 2700</td>
<td>270 98 6</td>
<td>5 $\times$ 10$^{-4}$ 0.001</td>
<td>293 893 1</td>
</tr>
<tr>
<td>A514- grade B</td>
<td>210.0 0.3 7850</td>
<td>796 510 0.26</td>
<td>1 $\times$ 10$^{-2}$ 0.014</td>
<td>293 1793 1</td>
</tr>
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that the density of the fast (first arriving) sand was less than 10 kg m\(^{-3}\), Figs. 15 and 16(b); it was less than 1% that of the original packed sand bed, and this may also have effected interactions with the air. This air drag might also have played a role in the formation of sand fingers observed ahead of the main sand front in Fig. 4.

While the first arriving sand for both standoff distances had a velocity and density that was unaffected by the presence of the sample, later arriving sand was slowed, and its density increased when a sample was present. This reduced velocity is consistent with sand particle direction reversal during impact with accumulated sand at the lower surface of the sample, and collision of these
reflected particles with later arriving particles. These collisions reduced the average incoming sand velocity measured by the monitors. As the density of arriving particles increased during the sand slab impact, sand continued to accumulate below the sample bottom surface since the particle escape rate through the gap at the sides of the sample was less than the particle arrival rate. This then resulted in a higher sand density at the monitor locations when a sample was present, Figs. 15 and 16(b).

Fig. 14. A sand particle propagation sequence for simulations with a solid block sample at a standoff distance of 40 cm.

Fig. 15. a) The sand velocity and b) sand density determined at monitors for simulation both with and without a sample for a standoff distance of 14 cm. The calculated sand hydrodynamic pressure c) and the sand impulse d) are also shown. The blue curves in c) and d) were directly calculated from the impact force on the sample front face using a contact algorithm. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Assuming that the hydrodynamic pressure exerted by sand that had stagnated against the test block is the product of sand density and the square of the velocity (Equation (11)), then the sand velocity and density data obtained with the monitors, Figs. 15 and 16, can be used to estimate the pressure applied to the front of the sample, and compared to that directly determined by the contact algorithm in the simulation code. These pressures are shown as a function of time in Fig. 15(c) for the 14 cm standoff distance simulation and Fig. 16(c) for a 40 cm standoff distance. The pressure for the 14 cm standoff distance test rose rapidly to a first peak, and then decreased before rising again to a second peak. This two peak pressure response was observed at the monitor locations regardless of whether a sample was present or not. It was also present when the contact pressure on the sample bottom surface was directly determined from the sample contact algorithm in the IMPETUS software, Fig. 15(c). The first pressure peak measured with the monitors and by the contact algorithm for the sample was 30 MPa. This was nearly identical to the pressure of the initial pressure spike measured using the Hopkinson pressure bars, Table 2 and Fig. 7(a), and corresponded to arrival of the fast (spalled) sand at the sample surface. A second, lower pressure (8.3 MPa) peak occurred at 0.55 ms after detonation, and corresponded to the arrival of the more densely packed sand slab at the monitors. Increasing the standoff distance to 40 cm, led to substantial reductions in sand density (due to axial stretching of the sand) and velocity (from air drag effects), Fig. 16(a) and (b), and replacement of the first pressure spike by a gradual ramp of pressure, Fig. 16(c). This was consistent with the disappearance of the initial spike in pressure observed experimentally as the standoff distance was increased, Fig. 7.

5.2. Impulse transmission

Integration of the pressure waveforms enables the impulse at the monitor locations to be determined and compared to those directly obtained from the sample contact algorithm. The impulse calculated at the monitor locations both with, and without the sample present are compared with those given by the sample contact algorithm for a standoff distance of 14 cm in Fig. 15(d). At 14 cm, the incident impulse with no sample present rose rapidly upon arrival of the sand and reached a maximum plateau value of ~14 kPa s within approximately 2 ms after detonation, and was approximately the same as that when the sample was present and determined by the contact algorithm. This impulse also agreed well with that measured by the vertical pendulum.

At the 40 cm standoff distance, Fig. 16(d), the measured and contact algorithm predicted impulse were in very good agreement. Both were slightly less than the predicted impulse of the sand that passed through the monitors. This appeared to be a consequence of the slower arrival rate of the sand particles which permitted a slightly higher fraction of the particles to undergo a glancing reflection and exit the system through the gap at the sample side. Similarly good agreement between the

<table>
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<th>Table 4</th>
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<td>Incident impulse at monitors, impulse transmitted to solid block and transmitted to incident impulse ratio.</td>
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<tr>
<td>Standoff distance (cm)</td>
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<tr>
<td>------------------------</td>
</tr>
<tr>
<td>14</td>
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<td>29</td>
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Fig. 17. Impulse intensity distribution measured on the underside of the steel aperture opening for a 34 cm standoff distance.

Fig. 18. Impulse intensity distribution measured on the underside of the steel aperture opening for a 40 cm standoff distance.
measured and simulated impulses using the contact algorithm was observed for the other two standoff distance experiments, and the negative slope of the simulated impulse versus standoff distance relation (−0.17 kPa s cm⁻¹) was similar to that observed experimentally (−0.2 kPa s cm⁻¹). Table 4 shows that the ratio between incident impulse and transferred impulse was close to unity for the four tested standoff distances.

It is interesting to note that the impulse acquired during the first 0.558 ms of sand loading for the 14 cm standoff distance case was about 9 kPa s. This was consistent with the impulse calculated by integration of the simulated pressure versus time response for 558 μs in the Hopkinson bar test mode, and with the experimental data obtained by integration of the experimental pressure-time data. The three results indicate that 9/13 of the impulse was transferred to the solid block over a period of about 0.588 ms. Similarly good agreement with the experimental data and Hopkinson bar mode simulations was observed at the other standoff distances, Fig. 6(a). The impulses obtained by integrating pressure data for the Hopkinson bar mode simulations for that experimentally recorded (4.0 ms after detonation) are shown on Fig. 8 and agree surprisingly well with the experimental impulse data obtained using the pendulum test mode. It appears that interactions between the many bar modes excited in the Hopkinson bars eventually converge to the transmitted impulse.

The gradual decline in total impulse transferred to the solid samples as the standoff distance was increased was a result of a small decrease in sand velocity with propagation distance (compare Figs. 15 and 16(a)) by momentum transfer to air particles, and lateral spreading of the sand slab as the distance to the sample increased. The effect of lateral spreading can be observed by calculating the impulse intensity distribution across the underside of the sand containment box lid and bottom face of the test block. These impulse distribution maps for the 14 and 40 cm standoff distance simulations are shown in Figs. 17 and 18 respectively. Close examination of the results shows the fast (spalled) sand impacted the test sample, Figs. 17 and 18(a). In the 14 cm case, most of the late arriving sand also impacted the sample, Fig. 17(b) and (c) or the edge of the aperture. However, examination of the impulse map for the 40 cm standoff simulation, Fig. 18, shows that substantial impulse was transferred to the underside of the cover plate by sand impact. The significance of the lateral spreading can be further quantified by plotting the specific impulse along a line that traversed the middle of the underside of the cover plate, Fig. 19. The area of the specific impulse curve inside the aperture at 14 cm was 1.08 times that at a 40 cm standoff as a result of the additional lateral scattering.

5.3. Containment box effects

The sand particle impact with the underside of the sand box lid caused it to suffer a displacement during the experiment. The underside of the test sample was also displaced vertically because of elastic compression (and extension) of the Hopkinson pressure bars. Fig. 20(a) to (d) show these two sets of displacements, and reveal the effect they had upon the gap at the side of the test sample through which sand escaped. The combination of the two displacements resulted in a variation in the gap between the top of the steel lid and the bottom of the sand though which sand escaped the system, Fig. 20(e). Initially, the distance between bottom of the sample and top surface of the sand containment box lid was 8.15 mm. During the first 1.25 ms following detonation, the lid was displaced towards the sample by a greater distance than the upward displacement suffered by the sample. This led to a decrease in gap (between points b) and c) on the sample front face deflection curve) from 8.15 mm to about 3 mm at around 1.2 ms after detonation. This reduction in area through which the sand could escape resulted in more sand accumulation below the bottom surface of the sample, but had little effect upon transfer impulse transfer to the sample. At approximately 1.25 ms, the steel lid began to spring back towards its original location, and the gap for sand escape began to increase reaching a maximum width of 13 cm at 2.95 ms, Fig. 20(d). This increased opening allowed the sand to escape from the sample front face, and relieve the pressure on the lower face of the sample.

6. Concluding remarks

A vertical pendulum test apparatus has been developed and used to experimentally investigate the impact of explosively accelerated wet sand with a flat sided, back supported solid 6061-T6 aluminum block test specimen. The apparatus used the pendulum jump height to determine the impulse transferred to the solid block when a 300 g sheet of explosive was used to accelerate a 5.08 cm thick layer of wet silica sand towards the sample at normal incidence. High speed video imaging indicated that the main sand front was accelerated perpendicular to the surface of the test charge, reaching a velocity of ~300 ms⁻¹. Small fingers of locally higher velocity sand could be observed moving ahead of the main front. Instrumented Hopkinson bars attached to the rear face of the solid block enabled the pressure exerted on the sample to be measured during the sand impact process. Integration of these pressure waveforms over time enabled an independent estimate of the transferred impulse to be obtained that was in good agreement with the value obtained from the pendulum. By varying the distance between the surface of the explosive layer and the impact face of the solid block from 14 to 40 cm, the transferred impulse and maximum pressure applied to the sample were both found to decrease with standoff distance.

A particle based simulation method implemented in the IMPETUS Afea Solver has been used to model the acceleration of
the sand and its impact with the test structure. Using sand particle contact models developed in previous studies of the same synthetic silica sand, the modeling approach has been used to investigate the sand-structure interaction during the experiments and predict the impulse and pressure measurements. This combined approach was able to successfully predict both the impulse transferred during the vertical pendulum mode tests and the pressure waveforms recorded with the instrumented Hopkinson pressure bars. Analysis of the experimentally validated simulations indicated that the transmitted impulse decreased with increasing standoff distance because of a small reduction in sand particle velocity (due to momentum transfer to air particles) and an increase in lateral spreading of the sand particles as the standoff distance increased. This spreading resulted in a smaller fraction of the sand impacting the (fixed) area of the test samples impact face.

The simulations reveal three regions of impulse transfer. The first region corresponded to the arrival of fast sand that had spalled from the top surface of the sand layer during reflection at the air-sand surface of the compressive shock launched into the sand by the explosive event. This fast sand appears to correlate with the sand fingers observed in the high speed video images. The pressure (and impulse) applied in this region decreased rapidly with standoff, and appears to be a consequence of sand stretching (density reduction) due to a velocity gradient in the sand, and to momentum transfer from the sand particles to those representing the air. The second region of loading corresponded to impact by the main body of sand which was pushed towards the sample by the expanding explosive reaction products. The third region corresponded to impact of explosive reaction product and slow sand particles with the sample. In the experiments conducted here this third regime contributed little additional impulse to the sample.

The experimentally validated simulations also indicate that the momentum transferred to a solid back supported planar structure whose surface is inclined normal to the sand propagation direction is almost identical to that of the incident sand. This affirms the conclusion of a previous study utilizing lower velocity sand columns, and indicates that the beneficial FSI effect present in underwater impulse transfer processes is absent for wet sand impacts at velocities of 300 ms\(^{-1}\).

Acknowledgments

The authors are grateful to Keith Williams of NEWTEC Services Group, Inc. for his excellent technical support and advice. We are also grateful to Dr. Kumar Dharmasena, Tommy Eanes, and to Adam Malcom for their help with various aspects of the experiments. We are grateful to both the U.S. Office of Naval Research (ONR grant number N00014-07-1-0764) managed by Dr. David Shifler and DARPA (DARPA grant number W911CR-11-1-0005), managed by Dr. Judah Goldwasser for co-support of this study.

Appendix A

Time resolved simulations of the initial stages of the detonation and sand acceleration process are shown in Fig. A1. They show that a compressive shock front was initiated in the sand as the detonation wave in the explosive reached the sand-explosive interface. This shock propagated through the 5.08 cm thick wet sand layer and was reflected at the sand-air interface with sign conversion to a tension wave at ~30 ms after initiation of the detonation process, Fig. A1(f). The shock velocity in wet sand was ~1690 ms\(^{-1}\), which is consistent with other studies of sound wave propagation in granular media [50]. As the compressive shock was reflected at the sand-air interface, it was transformed to a tension wave enabling elastic particle recoil from the surface. Fig. A1(g) shows that after 40.0 µs, the reflection was accompanied by sand ejecta from the leading edge of the Type I sand. At 50.0 µs the reaction products began pushing the wet Type I sand upwards as the reflective shock wave continued downward, causing some of the sand at the sides of the Type I slab to acquire a small horizontal momentum component, Fig. A1(h).
Fig. A1. Time resolved simulation sequence of the initial explosive event that demonstrates a compressive shock front propagated through the Type I sand (a–f) and being reflected at the sand–air interface into a tension wave (g–h).

References
