International Journal of Impact Engineering 76 (2015) 98–117

Contents lists available at ScienceDirect

International Journal of Impact Engineering

journal homepage: www.elsevier.com/locate/ijimpeng

# Impulse transfer during sand impact with a solid block

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ARTICLE INFO

*Article history:*
Received 22 May 2014
Received in revised form
17 September 2014
Accepted 20 September 2014
Available online 28 September 2014

*Keywords:*
Impulsive loading
Discrete particle simulation
Fluid structure interaction

ABSTRACT

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.



## 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

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http://dx.doi.org/10.1016/j.ijimpeng.2014.09.010
0734-743X/

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, but 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 micromechanics 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 ms$^{-1}$ 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 ms$^{-1}$ 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, $\rho v^2$ where $\rho$ 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 interfaced with a finite element package to analyze the response 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