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Research paper

Coupled discrete/continuum simulations of the impact of granular slugs with clamped beams: Stand-off effects

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ABSTRACT

Coupled discrete particle/continuum simulations of the normal (zero obliquity) impact of granular slugs against the centre of deformable, end-clamped beams are reported. The simulations analyse the experiments of Uth et al. (2015) enabling a detailed interpretation of their observations of temporal evolution of granular slug and a strong stand-off distance dependence of the structural response. The high velocity granular slugs were generated by the pushing action of a piston and develop a spatial velocity gradient due to elastic energy stored during the loading phase by the piston. The velocity gradient within the "stretching" slug is a strong function of the inter-particle contact stiffness and the time the piston takes to ramp up to its final velocity. Other inter-particle contact properties such as damping and friction are shown to have negligible effect on the evolution of the granular slug. The velocity gradients result in a slug density that decreases with increasing stand-off distance, and therefore the pressure imposed by the slug on the beams is reduced with increasing stand-off. This results in the stand-off dependence of the beam's deflection observed by Uth et al. (2015). The coupled simulations capture both the permanent deflections of the beams and their dynamic deformation modes with a high degree of fidelity. These simulations shed new light on the stand-off effect observed during the loading of structures by shallow-buried explosions.

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1. Introduction

Much attention has been devoted to the dynamic response of above-ground structures subjected to blast loading from a shallow-buried explosion (Anderson et al., 2011). Experimental as well as numerical studies have shown that compared to surface laid explosives, shallow-buried explosives result in higher impulse transmission and larger deflections of the afflicted structure (Deshpande et al., 2009; Peles et al., 2008; Pickering et al., 2012). This increased severity of loading has been attributed to the impact of the granular media that is ejected by the expansion of detonation products in shallow-buried explosives (Bergeron and Tremblay, 2000; Fairlie and Bergeron, 2002; Reichenbach et al., 1991) compared to explosions in air.

A number of experimental studies have proposed empirical relations to quantify the deformations of plates subjected to buried explosions; see for example Westine et al. (1985) and Neuberger et al. (2007). Based on such empirical relations, Morris (1993) proposed a design-for-survivability code for structures subjected to such impulsive loading events. A parallel effort has sought to numerically simulate the deformations of structures subjected to the complex loadings created by such explosions. For example, Rimoli et al. (2011) used a soil model (Deshpande et al., 2009) to deduce the impulse applied to structures by explosively driven spherical sand, and then simulated the ensuing (uncoupled) deformation of aluminium monolithic and sandwich plates using finite element calculations. Gruijicic et al. (2008a, 2008b, 2006) and Wang et al. (2004) have presented coupled Eulerian/Lagrangian simulations of landmine explosions and attempted to compare their predictions with blast impulse and plate deformation measurements from Bergeron and Temblay (2000) and Foedinger (2005).

More recently, coupled discrete particle/continuum simulations have been used to investigate the response of structures impacted by high velocity granular media. For example, Borvik et al. (2011) followed by Dharmesena et al. (2013), and Holloman et al. (2015a, 2015b) used this approach to simulate the response of a variety of monolithic and sandwich structures loaded by high velocity sand sprays generated by buried explosions. Various calibrated parameters are used to produce the high velocity

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sand spray generated by the expanding explosive and the measurements of the response of the structure impacted by this spray are compared against the predictions. In all cases, discrepancies exist between measurements and predictions. One issue arises from the ill-defined foundation upon which a buried explosive rests. With the use of concentric soil shells surrounding suspended explosive charges, Wadley et al. (2013) has overcome this issue, discrepancies still remain. The origin of these discrepancies remains unresolved with possible sources of error being:

(i) Inability of the simulations to accurately capture the details of the granular spray generated by the loading of the soil due to the expansion of the explosive gas; and/or
(ii) Failure of the simulations to correctly capture the interactions between the high velocity granular ejecta and the impacted structure.

The decoupling of these two possible sources of error is problematic in experiments involving detonation of an explosive since (i) typically spherically expanding, optically opaque sand sprays are generated (Hlady, 2004; Pickering et al., 2012; Dharmesena et al., 2013) wherein only the outer front is visible and (ii) the explosive gases obscure the view of the impacted structure after the first few milliseconds. Therefore, the only metric available to compare simulations and measurements is the permanent deformations of the structures. This metric is an integrated (and therefore very coarse) measure of the fidelity of the simulations and makes it difficult to determine the precise sources of any discrepancies.

In order to address this deficiency, Park et al. (2013) developed a technique to generate a high velocity sand slug within a laboratory setting and without the need for the detonation of an explosive. Uth and Deshpande (2014) and Uth et al. (2015) employed this setup to investigate the dynamic response of monolithic and sandwich structures impacted by such granular slugs. The key feature of these experiments was that the high velocity granular slugs were fully characterised both in terms of their density and spatial distribution of their velocity. Moreover, Uth and Deshpande (2014) and Uth et al. (2015) reported detailed observations of the dynamic response of the impacted structures visualised using high-speed photography.

Pingle et al. (2012) have analysed the interaction of spatially uniform granular slugs impacting rigid targets. This rather idealised, but fundamental fluid-structure interaction (FSI) problem is the "sand-blast" analogue to the classical water propagated shock FSI problem studied by Taylor (1963). Liu et al. (2013) extended the sand column model to investigate the impact of clamped sandwich and monolithic plates. Their numerical results indicate that some edge clamped sandwich panel designs suffer significantly smaller deflections than monolithic plates of identical span and of equal mass per unit area. The performance benefit was due to the higher bending strength of sandwich plates. This contrasts with water-blast of sandwich structures, where significant benefits accrue from fluid-structure interaction effects (Deshpande and Fleck, 2005; Dharmasena et al., 2010; Wadley et al., 2008; Wei et al., 2007). The loading of structures by a slug of high velocity granular particles not only provides physical insight into the interaction of granular media with structures, but is also directly representative of the ejecta created during a shallow-buried explosion as shown in the experiments reported by Joynt and Williams (private communication), Holloman et al. (2015a, 2015b) and Park et al. (2013). Thus, the impact of high velocity granular slugs against a test structure is of considerable theoretical and experimental interest.

Uth et al. (2015) reported experimental observations for the zero obliquity (normal) impact of granular slugs comprising tungsten carbide particles against clamped beams. These measurements provide extensive data that show the dependence of the dynamic response of the beams to not only the velocity of the slug but also the stand-off distance between the launch position of the slug and the location of the beam. While this data presented clear trends, a lack of numerical simulations precluded elucidation of the physical mechanisms at play in the experiments. In this study we report detailed numerical simulations of the experiments of Uth et al. (2015). Comparisons with the experiments are used to (i) provide a detailed test of the fidelity of the coupled discrete particle/continuum simulation methodology and (ii) provide mechanistic explanations for the temporal evolution of the granular slugs and the ensuing stand-off dependence of the beam's dynamic response observed in the experiments.

2. Summary of experimental findings

Uth et al. (2015) presented an experimental investigation of the response of monolithic beams impacted normally and centrally by slugs of Tungsten Carbide (WC) particles. Here we analyse the data from Uth et al. (2015) to test the fidelity of the coupled discrete particle/continuum numerical models.[1] It is thus instructive to first briefly describe the experimental setup and the key findings.

Cylindrical slugs of mass 22.7 g (diameter $D_0 = 12.7$ mm and resting length $L_0 = 20$ mm), comprising WC particles with a diameter range of 45–150 μm were impacted against monolithic clamped AISI 304 stainless steel beams. A sketch of the experimental setup is included in Fig. 1 and comprises four main components (from right to left): (i) a gas gun to fire a solid projectile, which then accelerates the piston of (ii) a slug launcher apparatus based upon that developed by Park et al. (2013); (iii) a WC slug that initially rests inside the cylindrical cavity of the launcher; and (iv) the beams clamped to a support rig. The projectile fired from the gas gun impacts the piston which in turn pushes the granular slug within the cylindrical cavity towards the clamped beam. The impact velocity of the projectile sets the speed with which the slug impacts the beam centre at normal incidence angle.

Clamped 304 stainless steel beams of span $L = 100$ mm, width 21.3 mm and thickness 0.69 mm were used in the experiments of Uth et al. (2015). High-speed photography was employed in the experiments to visualise both the granular slug in free-flight and the subsequent impact of the slug against the beam as well as the ensuing deformations.

2.1. Key experimental measurements

Uth et al. (2015) presented their data in terms of the projectile impact velocity V_0 and the average velocity of the granular slug. However, for the purposes of the numerical calculations presented here it is more convenient to present the results in terms of piston velocity v_p: details of the method employed to determine v_p from the measurements are presented in Section 4.2.

The evolution of the granular slug ejected by a piston velocity $v_p = 83.5$ m s^{-1} as visualised by high-speed photography is shown in Fig. 2a. Images at four instants in time are shown with time $t_s = 0$ chosen arbitrarily for the first snapshot corresponded to the time at which the distance s travelled by the slug was $s = 51$ mm. The travel distance s is defined in Fig. 2b, which shows the launcher section of the apparatus: s is equal to the distance travelled by the leading edge of the granular slug from its resting position within the launcher. The images clearly show that while the slug remains approximately cylindrical with an invariant diameter, it lengthens with increasing s. This is emphasised in Fig. 2c where the evolution

[1] We emphasise that while the data from the study of Uth et al. (2015) used here was gathered in the original investigation, we reanalyzed some of their data (especially the high-speed photographs) in order to extract some additional information (e.g. the velocity of the piston) required for the numerical calculations.

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