Response of Embedded Pipeline to Surface Blast Loading

P. Vivek, T.G. Sitharam, Gopalan Jagadeesh, and K.P.J. Reddy

Introduction

Due to various catastrophic accidents and increasing terrorist activities in recent years, there has been a considerable interest in studying structures exposed to explosive loads. The stability of underground structures like bunkers, tunnels, and pipeline networks are crucial under blast loading. Among the various buried structures, underground pipelines which are used to transport oil and gas are considered here in the study. The work presented here aims at investigating the behavior of an embedded pipe subjected to surface blast loading.

Understanding the explosion in soil and the subsequent response of buried structures like pipeline is extremely difficult because of its dynamic interaction with the soil and structure. Most of the transmission pipelines which are buried in the ground are made of carbon steel. Extensive work has been performed on blast induced effects on buried pipelines and most of the studies are focused on developing analytical expression [1] and numerical studies [2]. However, very few experimental studies have succeeded in the past, due to the limitation of using explosives.

The use of explosives in laboratory is a complex phenomenon, considering the lack of repeatability conditions and safety concerns. Hence, shock tube is used here to generate repeatable blast wave under controlled conditions. The shape of blast wave generated from the shock tube matches the Friedlander wave equation. The reflection and propagation of compression waves induced by the shock wave in a granular medium are studied by various researchers. Kitagawa et al. [3] investigated effect of pressure attenuation of shock wave by porous materials, while Britan et al. [4] investigated the phenomenon of shock wave attenuation by granular filters. The initial set of shock tube experiments were carried out to determine the parametric effect of soil on propagation of pressure wave upon a blast wave impact. This chapter also presents a fully coupled numerical analysis approach, in which the Coupled Eulerian Lagrangian (CEL) method is adopted to model the blast loading on the embedded pipe in the soil deposit. The finite element results were compared with the experiments to show the authority of numerical simulation of shock/blast impact on granular materials like soil.

Experimental Arrangement and Materials

Shock Tube

The vertical shock tube used in the following study consists of a long tube having an inner diameter of 135 mm, separated into driver section and driven section by a metal diaphragm. The driver section is 0.5 m in length, while the driven section is 4.5 m. The diaphragm is ruptured by a compressed high pressure driver gas. The pressure of the driver gas is increased until the diaphragm ruptures and thereby generating shock wave [5], which travels into the driven section. Piezoelectric pressure transducers are mounted on to the end of the driven section to measure the P_5 pressure signal. The vertical shock tube assembly is shown in Fig. 1a. In the present case, Helium was used as the driver gas, while the driven conditions were at atmospheric conditions. The test chamber is mounted at the open end of the driven section as shown in Fig. 1b.

P. Vivek (✉) • T.G. Sitharam
Department of Civil Engineering, Indian Institute of Science,
Bangalore, India
e-mail: vivek2387@gmail.com

G. Jagadeesh • K.P.J. Reddy
Department of Aerospace Engineering, Indian Institute of Science,
Bangalore 560012, India

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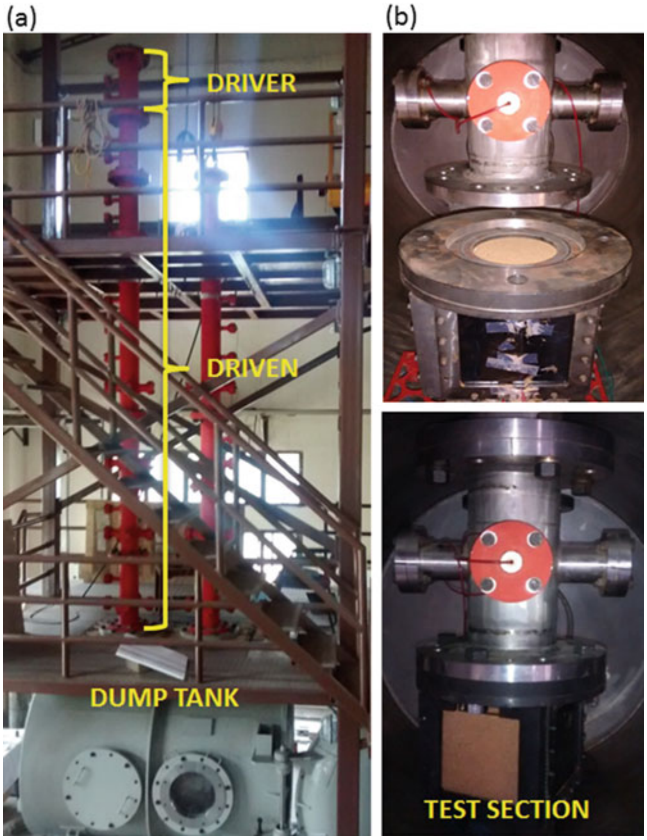


Fig. 1 (**a**) Complete assembly of vertical shock tube and (**b**) test section at the open end of the driven section

Table 1 Gradation property of sand

$e_{\min}$	$e_{\max}$	D_{10} (mm)	D_{30} (mm)	D_{60} (mm)	C_u
0.53	0.88	0.25	0.53	0.84	0.54

Material Properties

The sand used in this investigation was dry river sand, where the particle size distribution of the sand was determined by dry sieve analysis as per IS 2720 (part-4)-1985. The gradation properties of the sand are listed in Table 1, where $e_{\min}$ and $e_{\max}$ are the minimum and maximum void ratio. D_{10} represents grain size corresponding to 10 % passing, i.e., only 10 % of grains are smaller than 0.25 mm. Coefficient of uniformity C_u is calculated by taking the ratio of D_{60} and D_{10}. The aluminum pipe having outer diameter of 25 mm, with a wall thickness of 1.2 mm is used in the present study.

Test Chamber

The test chamber is made of square section box having the internal dimension of 150 mm. One face of the test chamber is fitted with high grade toughened glass for visualization purpose. Test chamber is where the sand deposit is prepared and is attached to the open end of the driven section of the shock tube. While preparing the sand deposit, it is important to maintain constant relative density such that the deposit can be reproducible for each test. For this purpose, the sand pluviation technique is used, where the sand was poured through a device which has a hopper fitted with a varying height pipe and welded with a 60° inverted cone at the bottom (Fig. 2). The height of fall determines the desired relative density of the sand deposit [6]. In the present study, two set of sand deposits were prepared with an approximate relative density of 63 % and 72 %. The piezoelectric type pressure transducers are placed inside the sand deposit at three different locations to capture the compressive wave propagation and the attenuation of the pressure pulse. The schematic diagram of the test chamber along with the actual sand deposit bed is shown in Fig. 3.

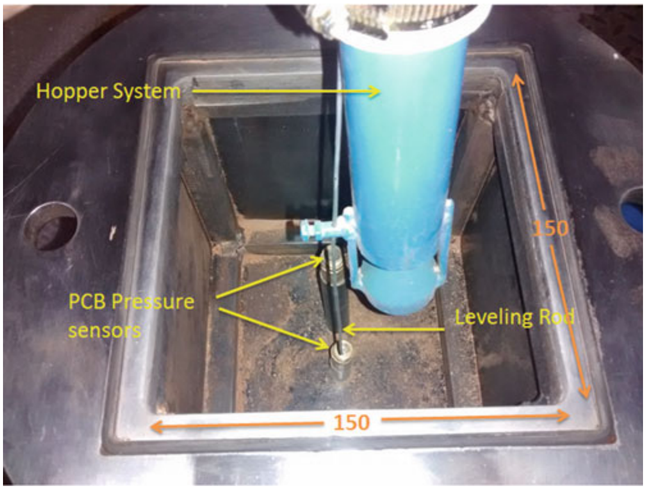


Fig. 2 Sand pluviation technique

Initial set of experiments were carried out only with sand deposit to determine the response of the sand to a blast loading. Later, experiments were performed by embedding an aluminum pipe at a depth of 75 mm from the bottom of the bed (Fig. 4a). The shock tube experiments were carried out with the pipe embedded in the soil. Soil-structure interaction response is captured by mounting a couple of strain gauges along circumferential and longitudinal direction of the pipe as shown in Fig. 4b.

Numerical Simulations

A CEL analysis was performed using Finite Element Package, ABAQUS/Explicit 6.12 [7]. A coupled analysis is performed to determine the soil-structure interaction response.

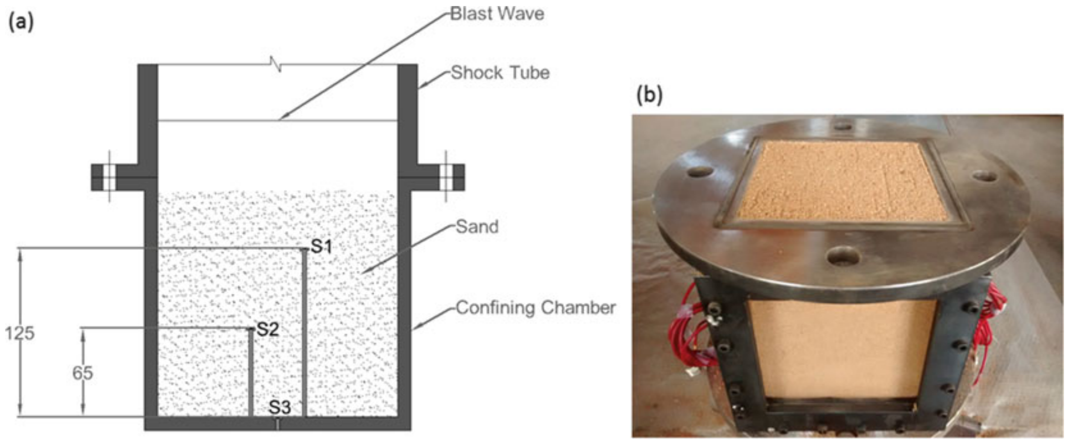
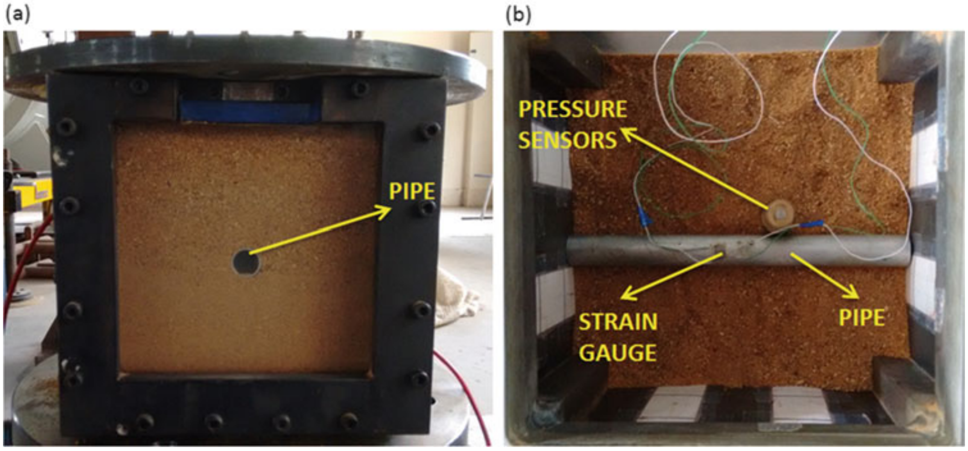


Fig. 3 (**a**) The schematic diagram of test chamber, (**b**) the sand filled test chamber

Fig. 4 Embedment of aluminum pipe in the sand deposit



Modeling and Constitutive Relation

The shock tube is modeled into driver and driven sections using Eulerian elements, considering ideal gas equation-of-state. Further, the sand is modeled as continuum medium using Drucker-Prager linear model and pipe is modeled using linear elastic model. For the shock tube geometry, a CEL model was developed using eight-node linear Eulerian brick element with reduced integration and hourglass control. While, the sand and pipe sample is modeled eight-node linear brick element with reduced integration and hourglass control. The desired initial pressure (P_4) is specified indirectly by using a predefined field for the initial temperature and the diaphragm rupture/burst condition is initiated at the start of the analysis, where the two gases interact with each other [8].

Table 2 Validation of Abaqus with analytical solutions

Shock parameters	Abaqus	Analytical	Error (%)
Incident shock pressure (kPa)	442.62	442.08	0.12
Reflected shock pressure (kPa)	1443.6	1445.1	0.11
Particle velocity (m/s)	420.14	414.54	1.33
Shock velocity (m/s)	712.71	684.51	3.96

Shock Tube Validation and Assembly

The shock tube condition is validated with the analytical solutions, popularly known as Rankine-Hugoniot relations. The constant pressure region behind the shock wave (P_2) and the constant pressure region behind the reflect shock wave (P_5) are matching perfectly with the analytical solutions. While the shock velocity and particle velocity has an error up to 4 %, the details are tabulated in Table 2.

The complete shock tube made of Eulerian element is assembled upon Lagrangian model of soil deposit, the contact between the two parts in considered frictionless. The assembly of the complete setup is shown in Fig. 5.

Results

The peak overpressure P_5 generated from the vertical shock tube as shown in Fig. 6 match very closely with the ideal Friedlander wave. Fig. 7 shows the overpressure measured by the embedded sensors when subjected to a blast wave having a peak overpressure of 14 bar. Upon the blast wave impact on the top of the sand deposit, the blast wave transfers the momentum to a two phase granular medium forming compression waves in the sand. The peak overpressure generated in the sand deposit gradually decay with the depth. In the case of sand with relative density of 72 %, the peak overpressure attenuate about 38 %, and 30 % attenuation is seen in sand with relative density of 63 %.

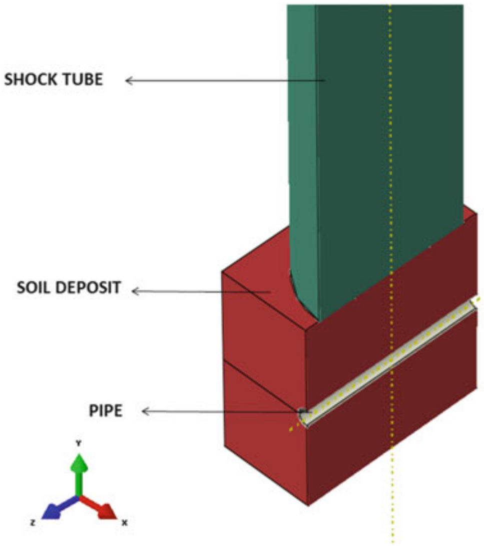


Fig. 5 Complete shock tube made of Eulerian element assembled upon Lagrangian model of soil deposit

The experiment with the embedded pipe was partially unsuccessful due to damage in strain gauge connectors upon the impact of the blast waves. However, the P_5 signal from the shock tube was captured and the condition was simulated in Abaqus explicit. Fig. 8a shows the pressure contours developed in the shock tube and strain contours in sand deposit. A blast wave of peak overpressure of 40 bar is applied to the sand deposit and subsequently to the embedded pipe. A visual comparison of the deformation of the pipe with the numerical simulation is shown in Fig. 8b. The maximum deformation of pipe physically measured is found to be 2 mm while the numerical simulation predicts it to be 1.2 mm.

Conclusion

The two phase granular medium can dominantly attenuate the compressive waves generated from surface blast wave to about 30–40 %. As the relative density increases, the voids present in the sand decrease. Hence, making it easier to interact with three-dimensional sand particles and thereby decreasing the peak overpressure substantially.

The numerical simulation overestimates the deformation compared to the physical measurement made in the experiment. Few more experiments need to be performed to predict

Fig. 6 Blast wave generated using vertical shock tube

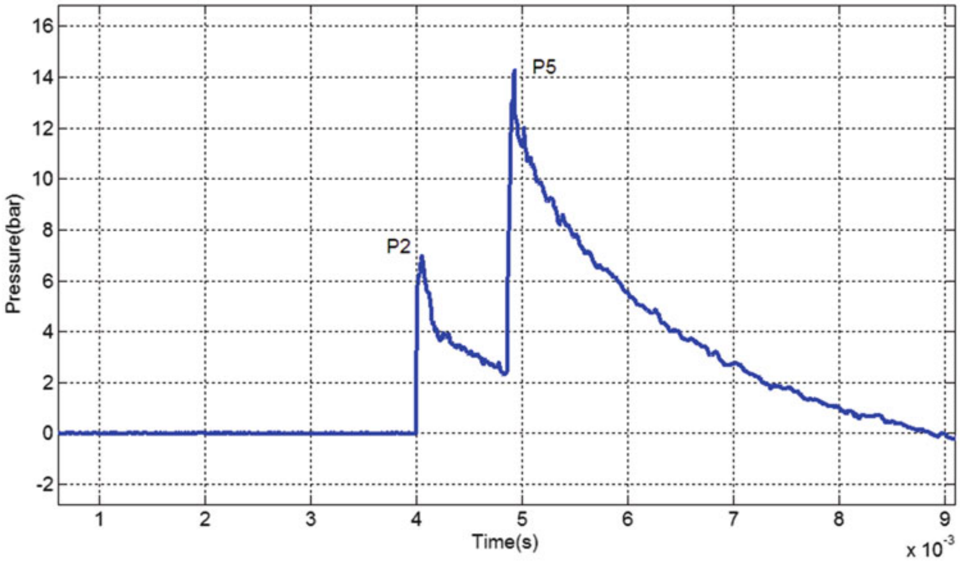
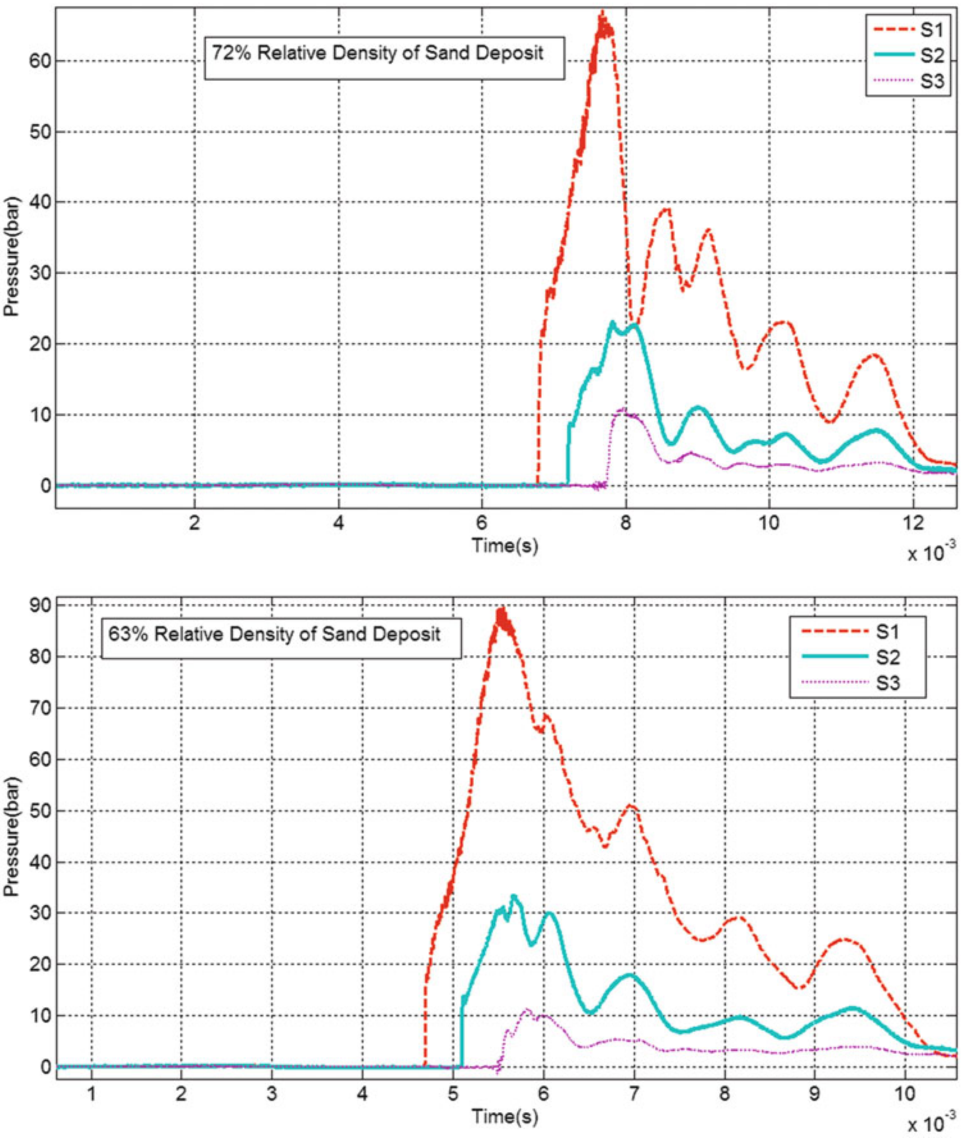


Fig. 7 Measured pressure signals in the sand at $S1$, $S2$, and $S3$ measuring 125, 65, and 0 mm from the bottom of the test chamber



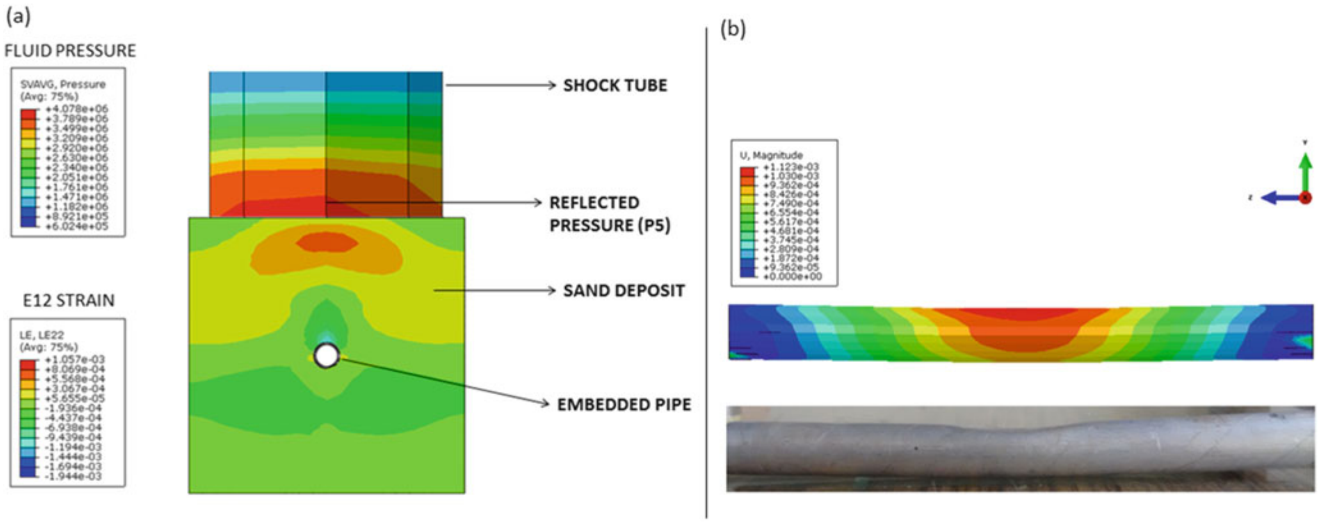


Fig. 8 (**a**) Strain distribution on the soil deposit, (**b**) comparison of the deformation with the experiment

the actual behavior of the embedded pipe along with the scaling law. Results of these experiments along with the important observations will be presented in the conference.

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