Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2017) 4752-4765

ECCOMAS
Proceedia

COMPDYN 2017
6th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Rhodes Island, Greece, 15–17 June 2017

NUMERICAL SIMULATION OF BLAST WAVE PROPAGATION IN LAYERED SOIL FEATURING SOIL-STRUCTURE INTERACTION

Abir. M[1], Arumugam. D[2], Dhana Sekaran. B[3], Subash. T. R[4]

[1] Senior Design Engineer, L&T Construction, Chennai, India, e-mail: abir-mandal@lntecc.com

[2] Asst. Engineering Manager, L&T Construction, Chennai, India, e-mail: darumugam@lntecc.com

[3] Chief Engineering Manager; [4] Joint General Manager, L&T Construction, Chennai, India.

Keywords: Blast Pressure, Wave Propagation, Soil-Structure Interaction, Numerical Method Simulation, Non-Linear Material Model.

Abstract. *In recent decades, the blast load impact on structures has acquired considerable attention due to magnified threats from various man-made activities. Understanding the shock wave propagation in soil and its interaction with structure are crucial in a blast scenario. In a surface or sub-surface blast, the shock wave mechanics and its subsequent impact on underground or above ground structures are extremely complex. This paper scrutinizes the problem of an underground explosion initiated by penetrated missile and thereby focuses on the characteristics of shock wave propagation and pressure attenuation in the surrounding soil. Analyzing empirical data for the same reflects different attenuation factor for different type of soil. Numerical simulations of blast wave propagation in soil and the effect of soil-structure interaction are implemented in a computationally efficient way using an advanced finite element analysis tool (LS-DYNA). Constitutive material models are used to simulate the non-linear behavior and damage profile in concrete and soil. Observations on the numerical model reveal a close tally with theoretical calculations in predicting shock wave characteristics in an undisturbed wave propagation. Numerical analysis is essential to study the exact conditions prevalent during a sub-surface blast. The above mentioned condition has been theoretically tested for a surface blast and results compared to confirm sub-surface blast having much greater impact at a longer distance. An attempt has been made to capture the Transmission and Reflection phenomena related to pressure wave propagation at the interfaces of multi layered media that is actually evident in the case of blast wave passing through layered soil. Preliminary study on wave propagation in rock media highlighting the difference in behavior of the shock waves in soil and rock is presented and discussed as well.*

Peer-review under responsibility of the organizing committee of COMPDYN 2017.
doi: 10.7712/120117.5759.16936

1 INTRODUCTION

The problem of underground structures subjected to dynamic load has always been a topic of interest to engineers, especially the effect of extreme event like blast loading which has acquired considerable attention due to magnified threats from various man-made activities. Studying the soil response, soil-structure interaction and dynamic behavior of structure subjected to blast loading are very crucial in design of military, pipeline construction, and tunneling and defense structures. As a result of an explosion in the soil media, various hidden complex mechanical processes get triggered which give rise to detrimental effects that are seen and felt by humans.

The explosion leads to the generation of high pressure shock waves that propagates radially outward from the detonation. Understanding the shock wave propagation and its attenuation in soil media is of paramount importance for the analysis and design of underground structures. Attenuation characteristics of the shock wave depends on the surrounding material medium, soil/rock and air for surface blast, different types of soil medium (layered soil) in case of an underground/sub-surface blast. The shock wave characteristics get altered due to reflection, transmission occurring at the interface of the layered soil strata with different densities and during its interaction with the structure.

The paper focus on pressure attenuation in different soil medium, comparison on effects of surface, air and subsurface explosion, and soil-structure interaction and pressure attenuation in layered soil media using a case study. Empirical relations are used to evaluate the preliminary response of the medium. As empirical equations act only as primary tool for validation, numerical analysis is vital to understand the attenuation characteristics and soil-structure interaction more realistically. TNT properties are used for the blast simulation in numerical analysis. The pressure wave propagation certainly gets influenced by the non-linear property of soil as well. This concern has been addressed in the numerical approach. A computationally efficient numerical model has been created incorporating all the soil and blast parameters in a finite element software, LS-DYNA, to capture a scenario as close as possible to the actual and tallied with the available empirical equations.

2 LITERATURE STUDIES

Limited research is available on response of a buried structure subjected to a subsurface blast and its attenuation effect in different soil medium and layered soil media. Some of the research available on response of an underground/buried structure response to blast is listed here. Some of the research focuses on validation against the experimental data and some against empirical relations. For numerical evaluation, mainly AUTODYN and LS-DYNA were used to capture the dynamic response of the soil.

Ya-Dong et al [1] studied the response of a RC frame subjected to a surface blast. Deformation, pressure and failure of the frame were modeled using FEA and validated against field experiments. Mohr-Coulomb material has been used to capture the soil behavior.

Dynamic response of a tunnel subjected to a surface burst has been studied by Mobaraki at al [2]. Response of the tunnel in three different type of soil domain were studied and validated against empirical equations. Evaluation of the damage of the materials were done using nonlinear material models (MAT_SOIL_AND_FOAM) and (MAT_PLASTIC_KINEMATIC) for soil and concrete respectively. Peak particle velocity in the soil medium has been used to characterize the failure criteria.

Numerical evaluation of rock mass subjected to a large scale underground explosion and validated against experimental data using PPV and PPA data were studied by Chenqing et al

[3]. A fully coupled SPH-FEM approach were used by Zhongqi et al [4] to validate the explosion effect in a soil against empirical calculations. Response of the structure such as pressure, velocity and acceleration were evaluated and validated.

3 SHOCK WAVE PROPAGATION

Weapons exploding above or near the ground surface and weapons that explode after penetrating the soil medium are the two cases that pose major threat to underground structures. Crater formation and ground vibrations are the major phenomena that dissipate the energy in a blast phenomenon.

Crater and Attenuation

Blast at or near to ground surface excavates the soil medium resulting in the formation of a large crater and the geological material thrown out of the crater is known as ejecta. The depth of burst is one of the major parameter that controls the shape and size of the crater. Depth of crater will increase with depth of burst to a certain optimum limit, beyond which it decreases. If the explosion is too deep inside ground, then the crater may not be visible at surface and it is termed as Camouflet [5].

The shock wave font with peak blast pressure travel as elastic waves as it passes through different geological strata and it attenuates as distance from the blast source increases. Variation in the wave propagation characteristics is directly related to the soil media density, moisture content and other soil parameters. Compression wave (P-wave) is the critical component for the analysis of underground structures that provides information on attenuation characteristics of the medium. The velocity of P-waves $\left(\sqrt{\frac{G}{\rho}}\right)$ can be calculated by using shear modulus (G) and density of the soil medium (ρ). Inference from the P-wave characteristics reveals that stiffer the soil medium, higher the shock wave velocity and lower the attenuation characteristics of the soil.

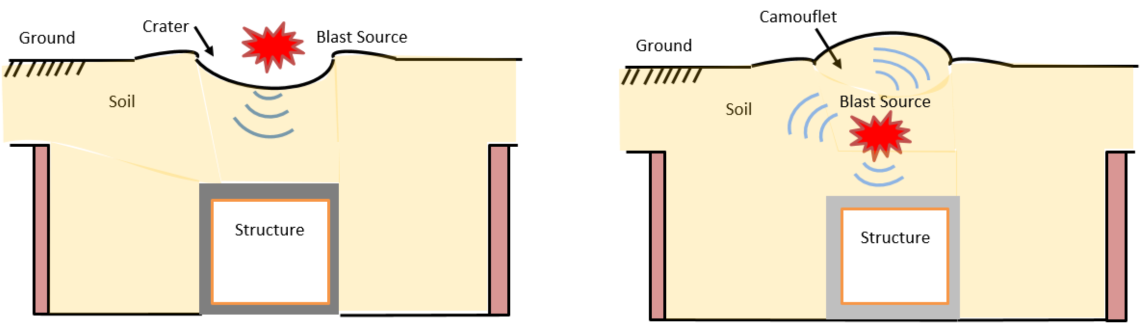

Figure 1: Surface/Sub-surface blast effects

Pressure Calculation

Pressure font varies as the waves travel away from origin depending mainly on the attenuation factor and acoustic impedance of the geological media. For relatively short distances from the explosion source, high pressures are developed, soil might exhibit a strain hardening behavior under this increased level of pressure. Empirical power law equations [5, 6] that is used to describe the magnitude of peak over pressure as a function of distance as shown below

$$P_o = Af(\rho c)\left[\frac{R}{W^{1/3}}\right]^{-n} \quad (1)$$

From the above equation, it can be observed that more the dense medium, higher the pressure value. Where, Po is the over pressure at any scaled depth, A is the constant, f is the coupling factor depending on the scaled depth of burst, ρc is acoustic impedance of the medium, R is the scaled distance where pressure is measured, W is the charge weight and n is the Attenuation factor of the medium. The Coupling factor is nothing but a value corresponding to the depth of burst in a medium that is obtained from Figure 2.

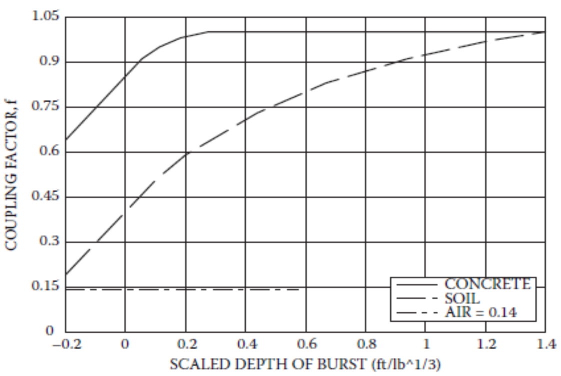

Figure 2: Coupling factor graph

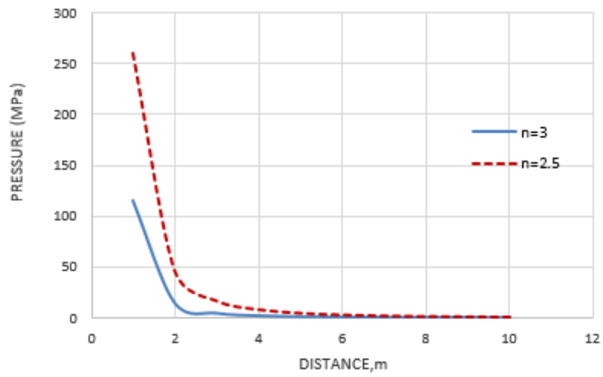

Figure 3: Shock wave attenuation

Shock Wave Attenuation in Soil

Shock wave propagation/attenuation for a 500 lb. charge weight located at 1m below the ground surface for two different soil properties are provided in Figure 3. From the results it can be observed that there is a drastic decrease in pressure initially and then the rate of decrease becomes gradual over the distance. Also, the importance of attenuation factor in attenuating the pressure at near-field can be observed.

Comparison of Sub –Surface Blast Pressure with Free-Air Burst and Surface Burst

For a close range explosion (750lb.), Sub-Surface Blast pressure has been compared with that of Free-Air Burst and Surface Burst to understand the wave propagation in soil and its attenuation effects. Theoretical values for Free- Air and Surface Blast Pressure are computed using UFC [7]. It is evident that the effect of sub-surface burst is much more as compared to the other types, especially in a close range.

Distance	3m	4m	5m	6m	7m	8m	9m
s-s P_{so} (MPa)	16.67	8.12	4.65	2.95	2	1.44	1.07
s-P_{so} (MPa)	5	3.09	2.04	1.4	1	0.75	0.57
a-P_{so} (MPa)	4	2.3	1.44	0.97	0.69	0.51	0.39

Table 1: Comparison of sub-surface (s-s), surface (s), and free-air (a) blast pressures vs. distance

4 INTERACTION WITH STRUCTURE

The ground shock with peak particle velocity impacts the underground structure and causes significant deformation or damage to the structure. Large deformation in soil might usually be associated with large deformation in a structure as well, if it is in the vicinity of the explosive. Net response of the structure subjected to ground motion can be evaluated using Soil-Structure Interaction (SSI) [2, 8]. The response of the structure depends on the soil structure interface, soil strata and intensity of the ground motion. Acoustic impedance can be used to calculate the pressure at structure when an explosion occurs at some distance from the structure.

Acoustic Impedance

Acoustic Impedance of a media is given by product of the seismic velocity and density of the soil medium as indicated below

$$Acoustic\ Impedance, \alpha = \rho C \quad (2)$$

Where Seismic Velocity (C) is equal to the P-wave velocity of the blast wave in the medium and ρ is the density of the medium. This shows how the wave propagation gets affected by density of the soil media at the interface. Acoustic impedance act as an important parameter in evaluating the pressure transmission and reflection in the media. Hence as the wave passes through layered geological strata, the pressure changes depending upon the acoustic impedance of the media.

Reflection & Transmission

As the blast wave traverses through different geological media, energy transmission and reflection occurs at the interface. The transmission/reflection purely depends on the ratio of the acoustic impedance of the two media at the interface. The ratio is expressed by acoustic impedance of the second media (α_2) to the acoustic impedance of the first media (α_1) and represented by (when the wave travels from first media to the second)

$$\alpha_z = \alpha_2/\alpha_1 \quad (3)$$

Higher the ratio, higher the transmission and lower the reflection. From the ratio, the amount of stress reflected can be calculated as follows

$$\sigma_r = \left(\frac{\alpha_z - 1}{1+\alpha_z}\right)\sigma_i \quad (4)$$

Where σ_i = incident pressure. Similar to reflection, transmission is also a function of impedance ratio and transmitted stress can be calculated

$$\sigma_t = \left(\frac{2\alpha_z}{1+\alpha_z}\right)\sigma_i \quad (5)$$

5 NUMERICAL ANALYSIS

For the numerical analysis of blast simulation and its effect on structure, LS-DYNA is used. Blast pressure generation is captured through the actual modeling of the explosive (TNT). Dimension of the problem changes as per the problem definition.

Finite Element Modeling

For simplicity, axisymmetric model is considered for the analysis as shown in Figure 4 and Figure 5. As initial detonation of the TNT and wave propagation is crucial for the accuracy of the simulation, a very fine mesh is required at the detonation point. Mapping techniques are generally used to capture the propagation more accurately at the detonation level [9, 10].

In this study, a varying mesh is used that is very fine (0.05) at the detonation location. As the number of elements is less than 1lakh it works out to be computationally efficient for the study. For the numerical model considered in the study, free-flow condition is provided on sides as shown in the Figure 4 and Figure 5. The material medium consist of Air, Soil and TNT. Air medium of suitable dimension is considered above the ground to model the wave propagation and crater effects to the precise.

Arbitrary Lagrangian Eulerian (ALE) algorithm which leverage the advantages of both the Lagrangian and Eulerian is adopted for modeling the blast simulation. Multi-material ALE modeling [MMALE] proves to be efficient in modeling the large deformation problems especially blast and impact [11] [12] [13]. In the study, ALE mesh (SECTION_ALE2D) is used to represent the fluid domain (air and TNT) and Lagrangian mesh (SECTION_SHELL) for the concrete domain. Contact between the ALE and Lagrangian domain is established using *CONSTRAINED_LAGRANGE_IN_SOLID [14]. And a suitable ALE advection algorithm is used such that energy conservation is achieved. To achieve the stable solution for the analysis, Energy Ratio (=1) and Hourglass Energy Ratio (<5% of Internal energy) and Sliding Energy Ratio (<10% of Internal energy) are checked [15].

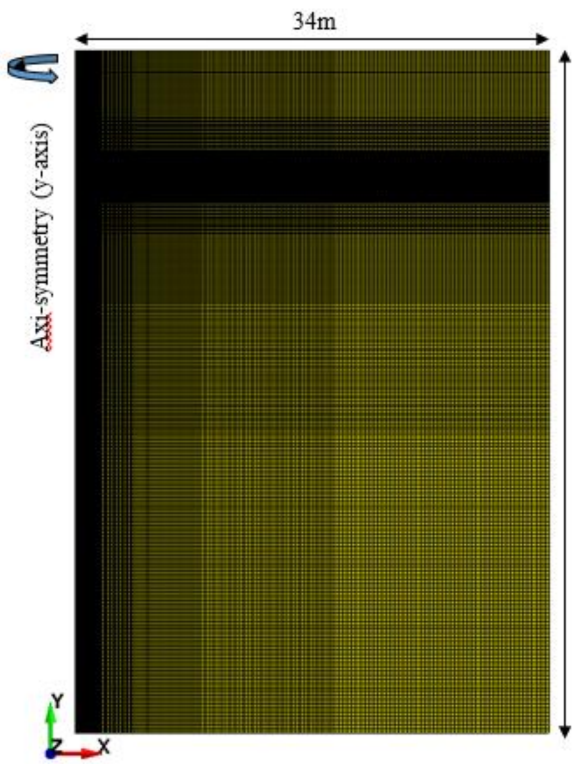

Figure 4: FE mesh

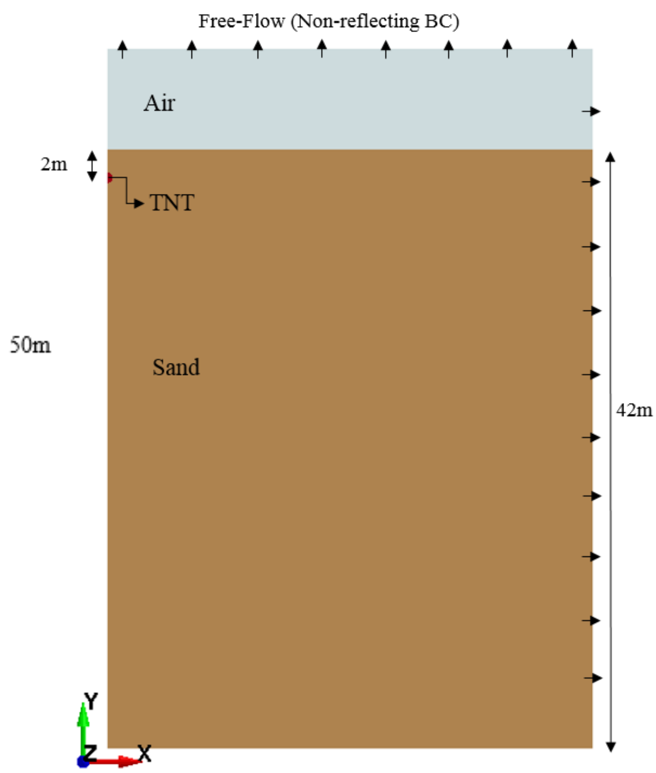

Figure 5: ALE Multi-Material model

Material Modeling

The explosive material behavior is modeled and simulated using *MAT_HIGH_EXPLOSIVE_BURN and EOS_JWL (Equation of State). *MAT_NULL and *EOS_LINEAR_POLYNOMIAL are used to model the air domain. Material properties are provided below.

Unit (kg, m, s)						
MAT_NULL						
R0	PC	MU	TEROD	CEROD	YM	PR
1.225	0	1.78 x 10^{-5}	0	0	0	0

EOS_LINEAR_POLYNOMIAL								
C0	C1	C2	C3	C4	C5	C6	E0	V0
0	0	0	0	0.4	0.4		$2.5\text{x}10^5$	1
MAT_HIGH_EXPLOSIVE_BURN								
R0	D	PCJ	BETA	K	G	SIGY		
1630	6930	$2.1\text{x}10^{10}$	0	0	0	0		
EOS_JWL								
A	B	R1	R2	ω	E0	V0		
$3.738\text{x}10^{11}$	$3.747\text{x}10^9$	4.15	0.9	0.35	$7\text{x}10^{10}$	1		

Table 2: Air and TNT material parameters

A nonlinear constitutive continuum model with damage modeling is used to capture the concrete behavior subjected to the blast and impact loading. Several constitutive models are available for the continuum modeling of concrete dynamic response [16]. MAT_RHT model is used to study the concrete behavior subjected to blast loading.

For modeling the soil medium, MAT_SOIL_AND_FOAM [17] is used which includes the pressure-volume relationship that is predominant during the blast wave propagation. Soil properties of the different soil medium are provided below.

R0	G	BULK	A0	A1	A2	PC
Low Dense Soil						
1293	$3.2 \text{ x } 10^6$	$1.7 \text{ x } 10^8$	1000	0.75	$1.5\text{x}10^{-4}$	0
Medium Dense Soil						
1453	$1.7\text{x } 10^7$	$1.2 \text{ x } 10^8$	$5.3 \text{ x } 10^5$	15.26	$1.1\text{x}10^{-4}$	$-1.4\text{x}10^4$
High Dense Soil						
2094	$2.3\text{x } 10^7$	$1.3 \text{ x } 10^8$	$4.3 \text{ x } 10^4$	3.71	$7.9\text{x}10^{-5}$	-6894.75

Table 3: Sand material properties [18]

6 CASE STUDY

The case study deals with a problem of an under-ground blast initiated by a penetrated missile. Penetrating missile has the capacity to penetrate and reach the structure as close as possible causing significant damage to the structure (Figure 6). The damage is significant if the missile penetration is not resisted by providing suitable mitigation procedure. As the interest is on shock wave propagation, penetration effect of the weapon on the soil is not discussed.

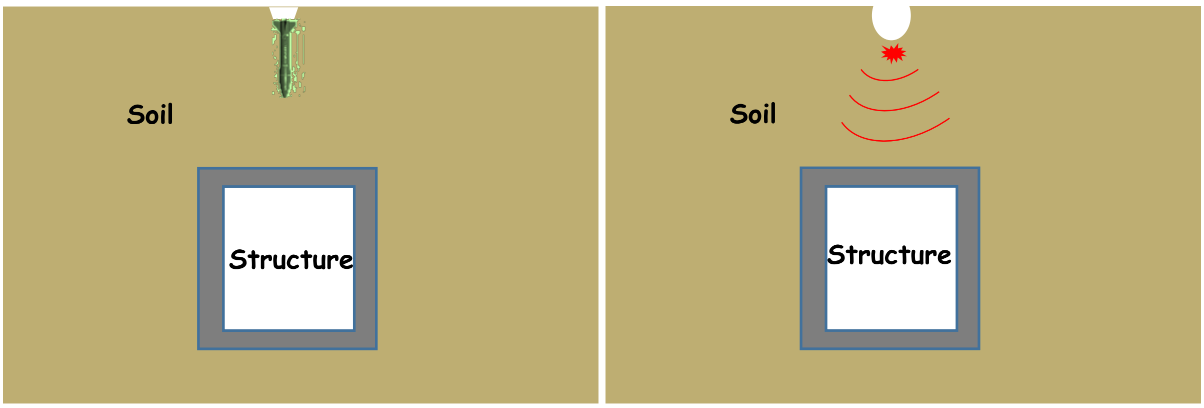

Figure 6: Penetration and blast scenario

Sub-Surface Blast – Shock Wave Propagation

The first part deals with the penetration blast effect on high dense soil medium. Soil medium property is as given below in Table 4. Coupling factor, f obtained for the scaled depth of burst ($D/W^{1/3}$) 0.286 $m/kg^{1/3}$ is 0.84. As our interest is on wave propagation and attenuation, the structure is not explicitly modeled, rather pressure is measured exactly above the structure. The progressive impact of the blast is measured at a regular interval using DATABASE_TRACER. Pressure at intervals are plotted in Figure 7. As the prime focus is on the structure located at 40m, pressure measured at 40m is 0.0218 MPa that matches with that of empirical calculation using equation (1) (0.0229MPa). Comparison graph of empirical and numerical is provided in Figure 9, from which it can be inferred that pressure at farther distances matches more accurately with that of UFC [1]. Pressure wave propagation in the soil is shown in the Figure 8, from which attenuation effect of soil can be visualized.

Charge Wt.(lb)	DOB (m)	ρ(kg/m^3)	c(m/s)	ρc (MPa/m/s)	f	n	A
750	2	2094	210	0.44	0.84	2.5	4.83

Table 4: Blast pressure calculation parameters

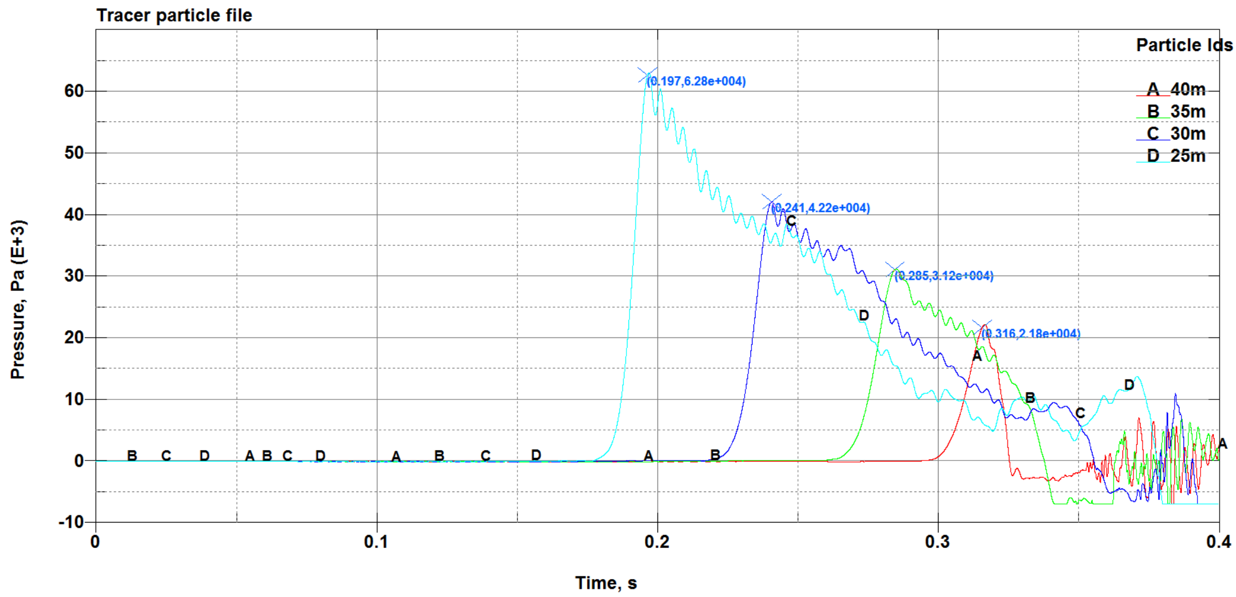

Figure 7: Pressure vs. time (for different locations)

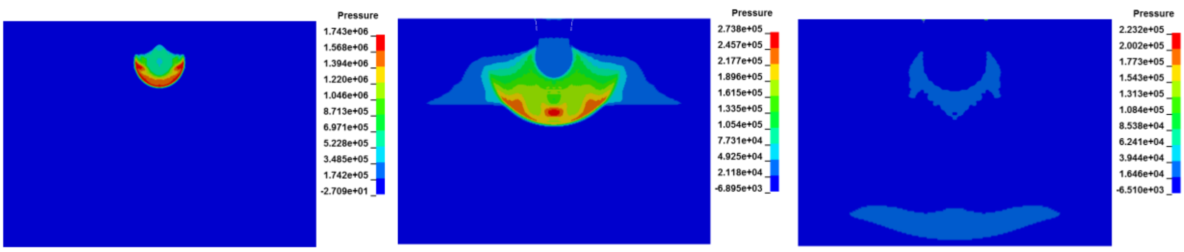

Figure 8: Blast – wave propagation (@30ms, 100ms & 300ms)

Using the graph from the literature [1] that is available for different types of soil, crater dimensions are computed. Since the literature data on crater formation is broadly classified, crater dimensions can be predicted only in a range. The crater dimension falls in the range of 3.32-4.43m of depth and 9.14-11.08m of crater diameter. Crater formation at stages are shown in Figure 9, the resulting crater size is 8m depth and 12.5m diameter. The values computed using the empirical is apparent whereas in numerical analysis, the true crater dimension is measured.

Figure 9: Blast – crater formation (@30ms, 100ms & 300ms)

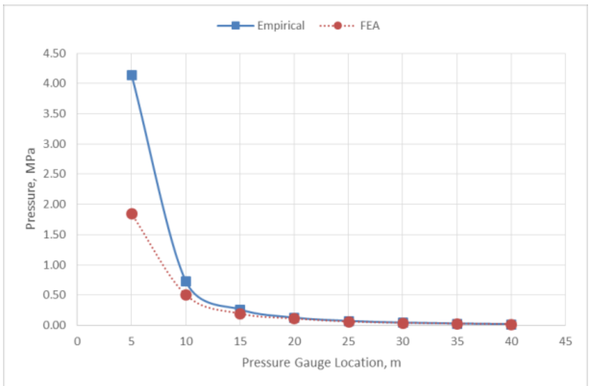

Figure 10: Pressure vs. distance (High Dense Soil) (Empirical vs. FEA)

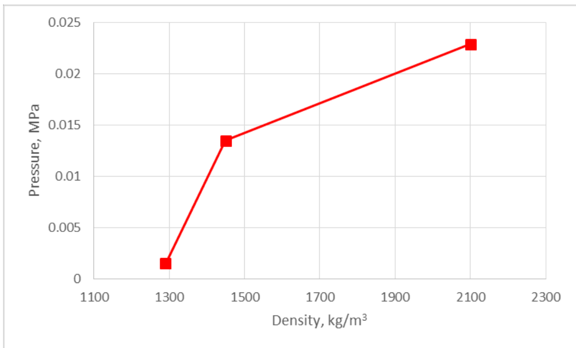

Figure 11: Pressure vs. distance for diff density (Empirical approach)

Effect of Soil Medium on Wave Propagation

In the second part of the case study, attenuation effects of different soil medium are studied for the same penetration blast explained above. The focus is on the difference in nature of the shock wave propagation due to the soil medium. Two additional soil types (medium dense and low dense soil) are considered for the analysis in addition to the high dense presented above. The different soil properties used are mentioned below.

ρ(kg/m^3)	c(m/s)	ρc (MPa/m/s)	f	n	A
1453	178	0.258	0.84	2.5	4.83
1453	178	0.258	0.84	3	3.04
1293	87.1	0.11	0.84	3	3.04
1293	87.1	0.11	0.84	3.5	1.91

Table 5: Low and medium dense sand properties

The overpressure calculated theoretically at the structure location depends on many factors as already discussed. A set of attenuation factors are considered for the study for each soil medium. For medium dense soil, the pressure at structure location is 0.0035 MPa (n=3) & 0.0135 MPa (n=2.5), and for low dense soil the pressure is 0.000406 MPa (n=3.5) & 0.0015 MPa (n=3). The attenuation effect of the soil is enormous as the soil density reduces (Figure 11).

Pressure at structure is 0.016 MPa and 0.0074 MPa respectively in numerical analysis. Numerical results are close to the range of empirical results [Figure 12] that has low attenuation factor value. Attenuation factor has huge impact on pressure wave attenuation. Since very limited information is available on attenuation factor computation, further investigation is not carried out to study the effects of same. However, the wave attenuation pattern is same as that of empirical and numerical results act as a more conservative approach for the pressure computation. In addition to the attenuation factor, information on the constant factor (A) is also minimal.

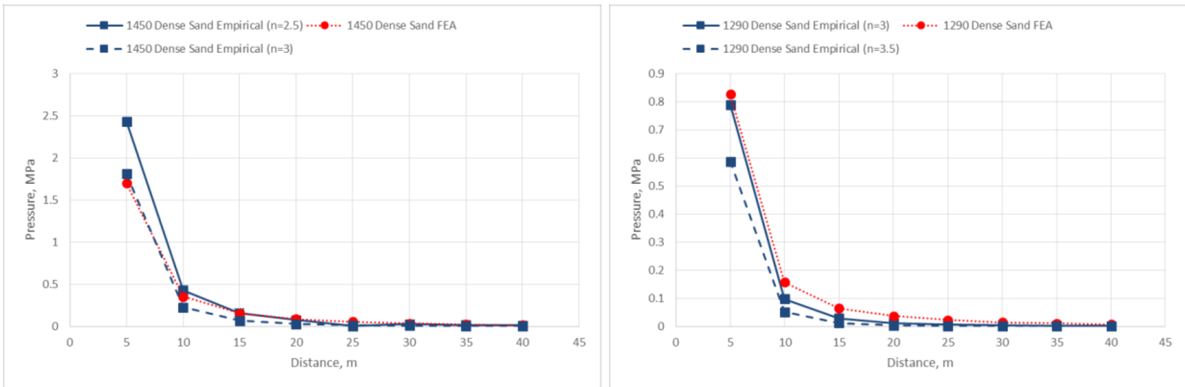

Figure 12: Pressure vs. distance a) medium dense soil b) low dense soil

Crater dimensions for the medium dense soil is 9m depth & 13.25m diameter and for the low dense soil is 9.8m depth & 14.5m. Thus, from the numerical analysis the crater dimension are in the range of 8-9.8m depth and 12.5-14.5m diameter. Through numerical analysis, true crater dimensions for a particular type of soil can be computed.

Blast on Layered Soil Medium

The third part refers to the interaction of blast pressure on structure subjected to sub-surface blast in high dense medium. Reflection and transmission phenomenon that takes place when the blast wave propagates in layered soil and during its interaction with under-ground structures are captured and explained here. When the blast waves travel from denser medium to lighter medium, the reflected stress is less but tensile in nature and the transmitted pressure is relatively more by compressional wave. A number of combination has been checked numerically and theoretically to study the behavior. The structure is located at 40m below the blast source and it is placed 10m above the soil with dimension of 15m width and 7.5m height. Concrete grade of M40 is used for the analysis. The effect of layered soil is considered for the study. Details of the different soil medium are provided in the Table 6.

Medium	ρ (kg/m^3)	c (m/s)	α= ρc (MPa/m/s)
Low density Soil	1293	87.1	0.11
Medium Density Soil	1453	178	0.258
High Density Soil	2094	210	0.44
Concrete	2548	3600	9.173

Table 6: Acoustic Impedance of different soil media

When the blast wave travels in soil and interacts with an under-ground structure made of concrete, the pressure wave hitting the structure surface gets reflected partly and rest gets transmitted into it. Where the transmitted stress will be high compared to the incident pressure. The same phenomenon is followed as the wave propagates through soil layers. Results of interaction at the soil strata and concrete are provided for numerical analysis and compared against UFC.

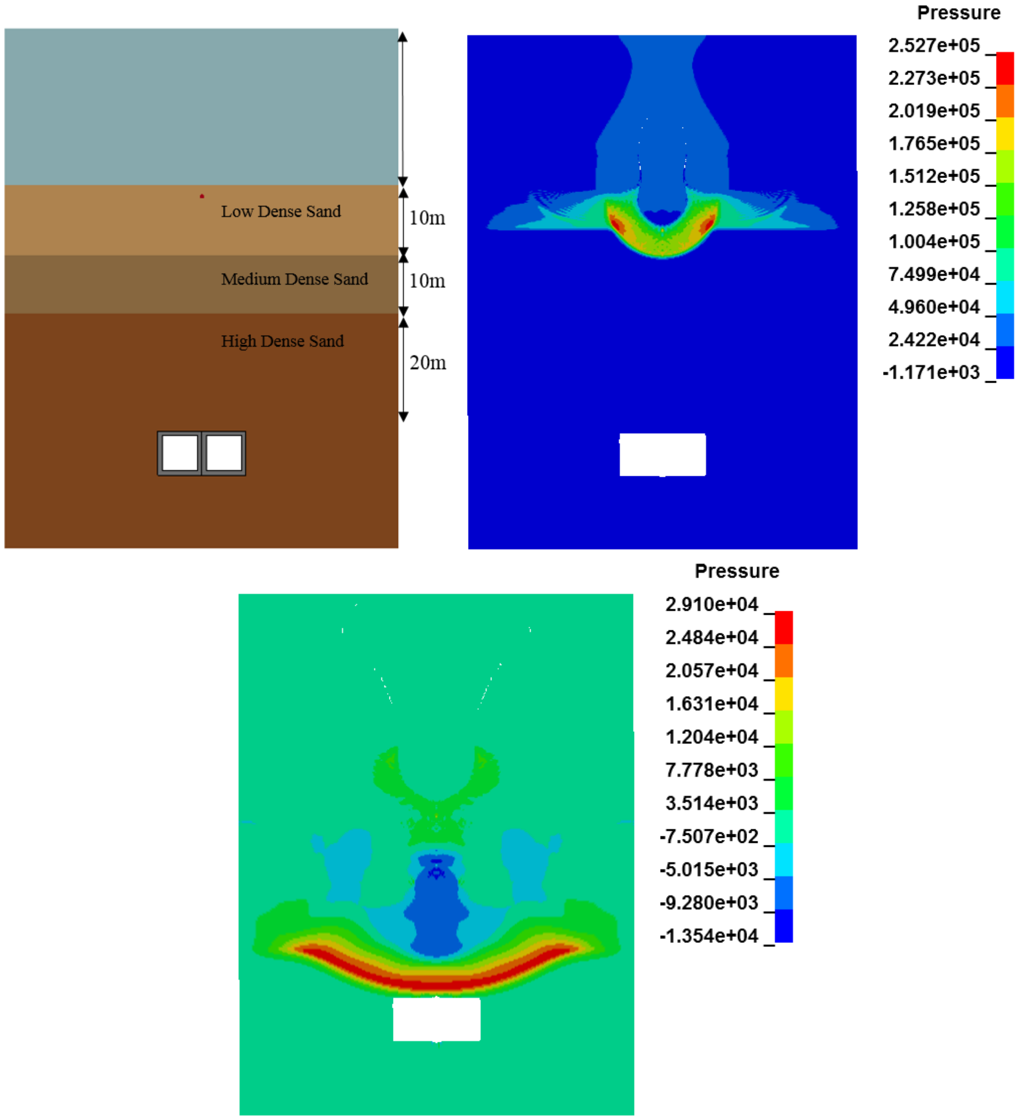

Figure 13: Layered soil numerical model

Media	$\alpha_z = \alpha_2/\alpha_1$	σ_i (MPa)	σ_r (MPa)	σ_t (MPa)
		E/N	E/N	E/N
Low Density Soil to Medium density soil	2.345			
Numerical		1.65E5	2.25E5	2.25E5
Empirical		1.65E5	2.34E5	2.34E5
Medium Density Soil to High density soil	1.705			
Numerical		4.69E4	6.71E4	5.88E4
Empirical		4.69E4	5.91E4	5.90E4
High Density Soil to Concrete	20.85			
Numerical		1.54E4	2.0E4	2.3E4
Empirical		1.54E	2.9E4	2.9E4

Table 7 Numerical and empirical results

From the comparison in Table 7, it can be inferred that numerical analysis captures the results within a range of +/- 5 percent variation of the theoretical calculations. Better visualization and understanding of the pressure wave propagation can be obtained from the simulation results as evident from Figure 15.

7 CONCLUSIONS

Following broad conclusions can be drawn from the empirical and numerical studies:

- Shock Wave attenuation plots show similar trend for soils of different densities marked by a rapid decrease in pressure in close range whereas a comparatively gradual decrease of pressure as the wave propagates further.
- Sub-Surface blast pressure when compared to Surface and Air blast pressures, indicates much higher intensity, especially in closer ranges.
- Attenuation of pressure waves in sub surface blast is greatly affected by the density of the soil medium, thus choosing the correct attenuation factor for theoretical calculation is vital. Attenuation as observed is less in highly dense medium when compared to a medium of low density.
- Numerical analysis were able to predict the wave propagation and crater formation accurately. The variation in the results (medium and medium dense soil) might be due to the chosen attenuation factor and constant factor (A). The constant factor used for the computation is based on the value of 160 (in FPS units system) from the literature. Any change in these factors will have impact on pressure wave propagation in soil.
- As the Shock wave passes from one medium to another having different densities, reflection and transmission phenomenon takes place at the interface. As observed theoretically as well as numerically when the shock wave passes from softer to harder medium (in terms of density) the interface has a reduced reflected pressure and an amplified transmitted pressure, values depending on acoustic impedances of both the media. Whereas in case when it passes from a harder to softer medium, the reflected pressure is less compared to the earlier case but tensile in nature and transmitted pressure gets amplified.

The numerical analysis carried out were able to predict the attenuation effect of the shockwave in different soil medium as well as in layered medium.

8 FUTURE STUDIES

Preliminary study has been done on blast wave propagation in rock. General arrangement of rock as we know is completely different than soil as it contains number of faults, fractures and uncertainties. Thus calculating pressure propagation will include a number of rock strength parameters like RQD and GSI. Basic calculation shows much higher pressure for sub surface blast in rocks at any distance when compared to blast in soil.

Future study focuses on wave propagation in rock and its constitutive modeling through numerical analysis.

REFERENCES

[1] Y. Zhang, Q.Fang, J. Liu, Experimental and numerical investigation into responses of buried R/C frames subjected to impulsive loadings. *Structures Under Shock and Impact VII,* 2002.

[2] B. Mobaraki, M.Vaghefi, Effect of the soil type on the dynamic response of a tunnel under surface detonation. *Combustion, Explosion and Shock Waves*, 52, 363-370, 2016.

[3] C. Wu, Y. Lu, H. Hao, Numerical prediction of blast-induced stress wave from large scale underground explosion. *International Journal for Numerical and Analytical Methods in Geomechanics*, 28, 93-109, 2008.

[4] Z. Wang, Y. Lu, H. Hao, K. Chong, A full coupled Numerical Analysis approach for buried structures subjected to sub-surface blast. *Computers and Structures*, 83, 339–356, 2005.

[5] T. Krauthammer, *Modern Protective Structures*, CRC Press, 2008.

[6] D.Z. Yankelevsky, Y.S Karinski, V.R. Feldgun, Re-examination of the shock wave's peak pressure attenuation in soil. *International Journal of Impact Engineering*, 38, 864-881, 2011.

[7] UFC, Structures to resist the effects of accidental explosions, 3-340-02, December 5, 2008.

[8] H.J Ma, S.T Quek, K.K Ang, Soil-Structure Interaction effect from Blast –Induced horizontal and vertical ground vibration. *Engineering Structures*, 26, 1661–1675, 2004.

[9] D.S. Cheng, C.W. Hung, S.J. Pi, Numerical simulation of near-field explosion. *Journal of Applied Science and Engineering*, 16, 61-67, 2013.

[10] V. Lapoujade, N.V. Dorssealaer, S. Kevorkian, K. Cheval, A Study of Mapping Technique for Air Blast Modeling. *11th International LS-DYNA Users Conference*, 2011.

[11] S.H. Tan, R. Chan, J.K. Poon, D. Chng, Verification of concrete materials for MM-ALE simulation. *13th International LS-DYNA Users Conference*, 2013.

[12] J.M.H. Puryear, D.J. Stevens, K.A. Marchand, E.B. Williamson and C.K. Crane, ALE modeling of explosive detonation on or near reinforced-concrete columns. *7th International LS-DYNA Users Conference*, 2012.

[13] Arumugam. D, Tamiselvan. K, Dhana Sekaran. B & Subash. T.R, Numerical analysis of missile penetration on concrete targets. *International NAFEMS Conference on Engineering Analysis, Modeling, Simulation and 3D Printing,* India, 2016.

[14] Livermore Software Technology Corporation (LSTC), *LS-DYNA Keywords user's manual*, California, 2016.

[15] A. Deivanayagam, A. Vaidya and S.D. Rajan, Enhancements to modeling dry fabrics for impact analysis. *Journal of Aerospace Engineering*, 27(3), 484, 490, 2014.

[16] Y. Wu, J.E. Crawford, J.M. Magallanes, Performance of LS-DYNA concrete constitutive models. *12th International LS-DYNA Users Conference*, 2012.

[17] Y. Wu, John E.Crawford, Shenguri Lan and Joseph M. Magallanes, Validation studies for concrete constitutive models with blast test data. *12th International LS-DYNA Users Conference*, 1994.

[18] E.Heymsfield and E.N. Fasanella, Using Numerical Modeling to Simulate Space Capsule Ground Landing. *International Proceeding of the 88 Transportation Research Board Annual Meeting*, Washington, July 30, 2008.