Relevancy of Peak Parameter Plots in Estimating Effects of Ground Shock

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Abstract

Studies on correlations of ground shock parameters from explosions began since 1870. Many field tests of various scales have been conducted to obtain the correlation of these parameters. One example is the U.S. Army Corp of Engineer's TM 5-855-1 (1986). The objective of this paper is to evaluate the relevancy of the plots in TM 5-855-1 (1986) given that many advances have been made in computational modeling. In the paper, ground shock parameters such as pressure, velocity, acceleration, impulse and scaled distance are firstly expressed as dimensionless parameters to develop dimensionless counterpart plots of the TM5-855-1 (1986) plots. Next, data from ground shock studies in the literature are examined using the dimensionless plots. It is found that the dimensionless plots provide good indicative values of the parameters and it is also possible to know how the parameters will change as degree of saturation of the soil and soil type changes.

Keywords: Ground Shock, pressure, velocity, acceleration, impulse.

Introduction

Ground shock parameters like pressure, velocity and density which are related to explosive detonation were investigated as early as 1870. The U.S. Army Corp of Engineers developed the TM 5-588-1 (1986) which provides correlations of peak parameters (pressure, velocity, acceleration, displacement and impulse) with variables like weight of explosive charge, distance and soil condition. However, the equations given by TM 5-855-1 (1986) are empirical based on field test data and do not take into consideration of consistency of units.

The objective of this paper is to evaluate the relevancy of the plots of ground shock parameters in TM5-855-1 (1986) given the current advances made in computational modeling. To achieve a sound basis, dimensionless ground shock parameters were firstly obtained using Buckingham's pi theorem. Using dimensionless ground shock parameters of TM5-855-1 (1986), data of ground shock studies from the literature are plotted. Through examination of these plots, a better understanding on how the peak ground shock parameters change with soil properties and soil type can be obtained.

Background

The equations in TM5-855-1 (1986) for peak pressure P_o, peak velocity V_0, peak acceleration a_0, peak displacement d_0 and impulse I_o are as follows:

Peak pressure:	$P_o = f.(\rho c).160.(\frac{R}{W^{1/3}})^{-n}$	(1.1)
Peak acceleration:	$a_o W^{1/3} = f.50.c(\frac{R}{W^{1/3}})^{(-n-1)}$	(1.2)
Peak velocity:	$V_o = f.160.(\frac{R}{W^{1/3}})^{-n}$	(1.3)
Peak displacement:	$\frac{d_o}{W^{1/3}} = f.500.\frac{1}{c}.(\frac{R}{W^{1/3}})^{(-n+1)}$	(1.4)
Impulse:	$\frac{I_o}{W^{1/3}} = f.\rho_o.1.1.(\frac{R}{W^{1/3}})^{(-n+1)}$	(1.5)

R is the distance away from the explosion and W is the weight of the charge. It is noted that the weight of the charge is based on TNT equivalent. It is also noted that these equations are in imperial units and are not dimensionally consistent. Westine et al. (1983) suggested using dimensionless scaled pressure $P_0/\rho c^2$ and dimensionless scaled distance $R(\rho c^2/W)^{1/3}$. Leong et al. (2006) also noted that W is in lb for imperial units and in newton for SI units and introduced a term k of 1m or 3.28ft in the dimensionless scaled distance $R(\rho c^2/kW)^{1/3}$ so that there will be a seamless conversion from imperial units to SI units. Henceforth, the scaled distance shall be $R(\rho c^2/kW)^{1/3}$. If the coupling factor (f) is taken to be unity, it implies that the explosive energy is fully contained within the soil.

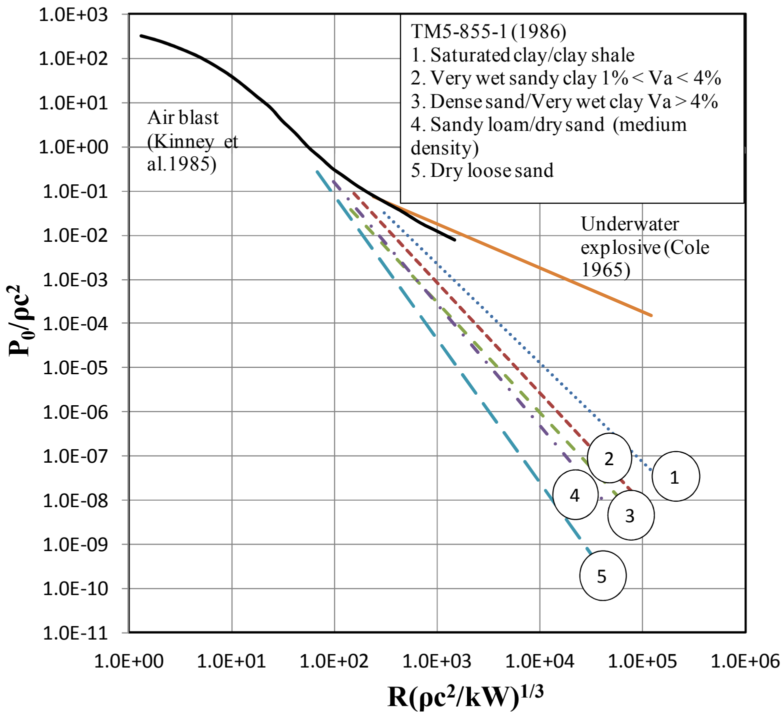

Figure 1. Relationship of peak pressures with scaled distance using dimensionless parameters (modified from Leong et al. 2006)

The TM5-855-1 (1986) plot for peak pressure is re-plotted with dimensionless parameters $P_0/\rho c^2$ and $R(\rho c^2/kW)^{1/3}$ as shown in Figure 1. The circled numbers represent the soil types as given by TM5-855-1 (1986) indicated in the legend of the plot. Leong et al. (2006) also suggested that the air blast and underwater explosion peak pressure curve be plotted in the dimensionless plot. The air blast peak pressure curves and underwater explosion peak pressure curve were obtained from Kinney's equation (Kinney and Graham, 1985) and Cole (1965), respectively. The air blast peak pressure curve merges with the underwater explosion curve and forms an upper boundary of the TM5-855-1 (1986) curves. Leong et al. (2006) observed that the peak pressure curves from TM 5-855-1 (1986) converged and merged into the air blast curve and fanned out with the increase in dimensionless scaled distance $R(\rho c^2/kW)^{1/3}$ as shown in Fig. 1.

Development of dimensionless plots

Buckingham's pi theorem was used to find dimensionless parameters for ground shock parameters of peak velocity, peak acceleration, peak displacement and impulse. Table 1 summarizes the dimensionless parameters of peak velocity, peak acceleration, peak displacement and impulse formed using Buckingham's pi theorem. The dimensionless parameters of peak pressure and scaled distance are also included in Table 1 for completeness. It is noted that both SI and imperial units can be used as long as the units are kept consistent. The dimensionless plots of peak acceleration, peak velocity, peak displacement and impulse with scaled distance for TM 5-85501 are shown in Fig. 2 to Fig. 5, respectively.

Table 1: Correlation of peak pressure, velocity, acceleration, displacement and impulse with dimensionless parameters

Parameter	Function	Dimensionless parameter
Peak pressure	$P_0 = f(\rho,c)$	$\frac{P_o}{\rho c^2}$
Peak acceleration	$a_0W^{1/3} = f(\rho,c,g)$	$\frac{a_0 W^{1/3}}{c^2 \rho^{1/3} g^{1/3}}$
Peak velocity	$V_0 = f(c)$	$\frac{V_0}{c}$
Peak displacement	$d_0/W^{1/3} = f(\rho,g)$	$\frac{d_0 \rho^{1/3} g^{1/3}}{W^{1/3}}$
Impulse	$I_0/W^{1/3} = f(\rho,c,g)$	$\frac{I_0 g^{1/3}}{w^{1/3} \rho^{2/3} c}$
Scaled distance	$R/W^{1/3} = f(k, \rho, c)$	$R(\frac{\rho c^2}{kW})^{1/3}$

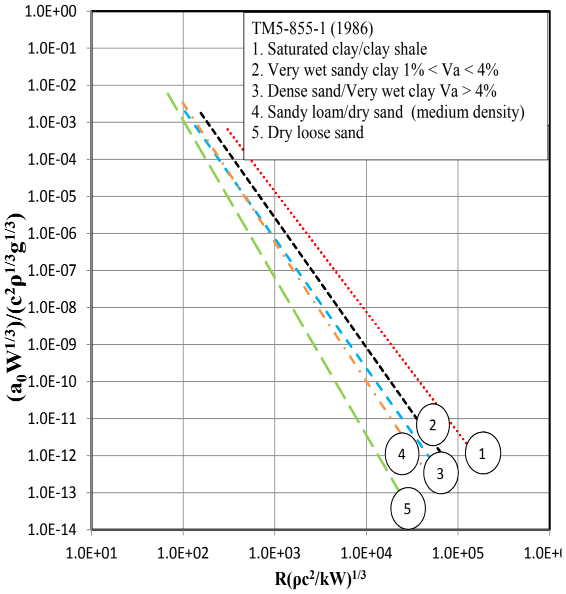

Figure 2. Dimensionless of peak acceleration with scaled distance

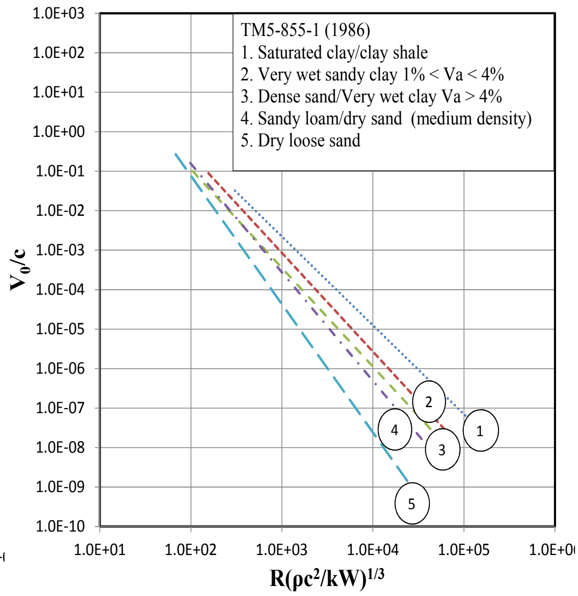

Figure 3. Dimensionless plot of peak velocity with scaled distance

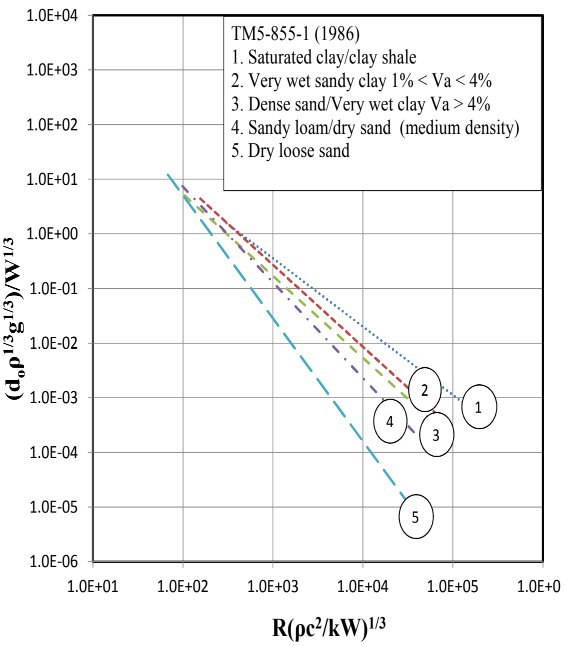

Figure 4. Dimensionless plot of peak displacement with scaled distance

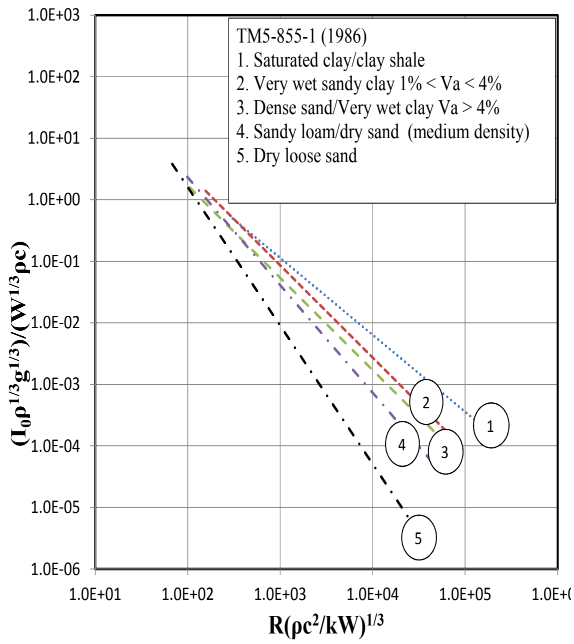

Figure 5. Dimensionless plot of impulse with scaled distance

Observations and Discussions

Ground shock data of peak pressure, peak velocity, peak acceleration and impulse were collated from the literature and plotted in the dimensionless plots. Peak displacement is not included as such data are not available in the literature. However, the data that are plotted into the plots are dependent on factors such as the placement of the instruments, depth of burial of explosives and type of explosives used. For the purpose of measuring free-field ground shock parameters, the instruments should not be placed at the ground surface or poorly coupled to the ground as this will not accurately measure the ground shock waves. The depth of burial of the explosives determines the energy dissipated in the ground. Shallowly buried explosive does not have a coupling factor of one which is assumed in the dimensionless plot of the equations from TM5-855-1 (1986).

Peak pressure versus scaled distance plots

Leong et al. (2006) performed small scale tests using PETN in both wet and partially saturated soils with various charge weights (1, 4 and 10 kg) at various depths. The pressure gauges were located at the same level as the burial depth of the PETN charge. The burial depths of the PETN charge were 1kg at 2m depth, 4kg at 2.5m and 10kg at 2.5m. The test results are plotted in Fig. 6. The wet soil has a density of 1900 kg/m^3 and wave velocity of 1380 m/s. The partially saturated soil has a density of 1650 kg/m^3 and a wave velocity of 225 m/s. It is observed that the peak pressure for wet soil which was fully saturated is nearer to the underwater explosion curve by Cole (1948) compare to the peak pressure for partially saturated soil (85% saturated). The data from wet soil, composed of 93% clay and 7% sand, fall on the very wet sandy clay curve of TM5-855-1 (1986) whereas the data from the partially saturated soil, composed of 95% sand and 3% clay, fall on the sandy loam/dry sand curve. Both sets of data are observed to agree with the TM5-855-1 (1986) soil descriptions.

Peak acceleration versus scaled distance plots

Wu et al. (2003) performed a small scale test involving detonations of 2.5kg to 50kg of TNT with a depth of 14m in rock. The rock has a density of 2610 kg/m^3 and wave speed of 5790 m/s. The accelerometers were placed on the surface and inside the rock mass at horizontal distances of 2.5m, 5m, 10m, 25m and 50m from the charge. The data in term of acceleration inside the rock mass are plotted in Fig. 7. It is observed from Fig. 7 that the peak acceleration data fall above the soil curves with a much lower attenuation. The explosive was detonated in a charged hole and the coupling factor may not be unity.

Peak velocity versus scaled distance plots

Charlie et al. (2007) performed a small scale test in a centrifuge and a field prototype test. The tests were carried out on Poudre valley sand which has a density of 1635 kg/m^3, wave speed of 170 m/s and degree of saturation ranging from 0 to 40%. The explosive used was 7 kg of TNT buried at a depth of 1.4 m. The experimental set-up and placement of accelerometers were not mentioned. The data are plotted in Fig. 8 and Fig. 9 for centrifuge test and prototype test, respectively. From Fig. 8 and Fig. 9, it is observed that as degree of saturation increases, the peak velocity data points move towards the saturated clay line of TM5-855-1 (1986). The data for both the centrifuge test and field prototype test are between the curves of dense sand and saturated clay from TM 5-855-1 (1986).

Peak impulse versus scaled distance plots

Grujicic et al. (2005) performed a numerical simulation using Autodyn (ANSYS INC). Buried C-4 explosives were assumed in the simulation. The modeled soil is assumed to have a density of 2000 kg/m^3 and a wave velocity of 700 m/s with different degrees of saturation ranging from 62.5 % to 100 %. It is observed from the impulse data in Fig. 10 that with the increase of degree of saturation, the data have a tendency to shift upwards towards the saturated clay curve of TM 5-855-1 (1986).

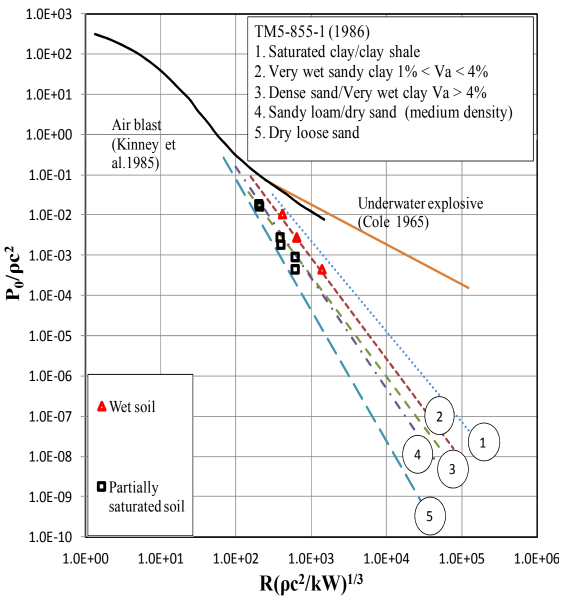

Figure 6. Peak pressure versus scaled distance plot for Leong et al. (2006) data

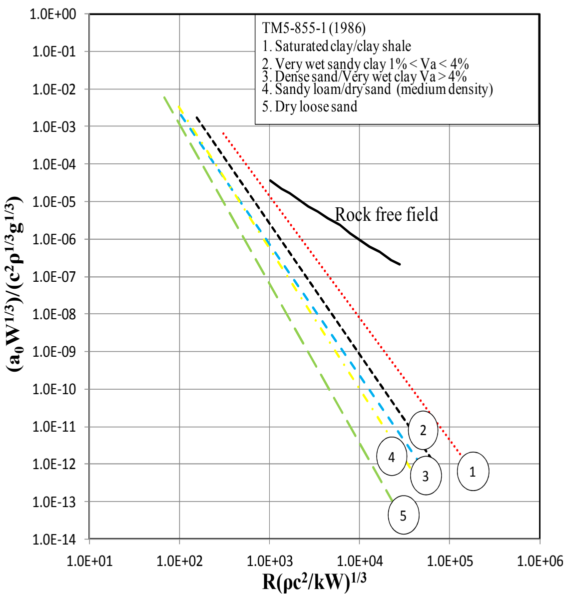

Figure 7. Peak acceleration versus scaled distance plot for Wu et al. (2003) data

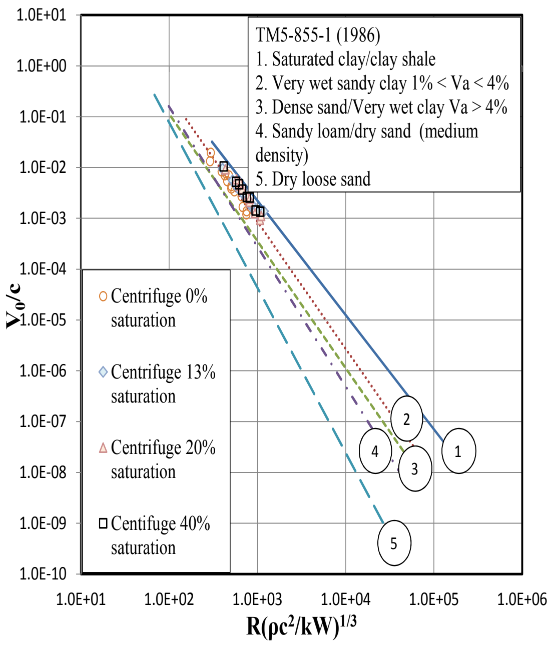

Figure 8. Peak velocity versus scaled distance plot for Charlie et al. (2007) centrifuge test data.

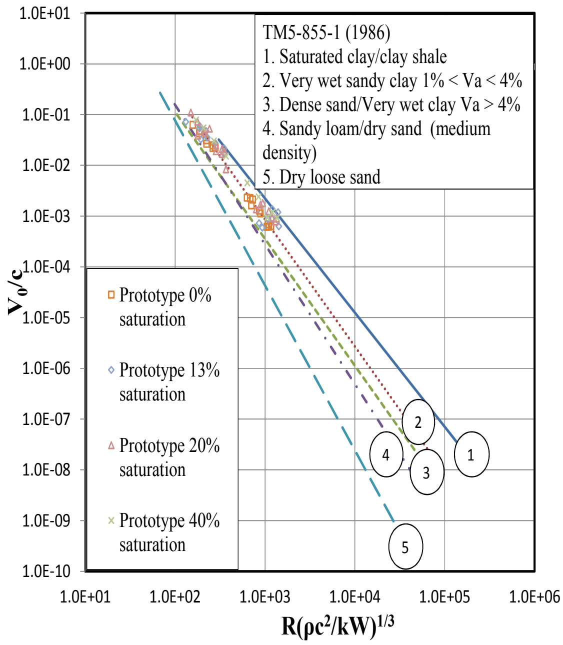

Figure 9. Peak velocity versus scaled distance plot for Charlie et al. (2007) prototype test data

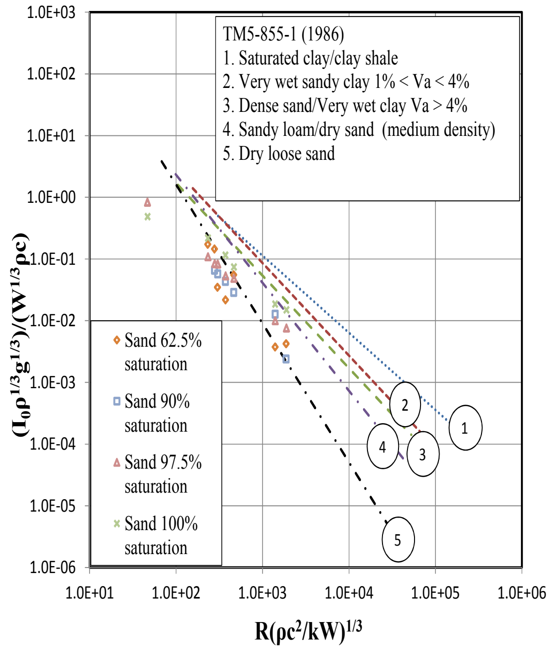

Figure 10. Impulse versus scaled distance plot for Grujicic et al. (2005) data

Conclusion

Peak velocity, peak acceleration, peak displacement and impulse were converted into dimensionless parameters using Buckingham's pi theorem. Dimensionless plots of these parameters with scaled distance of TM5-855-1 (1986) equations were presented. Data from field tests and numerical simulations were collated from the literature and plotted into the dimensionless plots. For peak pressure and peak velocity versus scaled distance, the soil description showed general agreement with TM5-855-1 (1986) soil description. However, for peak acceleration and impulse versus scaled distance, the data collated from the literature do not fall on any of the TM5-855-1 (1986) curves and they showed lower attenuation than the soil curves. It is observed in the peak pressure and peak velocity versus scaled distance dimensionless plots that the data have a tendency to shift towards the saturated clay curve with the increase in degree of saturation. The dimensionless plots of ground shock parameters versus scaled distance of equations from TM 5-855-1 (1986) can be used as benchmarks for numerical simulations.

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