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THE DEVELOPMENT OF SOIL STOCHASTICS MODEL

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ABSTRACT

In this study, the water content and dry density data from field measurement of the ATC Engineered Roadway Soil (E-RW) were analyzed first, and their means and standard deviations were derived. Based on corresponding ERDC lab test data, each soil parameter in both material model and EOS equation was then expressed as a function of soil water content and dry density by 3D or 4D surface fitting. Thus mapping equations from soil water content and dry density to soil parameters were established. With an assumption of normal distribution for both soil water content and dry density, a stochastic soil model was developed for the ATC Engineered Roadway Soil. Modeling and simulation examples were provided to demonstrate how to apply the developed stochastic soil model to carry out underbody blast Monte Carlo simulation for generating vehicle and occupant responses clouds, and how to estimate the low and up bounds of occupant and structure response with certain confidence level.

1. INTRODUCTION

Occupant safety and vehicle survivability are very important performance indices for modern military ground vehicles. Soil properties or characteristics plays critical roles in generating underbody blast loading from buried land mine or IED threat. For any given soil its properties have variations from nominal specification either in proving ground or theater, due to the stochastic nature of geo materials. However, all current soil models used in modelling and simulation so far [1-4] are deterministic models. That is, their parameters are constants and set to their mean values. In general engineers and researchers do not take into account the stochastic variations occurring in real world. The stochastic soil model developed and presented in this paper will be able to improve underbody blast M&S quality and enhance soldier survivability. The validation of an underbody mine blast model will make more sense when the stochastics of the materials and test setups during a liver fire are taken into account.

For a given soil type, its water content and dry density are identified as the two important independent parameters which can be used to calculate other soil parameters like wet density, air-filled void (AFV or volume fraction of air), volume fractions of soil solids and water, porosity and degree of saturation. Soil water content and dry density specification window is used as a soil quality condition control in ATC live firing tests, as specified in various Army Internal Operating Procedure (IOP) [5-9].

In this study, the ATC Engineered Roadway Soil (E-RW) field measurements, the corresponding lab test data and the soil model parameters generated by ERDC were fully reviewed and analyzed for their consistency and completeness[6,7]. The water content and dry density data from field measurement of the soil were analyzed first, and their means and standard deviations were derived. Based on corresponding ERDC lab test data [7], each soil parameter in both material model and EOS equation was then expressed as a function of soil water content and dry density by 3D or 4D surface fitting. The correlation among the basis soil properties (water content and dry density) and the soil elastic-plastic hydrodynamic spalling model [10] were developed. With an assumption of normal distribution for both soil water content and dry density, a stochastic soil model was developed for the ATC Engineered Roadway Soil. Modeling and simulation examples were provided to demonstrate how to apply the developed stochastic soil model to carry out underbody blast Monte Carlo simulation for generating vehicle and occupant responses clouds, and how to estimate the low and up bounds of occupant and structure response with certain confidence level.

This study provided a methodology for soil stochastic model development. It filled a gap between field soil variations and the current deterministic underbody blast M&S approach, increased TARDEC Analysis M&S prediction capability and improved M&S quality.

2. SOIL MATERIAL MODELING

A nonlinear structural FEA simulation tool LS-Dyna with fluid-structure-interaction capabilities was used in TARDEC underbody blast modeling and simulation. An elastic-plastic hydrodynamic material model in LS-Dyna (*Mat_Elastic_Plastic_Hydro_Spall or EPH) [10] was utilized to characterize the strength and compressibility behavior of the E-RW soil in this soil stochastic study. The EPH model is a constant shear modulus (G) model used to define the shear and failure response of a material, and is applicable to a wide range of materials, including those with pressure-dependent yield behavior. The spall model options permit incorporation of material failure, fracture, and disintegration effects under tensile loads. For the current soil stochastic study, two important material parameters in this soil model are shear modulus G and initial yield stress SIGY.

The EPH material model requires an equation of state to work together. A tabular equation of state in LS-Dyna (*EOS_Tabulated_Compaction) was chosen to define the soil loading and unloading pressure-volume response, where a pressure-volumetric strain curve (P-ln(V/V0)) specifies the loading path while a bulk unloading modulus-volumetric strain curve (K-ln(V/V0)) gives unloading relation. The effect of internal energy on pressure was neglected in this study.

3. ENGINEERED ROADWAY SOIL AND TESTING

The Engineered Roadway Soil (E-RW) is a blend of earthen material tailored to consistently meet a specific set of material properties, with the express purpose of minimizing variability in underbody blast testing. It is expected that the E-RW soil shall be used as a primary soil in ATC underbody blast testing of future Army ground vehicles.

The E-RW soil is classified as a silty sand (SM) according to the Unified Soil Classification System [11]. A specific gravity of 2.76 g/cc for the soil was deduced from the dry density and water content data and the volumetric strain at 100% saturation from the uniaxial strain (UX) test results reported in Graham et al. [6]. The grain-size distribution from sieve (ASTM 2004) and hydrometer (ASTM 1963) tests on samples of the E-RW soil is presented in Figure 1

3.1 E-RW Soil Parameter Variation

The test field variations of the E-RW soil water content and dry density were measured and recorded in ATC testing ground, with total 67 soil samples collected from 5 test series [2,5]. The corresponding mean, standard deviation and coefficient of variation were calculated and listed in Table 1. With assumed normal distributions for both water content and dry density, their probability density functions and histograms are shown in Figures 2 and 3, respectively. The mean value data is also given in Figure 4, a water content – dry density graph.

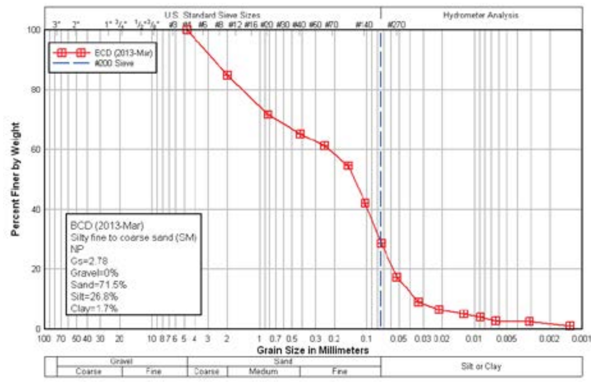


Figure 1 E-RW Soil Grain-Size Distribution

Table 1 Mean, Sigma and CV of E-RW Soil Water Content and Dry Density

	Water Content	Dry Density
	%	pcf
Mean	10.9	114.0
Sigma	0.584	1.351
CV	0.054	0.012

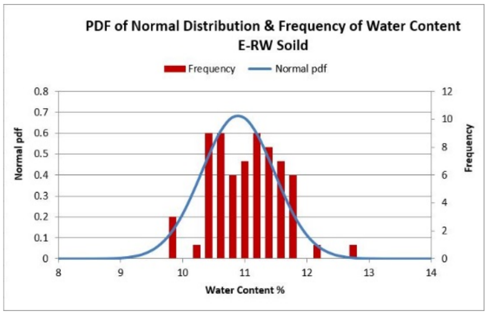


Figure 2 E-RW Soil Water Content Pdf and Histogram

3.2 E-RW Soil ERDC Testing

Under TARDEC's Near Term Underbody Blast (NTUBB) program, laboratory mechanical property and index property tests were conducted by the U.S. Army Engineer Research and Development Center (ERDC) in Vicksburg, Mississippi, on the E-RW soil [2]. The purpose of the investigation was to characterize the strength and compressibility properties of the soil at several different water contents and densities, and to develop recommended properties from the laboratory results for each water content-dry density pair. Results of nine test series were analyzed, and corresponding material properties like shear modulus G and initial yield stress SIGY for LS-Dyna material model *Mat_Elastic_Plastic_Hydro_Spall and pressure-volumetric strain curves for EOS model *EOS_Tabulated_Compaction were generated. Those properties are given in Table 2, together with related soil water content W_c and dry density ρ_d. The normalized EOS curves for pressure and bulk unloading modulus as a function of volumetric strain are plotted in Figs 5 and 6.

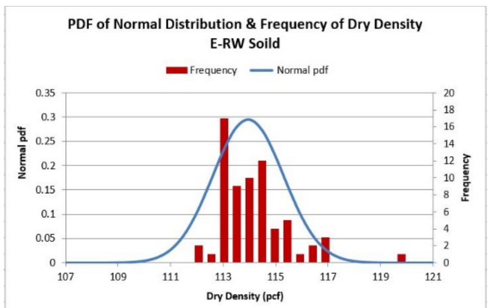


Figure 3 E-RW Soil Dry Density PDF and Histogram

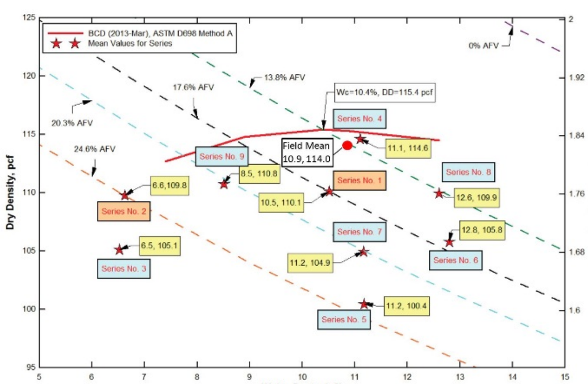


Figure 4 E-RW Soil Water Content - Dry Density Pairs Of Nine Test Series

With the data given in Table 2, the soil shear modulus G and initial yield stress SIGY can be related to water content and dry density. This was achieved by using 3D bi-quadratic surface fitting in MATLAB, and fitting equations are obtained. The fitting surfaces are illustrated in Figs 7 and 8.

Table 2 Soil Water Content, Dry Density and Their Material Properties for Nine Test Series

Test Series	W_c (%)	ρ_d (pcf)	G (Mpa)	SIGY (Mpa)
S#1	10.51	110.1	57.80	27.00
S#2	6.62	109.8	34.51	104.97
S#3	6.52	105.1	26.96	108.97
S#4	11.10	114.6	45.77	20.69
S#5	11.18	100.4	19.70	21.99
S#6	12.80	105.8	11.41	4.50
S#7	11.17	104.9	27.90	22.66
S#8	12.60	109.9	17.19	4.50
S#9	8.51	110.7	13.79	40.43

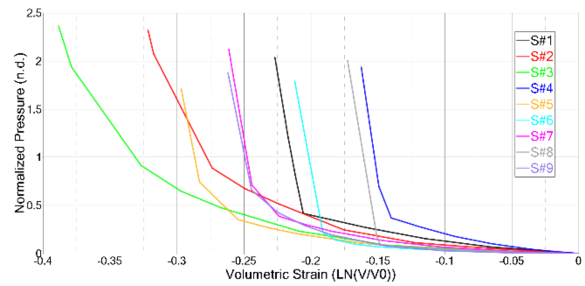


Figure 5 Pressure-Volume Relations for Nine Test Series

Similarly, the pressure and bulk unloading modulus shown in Figs. 5 and 6 could also be related to water content, dry density and volumetric strain by using a 4D surface, tri-quadratic fitting. It can be observed from Fig. 5 that the E-RW material has essentially a bilinear P-V response, with a soft bulk loading modulus prior to void closure and a stiffer

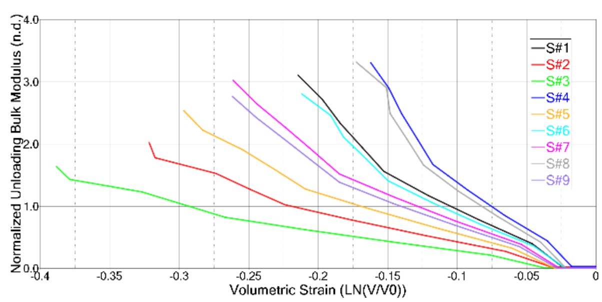


Figure 6 Bulk Unloading Modulus-Volume Relations for Nine Test Series

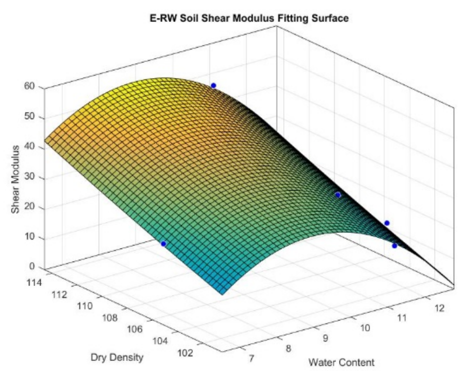


Figure 7 Fitting Surface of the Soil Shear Modulus

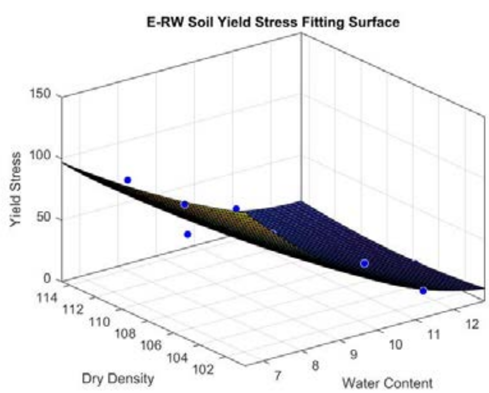


Figure 8 Fitting Surface of the Soil Yield Stress

one at pressures above void closure. For this reason, both the pressure and bulk unloading modulus were fitted separately, one portion before the void closure and another after void closure, to get better fitting correlation. The 4D surface fitting equations for the pressure and bulk unloading modulus were obtained by applying MATLAB.

With the statistical parameters given in the Table 1 and mapping functions obtained in the Section 3.2, a stochastic material model for the E-RW soil has been developed.

4. APPLICATION EXAMPLES OF THE DEVELOPED STOCHASTIC SOIL MATERIAL MODEL

4.1 The Live Fire Test Setup and Measurements

The developed soil stochastics model is applied to a simple rigid plate test setup. The series of simplified physical tests are conducted by using a rigid plate standing above a buried charge inside the studied soil. The blast test set-up is shown in Fig. 9. [5] The steel plate is very thick and its deformation during an underbody blast load is negligible and no instrumentation is equipped with the plate. The rigid plate has dimensions of 0.914 m in radius and 0.203 m in thickness, which is made of mild steel and has a mass of 4209 kg. The objective of this series of tests is to measure the soil loading to the plate by using the plate kinematic movement, such as impulse and velocity. The maximum height of the rigid plate travel (also called jump height) is obtained from high speed video record of the plate movement, from which the maximum velocity of the rigid plate is then calculated.

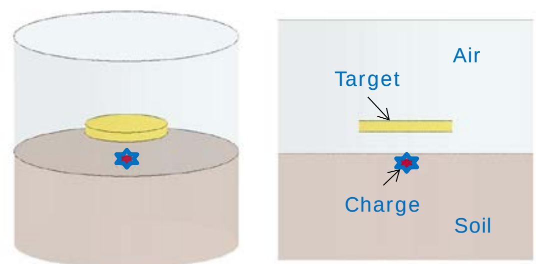


Figure 9 Rigid Plate Blast Model

Table 3 Rigid plate maximum velocity in Low-charge case

Test	Water Content		Dry Density		Vmax
	Mean	Sigma	Mean	Sigma	
A	10.85	0.623	113.5	1.260	1.0
B	10.96	0.686	112.8	1.35	0.915
C	11.82	0.653	114.2	1.275	0.937

Five live fire blast tests were performed using the rigid plate [5]. Three of these were detonated with Charge-Low, and the other two were loaded with Charge-High. Before each live fire test, the dry density and water content are measured at 12 different locations in the test bed. The distributions, mean value and variance are determined based on these pre-test measurements. The overall distributions of the soil water content and dry density are shown in Figs. 2 and 3, and their mean value and variance are listed in Table 3.

4.2 LS-Dyna Model

A LS-Dyna model is developed and validated initially using the above-described live fire tests with a difference of only about 4% [5]. In this model, the elements used in this model are 3D 8-node solids. The mesh size, i.e., the length of each side in the solids, is critical to the analysis of any finite element problem. A mesh size of 20mm is used herein for all the parts. It is deemed to be a good compromise between solution accuracy and analysis time for this type of UBB simulation problems [5]. Material modeling in LS-Dyna uses both a Constitutive Model (CM) and an Equation of State (EOS) to describe some materials [10]. The former defines the stress-strain relationship and failure criteria, while the EOS relates the pressure to the specific volume, and temperature of a material at a physical state. The material and EOS for air are specified, respectively, by LS-DYNA cards *MAT_NULL and EOS_LINEAR_POLYNOMIAL [10] in this model [5, 6]. The charge properties are modeled by *MAT_HIGH_EXPLOSIVE_BURN and *EOS_JWL [10]. This modeling approach is commonly employed in blast analysis [1, 3].

The keyword *MAT_RIGID [4] is used to model the rigid plate to save simulation time. Also, no EOS card is required for such a material type. For the flexible plate case, the holding fixture is also considered rigid due to the large thickness. The flexible flat plate is modeled by the keyword *MAT_PIECEWISE_LINEAR_PLASTICITY [4].

For the soil, the same keywords are used as in [8]. That is, *MAT_ELASTIC_PLASTIC_HYDRO_SPALL and *EOS_TABULATED_COMPACTION. This will be explained in details later. The key properties in *MAT_ELASTIC_PLASTIC_ HYDRO_SPALL are density (*r0*), shear modulus (*g*), yield stress (*sigy*), plastic hardening modulus (*eh*) and cut-off pressure (*pc*).

A tabular EOS with LS-DYNA keyword *EOS_ TABULATED_COMPACTION is used herein to define the loading and unloading Pressure-Volume (P-V) strain response. The P-V response also defines the bulk modulus (*K*) of the material. LS-DYNA performs a linear interpolation between the points in the lookup table resulting in a piecewise linear functional approximation of the pressure-volume relation. Ref. [8] shows how to obtain the material properties, and also how to convert a P-V response into the format used by *EOS_TABULATED_ COMPACTION, which is represented by ten points from (*ev1*, *c1*) to (*ev10*, *c10*) for DS Topsoil. The notations *evi* and *ci* are the volume strain and pressure, respectively, for the *i-th* point.

In the simulation model, the time history of the rigid plate vertical velocity is extracted and the maximum velocity is determined from the velocity history. The maximum velocity is then used to determine the impulse of the plate. The impulse of the plate is used as the responses in the stochastics model.

4.3 Metamodel of the Plate Impulse

Fig. 10 Plate Impulse Metamodel

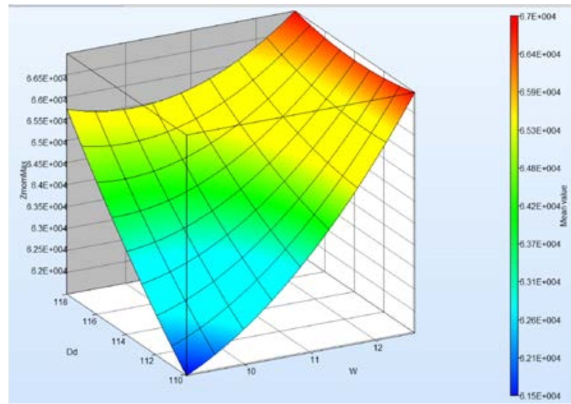
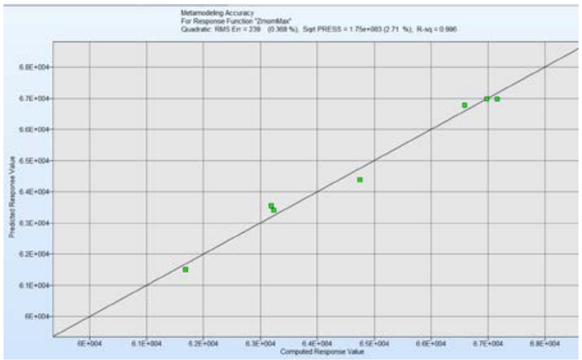


Fig. 11 Metamodel of the Maximum Rigid Plate Velocity

Although the model is very simple, it takes more than 640 cpu hours for a 20 milliseconds of simulation. In general, it is impractical to conduct stochastics modeling and simulation directly using the original computational aided engineering (CAE) models. Scientists have devoted many years of efforts to develop efficient and accurate metamodels for design optimization and robust design studies. In this study, metamodel-based stochastics modeling and simulation is used. Therefore, a metamodel is developed first using the FEA model developed and a factorial design of experiments (DOE) method. Based on the studies of different types of metamodels, a quadratic polynomial model is selected based on the accuracy of the model and residual error analysis. The metamodels of the plate impulse and the rigid plate maximum velocity are illustrated in Figs. 10, and 11 respectively.

Fig. 12 Metamodeling Accuracy



The metamodel accuracies of both metamodels are identical and one of them is shown in Fig. 12. The R-Square of the metamodel is 0.986. The residual error analysis indicates that the developed metamodels of the rigid plate maximum velocity and impulse are very accurate to represent the original computational blast model of the plate in the prediction of the plate maximum velocity and impulse.

Using the metamodels developed, the response of the plate, its impulse and the maximum vertical velocity can be determined and correlated to the water content and soil dry density. Their correlation are shown in Fig. 13.

Fig. 13 The Correlation of the maximum plate velocity and impulse

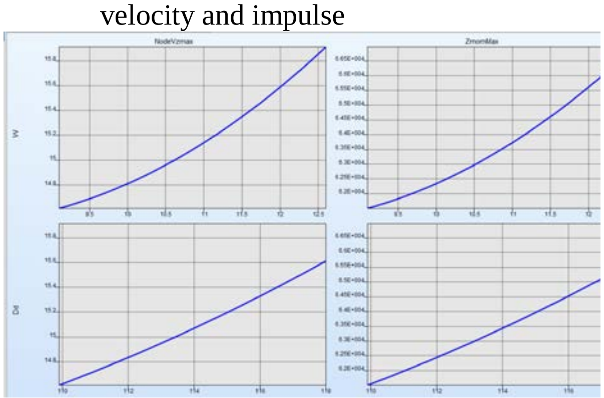
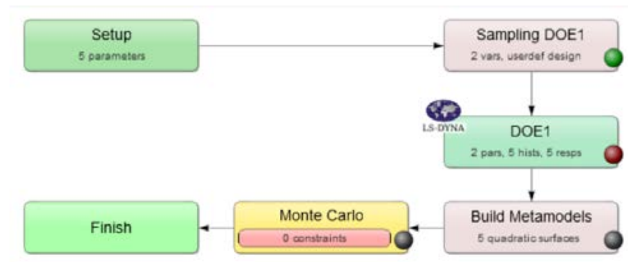


Plate Velocity Impulse

4.4 Stochastic Modeling and Simulation

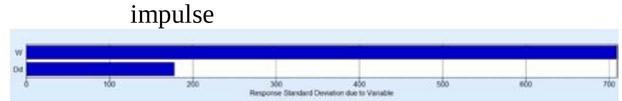
After the metamodel of the plate velocity and impulse is developed, the stochastics modeling and simulation of the plate responses to the statistical variation of the soil water content and dry density is conducted. The stochastics modeling and simulation process is shown in Fig. 14. The following stochastic modeling and simulation analysis uses a test case with the statistic data of soil water content and dry density listed in Table 3.

Fig. 14 Stochastics Modeling and Simulation Flow Chart



The Monte-Carlo sampling method is used in the stochastics modeling and simulation. 10,000 sampling population is used in this analysis. The variations of soil water content and dri density have normal distribution. Their mean value and variance are listed in Table 3. The contribution of variable noise (the stochastics soil inputs) to the variation of the plate impulse is found and illustrated in Fig. 15. The analysis found that water content variations have contributed significantly more than the contribution of the soil dry density.

Fig. 15 Contribution of variable noise to plate impulse



Using the variations of the soil water content and dry density, the responses of the plate under the blast loading condition are determined using the metamodels described in the previous section. The statistical distributions of the plate maximum vertical velocity and impulse are then determined and shown in Figs. 16 and 17 respectively.

The predicted mean plate maximum velocity is 14.6 m/s with a sigma equal to 0.171 m/s. Therefore, the 95% confidence band of the prediction of the plate maximum velocity is from 14.25 m/s to 14.94 m/s. The 95% confidence intervals of the plate maximum impulse is from 60000 (N-s) to 63000 (N-s). In other words, if a live fire test is conducted with the pre-test measurement of soil water content and dry density of the statistical distributions as illustrated in Table 3, the live fire measurement of the plate velocity or impulse will have 95% of probability to be in the range of 14.25~14.94 m/s.

Fig. 16 Statistical Distribution of the Plate Velocity

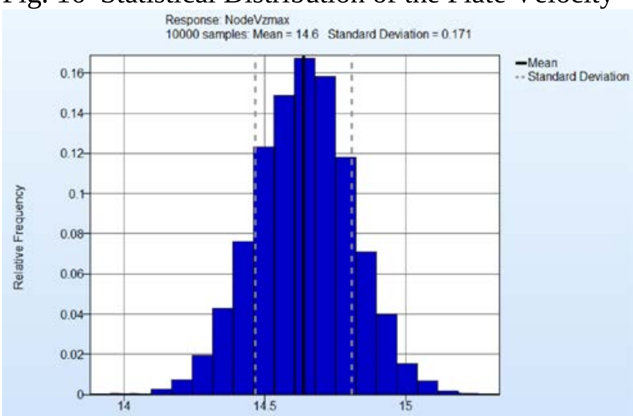
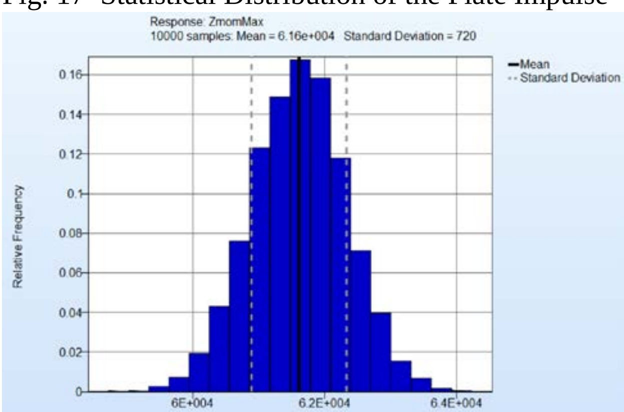


Fig. 17 Statistical Distribution of the Plate Impulse



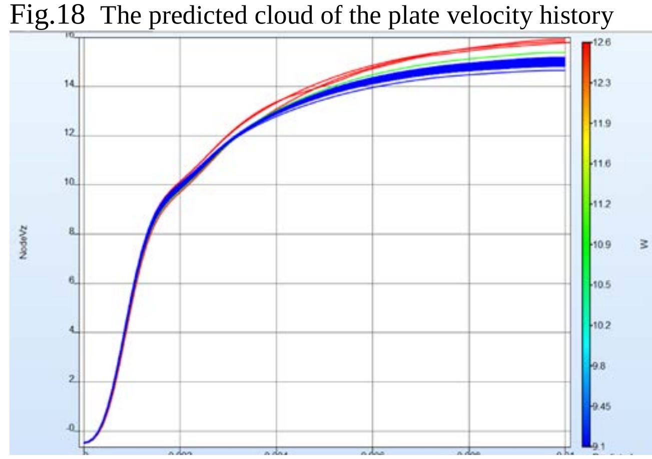
The predicted cloud of the plate velocity history is shown in Fig. 18.

5. SUMMARY AND CONCLUSIONS

Soil properties or characteristics plays critical roles in generating underbody blast loading from buried land mine or IED threat. For a given soil type, its water content and dry density are two important independent parameters which can be used to calculate other soil parameters. However, these soil parameters have variations from nominal specification either in proving ground or theater, due to stochastic nature.

In this study, the ATC Engineered Roadway Soil (E-RW) field measurements, the corresponding lab test data and the soil model parameters generated by ERDC were fully reviewed and analyzed for their consistency and completeness. The water content and dry density data from field measurement of the soil were analyzed first, and their means and standard deviations were derived. Based on corresponding ERDC lab test data, each soil parameter in both material model (shear modulus G and initial yield stress SIGY) and EOS equation (pressure and bulk unloading modulus as a function of volume strain) was then expressed as a function of soil water content and dry density by 3D or 4D surface fitting. Thus mapping equations from soil water content and dry density to soil parameters were established. With an assumption of normal distribution for both soil water content and dry density, a stochastic soil model was developed for the ATC Engineered Roadway Soil. A stochastic model of a rigid plate under blast loading was developed to demonstrate how to apply the developed stochastic soil model to carry out underbody blast Monte Carlo simulation for generating vehicle responses clouds, and how to estimate the low and up bounds of structure response with certain confidence level.

Fig.18 The predicted cloud of the plate velocity history



This study provided a methodology for soil stochastic model development. It filled a gap between field soil variation and the current deterministic underbody blast M&S approach, increased TARDEC Analysis M&S prediction capability and improved M&S quality.

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