Modeling of Cone Penetration Test Using SPH and MM-ALE Approaches

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Abstract

The American Society of Association Executives (ASAE) Soil Cone Penetrometer Standard (S313.2) is designed to characterize general soil mechanical conditions. Its results are used predominantly for comparative purposes. Variations of this test are used for in-situ determination of the geotechnical engineering properties of soils and delineating soil stratigraphy.

This paper presents a comparison between experimentally obtained results of cone penetration test with results from LS-DYNA®/MPP simulations performed on a high performance cluster computer. The previously reported experiments (conducted by USDA-ARS National Soil Dynamics Laboratory, Auburn, AL, USA) were performed on Norfolk Sand. These experiments show the variation in results for test conducted under identical conditions. In the LS-DYNA simulations, the soil was modeled using the material model MAT_005 Soil and Crushable Foam. Two approaches were used to represent the soil: a hybrid approach that combined Lagrange and Smoothed Particle Hydrodynamic (SPH) methods and the Multi Material Arbitrary Lagrangian - Eulerian (MM-ALE) method.

The vertical resistance force versus penetration distance of the penetrometer cone was compared to the experimental results. A close match between numerical results and experimental data was obtained in the study for the Norfork Sand. The response simulated using the two numerical approaches were almost identical. A sensitivity study revealed that the penetrometer force was most sensitive to the soil density followed by sensitivity to a failure surface parameter.

Keywords: *cone penetrometer, MAT_005 Soil and Foam model, smooth particle hydrodynamics, multi-material arbitrary Lagrangian Eulerian, ANOVA sensitivity, cluster computing, MPP-DYNA*

1. Introduction

Ongoing research at the USDOT funded Transportation Research and Analysis Computing Center (TRACC) at Argonne National Laboratory on stability of bridges with piers in scour holes relies greatly on LS-DYNA® capabilities for modeling large deformations in soil. Due to riverbed erosion around bridge support piers, scour holes developed and when the depth of the hole approaches the pier footing, it is possible that the fast-moving water can create a large enough moment to cause pier failure at the bent. This is what happened to the Oat Ditch Bridge on I-15 in California (Bridge ID: 54-0270R) [1].

As part of the effort to build confidence in modeling and simulation of soils, a series of comparisons between previously performed experiments and simulation results was undertaken. In [1], a study of four approaches to soil-structure interaction modeling was presented: Lagrangian, SPH, MM-ALE and Hybrid (Lagrangian plus SPH). The physical problem simulated [2] was a 20 inch square steel platen being pushed into a 6 foot square by 5 foot deep test trench filled with loose silty clay sand. In that study, most of the vertical resistance force came from compression of the soil under the platen; friction was not of concern in this test. However, friction between the pier footing and the surrounding soil may be a crucial factor in providing resistance to movement by the pier and footing in deep scour holes. Thus friction resistance of the soil needs to be appropriately modeled as well, and this is the main focus of this paper.

In this paper, a study on the standard cone penetration test (CPT) was performed. In this test, friction between the soil and the cone surface plays a crucial role in providing the vertical resistance force. The aim of the study was to evaluate the MM-ALE and Hybrid formulations. The Lagrangian formulation was not considered here because of the acute geometry of the cone tip and the need to use a spurious hole in the soil under the cone tip. The full SPH model was not considered because of the longer CPU time required.

2. Cone Penetration Test Model

The numerical simulations were performed to compare to the experimental results reported by Pearman [3]. The CPT procedure was based on ASAE Standard S313.2. The cone penetrometer had a 30 degree apex angle with a base area of 323 mm^2 (radius of 10.14 mm). The penetrometer was modeled with shell elements and the material was treated as rigid. All but vertical translational degrees of freedom of the cone were restrained. The full geometry of the cone was modeled. In the test, the cone penetrated the soil at a constant rate of 30.48 mm/sec (1.2 in/sec). 210 mm of penetration were simulated, which required approximately 7 seconds of simulation. Only a quarter of a cylindrical soil sample with radius 161 mm and depth of 400 mm was modeled. The soil model was constrained on the external, cylindrical side and on its bottom. Appropriate symmetry boundary conditions were applied on the internal faces. In the current study, two approaches were used to model the soil: 1) hybrid model which was a combination of the Lagrangian and SPH formulations and 2) Multi Material Arbitrary Lagrangian Eulerian method. Both models are presented in Figure 1.

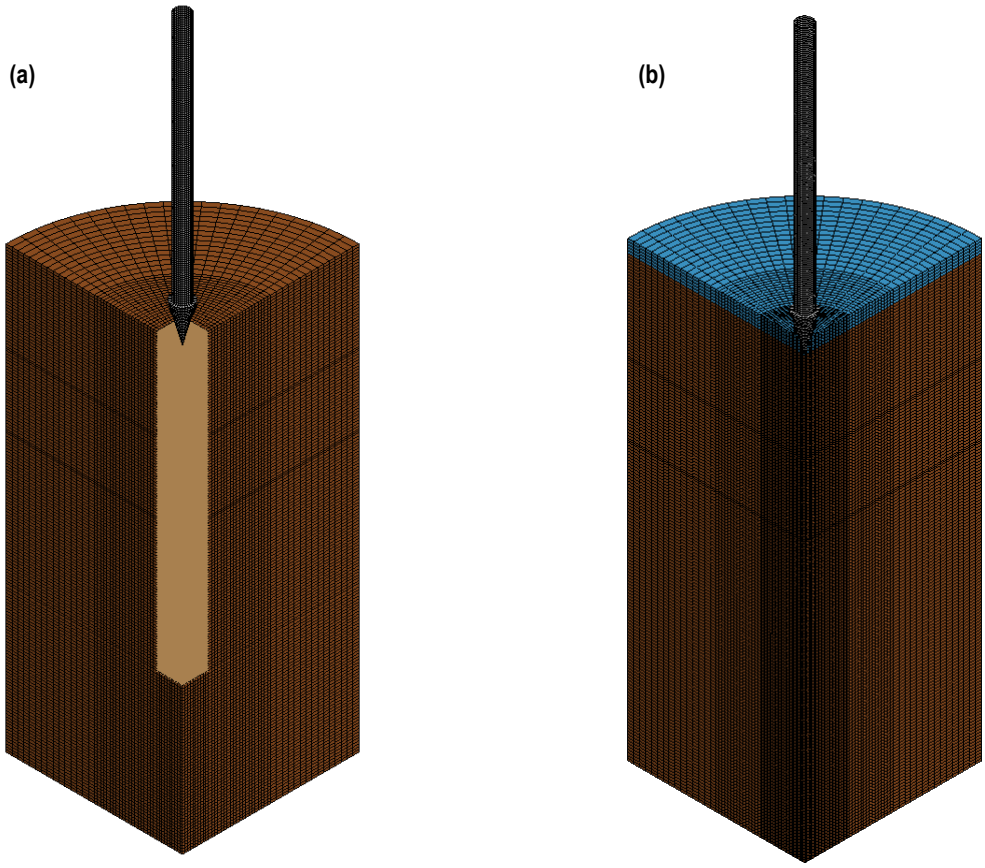

Figure 1: Numerical models for the simulation of the cone penetration test: (a) Hybrid Lagrangian-SPH model (b) MM-ALE model

In the hybrid Lagrangian-SPH model, a square core with width of 23.5 mm and depth of 267 mm was modeled with SPH particles. This assures that only SPH particles will be in the region where large penetrations are expected. The Lagrangian elements in the rest of the model assure reasonable size of the model and computational efficiency. The hybrid model had in total 214,600 elements (124,600 hexahedral solid and 90,000 SPH). The MM-ALE model had 192,500 hexahedral elements.

It should be mentioned that the pure Lagrangian and Element Free Galerkin approaches were attempted, but the simulations were failing soon after the start. So it was decided not to pursue these approaches.

As in [1], the soil material was modeled using LS-DYNA constitutive model MAT_SOIL_AND_CRUSHABLE_FOAM (MAT_005). The soil considered was Norfolk sandy loam. The material properties of the soil were reported by Foster [4], and the properties were estimated from the National Soil Dynamics and Auburn University (NSDL-AU) soil compaction model components [5, 6]. The true volumetric strain versus pressure is presented in Figure 2. The remaining material properties needed for MAT_005 definition are listed in Table 1.

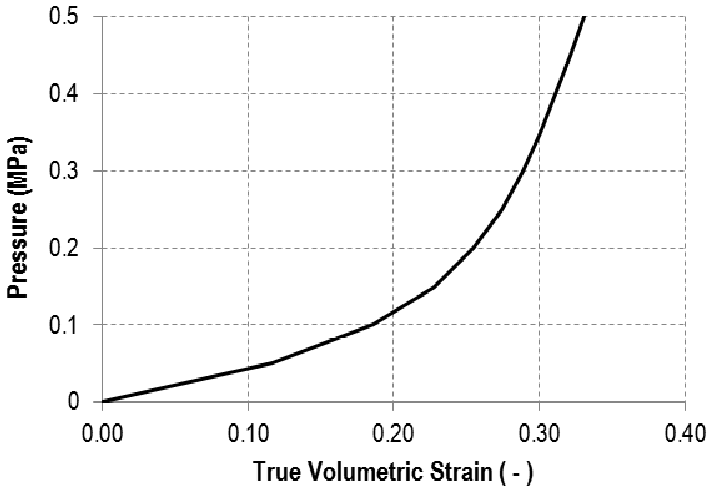

Figure 2: Triaxial hydrostatic compression data for Sandy Loam

Table 1: Parameters used to define soil materials using formulation MAT_005 (SI units: mm-second-tonne)

Parameter	Description	Norfolk Sandy Loam
RO	Mass density	1.2550e-009 t/mm^3
G	Shear modulus	1.7240 MPa
K	Bulk modulus for unloading	5.5160 MPa
a0	Yield function constant	0
a1	Yield function constant	0
a2	Yield function constant	0.8702
PC	Pressure cutoff for tensile fracture (<0)	0
VCR	Volumetric crushing option	0 (on)
REF	Use reference geometry to initialize pressure	0 (off)
EPS1 ...	Volumetric strain values (natural log values)	see Figure 2
P1 ...	Pressures corresponding to volumetric strain	see Figure 2

3. Simulation Results

Figure 3 shows the experimental test results [3] and the Hybrid and MM-ALE simulation results. The four test curves show the dependency of the soil vertical resistance force on the cone penetration depth. Three of the four test results showed an initial slope whereas the fourth test result had a near zero slope. The three test results that were relatively close together reached a maximum at just beyond 150 mm of penetration; the fourth test result reached a maximum closer to 200 mm of penetration. The computed response for the sand was very smooth. The SPH and MM-ALE methods gave very similar responses for most of the simulation. However in the final stage of loading, numerical problems occurred in the SPH simulation, and the soil resistance was weaker. Because the starting penetration force should be zero, the experimental data points needed to be shifted on the y-axis to the origin. It is speculated that the non-zero

starting force could be due to initial slack in the testing apparatus.

Figure 4 shows the translated data together with the numerical results. The simulation results match the experimental test result for the test with zero initial slope up to about 125 mm of penetration and then remain in the band of test results up to 175 mm of penetration. The penetration force for the Hybrid model starts to decrease around 180 mm of penetration, and the response using the MM-ALE formulation continues to increase. Overall the simulations compare favorably with the experimental test data.

The simulation results of Foster [4] are also shown in Figure 4. These results were obtained using the traditional finite element approach (Lagrangian) in MSC/DYTRAN and DYTRAN's crushable foam and soil constitutive model, DYMAT14. As shown, the numerical simulations are very oscillatory with the final penetrator force value was very high.

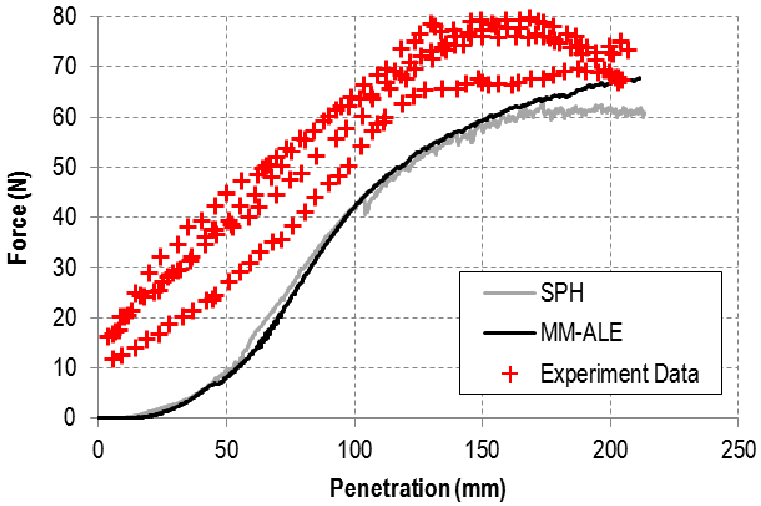

Figure 3: Comparison of simulation results with raw CPT experimental test data[3] for Norfolk Sand

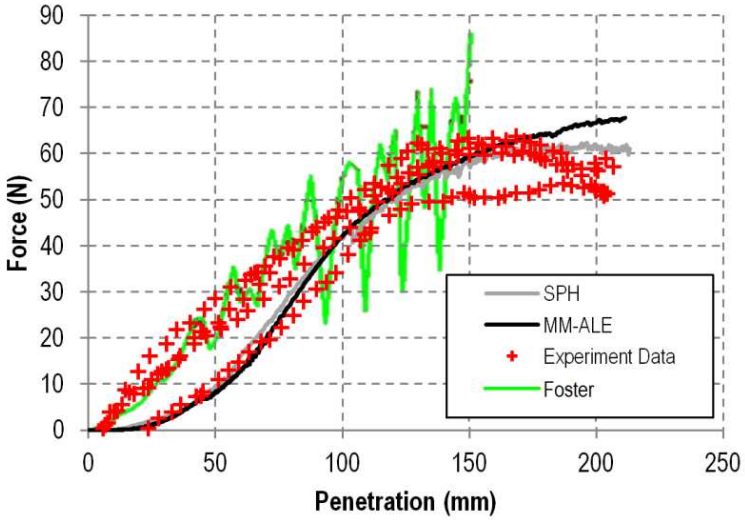

Figure 4: Comparison of simulation results with CPT experimental test data [3] for Norfolk Sand and with simulation results by Foster [3]. Experimental data was shifted downward to the origin

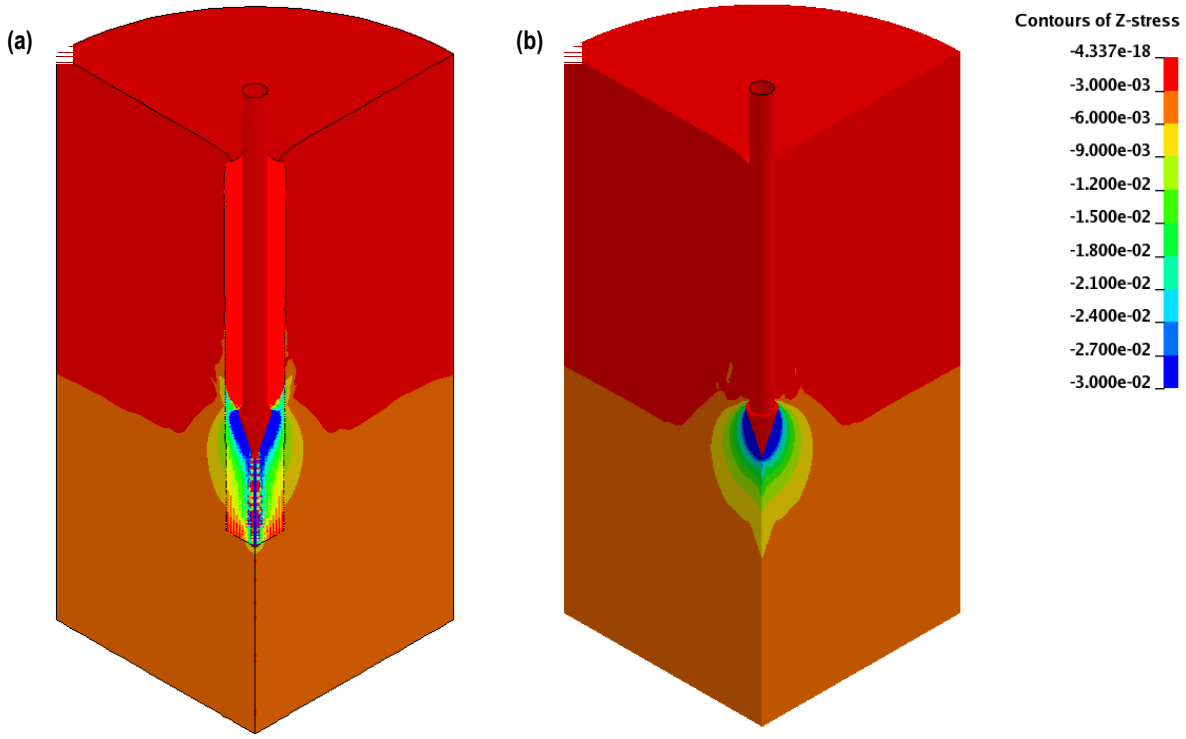

Figure 5: Deformations and vertical stresses at 210 mm of penetration: (a) Hybrid, (b) MM-ALE

Figure 5 presents the vertical stresses in the soil from the hybrid SPH-Lagrangian (a), and the MM-ALE models (b). The distribution of stresses is much smoother in the MM-ALE method. Note, the SPH method produced non-uniform stresses in the vicinity of the loading point. This behavior was eliminated when a full cylindrical model (not shown here) was used.

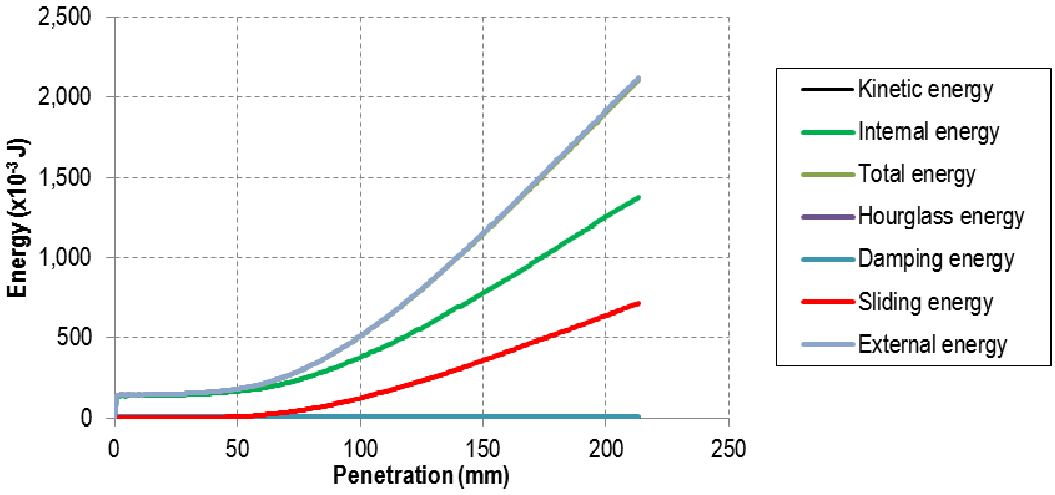

Figure 6: Energy Balance for CPT test simulation

As mentioned in the introduction, the resistance of the soil in a CPT test depends greatly on friction. Figure 6 shows the energy balance for the simulation of a CPT using the hybrid model. The overall energy balance was very good because the total energy and external energy curves

(the uppermost curve) directly overlay each other. The next lower curve is the internal energy, which is about 65% of the total energy. Approximately 35% of the total energy is sliding energy, which in this case is energy due to friction. That indicates a possible sensitivity of the results to the friction coefficient between the cone and the soil. The remaining energies are very small and lie along the Penetration axis.

4. Sensitivity Study

A sensitivity analysis was performed with the LS-OPT software. The design of experiments was performed for four material parameters: friction coefficient between the cone and the sand, density of sand, a yield surface parameter, and scaling factor for pressure vs. volumetric strain curve. A +/- 10% of variance in their initial value was assumed. Altogether 23 simulations were performed. ANOVA plots are presented in Figure 7 and show the normalized coefficients of the linear response surface. The largest sensitivity was associated with the soil density *(rho*) followed by a yield surface parameter (*atwo*), the pressure scaling factor *(fpres)* and the coefficient of friction *(fric_coe)*. In the previous investigation of a square platen being pushed into soil [1], preliminary simulations showed that friction had minor effects on the platen force, and the yield function constant, a_2, was the most important.

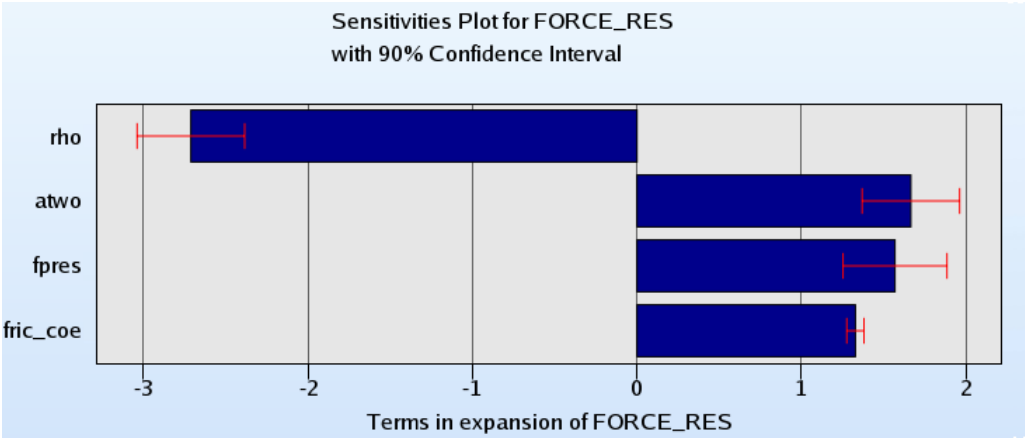

Figure 7: ANOVA sensitivity bars for selected input parameters

Five [c1]simulations were additionally performed with the friction coefficient varying from 0.27 to 0.419. Recall the value used in our simulations was 0.3, which was for a moisture content of 7.2% [3]. The vertical soil resistance forces for these cases are plotted in Figure 8. The maximum force varied from 59.8 N to 72.2 N. [c2]

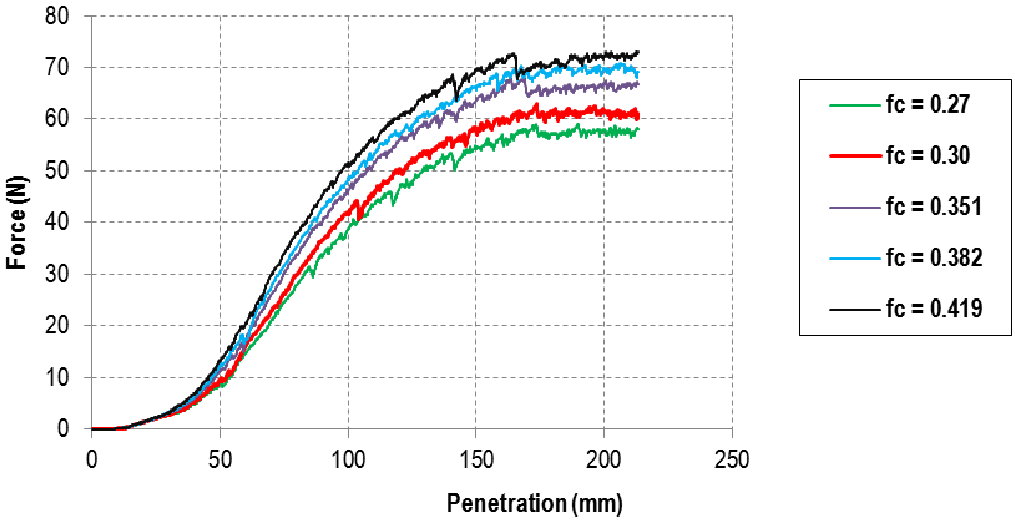

Figure 8: CPT simulations results for different friction coefficients between cone and soil

5. Computational Statistics

An assessment of the computational efficiency of the Hybrid and MM-ALE approaches was made by running the simulations on 32 cores. Table 2 shows the model parameters and compute statics for the discretization chosen for each method. The Hybrid model had a total of 214,600 elements of which 124,600 were Lagrangian hexahedral elements and 90,000 were SPH elements. The MM-ALE model had 192,500 elements. The initial timestep was 12.6 µsec and the final timestep was 12.1 µsec for the Hybrid simulation. For the MM-ALE simulation, the time steps were much smaller: initial timestep of 9.65 µsec and final timestep of 6.74 µsec. For the Hybrid approach, the total CPU time was about 20 hours and 9 minutes which was less than the 36 hours and 56 minutes required for the MM-ALE simulation. The contact algorithm required 53.2% of the total CPU time for the MM-ALE simulation and only 4.7% for the Hybrid analysis.

Table 2: Model and Compute- Related Statistics

	Hybrid (Lagrangian + SPH)	**MM-ALE**
No. of Hexahedral Elements	124,600	192,500
No. of SPH Elements	90,000	0
Initial timestep	1.26E-05	9.65E-06
Final timestep	1.21E-05	6.74E-06
Total CPU time (hh:mm:ss)	20:08:56	35:55:53
Element processing time (% of total CPU time)	94.30	46.41
Contact algorithm (% of total CPU time)	4.77	53.16

6. Conclusions

This paper presents an evaluation of the use of a Hybrid (Lagrangian plus SPH) model and multi-material Arbitrary Lagrangian Eulerian model for computing the penetrometer force in a standard cone penetration test. Because the underlying formulations used in the models can treat large deformations, they were well suited to this type of simulation. The Lagrangian formulation and the Element Free Galerkin formulation were also exercised, but because of numerical issues they were not pursued after several initial attempts.

Experimental cone penetration tests were reported in the literature, and the numerical simulations were compared to them. The four experimental tests were performed on the same soil. The results from the four test were not identical, but taken together they formed a band. A comparison of the simulations to the four test showed that the simulation results for both models, for the most part, fell within the band. A comparison between the Hybrid and MM-ALE simulations showed near identical results except near the end when the Hybrid model started to develop numerical problems. Having results from four tests illustrates the uncertainty when doing comparisons to only one set of experiment results.

A sensitivity study of the input parameters revealed that the penetrometer force is most sensitive to the soil density followed by the yield surface parameter. When run on 32 cores and for the model discretization chosen for each model, the Hybrid model ran faster (20:08:56) than the MM-ALE (35:55:53).

Overall, the comparison of simulations to the experimental results was very good. The MM-ALE approach gave slightly better results than the Hybrid approach; both the Lagrangian and Element Free Galerkin approaches were not successful.

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