Comparison of Lagrangian, SPH and MM-ALE Approaches for Modeling Large Deformations in Soil

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Abstract

Ongoing research at the USDOT funded Transportation Research and Analysis Computing Center (TRACC) at Argonne National Laboratory on bridge stability for bridges with piers in scour holes relies greatly on LS-DYNA® capabilities for modeling large deformations in soil and fluid structure interaction. When it comes to soil modeling, material model MAT_005 Soil and Crushable Foam is often used as a first approximation. It is especially useful when little material characterization is performed--which is usually the case for riverbed soil. Although an abundance of reports can be found where MAT_005 was used with the Lagrangian approach, its use in Smoothed Particle Hydrodynamic (SPH) and Multi Material Arbitrary Lagrangian - Eulerian (MM-ALE) approaches is considerably less documented.

This paper presents a comparative study of the performance of MAT_005 with Lagrangian, SPH and MM-ALE approaches for predicting large deformation soil response. For the purpose of validation, simulations were performed for the in-situ experiment of a steel loading pad penetrating into silty clay sand. Using LS-OPT® metamodel based sensitivity analysis was conducted to identify the most relevant material and loading parameters.

The results show that the three formulations can produce reasonable predictions at large penetrations. Although very suitable for soil penetration problems, MM-ALE requires iterative adjustments of contact parameters to eliminate spurious leakage. The LS-OPT sensitivity analysis on material parameters indicates the yield function parameters have the greatest influence on the results. Further important parameters are the soil density and appropriate modeling of the soil island boundaries. It was also noted that the choice of the type of domain decomposition greatly affects the compute time.

Keywords: *MAT_005 Soil and Foam model, Lagrangian, MM-ALE, SPH, sensitivity study, LS-OPT, domain decomposition*

1. Introduction

The Oat Ditch Bridge on I-15 in California (Bridge ID: 54-0270R) is a 5-span continuous reinforced concrete slab on 4 reinforced concrete bent columns (see Figure 1a). Each column was first supported by an individual rectangular footing pad as shown in Figure 1b. Although analyzed for scour in 2000 and found to be not scour critical, three columns at bent five of the bridge failed during the flood on 08/19-20/2003. As reported by California DOT, during the flood the bending moment created by hydraulic forces caused the concrete failure at the abutment of columns in the pier bent. Additionally, the soil material around the pier was partially washed out and the support to the footing was weakened, what allowed for displacement of the columns.

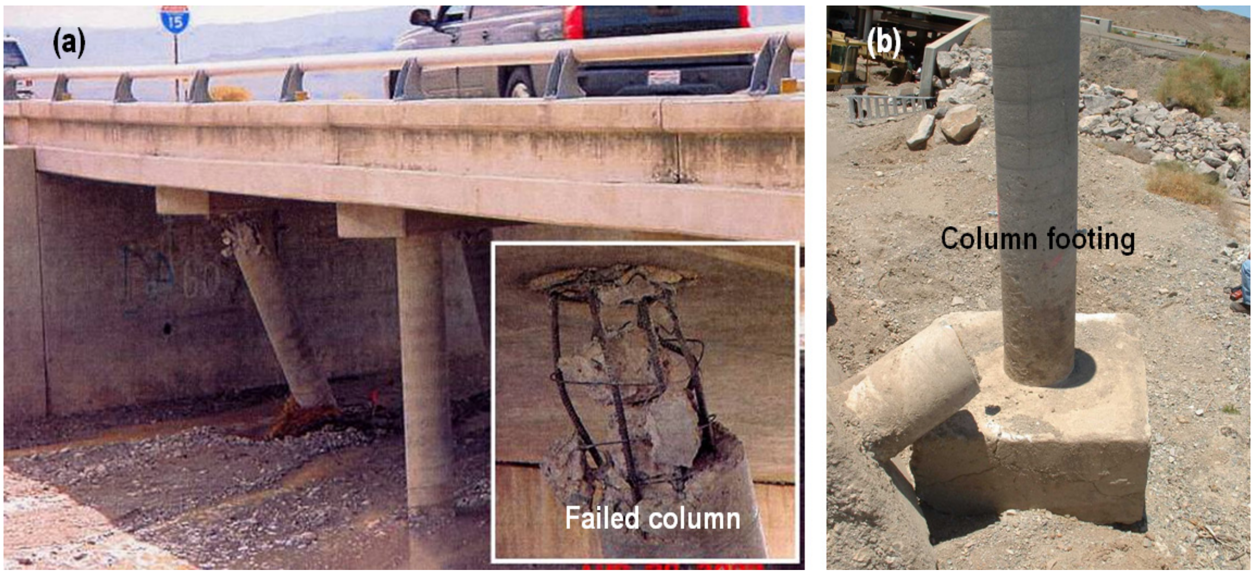

Figure 1: Oat Ditch Bridge on I-15 in California (a) failed column (b) column footing

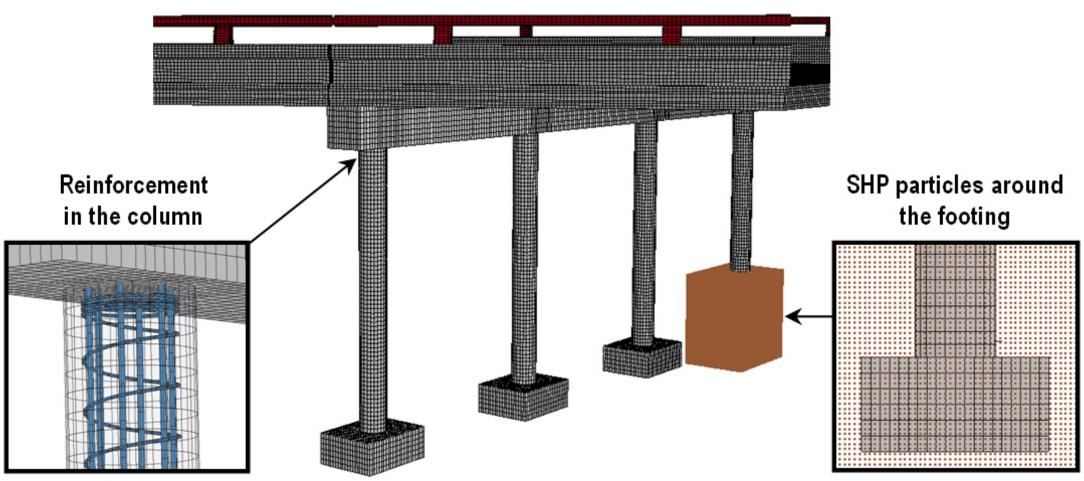

Figure 2: FE model of Oat Ditch Bridge

The USDOT funded Transportation Research and Analysis Computing Center at Argonne National Laboratory is performing research on scour and stability of bridges during flood conditions. A finite element model of the Oat Ditch Bridge was developed to reconstruct and analyze the 2003 failure using LS-DYNA software. The study presented in this paper focuses on determining the most suitable approach to model soil around the footings and their mutual interaction when large soil deformations occur. Three approaches to the soil modeling are considered: Lagrange, SPH and MM-ALE. Modeling aspects and computation efficiency for these methods were investigated. Solution sensitivity to variations in material and loading parameters were studied.

1. Models Development

The problem selected involves a previously reported quasi static soil penetration test [1]; parts of our modeling approach also follow from [1]. A 6 foot square by 5 foot deep test trench was filled with loose silty clay sand that was loaded using a 20 inch square steel plate. The displacement of the plate, the force exerted by it and the vertical stresses in the soil were recorded during the test.

In the simulations reported in [1, 2], the soil was modeled using material formulation MAT_005 (soil and foam). It is widely used in research areas like earth landing, roadside safety and others [3-6]. MAT_005 is very attractive to LS-DYNA users because of the small number of material constants needed.

MAT_005 uses a pressure dependent nonlinear Drucker-Prager yield function, ϕ, that is described in terms of the second invariant, J_2, of the deviatoric stress tensor, s_{ij}, , pressure, p, and constants a_0, a_1, a_2 as:

$$\phi = J_2 - \left[a_0 + a_1 p + a_2 p^2\right] \tag{1}$$

Where:

$$J_2 = \frac{1}{2} s_{ij} s_{ij} \tag{2}$$

and the three constants are fit from laboratory triaxial test data points using the relation:

$$\sigma_1 - \sigma_2 = \sqrt{3J_2^{'}} \tag{3}$$

Table 1 contains the input parameters used to define the soil material for the comparison of methods and sensitivity studies. For the validation study, the density was set to the experimentally determined value. Figure 3 shows data from hydrostatic compression test -- pressure vs. logarithmic strain dependency -- used as an input for LS-DYNA model.

Table 1: Parameters used to define soil material using formulation MAT_005 (units mm-s-tonne)

Parameter	***Description***	***Value***
RO	Mass density	2.350e-009
G	Shear modulus	34.474
K	Bulk modulus for unloading	15.024
A0	Yield function constant	0
A1	Yield function constant	0
A2	Yield function constant	0.602
PC	Pressure cutoff for tensile fracture (<0)	0
VCR	Volumetric crushing option	0.0 (on)
REF	Use reference geometry to initialize pressure	0.0 (off)
EPS1 ...	Volumetric strain values (natural log values)	see Figure 1
P1 ...	Pressures corresponding to volumetric strain	see Figure 1

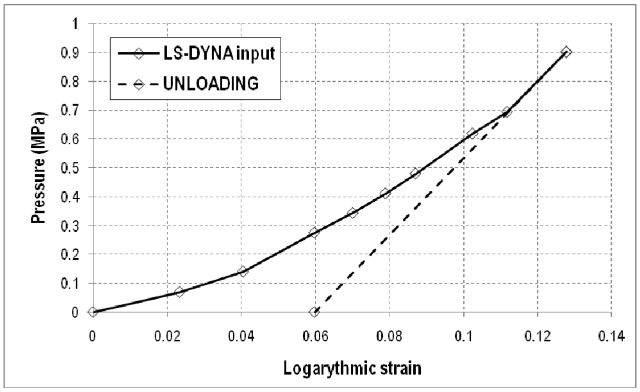

Figure 3: Hydrostatic compression data for soil material [1]

The soil was modeled as a cylinder with a radius of 1219.2 mm (48 in) and a depth of 1778.0 mm (70 in). The remainder of the semi-infinite soil domain was represented by a 127 mm (5 in) thick cylindrical encasement (MAT_001_ELASTIC) surrounding the soil island. Auxiliary calculations were done to estimate the equivalent stiffness of the encasement that would approximate an infinite medium. Contact between the soil and the encasement was modeled with CONTAC_AUTOMATIC_SURFACE_TO_SURFACE. On the outer face and bottom of the encasement, translational degrees of freedom were constrained. The loading pad with a radius of 286.6 mm ($20/\pi$ in) was modeled with MAT_020_RIGID material. The Young's modulus was taken to be two times greater than the shear modulus of the soil. This value was only necessary for computation of the contact stiffness. A quarter of the Lagrangian model is shown in Figure 4a.

Two SPH models were built and identified as SPH_reduced and SPH_full. In the SPH_reduced model, only the portion of the soil experiencing the largest deformations was modeled with SPH particles. The rest of the model was based on Lagrangian elements. The portion filled with SPH particles had the diameter equal to 1083.1 mm and depth of 533.4 mm. The SPH particles at the Lagrange element interface were tied to the Lagrangian portion of the soil material by using CONTACT_TIED_NODES_TO_SURFACE_OFFSET_MPP. The contact between the pad and SPH particles was modeled using CONTACT_AUTOMATIC_NODES_TO_SURFACE_ MPP. A quarter of the SPH_reduced model is shown in Figure 4b. In the SPH_full model, all the soil was modeled using SPH particles. A quarter of these models are shown in Figure 4b and 4c.

The Lagrangian mesh was used as a basis for MM-ALE model. An additional part representing air (background mesh) was developed. MAT_140_VACUUM was used for that purpose. Element formulation ELFORM=11 (1 point ALE multi-material element) was used to model the soil and the air. Interaction between the soil and the encasement was modeled through CONSTRAINED_LAGRANGE_IN_SOLID command. Penalty type coupling was selected with coupling activated only in compression (CTYPE=4, DIREC=2). The force exerted by the pad was read from DBFSI ASCII file. This force is the sum of estimated coupling forces over the whole surface entity that is being pushed on by the fluid (i.e., soil). The coupling forces are only estimated and are approaching the solution after coupling is fine tuned such that there is just enough coupling force to prevent leakage. This state was achieved by using the load curve for coupling penalty stiffness (negative PFAC in CONSTRAINED_LAGRANGE_IN_SOLID command). Figure 4d shows the model used in MM-ALE approach.

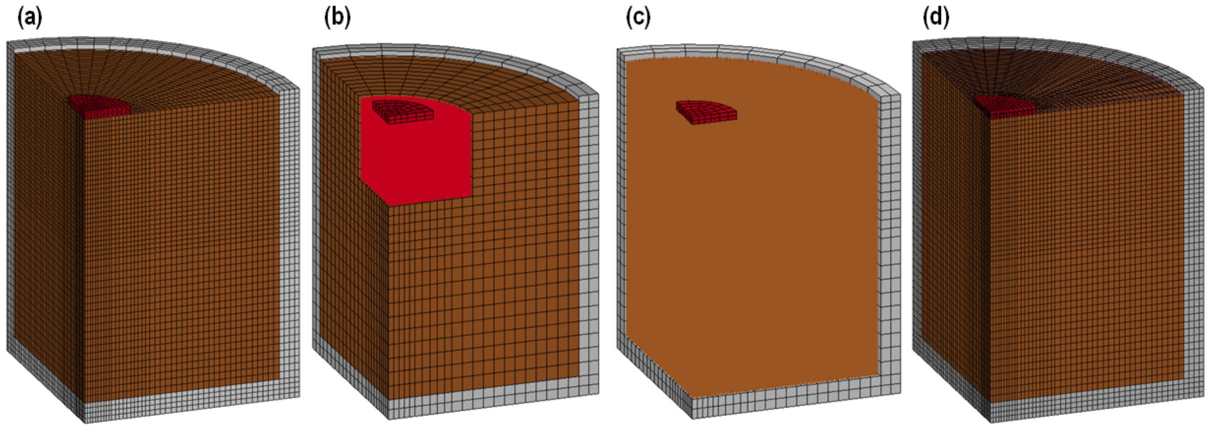

Figure 4: FE model for the soil penetration test simulation.

2. Timing and Decomposition Study

The initial 5 inches of penetration was simulated using each approach to assess computational efficiency. All simulations for this portion of the study were run using double precision MPP-DYNA 4.2.1 on 32 cores. Table 2 contains comparison of model size and the statistics on the running time for these models. The MM-ALE model took exactly 3.0 times more time for completion than the SPH_reduced model and 20.6 times more than Lagrangian simulation. The SPH_full model took 11.3 times more than SPH_reduced and 77.5 times more than Lagrangian model.

Table 2: Statistics on three models – simulation of 5in penetration

	Lagrange	***MM-ALE***	***SPH_reduced***	***SPH_full***
No. of elements	189,408	242,368	20,256 + 104,512 SPH particles	4.016 + 1,832,112 SPH particles
Initial timestep	6.82E-05	6.82E-05	1.44E-04	1.44E-04
Final timestep	2.18E-05	1.22E-05	1.14E-04	1.35E-04
Total CPU time	0:33:12	11:20:18	3:46:33	42:39:10
Element processing time (% of total CPU time)	76.97	68.42	97.64	96.66
Contact algorithm (% of total CPU time)	16.21	30.98	1.96	2.39

A study on the effects of domain decomposition on the execution time was performed. Three different decomposition patterns for 8 cores were studied within the Recursive Coordinate Bisection algorithm: default (patch type), wedge type and cylindrical type. The actual pfiles used for these decompositions are shown in Table 3.

Table 3: Design variables used for sensitivity study

default – patch type	***wedge type***	***cylindrical type***
decomposition { numproc 8 show}	decomposition { numproc 8 C2R 0 0 0 0 0 1 1 0 0 SY 5000}	decomposition { numproc 8 C2R 0 0 0 0 0 1 1 0 0 SX 100}

Figure 5 shows the model decomposed into 8 sub-domains for two quad-core nodes. The first two inches of penetration were simulated.

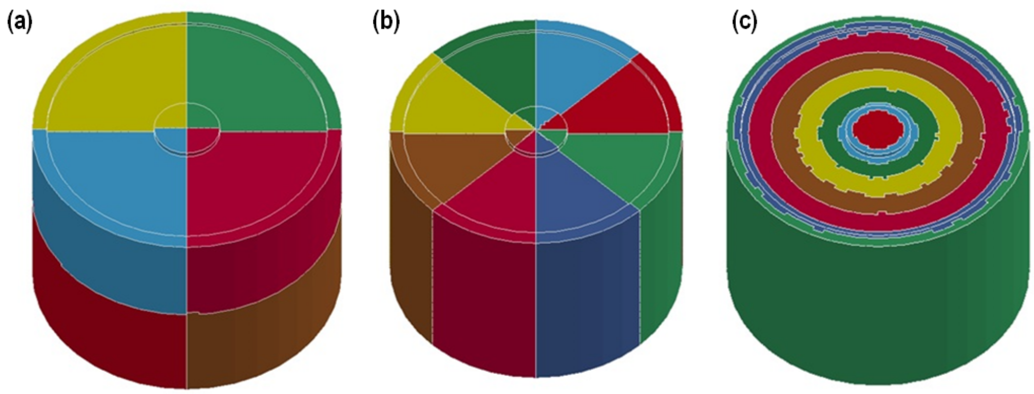

Figure 5: Decomposition methods (a) default, (b) wedge type, (c) cylindrical

The run time for these jobs is shown in a bar chart form in Figure 6. The cylindrical decomposition pattern was most efficient.

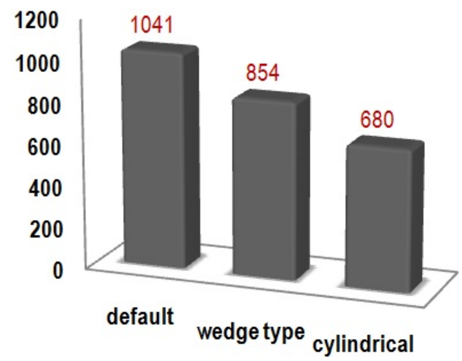

Figure 6: The run time (in seconds) for models decomposed in default, wedge and cylindrical patterns

3. Base Results

Figures 7 - 9 show deformations for the three models at 10 inches of penetration and their respective final stage. For the Lagrangian model (Figure 7), even at small penetrations the elements in the vicinity of the loading pad were heavily distorted. The simulation was terminated due to a substantial decrease of the time step at about 16.40 in of penetration. The SPH (Figure 8) and MM-ALE (Figure 9) simulations reached the termination time of 20 seconds (i.e., 20 inches of penetration). As expected, the MM-ALE formulation eliminated the problem of mesh distortion. However, several initial simulations had to be performed to find values for the penalty factors that prevented leakage between the fluid domain (soil) and Lagrangian body (pad and encasement). In the SPH model, the number of neighbors per particle (MEMORY in CONTROL_SPH command) was initially fixed to avoid problems with the memory. However, this needed to be used with caution since it can lead to a softer response of the model. As it turned out the difference may be significant and the MEMORY parameter was left adjustable by LS-DYNA.

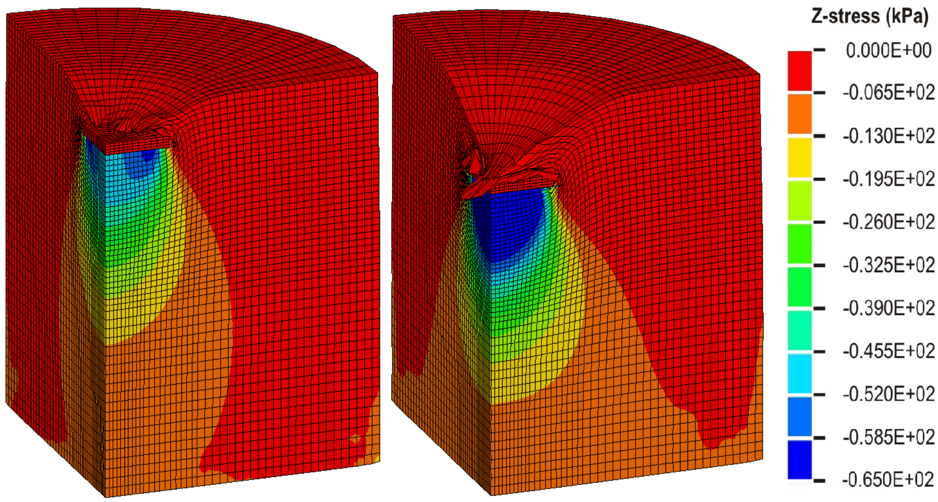

Figure 7: Deformations and Z stresses in Lagrange model
(a) 10.00 inches of penetration (b) 16.40 inches of penetration

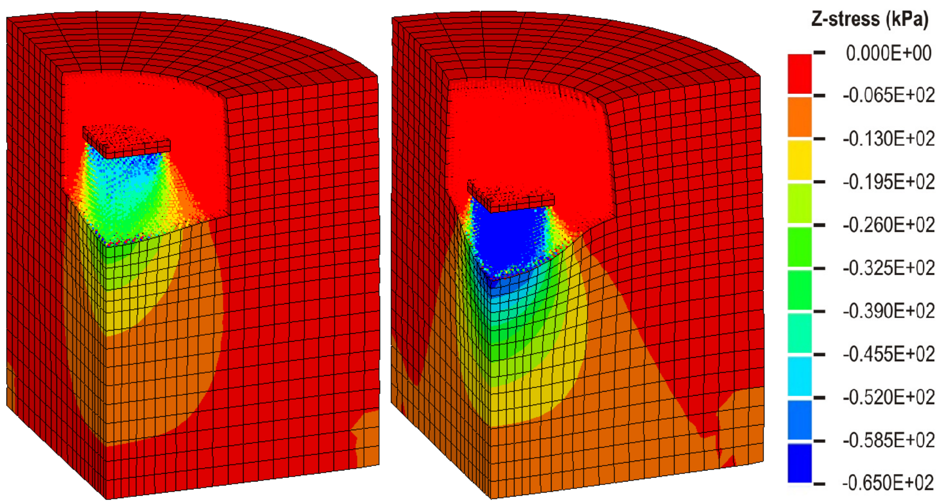

Figure 8: Deformations and Z stresses in SPH model
(a) 10.00 inches of penetration (b) 20.00 inches of penetration

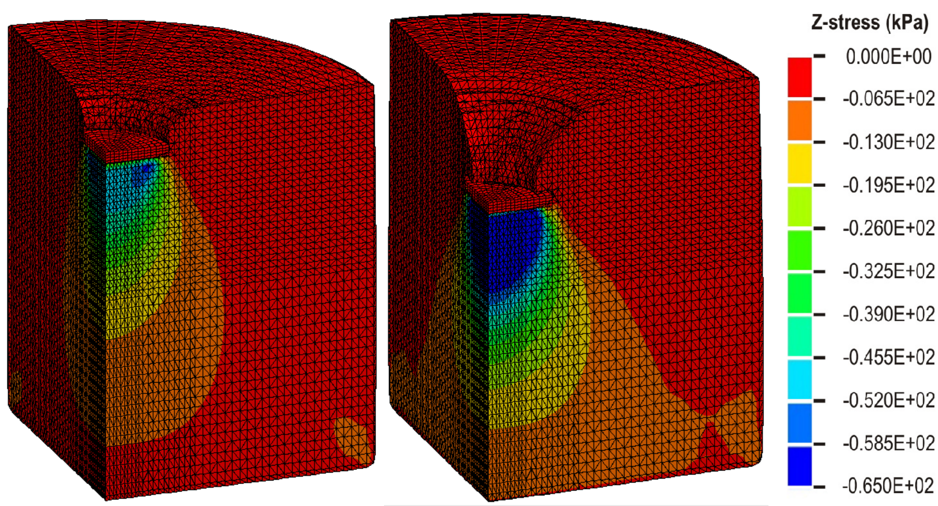

Figure 9: Deformations and Z stresses in MM-ALE model
(a) 10.00 inches of penetration (b) 20.00 inches of penetration

Figure 10 shows the comparison of the resultant force as a function of the load pad penetration for each of the three models. Note MM-ALE shows nearly linear response which is slightly different from the response of SPH and Lagrangian models.

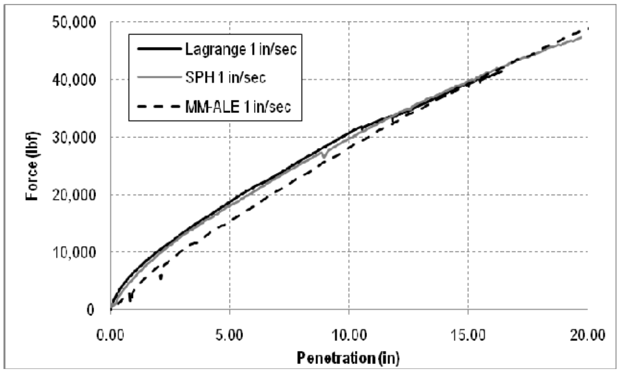

Figure 10: Force as a function of loading pad penetration for three models: Lagrangian, SPH_reduced and MM-ALE

4. Sensitivity Study

4.1. Influence of the material properties

Using LS-OPT, a sensitivity study was performed on the Lagrangian model. The vertical force exerted by the loading pad was defined as the model response metric. The chosen design variables are listed in Table 4. Assumed variations of +/- 10% of the nominal values defined their upper and lower bounds. Using the Latin Hypercube Sampling algorithm, 43 sampling points were selected. LS-DYNA simulations were performed for 10 sec (about 10 inches of penetration). The linear response surface was built, and the ANOVA based sensitivity study was performed.

Table 4: Design variables used for sensitivity study (units mm-s-tonne)

Design variable	***Description***	***initial value***	***lower bound***	***upper bound***
eencase	Young’s modulus of the elastic encasement	0.3400	0.306	0.374
rho	density of the soil	2.35e-09	2.115e-09	2.585e-09
bulk	unloading bulk modulus of the soli	15.024	13.521	16.526
shear	shear modulus of the soil	34.474	31.026	37.921
atwo	a2 parameter for yield function in soil material model	0.602	0.542	0.666
fpres	scaling factor for pressure in pressure vs. logarithmic strain relationship	1	0.9	1.1

ANOVA plots (Figure 11) show normalized coefficients of the linear response surface. The most significant variable turned out to be “atwo” (a_2), which is a yield surface (Eq. 1) parameter, followed by the soil density and young’s modulus of the encasement. Figure12 shows the loading pad force as a function of the pad’s vertical displacement for all the LS-OPT runs. For the +/- 10% variation in design variables, the final reading of the force at 10 inches of penetration ranged from 96.94 kN (21,791 lbf) to 155.35 kN (34,922 lbf) with the force of 126.34 kN (28,400 lbf) at the nominal value.

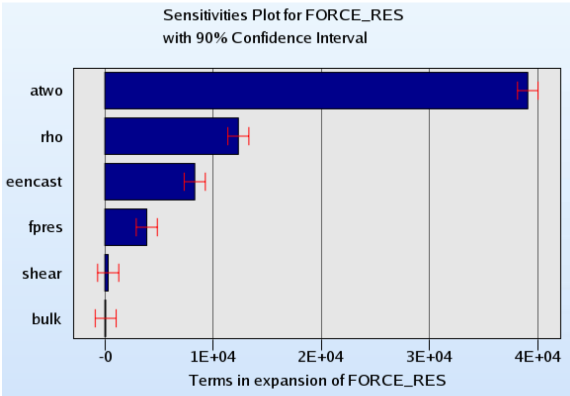

Figure 11: Sensitivities study for resultant force.

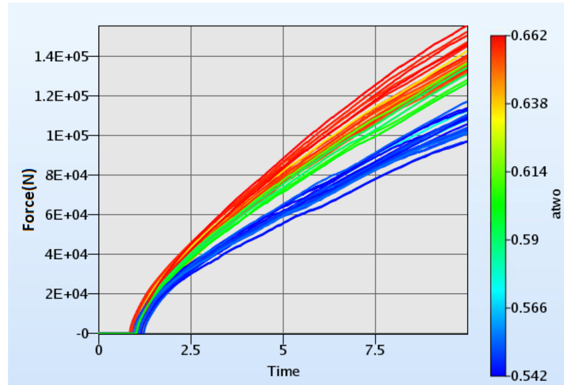

Figure 12: Resultant force history for all LS-OPT simulations.

4.2. Influence of the loading rate

Quasi static loading is often hard to replicate in explicit simulations. For that reason penetration test simulations with different loading rates were performed to evaluate the sensitivity of the model to loading rates. Figure 13a shows results for the Lagrangian model for five different loading rates. Up to 5 inches of penetration, there is no difference in the response, and thus, no effect due to loading rate. After 5 inches, an "apparent" rate dependency shows up. The slower the soil is loaded the less stable the model. It was noted that hourglass and sliding energy were building up indicating spurious results. In contrast, the SPH models were insensitive to the loading rates used.

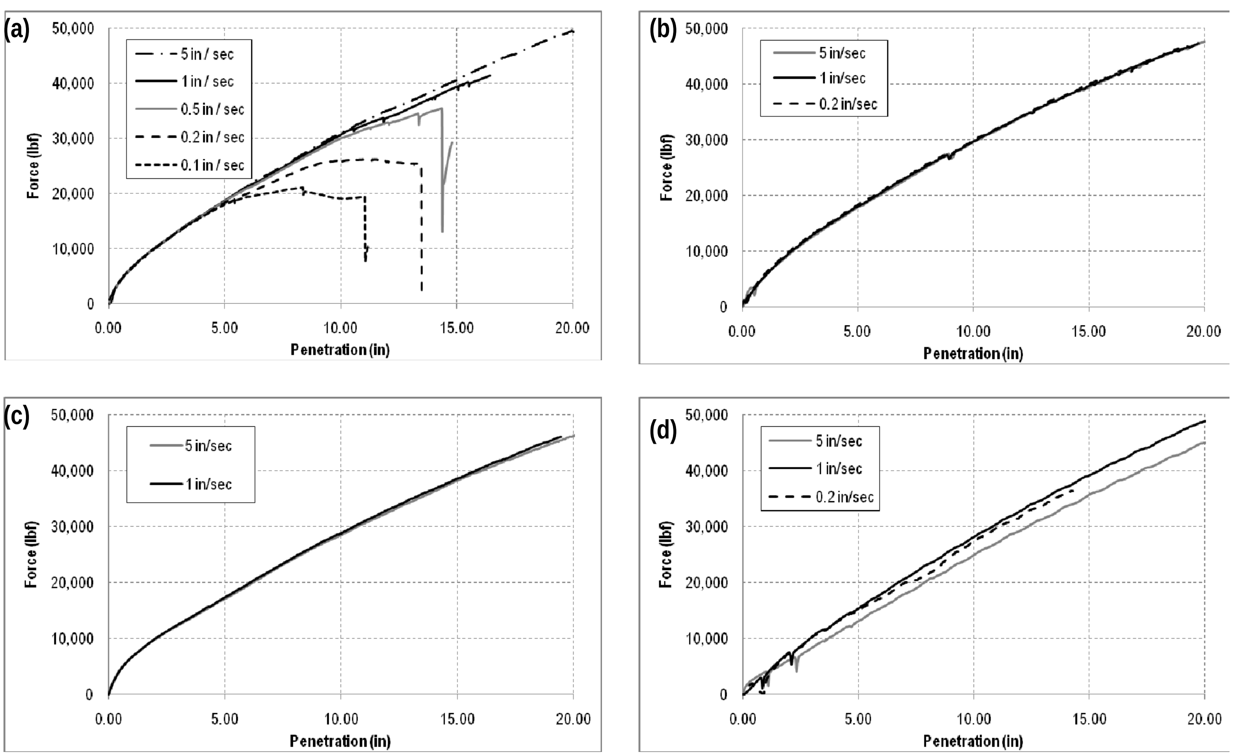

Figure 13: Force as a function of loading pad penetration for models:
(a) Lagrangian (b) SPH_reduced (c) SPH_full (d) MM-ALE

5. Model Validation

To validate the model, the results were compared with the experimental data published in [1]. The soil used in this experiment had a lower density (1.44e-9 tonne/mm^3) compared to the density (2.35e-9 tonne/mm^3) used in the sensitivity analysis above. The resultant forces from simulations with the experimentally measured density are shown in Figure 14.

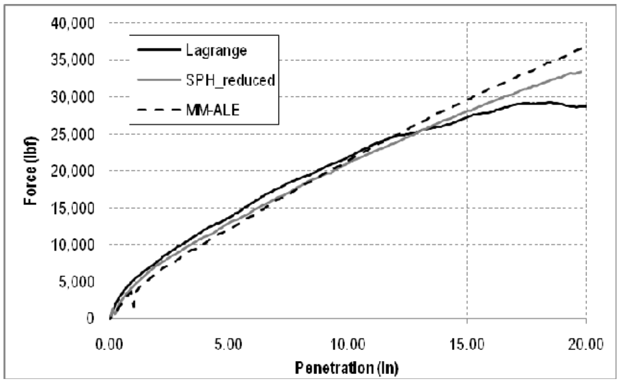

Figure 14: Force as a function of loading pad penetration for soil with low density

In the experiment, the force reading was zeroed at 1.27 inches of pad penetration. For comparison of the results, the simulation results were similarly adjusted. Experimental and simulation results are shown in Figure 15 along with Schwer's simulation results. The results give good correlation with the experiments. Figure 16 compares simulation (Lagrangian model) and experimental results for soil stresses at 2 and 4 feet und the loading pad. Again very good correlation was obtained.

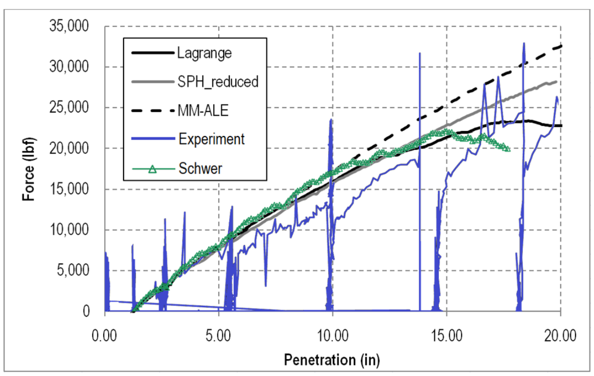

Figure 15: Comparison of the measured force versus displacement [1]

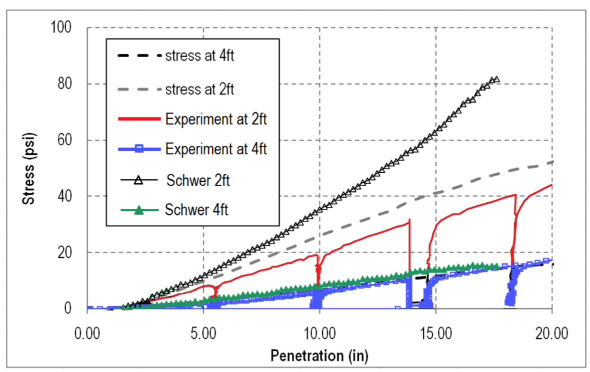

Figure 16: Comparison of the measured stresses under the pad versus displacement [1]

6. Conclusions

In this study, large penetrations into soil were simulated using three formulations: Lagrangian, SPH and MM-ALE. Although the Lagrangian approach was the fastest and gave reasonably good results, the mesh around the loading pad was highly distorted. Moreover, the model was giving different results for different loading rates. This apparent rate sensitivity was found to be caused by mesh degradation due to hourglassing that produced spurious energies in the simulation.

The MM-ALE approach eliminated the problem of mesh distortion. However, the time spent on adjusting the contact parameters and the CPU time required for the simulation itself makes this approach less attractive.

The most robust and reliable approach turned out to be a hybrid approach that used the SPH formulation in the soil region with high material distortion and the Lagrangian formulation away from the highly distorted soil. This approach was insensitive to loading rates, and the CPU time required with this model was much more favorable than MM-ALE or SPH_full models. This method will be used in future studies on bridge pier – soil interaction.

The sensitivity study revealed a great influence of the a_2 yield function parameter on the results. It must be determined experimentally with great accuracy. Soil density and encasement stiffness were also important factors.

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