Effect of Soil Material Models on SPH Simulations for Soil-Structure Interaction

Ronald F. Kulak[1]
Len Schwer[2]
1) RFK Engineering Mechanics Consultants
307 Warwick Drive
Naperville, IL 60565, USA
rfkemc@aol.com
2) Schwer Engineering & Consulting Services
6122 Aaron Court
Windsor CA 95492-8651
Len@schwer.net

Abstract

The analysis of bridges and highway structures often involves the interaction between the structural components and the soil they are embedded in. Modeling and simulation is currently capable of treating soil-structure interaction problems in which large soil and structural deformations occur. This type of interaction occurs in the analysis of bridge pier stability during riverbed scour. With the use of parallel computers, large-scale problems can routinely be solved. For these nonlinear problems, two of the critical steps are the choice of the constitutive models used to represent the components and the parameters for the models. Mature computer codes such as LS-DYNA have a large number of material models to choose from. So it is important to know the difference in prognostic capability of each model. Predictive accuracy cannot be known, only estimated.

This paper presents material parameters for the following models used to represent soil: (1) MAT005, Soil and Crushable Foam; (2) MAT010, Elastic Plastic Hydro; (3) MAT025, Geological Cap; and (4) MAT079, Hysteretic Soil. The hydrostatic compression response predicted by each model is compared to experimental data.

The material models were used in the large deformation analysis of a rectangular platen that was pushed into sand at a rate of 2.54 cm/sec (1 in/sec). The vertical resistance force versus penetration distance was found to be nonlinear during initial penetration and then transition into a linear response. A hybrid approach that combined Lagrange and Smoothed Particle Hydrodynamic (SPH) method was used to represent the soil.

Introduction

Currently, civil engineering design practice uses liner elastic soil properties for many soil-structure interaction problems. However, this approach falls short for problems in which the structure and soil undergo large deformations. With the availability of the high-performance computing (HPC) cluster at the United States Department of Transportation's Transportation Research and Analysis Computing Center [1], transportation researchers can investigate complex soil-structure interaction problems.

One of these problems is the stability of bridge piers during flash floods [2]. For certain riverbed soils, the high-velocity water washes away the soil covering the bridge piers, and this scour action can eventually expose the bottom of the pier and footing. In order to simulate this complex behavior, it is necessary to model the response of the reinforced concrete column – including concrete material failure – and the nonlinear soil behavior.

This paper addresses some of the issues related to soil modeling. The following four material models were studied: (1) MAT005, Soil and Crushable Foam; (2) MAT010, Elastic Plastic Hydro; (3) MAT025, Geological Cap; and (4) MAT079, Hysteretic Soil. The first step in modeling the soil is to choose an appropriate model. The second step is to obtain the material parameters required by the specific model chosen. Some basic models require only a few parameters while the more complex models require many more. For site specific analysis, soil testing is required and then skilled analysts extract the needed parameters. The parameters obtained from soil test are given for the above four soil models. The hydrostatic compression response predicted by each model is compared to experimental data. The MAT005 and MAT025 materials were used in a three-dimensional SPH simulation of a rigid platen being pushed into sand.

Material Models and Parameters

From the large suite of material models available to the LS-DYNA user, the following four models were selected: (1) MAT005, Soil and Crushable Foam; (2) MAT010, Elastic Plastic Hydro; (3) MAT025, Geological Cap; and (4) MAT079, Hysteretic Soil. The reasons for selecting these four were they encompass a good range from fairly simple to complex and soil test data was available, which allowed calibration of the material parameters. Descriptions of these models are not presented here. Note, all of these models are two invariant models.

Standard soil tests for determining mechanical properties include the hydrostatic compression (HSC), triaxial compression (TXC), triaxial extension (TXE), unconfined compression (UCT) and uniaxial strain (UXE). The standard test specimen for soil is a right circular cylinder. The test is performed by applying axial (σ_1) and lateral stresses (σ_2, σ_3) to the cylinder. The hydrostatic compression test is performed to determine the compaction behavior of soil. The test is performed by having all three principle stresses equal:

$$\sigma_1 = \sigma_2 = \sigma_3 \qquad (1)$$

Triaxial compression tests are used to define the shear strength envelope of the soil. Unlike the hydrostatic compression test, the axial and lateral stresses are not equal, and thus, the cylindrical test specimen experiences shear stress, which is equal to the difference between the principal stresses and is denoted either by SD or σ_Δ:

$$SD = \sigma_\Delta = \sigma_a - \sigma_c \qquad (2)$$

The specimen is loaded to a predetermined pressure under hydrostatic compression conditions, and then the lateral stress is held constant and the axial stress is increased. The unconfined compression test is performed by having a zero lateral stress. This is the lowest estimate of the material strength.

The triaxial extension test is performed in a similar manner. First, the specimen is loaded to a predetermined pressure under hydrostatic compression conditions, and then the axial stress is held constant and the lateral stress is increased. For soils the uniaxial strain test is usually performed by placing the soil in a "rigid" cylinder to prevent lateral strain.

Table 1 below list the standard soil tests required by each material model.

Table 1: Soil tests required by the material models

Test	Symbol	Material Model			
		005	010	025	079
Hydrostatic Compression	HSC	☑	☑	☑	☑
Triaxial Compression	TXC	☑	☑	☑	☑
Triaxial Extension	TXE	☒	☒	☒	☒
Unconfined Compression	UCT	☒	☒	☒	☒
Uniaxial Strain	UXE	☑	☑	☑	☑

Using the data from the soil tests, parameters for each model were obtained previously. The parameters used for each model and their values are listed in Table 2 below. The units were in the gm-MPa-mm-ms system. It is seen that MAT005 required four parameters, and MAT025 required eight. Note, these models have more parameters available than shown, but the values for these missing parameters were chosen to be zero. The definition of each parameter can be found in the LS-DYNA user's manual [3].

Table 2: Parameter values

Mat 005		MAT 010		MAT 025		MAT 079	
Parameter	Value	Parameter	Value	Parameter	Value	Parameter	Value
density	1.64e-3	density	1.64e-3	density	1.64e-3	density	1.64e-3
G	136	G	136	Bulk	15000	k_0	68.6
$\mathbf{k_{un}}$	4700	PC	-0.51	G	5289	p_0	-0.0138
$\mathbf{a_2}$	0.3736	a_1	1.0578	Theta	0.20375	b	0.39
				R	2.3	a_2	0.373
				D	1.6e-3		
				W	0.49		
				X_0	46.5		

Comparison to Hydrostatic Compression Test

With the parameters determined for each material model, a one-hexahedral-element model was run to simulate hydrostatic compression. Figure 1 shows the results for the four material models up to 32 percent volumetric strain. It should be noted that the results for MAT005 and MAT010 overlay each other. Furthermore, both MAT005 and MAT010 replicate exactly the experimental values since the experiment data for the hydrostatic compression test is part of the input and used directly by these two models. MAT025 over predicts the experimental response and over predicts the r esponse of M AT079 up t o a bout 16% v olumetric s train. M AT079 unde r pr edicts the response.

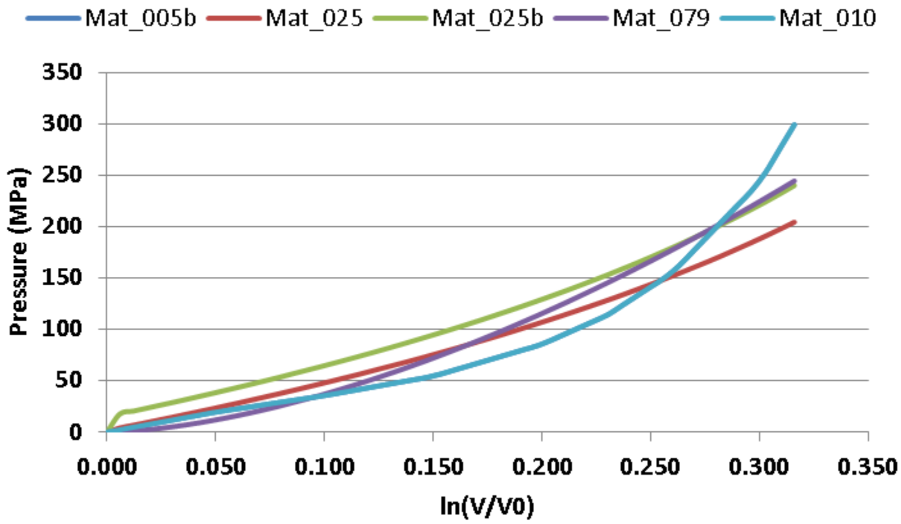

Figure 1: Comparison of Model Response to Hydrostatic Compression up to 32 percent volume strain

Figure 2 compares the model responses up to a volumetric strain of 10 percent. At about the 10 percent natural volumetric strain, MAT025b shows a pressure about 80 percent larger than MAT005.

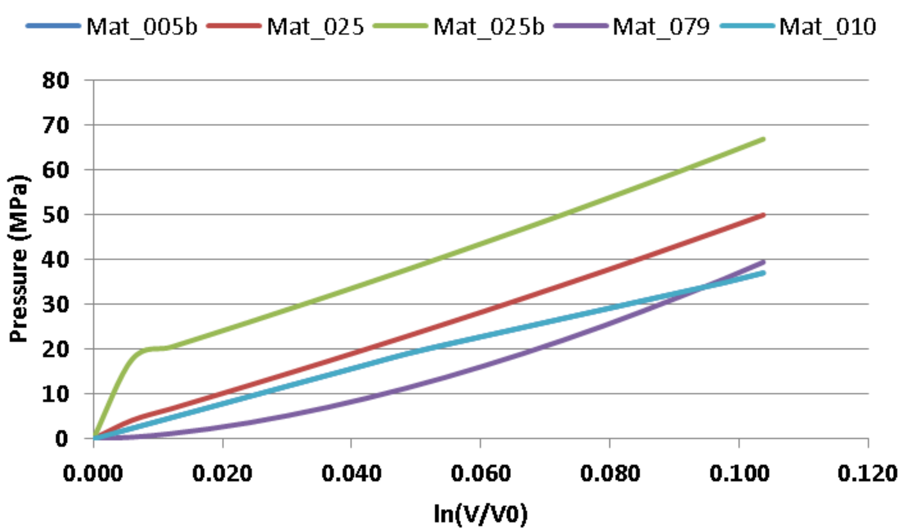

Figure 2: Comparison of Model Responses to Hydrostatic Compression up to 10 percent natural volumetric strain

Simulation of Platen Penetration into Soil

To assess the performance of the models, the platen penetration example reported by Schwer [4] was exercised using MAT005 and MAT025 material models. The example consisted of pressing a loading platen into soil. The numerical model represented one-quarter of the physical problem: 2439 mm long, 2439 mm wide and 1778 mm deep Figure 3a. The platen was a square with 508 mm sides. Symmetry boundary conditions were applied to the two inside surfaces of the model to simulate the whole model. The translational degrees-of-freedom were constrained on the bottom and outer surfaces of the model. To decrease the large computational time required by the Smooth Particle Hydrodynamics formulation, a hybrid model was developed. For the hybrid model, the Smooth Particle Hydrodynamics formulation was used in the high deformation region and the Lagrangian formulation in the small deformation region. The quarter model 508 mm long by 508 mm wide by 889 mm deep SPH zone was under the platen Figure 3b.

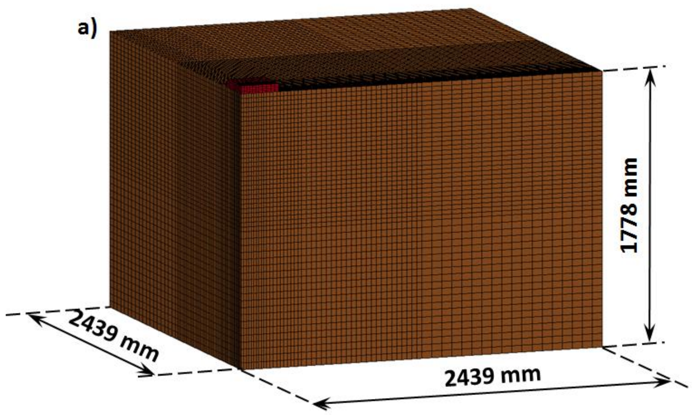

Figure 3: Hybrid model for platen penetration simulation

Because this is considered to be a quasi-static loading soil penetration problem, strain-rate sensitivity is not a consideration. Also, since explicit time integration can easily handle large deformation soil-structure interaction problems in which highly nonlinear material response occurs, the explicit option of LS-DYNA was chosen as the solver. Figure 4 shows the deformed configuration and contours of the vertical stress under the loading platen.

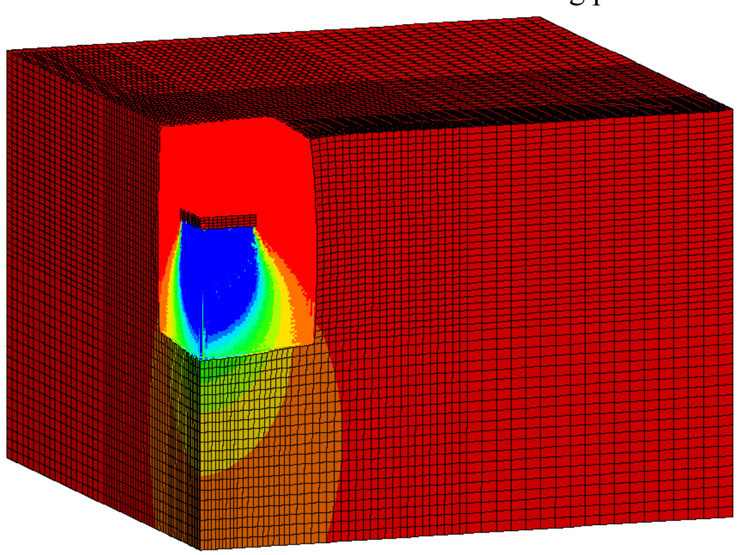

Figure 4: Deformed configuration for platen penetration into soil

The platen penetration force for MAT005 and MAT025 are shown in Figure 5. It is seen that a relatively large difference in response magnitude occurred. The initial near zero force occurred during gravity loading of the model. Once the platen begins to penetrate into the soil, the platen force for MAT005 gradually begins to increase to a value of 2 MN at time equal to 5. In contrast for MAT025, the penetration force initially rises sharply and then gradually increases to a value of 5.5 MN. This was to be expected since the MAT025 model response to hydrostatic compression showed similar behavior.

The response labeled MAT025a in Figure 5 was obtained by subtracting the initial sharp rise in the MAT025 response. This brought the two force histories closer, but the MAT025a response is still much higher than that of MAT005.

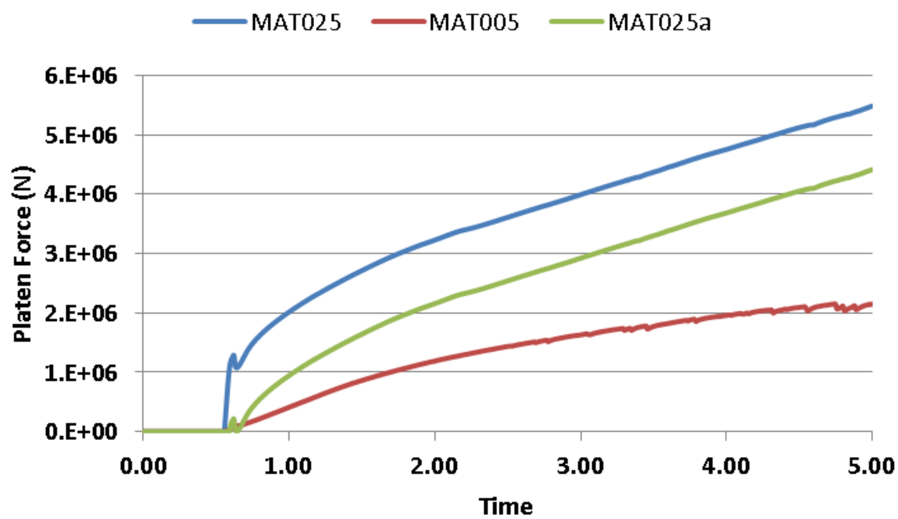

Figure 5: Penetration force history for MAT005 and MAT025

A look at several SPH elements in SD (stress difference)-Pressure space provides a comparison of the stress state evolution relative to the failure surface, F_e. For MAT025, Figure 6 shows the stress trajectory of SPH element 351660, which is directly under the platen, and it is seen that the trajectory starts out and remains under the failure envelop, Fe.

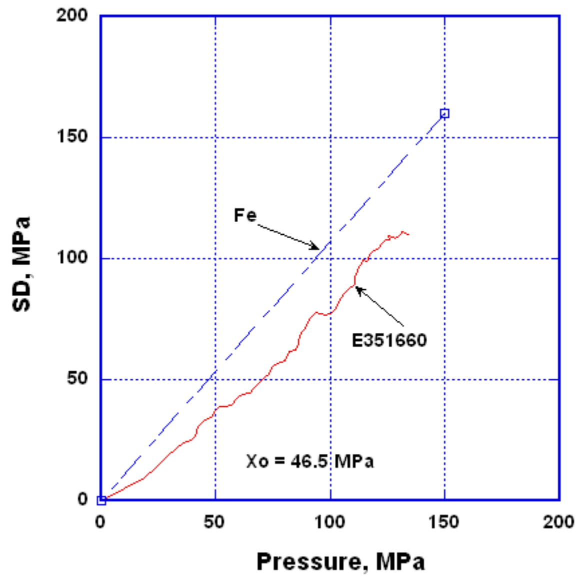

Figure 6: SPH element 351660 stress trajectory in Stress Difference-Pressure space

Figure 7 shows the trajectory for SPH element 36158, which is under the platen but deeper into the soil. Initially, the trajectory shows that the failure surface is penetrated, but as the platen continues to penetrate the soil, the trajectory moves below the failure surface.

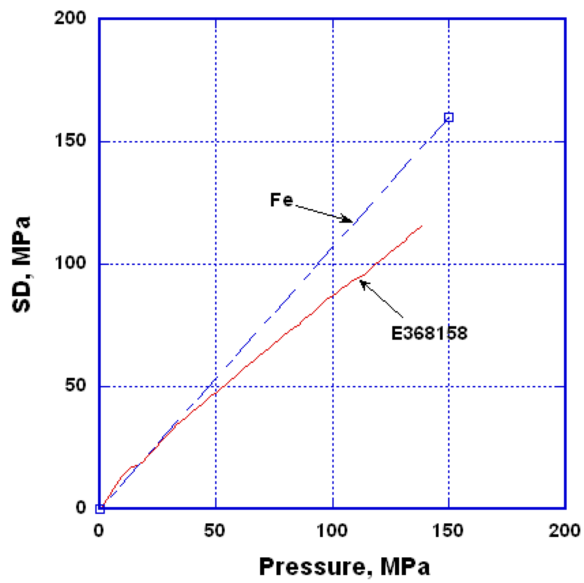

Figure 7: SPH element 368158 stress trajectory in Stress Difference-Pressure space

The final SPH element studied was element 335130, which is initially just under the outer edge of the platen. As the platen moves down, element 335130 moves out from under the platen and around the edge of the platen. Figure 8 shows the trajectory during the initial downward movement, which is then followed by lateral motion that pulls the element out of the range of direct platen loading. This effect is shown by the initial increase in pressure and the subsequent drop in pressure as the element moves laterally. Here also, the failure envelope is slightly violated.

From Figure 7 and Figure 8, it is seen that for MAT025 the stress state of several SPH elements slightly penetrated the failure surface during the loading process. This is probably due to the lack of strain sub-incrementation in the model.

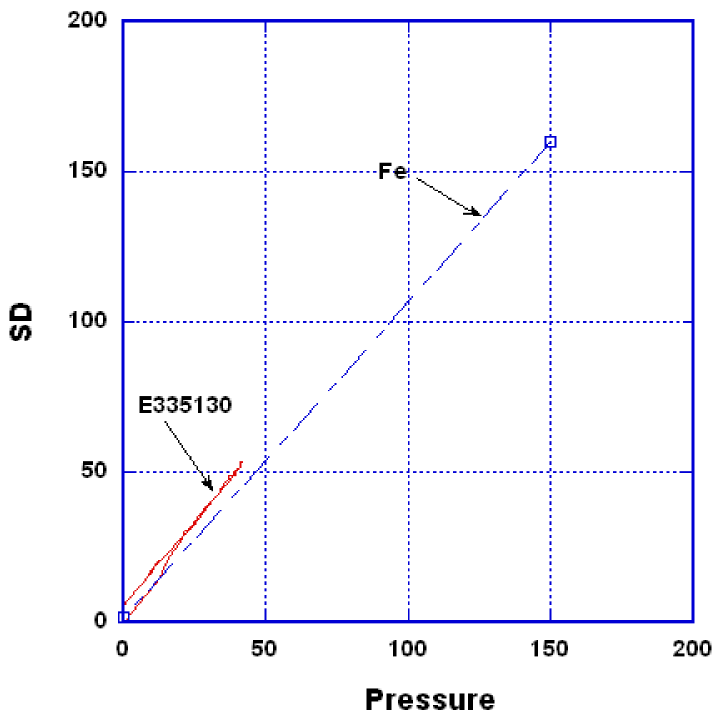

Figure 8: SPH element 335130 stress trajectory in Stress Difference-Pressure space

Summary and Conclusions

A study was performed to investigate how the choice of material models and their parameters used to represent nonlinear soil behavior affects the response of a structure undergoing large displacements within the soil. The following material models were used: (1) MAT005, Soil and Crushable Foam; (2) MAT010, Elastic Plastic Hydro; (3) MAT025, Geological Cap; and (4) MAT079, Hysteretic Soil. Parameters for these models were obtained previously, but these parameters were based on using the model for a different application than the one exercised here. A one Lagrangian element model was used to compute the hydrostatic compression response for each material model. MAT005 and MAT010 replicated the experimental hydrostatic compression response because exact hydrostatic compression data is used as input to these material models. For the parameters used, MAT025 gave the stiffest response, and MAT079 produced the softest. It should be noted that the MAT025 and MAT079 pressure-volume strain relationship is difficult to fit to pressure-volume strain data – especially for soil.

The MAT005 and MAT025 models were used in the SPH simulation of a platen being pushed into soil. Similar to the one Lagrangian element hydrostatic compression simulation, MAT025 required much higher vertical forces to push the platen into the sand. In addition, since MAT005 has a flat cap, MAT025 would encounter the cap sooner than MAT005 for the parts of the soil whose stress trajectory is further away from hydrostatic compression. It was noted that for MAT025, several SPH elements slightly penetrated the failure surface during the loading process. This is probably due to the lack of strain sub-incrementation in the model.

The successful estimation of the response of soil-structure interaction problems requires calibrated material models for the specific problem. To calibrate the material models, the analysts should have an idea of the expected strains – for example, volumetric strain – that will occur in the soil. Soil testing should be done in this range to ensure that the most accurate material parameters can be obtained. Most likely, this will involve an iterative process between material model calibration and computer simulations.

Acknowledgement

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References

[1] http://web.anl.gov/TRACC/
[2] Kulak R.F. and Bojanowski C., Modeling of Soil-Structure Interaction in Presence of Large Deformations in Soil, Paper No. 11-2287, 90th Transportation Research Board Annual Meeting, Washington, D.C., January 23-27, 2011
[3] Livermore Software Technology Corporation (LSTC), LS-DYNA Keyword User's Manual
[4] Schwer L., Soils and Foams Model Case Study Class Notes: Concrete & Geomaterial Modeling with LS-DYNA, Schwer Engineering and Consulting Services 2002