A COMPUTATIONAL FRAMEWORK FOR SCALE-BRIDGING IN MULTI-SCALE OFF-ROAD MOBILITY SIMULATIONS

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ABSTRACT

The mobility performance of off-road vehicles involves the interaction between the vehicle tires and soil that requires more advanced and robust simulation methods to accurately model [4]. The finite element method (FEM) [6][7][8][9] can be a good approach to compute deformations of the tire and soil, but analytical constitutive models of soil used in FEM typically lack accuracy, for example in problems involving large deformations. Discrete element method (DEM) [12][13][14] is a more accurate approach to capture the soil constitutive features, but for the simulations of a large ground vehicle traversing over deformable terrain, the current DEM methods require modeling of soil particles at a size too large to be real, and the simulation times are prohibitively large. It is proposed in this work to develop a multi-scale FEM-DEM deformable terrain model for physics-based off-road mobility simulation to facilitate a cross-scale understanding of granular material behavior that benefits from the strengths of both FEM and DEM methods. In this article, a hierarchical multi-scale (HMS) computational framework is used to develop a hybrid parallel computational model for off-road mobility tire-soil interaction problems on high performance computer (HPC) systems. The HMS computational multi-scale framework for scale-bridging was first proposed and developed by Knap et al [1] at CCDC US Army Research Laboratory. The HMS framework is capable of fully asynchronous operation to enable seamless combination of sub-models into highly dynamic hierarchies to form a multi-scale model and has been successfully used to develop many multi-scale applications. In this work, the HMS framework is utilized to develop a multi-scale model of tire-soil interaction consisting of an FEM upper-scale model and DEM lower-scale model. The simulation results demonstrate the proposed FEM-DEM multi-scale method with HMS framework to be fast, accurate and robust for tire-soil interaction mobility simulations.

1. INTRODUCTION

Multi-scale modeling has emerged in recent years as a powerful organizing principle for modeling the behavior of complex systems. A multi-scale model is a composite model for a complex system that incorporates two or more sub-models. Each sub-model captures the behavior of the system at a single spatial and temporal scale relevant to the overall behavior of the system. The development of a multi-scale model requires the identification of the individual scales to be included in a multi-scale model. Then suitable sub-models are developed for each scale and the sub-models are linked together to form a multi-scale model. Multi-scale modeling is widely applicable and has led to successful development of high-fidelity models in many fields including materials science, biology, chemical engineering, and atmospheric science.

Recently, computational aspects of multi-scale modeling have become a focus of research and computational frameworks to facilitate the development of multi-scale models are under development. A review of available multiscale computing software and multiscale computational frameworks can be found in [22]. Knap et al. [1] have recently introduced the hierarchical multi-scale

(HMS) scale-bridging framework aimed at the development of highly dynamic multi-scale models on HPC systems. The HMS framework offers a number of practical advantages for multi-scale model development. A primary feature of the HMS framework is that it allows for the incorporation of sub-models into a multi-scale model without requiring any software modifications to the sub-models, allowing the use of a wide-variety of existing complex computer models as sub-models including proprietary or closed-source codes. The HMS framework also facilitates the massively parallel concurrent evaluation of sub-models across heterogeneous computing resources and includes capabilities to balance the computational load to achieve parallel scalability [1]. As multi-scale models are often extremely computationally demanding, the HMS framework also includes the ability to dynamically construct surrogate models to lessen the computational burden [21]. A recently developed Vectorized User Material (VUMAT) interface to the HMS framework permits developed multi-scale material models to be used seamlessly within a variety of commercial and government modeling and simulation codes.

In this article, we introduce a multi-scale FEM-DEM model developed with the HMS scale-bridging framework. The upper-scale FEM model obtains the material constitutive relation of the soil through a constrained evaluation of the lower-scale DEM model. The developed multi-scale FEM-DEM model can be used for mobility simulation with the numerical accuracy of DEM and the computational speed of FEM. The computational performance of the developed multi-scale model is evaluated for two challenging problems pertaining to vehicle mobility applications. One is a tri-axial compression problem of granular soil and the second is a single wheel tire-soil interaction problem. We will demonstrate the accuracy and parallel scalability of the multi-scale model and draw conclusions about the future directions of our approach.

2. MULTI-SCALE FEM-DEM METHOD

To support the mission to develop, integrate, and sustain the right technology solutions for all manned and unmanned ground systems with off-road mobility capabilities, a numerical simulation method to solve tire-soil interaction problems is needed[16]. The hierarchical multiscale FEM-DEM simulation method, with finite element method as the upper scale model and discrete element method as the lower scale model, has the advantages of computational speed and numerical accuracy. The numerical modeling process of the proposed multiscale method, which was introduced by Yamashita et al [2][3][10], is shown in Fig. 1, and the details of the method are described as the following.

2.1 Upper-Scale Finite-Element Model (FEM)

The upper-scale continuum model is developed using the nonlinear finite element method. A brick element integrated in the monolithic multibody dynamics solver is generalized to account for the grain-scale granular material behavior using the lower-scale DEM model at the quadrature points within the element. The global position vector of an arbitrary point in the element is defined by

$$\mathbf{r} = \mathbf{N}(\xi, \eta, \zeta)\mathbf{e} \tag{1}$$

where $\mathbf{N}$ is the shape function matrix and $\mathbf{e}$ is the nodal coordinate vector ξ, η, ζ are the element natural coordinates. The Green-Lagrange strain tensor is given by

$$\mathbf{E} = \frac{1}{2}(\mathbf{F}^T\mathbf{F} - \mathbf{I}) \tag{2}$$

where $\mathbf{F}$ is the global position vector gradient tensor defined by

$$\mathbf{F} = \frac{\partial \mathbf{r}}{\partial \mathbf{X}} = \bar{\mathbf{J}}(\mathbf{J})^{-1} \tag{3}$$

and $\bar{\mathbf{J}} = \partial\mathbf{r}/\partial\mathbf{x}$, and $\mathbf{J} = \partial\mathbf{X}/\partial\mathbf{x}$. The vector $\mathbf{X}$ defines the global position vector at an arbitrary reference configuration. The generalized internal force $\mathbf{Q}_s$ can then be obtained as:

$$\mathbf{Q}_s = \int_{V_0} \left(\frac{\partial \boldsymbol{E}}{\partial \mathbf{e}} \right)^T \boldsymbol{S}\, dV_0 \tag{4}$$

where $\boldsymbol{E}$ is a vector of the Green-Lagrange strain tensor obtained from Eq. 2, while $\boldsymbol{S}$ is a vector of the second Piola–Kirchhoff (PK) stresses and dV_0 is the infinitesimal volume at the reference configuration. Using the principle of virtual work in dynamics, the equations of motion of the element can be obtained as:

$$\mathbf{M}\ddot{\mathbf{e}} = \mathbf{Q}_s + \mathbf{Q}_e \tag{5}$$

where $\mathbf{M}$ is the generalized mass matrix and $\mathbf{Q}_e$ is the generalized external force vector that can include the contact forces with the rolling tire.

2.2 Lower-Scale Discrete-Element Model (DEM)

To define the stress response at a quadrature point within the element, the Representative Volume Element (RVE) is defined using the DEM approach as shown in Fig. 1. The RVE is subjected to spatial periodic boundaries to predict homogenized stress responses of granular material at the material point within the element. In the DEM simulation, the Hertzian compliant normal contact force model is used as:

$$F_n = \frac{2E}{3(1-\nu^2)} \sqrt{r_e\, \delta_n} \cdot \delta_n \tag{6}$$

where E, ν, r_e, and δ_n are, respectively, Young's modulus, Poisson's ratio, equivalent particle radius, and assumed penetration between two particles in contact. A Mindlin-type tangential force model is used to define the state of sticking, while the Coulomb friction model is used in the sliding state as:

$$F_t = \begin{cases} \dfrac{4G}{2-\nu} \sqrt{r_e \delta_n} \cdot \delta_t & \cdots \text{ sticking} \\ \mu F_n & \cdots \text{ sliding} \end{cases} \tag{7}$$

where □ and δ_t are, respectively, the friction coefficient and tangential deformation between two particles in contact. The rolling resistance moment is also considered to describe moments exerted on non-spherical particles in contact as:

$$M_r = \begin{cases} \beta K_n r_e^2 \eta^2 \cdot \theta_r & \cdots \text{ sticking} \\ \eta F_n r_e & \cdots \text{ sliding} \end{cases} \tag{8}$$

where β and η are rolling resistance parameters, while θ_r is torsional deflection between two particles.

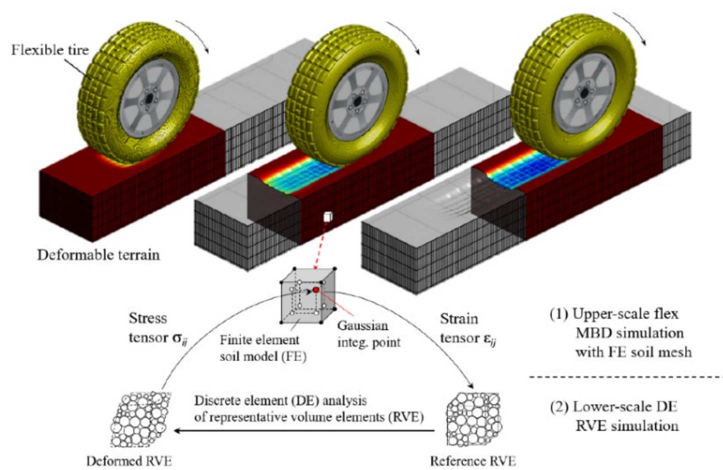


Figure 1: Hierarchical multi-scale tire-soil interaction simulation model (Yamashita et al, [2])

To obtain the history-dependent stress response using the RVE, incremental strain tensor $\Delta\boldsymbol{\varepsilon}$ at the quadrature point in the finite element is calculated at each time step and is used to deform the corresponding RVE by changing the coordinates of the RVE planes. For this, the logarithmic strains (i.e., true strains) in reference to the current configuration are evaluated as:

$$\epsilon = \sum_{i=1}^{3} \ln(\lambda_i) n_i \otimes n_i \tag{9}$$

where λ_i is the i-th eigenvalue of spatial stretch tensor V given from the polar decomposition of the displacement gradient tensor $\mathbf{F} = \mathbf{VR}$ with the rotation tensor R. The vector $\mathbf{n}_i$ is the associated eigenvector. Having completed the DEM simulation under the prescribed strain boundary condition at each time step of the upper-scale model, the RVE particle data at the deformed configuration is saved for use in the next time step and the homogenized Cauchy stress tensor of the deformed RVE can then be calculated as:

$$\boldsymbol{\sigma} = \frac{1}{V} \sum_{N_c} \mathbf{d}^c \otimes \mathbf{f}^c \tag{10}$$

Where $\mathbf{f}^c$ is the inter-particle contact force vector, while $\mathbf{d}^c$ is the relative displacement vector of particles in contact. V is the volume of the deformed RVE and Nc is the total number of contact in the RVE. Furthermore, the homogenized tangent moduli tensor can be obtained as:

$$\frac{\partial \boldsymbol{\sigma}}{\partial \boldsymbol{\varepsilon}} = \frac{1}{V} \sum_{N_c} (k_n \mathbf{n}^c \otimes \mathbf{d}^c \otimes \mathbf{n}^c \otimes \mathbf{d}^c + k_t \mathbf{t}^c \otimes \mathbf{d}^c \otimes \mathbf{t}^c \otimes \mathbf{d}^c) \tag{11}$$

where $\mathbf{n}^c$ and $\mathbf{t}^c$ are unit normal and tangent vectors of contact plane between two particles in contact. To obtain the generalized internal force vector of the FE model in Eq. 4, the homogenized Cauchy stress tensor is converted to the second PK stress tensor as:

$$\mathbf{S} = J\,\mathbf{F}^{-1} \boldsymbol{\sigma} \mathbf{F}^{-T} \tag{12}$$

where $J = \det|\mathbf{F}|$. The preceding equation is used to define the internal forces of the upper-scale FEM model in Eq. 4. Accordingly, history-dependent stress responses of granular materials, predicted by the DEM models, can be incorporated in the FEM model and the conventional phenomenological constitutive assumption can be eliminated.

3. COMPUTATIONAL FRAMEWORK

The multi-scale FEM-DEM model described in Section 2 is implemented using the HMS scale-bridging framework. Details of the HMS framework can be found in [1]. Here we summarize the relevant features of the HMS framework for development of the FEM-DEM multiscale soil model.

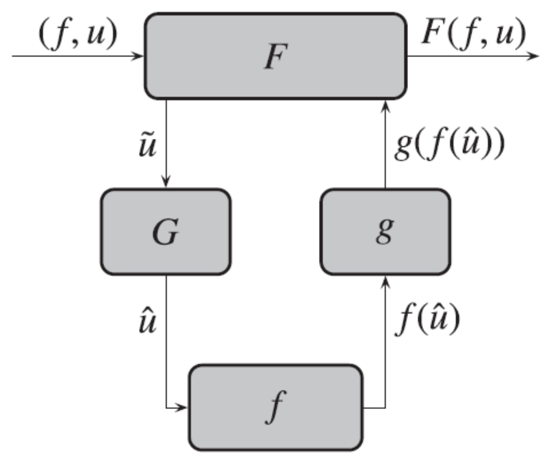


Figure 2: The two-scale model building block for development of multi-scale models in the HMS framework

3.1 HMS Computational Framework for Scale-Bridging

The HMS framework decomposes a multi-scale model into a collection of two-scale model building blocks. Each two-scale model building block consists of an upper-scale model F, lower-scale model f, and two mappings, G and g, that transform data communicated between the two models. A schematic of the two-scale model building block is shown in Fig. 2. The data $\tilde{u}$, passed from the upper-scale model to the lower-scale model is transformed by G into an appropriate form for the lower-scale model, denoted by $\hat{u}$. For example, G may compute the strain tensor $\hat{u}$ from the deformation gradient

$\tilde{u}$ provided by the upper-scale model. In a complementary manner, the mapping g extracts and transforms the data obtained from the lower-scale model into the form required by the upper-scale model. The FEM-DEM multi-scale model consists of a single two-scale model building block with FEM as the upper-scale model and DEM as the lower-scale model.

3.2 HMS Evaluation Model

The HMS Evaluation Module is the main component of the HMS framework responsible for coordinating the interaction between the upper-scale and lower-scale model. A schematic of the HMS Evaluation Module is provided in Fig. 3 and we refer the reader to [1] for details on the internal operation of the Evaluation Module.

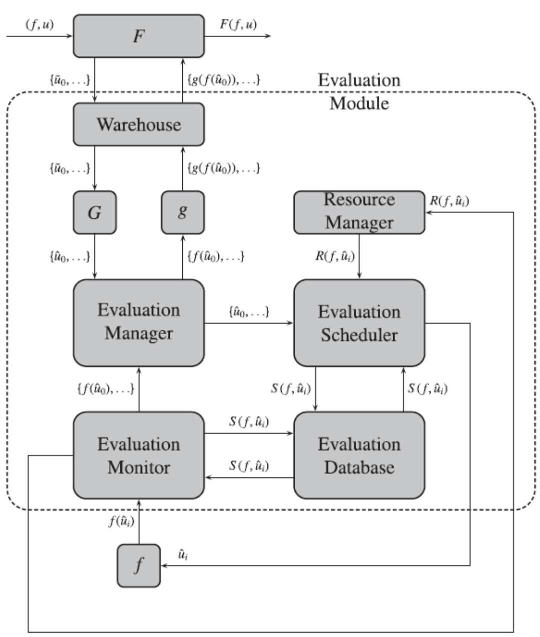


Figure 3: A schematic of the process of the evaluation of f. The dashed line encloses all the components of Evaluation Module (Knap et al, [1])

The main purposes of the Evaluation Module are (i) to collect requests for evaluation of the lower-scale model f, (ii) to schedule computation of individual evaluation requests on available computational resources, (iii) to communicate the results of the individual evaluation requests back to the upper-scale model F, and (iv) to detect and handle errors encountered during the evaluation of f. The Evaluation Module allows for fully asynchronous interactions between F and f so that both the upper-scale and lower-scale models can proceed concurrently with limited synchronization. Such a feature is particularly desirable for numerous practical applications. For example, in the case of the FEM-DEM multi-scale model, the computation of stresses at all required locations within the FEM domain can be carried out with some level of concurrency and if sufficient computational resources are available all of the lower scale model computations can be performed at once.

4. MULTI-SCALE TIRE-SOIL INTERACTION MODEL IMPLEMENTATION

4.1 Multi-scale FEM-DEM Model with HMS Framework

The algorithm for the multi-scale FEM-DEM tire-soil interaction model is depicted in Fig. 4. The upper scale model is a fully integrated monolithic flexible multibody dynamics code developed to solve vehicle mobility problems in which tire and soil are modeled using the finite element method. The proposed multiscale FEM-DEM method is used to obtain the constitutive response of the soil. In the upper-scale soil FEM model, the deformation gradient tensor at a quadrature point is computed and communicated to the HMS Evaluation Module. The mapping G computes the logarithmic strain increment from the deformation gradient by first computing the left Cauchy-Green deformation tensor, $\mathbf{B}$, from the deformation gradient $\mathbf{F}$:

$$\boldsymbol{B} = \boldsymbol{F}\boldsymbol{F}^{\boldsymbol{T}}$$

The eigen-decomposition of $\mathbf{B}$ yields orthogonal eigenvectors $\boldsymbol{n}_1$, $\boldsymbol{n}_2$, $\boldsymbol{n}_3$ and eigenvalues λ_1^2, λ_2^2, λ_3^2. The spatial logarithmic strain tensor is then computed according to Equation 9. The incremental spatial logarithmic strain tensor (denoted as $\hat{u}$) is supplied to the lower scale DEM model and defines the boundary condition imposed on the soil RVE. The DEM model of soil is implemented in the

LIGGGHTS open source discrete element method particle simulation code [24]. Each DEM simulation under the prescribed strain boundary condition is run in parallel using the Message Passing Interface (MPI). It is important to notice here that each RVE has no physical interaction with any other RVEs, thus the parallel computing scheme for evaluating multiple RVEs is more straightforward than the single-scale pure DEM model that requires sophisticated domain decomposition techniques due to strong force coupling between DEM subdomains. Having completed the RVE simulation, the homogenized Cauchy stress tensor as well as the tangent moduli tensor are outputted from the DEM model. These quantities are extracted by the HMS Evaluation Module in the mapping *g* and communicated back to the upper-scale FEM model which uses the returned quantities to compute the generalized internal forces and integrate the simulation forward in time using an implicit time integrator. It is important to note that for running the large-scale tire-soil interaction simulation on a HPC, the scale-bridging algorithm needs to be optimized to avoid frequent data transfer across multiple compute nodes which imposes additional loads on the HPC cluster. For this reason, strain tensor data from the upper-scale FEM models are stored on a RAM-based Linux *tmpfs* filesystem to enable efficient access. In a similar manner, RVE simulation outputs are stored on a *tmpfs* filesystem so that they can be quickly read to initialize the RVE simulation at the next FEM time step. Use of the *tmpfs* filesystem avoids the use of much slower shared filesystem that can slow down the multi-scale model evaluation substantially.

The HMS framework has many practical advantages over the previous FEM-DEM multi-scale implementation where the DEM model is directly integrated into the FEM code in [2]. A major advantage is that the HMS framework allows the LIGGGHTS DEM model to be incorporated into the FEM model with minimal changes to the FEM model and no changes to the DEM model. Furthermore, the HMS framework provides flexibility to allow the DEM model to be evaluated across a wide range of computing resources. For example, the FEM model can be executed on a desktop computer and the lower-scale DEM simulations across a large supercomputer. In addition, the HMS VUMAT implementation of the multiscale model, as described in the next subsection, enables the use of the model within many widely-used commercial and government modeling codes.

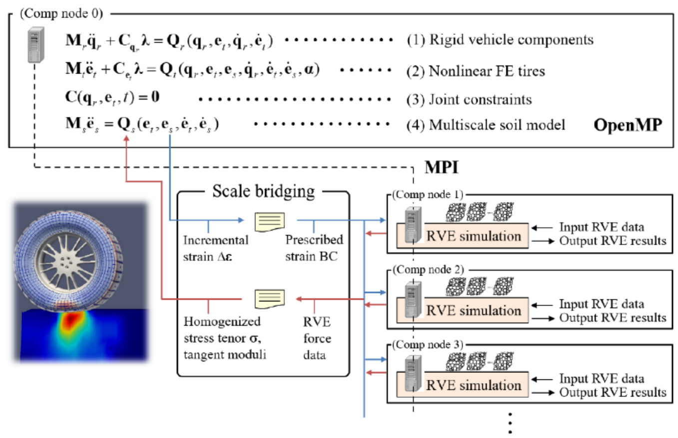


Figure 4: Parallelized scale-bridging algorithm for hierarchical multi-scale tire-soil interaction simulation

4.2 HMS VUMAT Implementation of the Multiscale Soil Model

The FEM-DEM multi-scale model is also implemented with the HMS Vectorized User Material (VUMAT) interface. A VUMAT is a standardized interface for the development of customized material models for FEM software. The VUMAT interface was originally developed for the ABAQUS FEM solver and over the years has become a standard that is implemented in a variety of commercial and government codes, including LS-DYNA, ALE3D, EPIC, ALEGRA, and Sierra. A constitutive model implemented with the VUMAT can therefore be used in a variety of different FEM codes without the need to customize the model for individual codes. Recently, an HMS-based VUMAT has been developed to allow for the creation of multiscale constitutive models of materials that can be used in any FEA code which implements the VUMAT interface. Prior to development of the

HMS-based VUMAT, HMS material models required direct integration into a FEM codes through modification to the FEM source code (Fig. 5).

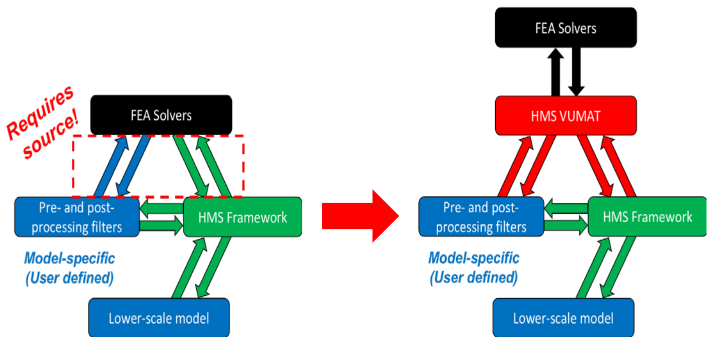


Figure 5: HMS VUMAT for FEA solvers. On the left is the original HMS approach that requires the FEA solver to interact directly with the HMS framework and requires modification of the FEA source code. On the right is the HMS VUMAT approach in which the HMS framework interacts with an FEA solver through a VUMAT interface and requires no source code modification to the FEA solver.

Using the VUMAT interface, the FEM solver provides the deformation gradient tensor at each integration point of the finite element mesh and requires the Cauchy stress in return. In the case of multiscale models implemented with the HMS VUMAT, the Cauchy stress is obtained through the evaluation of the lower-scale model. The implementation for the multi-scale FEM-DEM model is extremely similar to the description provided in the previous section. One difference is the VUMAT is formulated in a corotational coordinate system so the Cauchy stress returned from the DEM lower-scale model must be rotated into the corotational frame before being returned to the FEA solver. This rotation is performed in the mapping g. In addition, the VUMAT is restricted to the use of explicit time integrators so the tangent moduli computed by the DEM model are ignored and not returned through the VUMAT interface.

5. NUMERICAL EVALUATIONS

The performance of the proposed methods and the HMS implementation are evaluated for the two test problems that we describe in detail. In what follows, two numerical examples, a tri-axial compression simulation and a single wheel tire-soil interaction simulation, are presented to demonstrate capabilities of the hierarchical FEM-DEM multi-scale soil model and highlight the performance of the multi-scale computational framework.

We assess the performance of the multiscale methods in three aspects: accuracy, efficiency, and scalability. The simulation results from the multiscale models are compared with experimental data to evaluate the accuracies of the numerical method. The simulation results of multiscale models are compared with the single scale pure discrete model to evaluate the efficiencies of the method. The multiscale model scalabilities for both cases will be evaluated to demonstrate that with the availability of large-scale computation resources the proposed multiscale method is practical for real world off-road mobility simulations.

The examples demonstrate the HMS framework to be an effective and robust tool for FEM-DEM multiscale simulation. The HMS framework is a well-established software with rich features that make it adapted for use with many other open source or commercial codes. The built-in features also makes it possible to derive lower scale surrogate models which can improve the computational time significantly. An additional example shown here demonstrates an HMS VUMAT Implementation of the FEM-DEM soil model for a uniaxial compression problem and serves to highlight that with the HMS framework, the upper scale FEM model can be replaced by a variety of other commercial or government FEM codes.

5.1 Tri-axial Compression Test Simulation

In order to validate the hierarchical FEM-DEM multi-scale soil model implemented in the multibody dynamic computer algorithm, a tri-axial compression soil test model is developed and then results are compared with the test data as well as the pure DEM simulation results. The soil specimen is consolidated by applying a uniform confining pressure of 25 kPa and then the deviatoric stress is applied vertically to obtain the stress and strain relationship. The volume, height, and the cross-section diameter of the initial specimen are 564.86 cm^3, 142.27 mm, and 71.10 mm, respectively. The water content is 11.20% and the dry density of the specimen is 1.933 g/cm^3. The DEM model parameters are calibrated using a pure DEM model with LIGGGHTS and the following parameters are used in this study: $E = 1.5 \times 10^9$ Pa, $\nu = 0.293$, $\mu = 0.452$, $\beta = 2.25$, and $\eta = 0.99$. Fig. 6 shows the tri-axial compression experiment setup, and the computational time of pure discrete element model and multiscale FEM-DEM model. For pure discrete element method, model with 160,000 particles leads to a convergent solution and the results are in good agreement with the test data.

The hierarchical FEM-DEM multi-scale model for this tri-axial compression test scenario is developed with the DE parameters used for the pure DE model. The stress-strain curves obtained using 1 and 8 elements with 1,000 and 2,000 particles per RVE are presented in Fig. 7 and they are compared with the pure DE and test results. It is observed from this

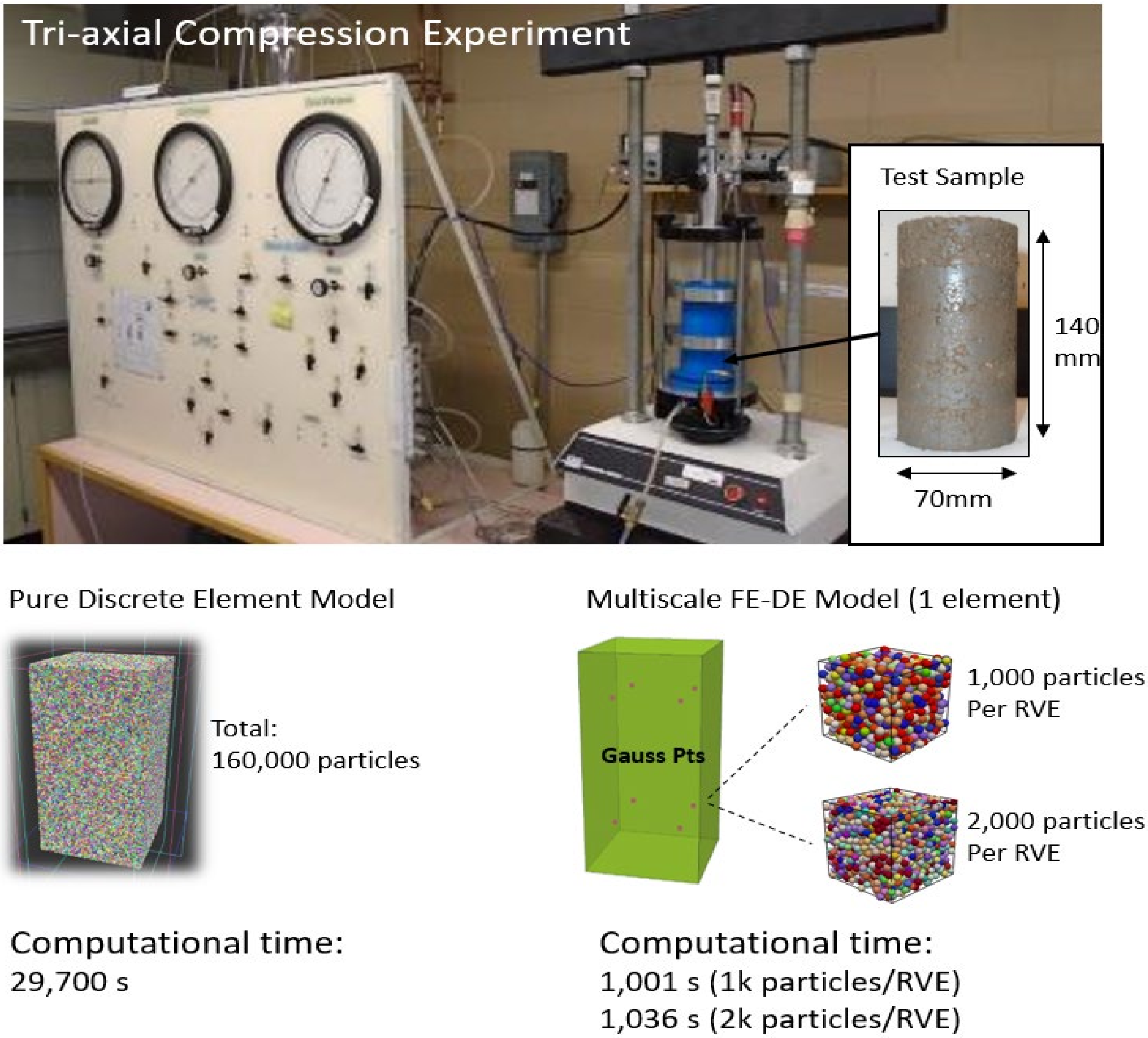


Figure 6: Tri-axial experiment setup and simulation results (Yamashita et al, [2])

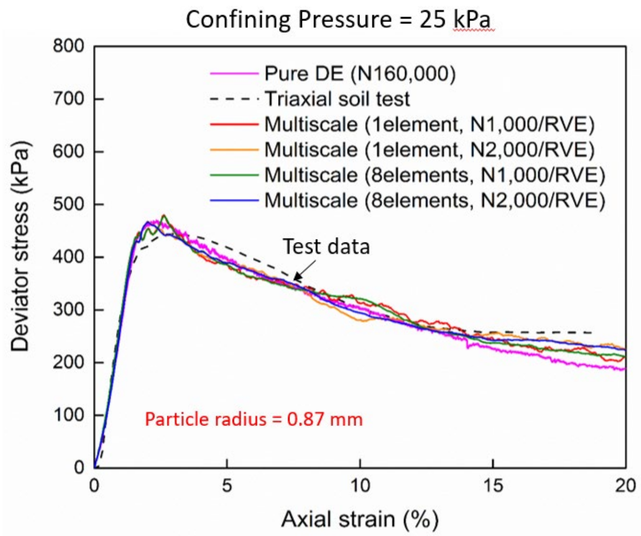


figure that use of 1,000 and 2,000 particles per RVE

Figure 7: Tri-axial strain-stress relationship

leads to the solution that is in agreement with the original pure DEM model as well as the test data. Furthermore, use of single element with 8 quadrature points (i.e., 8 RVEs) is good enough to obtain accurate solution in this tri-axial test condition and the result is in good agreement with that of the 8 element model with 64 RVEs. As they are shown in Fig. 6, the computation time of the single element model with 8 RVEs with 2,000 particles per RVE is 1036 sec using 80 processors, while that of the pure DEM model with 160,000 particles is 29,700 sec using 80 processors. It can be seen that the proposed FEM-DEM multiscale model results in substantial reduction in computational time compared to the pure discrete element model while maintaining the same accuracy.

While the 8-RVE model is good enough to obtain the result that agrees well with the pure DEM model, the parallel computing scalability analysis is performed for the multi-scale model with different number of elements (8 and 64). 2000 particles per RVE is assumed in these models and the results are shown in Fig. 8. Since there are 8 quadrature points per element, these models have total of 64, and 512 RVEs, respectively. It is observed from Fig. 8 that similar scalability characteristics are achieved regardless of the number of elements. The RVE models in the multi-scale model are independent and there is no force coupling among them, thus good parallel computing scalability can be achieved regardless of the number of RVEs considered in the model. Maintaining good parallel computing scalability is critically important in this study since off-road mobility simulation requires a large number of multi-scale elements and one can then gain substantial benefit from the high-performance computing capability of the multi-scale tire-soil interaction simulation. The computational time is substantially lower than that of the pure DEM model, and the higher computational efficiency of the

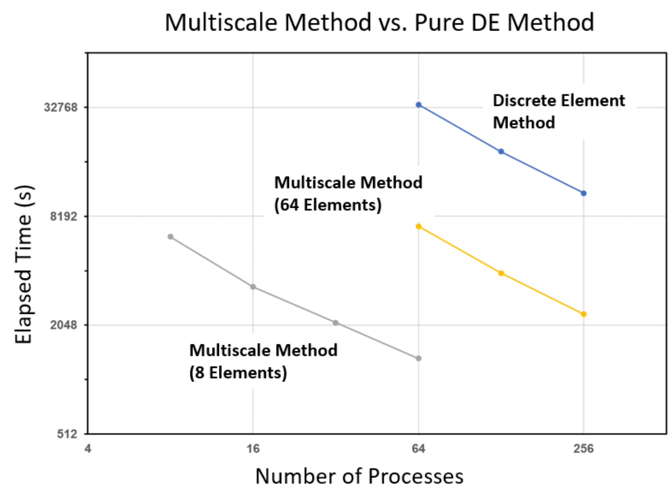


Figure 8: Numerical scalability of pure DEM and multi-scale models for tri-axial case

hierarchical multi-scale soil model, as compared to the pure DEM model, is clearly evident from this result.

The results of tri-axial compression case showed that the multiscale model improves the computational speed significantly, and the HMS framework is a robust scale bridging method for multiscale FEM-DEM models.

5.2 Single Wheel Tire-Soil Interaction Test Simulation

To

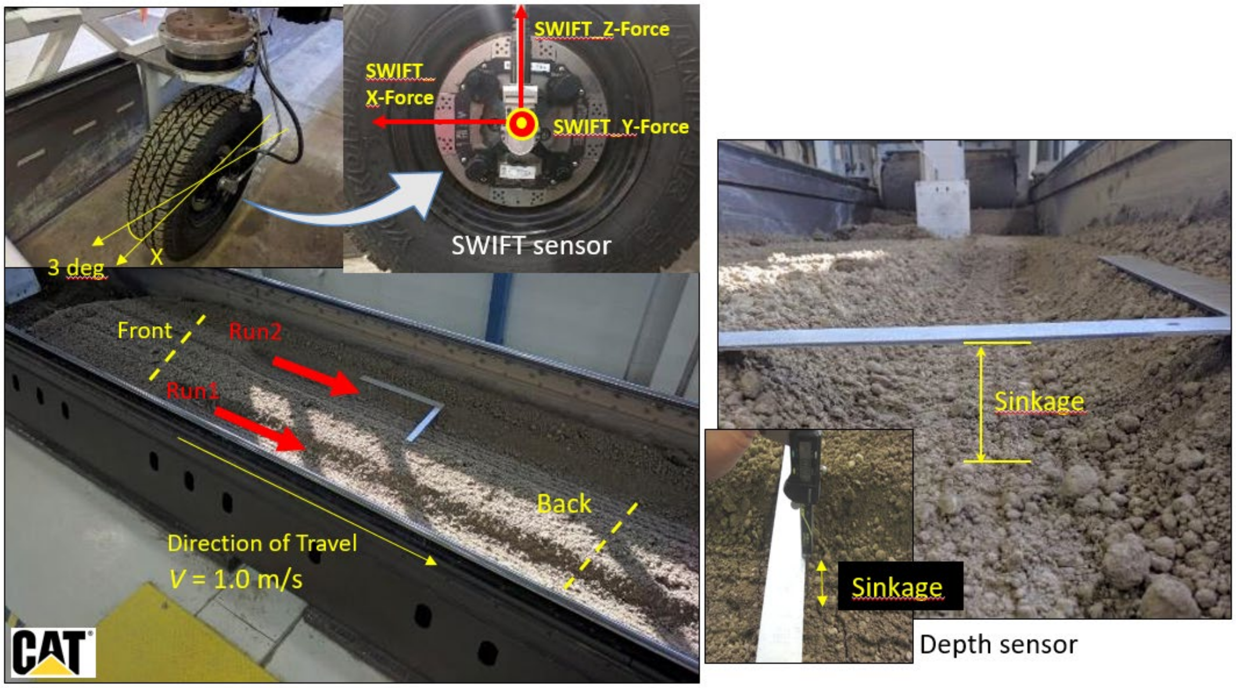
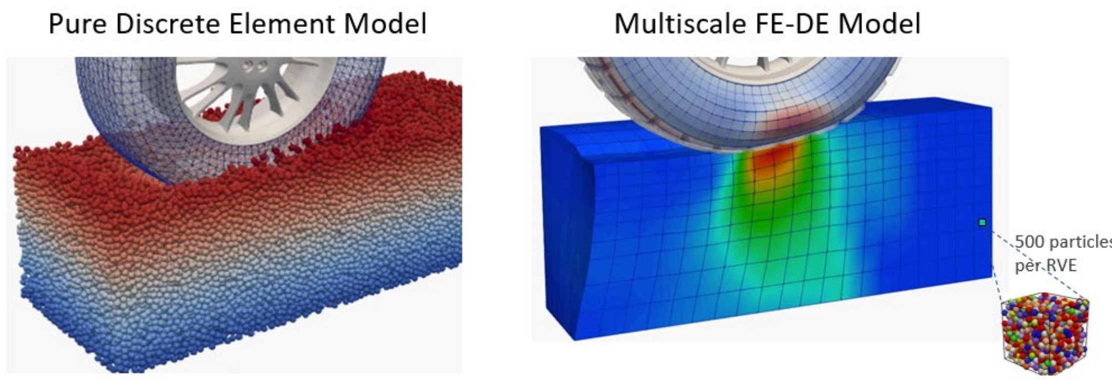


Figure 9: Vehicle-terrain interaction with multi-scale terrain dynamics model (Yamashita et al, [2])

demonstrate the multi-scale off-road mobility simulation capability, soil bin mobility test for a single tire, as show in Fig. 9, is considered and the numerical results obtained using the multi-scale terrain dynamics model are validated against the test data. A commercial off-road tire of 235/75R15 used in the test is modeled with the nonlinear shear deformable composite shell element based on the absolute nodal coordinate formulation and details on the modeling procedure and validation of the tire model are found in the literature [5]. The traveling speed of the tire is 1 m/s and the tire attached to the moving carriage is free to rotate about its spin axis without traction. Two different wheel loads of 6 and 8 kN are considered, for which three tire inflation pressures of 180, 230, and 280 kPa are tested. The steering angle is set to zero. The tire forces are measured by the 3-axis tire force transducer embedded in the rim, while the soil sinkage is measured in the middle of the rut by a depth sensor. Soil sample data was collected from the soil bin in different test cases. The mean soil density is 1,556 kg/m3, the mean water content is 8.21%, and the mean void ratio, defined as a ratio of the volume of void space to the volume of solids, is 0.893. Those values are used to determine parameters for the lower-scale DEM RVE models. The other DEM parameters are assumed to be same as those of the tri-axial compression test model since the same soil is used in both tests. The running test is repeated twice for each test scenario. The soil is not compacted by a roller in each test condition.

In the simulation model, the moving soil patch length, width and height are, respectively, 1.0 m, 0.48 m and 0.4 m. The soil patch width is selected such that the boundary effect is negligible. The soil patch is updated and shifted forward at every traveled distance of 0.2 m of the tire. This results in the tire-soil interaction occurring around the center of the patch and the boundary effect can be neglected. The number of elements for the soil patch is 2,400, while the total number of RVEs is 19,200. Each RVE has 2,000 particles with the particle radius of 0.87 mm as in the tri-axial soil test model. The void ratio of the



	Pure DE Model	Multiscale FE-DE Model
Particle radius	2.0 mm	0.87 mm
Number of particles in moving soil patch (0.4 x 0.48 x 1.0 m)	2.8 million	9.6 millions (500/RVE)
Computational time for 1 m traveled distance	1,800 hrs	2 hrs

Figure 10: Computational time comparison of pure DEM and multi-scale models

RVE is set to be the same as the measured data and the initial confining pressure is assumed to be zero since the soil is not compacted after loosening the soil in each test scenario.

The deformed shapes of the rolling tire on the multiscale soil with the moving soil patch technique are shown in Fig. 11 along with the von Mises stress distribution under the vertical load of 6 kN and the tire inflation pressure of 230 kPa. The deformed shapes of RVEs at different location in the soil are also shown in Fig. 11. Compressive deformation is dominant in the RVE at positon (a) since the soil is compacted after the tire rolls over this portion, while noticeable compressive and shear deformation is exhibited in the RVE at position (b) under the rolling tire. The RVE ahead of the tire at position (c) remains initially packed, while shear deformation is observed for the RVE at position (d) around the edge of the rut. As such, use of the hierarchical multiscale model allows for facilitating cross-scale understanding of the soil behavior resulting from the interaction with the rolling tire. The tire forces obtained by the test and the simulation are compared in Figs. 12 and 13 for the wheel load of 6 and 8 kN, respectively. The coefficient of friction is assumed to be 0.25. Since the vertical wheel load is regulated, the vertical force Fz must be in good agreement. The lateral force Fy is zero due to zero steering angle. The longitudinal force Fx represents the rolling resistance force of the

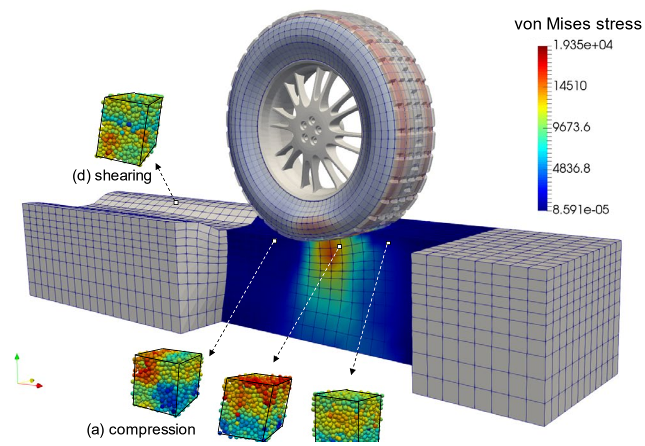


Figure 11: Multi-scale tire-soil interaction simulation using moving soil patch approach

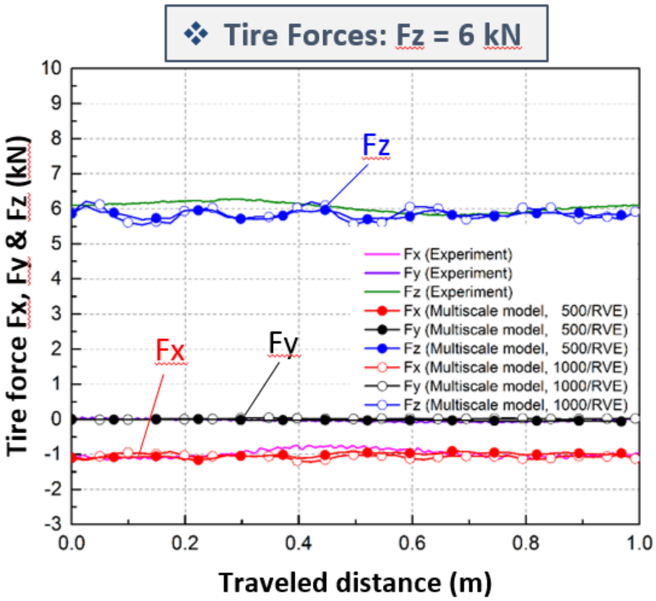


Figure 12: Comparison of tire forces for 6kN wheel load with 230 kPa inflation pressure

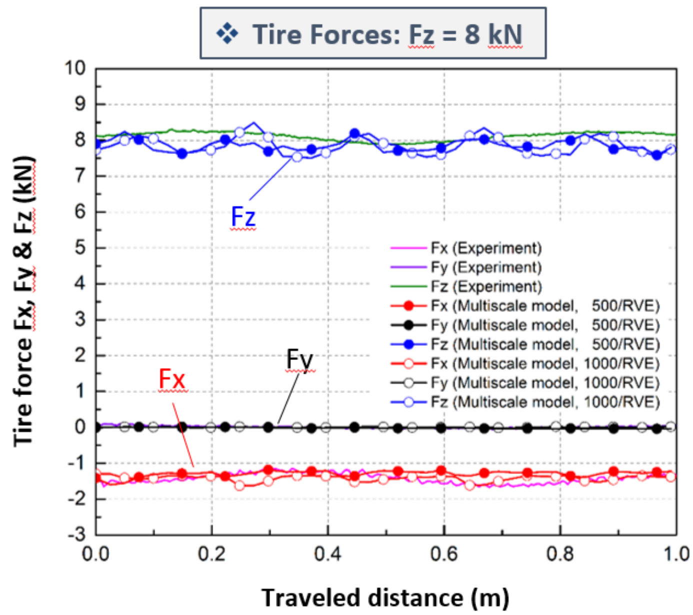


Figure 13: Comparison of tire forces for 8kN wheel load with 230 kPa inflation pressure

tire. The larger wheel load leads to larger longitudinal forces. The multiscale model simulation and test results are in good agreement in magnitude. Fig. 10 shows both pure discrete element model and multiscale FEM-DEM model and the simulation time comparison. For a single wheel tire-soil interaction simulation, it takes 1800 computational hours to complete 1 meter traveling distance with the pure DEM model and 512 computer processors. For the same simulation, it only takes 2 hours computational time with the proposed multiscale FEM-DEM model and 512 computer processors. The multiscale model improves the computation time significantly without compromising the accuracy.
Figure 14 plots the scalability of multiscale FEM-DEM simulation for tire-soil interaction model with moving soil patch technique. The model shows good parallel computing scalability and it demonstrates the effectiveness of the parallelization implementation. With the availability of high power computer, the proposed FEM-DEM multiscale method can be a practical numerical method for off-road mobility simulation.

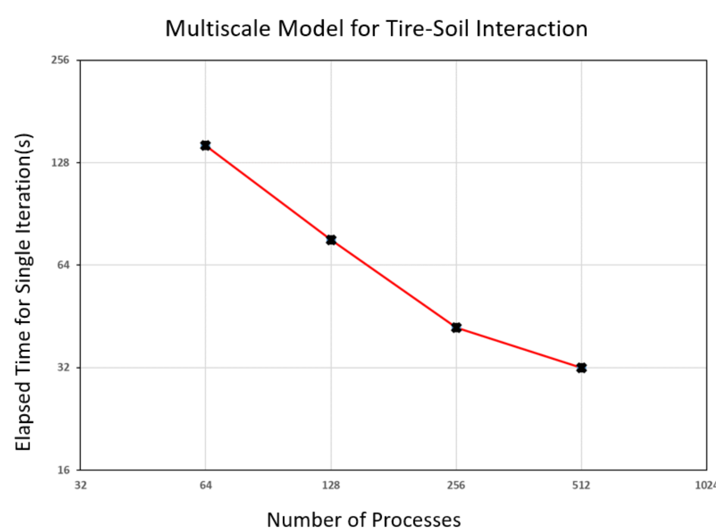


Figure 14: Numerical scalability of multi-scale models for tire-soil interaction case

5.3 HMS VUMAT Implementation for a uniaxial compression

A simple uniaxial compression simulation is performed to verify implementation of the multiscale deformable soil model developed with the HMS VUMAT interface. The multiphysics code ALE3D is used as the upper scale FEM solver. A single finite element of initial dimension 1 m x 1 m x 1 m is deformed along the x-axis by applying a constant-velocity boundary condition of 0.01 m/s to one surface. The simulation is run at a fixed timestep of 0.05 s for 200 timesteps in order to reach -10% strain. The axial stress/strain obtained in the simulation is given in Fig. 15. As the simulation consists of only a single finite element the simulation only takes 50 s to complete using 40 total processors.

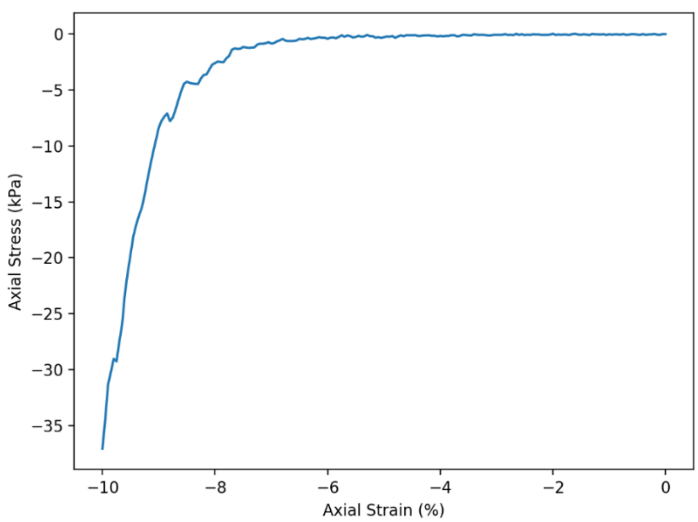


Figure 15: Axial stress/strain of a soil sample subject to uniaxial compression along the x-axis obtained from the ALE3D / HMS multi-scale deformable soil model

6. CONCLUSIONS

A multiscale FEM-DEM model is developed using the HMS scale-bridging framework to model tire-soil interactions for off-road mobility simulation. The analysis results demonstrate the multiscale FEM-DEM model matches well with experimental test data. It is also shown that high parallel computing scalability is maintained regardless of the number of multiscale elements considered. Table 1 summarizes the computational time of tri-axial and single wheel test cases.

Table 1: Computational Time Summary

	Tri-axial Compression Case		Single Wheel Tire-Soil Interaction Case	
	No. of Process	Computational Time	No. of Process	Computational Time
Pure DEM	64	9.2 hrs	512	1800 hrs
Multi-Scale Method	64	0.3 hrs (8 elements)	512	2 hrs

In the tri-axial compression test model, it is shown that the computational cost is substantially lower in the multiscale soil model as compared to the corresponding pure DEM model while maintaining accuracy. This is attributed to the smaller number of DEM particles that can be used in the multi-scale model and high parallel computing scalability achieved. A multiscale tire-soil interaction model is also developed and the moving soil patch technique is generalized for the multiscale terrain model to maintain the terrain model dimensionality the same regardless of the traveling distance considered. The simulation results are validated against the soil bin mobility test data for the soil sinkage, longitudinal force, and the rolling resistance coefficient under various wheel load and tire inflation pressure conditions, thereby demonstrating the potential of the proposed approach to resolve challenging vehicle-terrain interaction problems. Based on its success for this application, the HMS framework has potential applicability to more general mobility applications. Future work based on the approach demonstrated here include building high fidelity vehicle models using other well-developed upper scale models. Furthermore, we plan to build simplified surrogate lower scale models using techniques implemented in the HMS framework in order to lessen the computational cost of the multiscale model. We also plan to extend the proposed multiscale method to full vehicle simulations with improved computational load balancing.

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