Computational Mechanics and Modeling

a) Novel FE and Mesh-Free Methods for Solution of Nonlinear Problems

Investigations on local linearization have led to a new linearization paradigm, referred to as the transversal linearization, which bypasses the derivation of tangent matrices in nonlinear dynamical systems. Due to the use of an exponential form of the update, the transversal linearization, especially its multi-step variety, may be interpreted as a *"Lie group"* based algorithm and this results in conspicuously lesser accumulation of error over time vis-à-vis its tangential counterpart. Yet another semi-analytical form of integration, applicable for stochastically excited nonlinear dynamical systems, is provided by the Girsanov linearization, which can weakly correct for the linearization error by suitably constructing the Radon-Nikodym derivative. In short, transversal and Girsanov linearizations have provided twin simulation strategies achieving hitherto unattainable numerical accuracy (Figure 25).

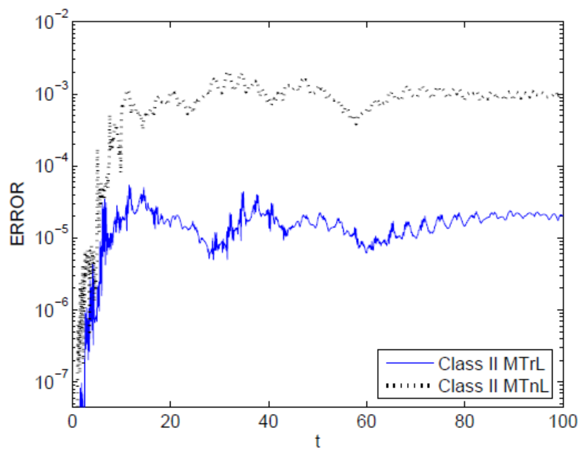


Figure 25: Lesser error propagation via (a version of) the transversal linearization (MTrL) vis-à-vis (a similar version of) the tangential linearization (MTnL); the dynamical system is a nonlinear 3-DOF oscillator

Research in computational mechanics includes development of new discretization schemes that exploit the globally reproducing nature of shape functions, characteristic of mesh-free methods, within the element-based framework of domain discretization, provided by the finite element method (FEM). Element-based domain discretization is enabled through the use of non-uniform rational B-splines (NURBS). In this sense, this class of methods may be considered as a bridge between mesh-free methods and the FEM (Figures 4.26 and 4.27). Use of NURBS as the basic building block for geometric and functional discretizations also ensures a faster interface between the solid modeler and the solver and thus avoids slow data transfers between the two modules. A new strategy to obtain mesh-free approximations to the derivatives of a (sufficiently smooth) target function without differentiating the shape functions has also been proposed.

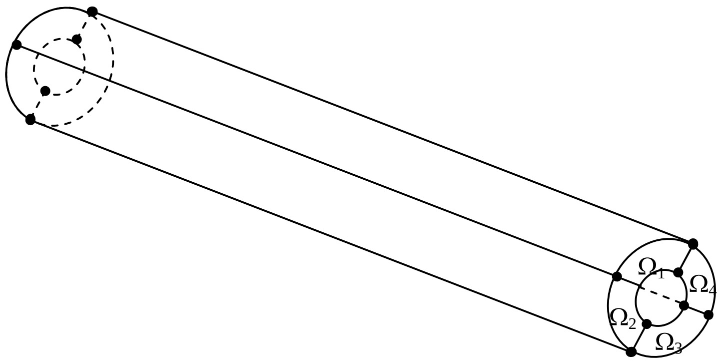


Figure 26: NURBS-based approach bridging mesh-free and finite element methods: discretization of a hollow cylinder into just four elements (or sub-domains)

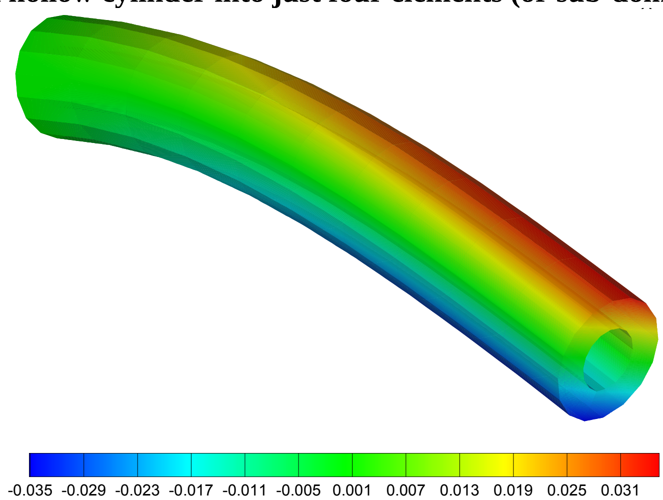


Figure 27: NURBS-based approach bridging mesh-free and finite element methods: horizontal displacement profile of the hollow cylinder

Research is also being done on the analyses of wrinkled membranes and inflatable structures that are often employed in space applications. Other than applications of new mesh-free schemes, as above, to the discretization of such structures, the development of a novel numerical approach for the discretized membrane equations, which are ill-conditioned due to the inability of such structures to resist compression has been realized. While a 2-D tension field approach, based on a discretization through plane stress finite elements, has been adopted for obtaining the wrinkled/slack regions, the 3D nonlinear elasticity equations, discretized through 8-noded Cosserat point elements, towards obtaining precisely the out-of-plane deformations of such structures has been exploited (Figure 28). The (nearly) singular nature of the discretized and linearized system equations, derived via both the approaches, has been treated through a pseudo-time recursion along with an error-corrected version of Tikhonov regularization.

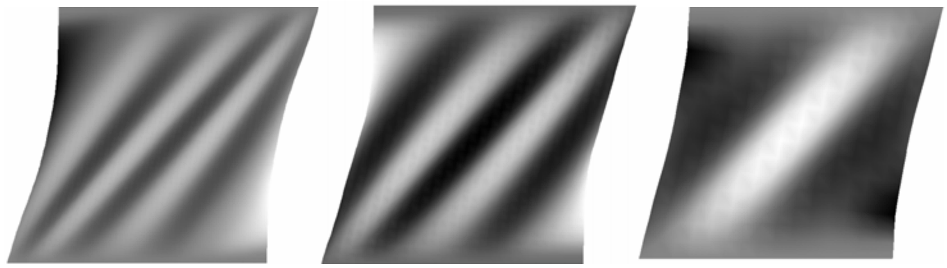


Figure 28: Cosserat point solution for out-of-plane deformation of an ultra-thin membrane using a regularized form of 3-D nonlinear elasticity equations; (left) 2500 Cosserat points; (middle) 900 Cosserat points; (right) 100 Cosserat points

Research is also being carried out on inverse problems, providing continuity across developments in stochastic dynamics and computational mechanics and fostering a fruitful collaboration across several departments. The development of pseudo-dynamic filters again charts new ground by combining Newton-like updates with the powerful concepts of stochastic filters resulting in regularization-insensitive schemes for large dimensional inverse problems with static measurements (Figure 29). These schemes have been successfully applied to problems in structural health monitoring and a few interface disciplines, e.g. medical imaging.

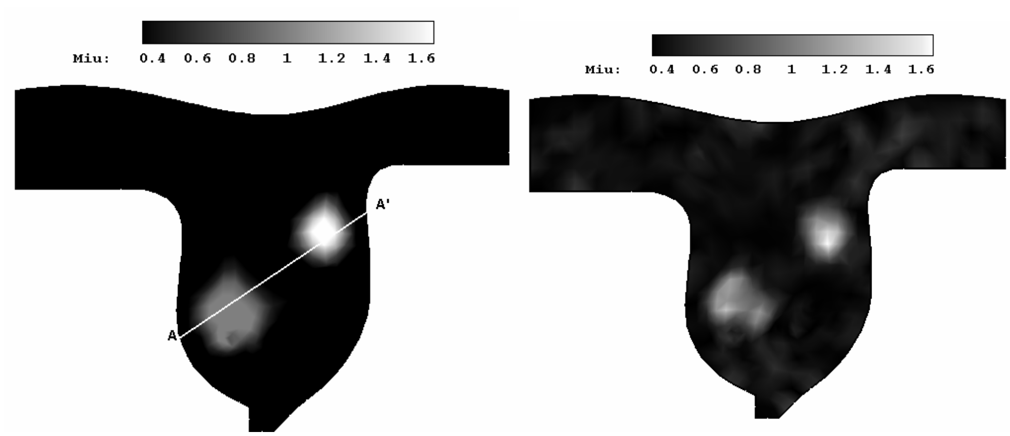


Figure 29: Pseudo-dynamic filter based reconstruction of the shear modulus profile for a model of a soft-tissue organ with two inhomogeneous inclusions; (left) reference shear modulus profile; (right) reconstructed shear modulus profile with 5% noise in the data

b) Integrated Force Method(IFM)

The Integrated Force Method (IFM) which is a modification of classical Force Method for automated computerization and is found to yield more accurate stress-values as compared to conventional displacement-based finite-elements has been adopted to develop a family of Plate-bending elements.

The contributions made here can be summarized as a systematic development of a family of finite elements both under thin and thick plate categories. In addition, development of finite-element for laminated composites has also been attempted. An important aspect of computerization of IFM is the automatic generation of compatibility conditions, for which an efficient algorithm has been developed.

c) High-Performance Computation in Uncertainty Quantification

The computational cost of uncertainty quantification grows with the complexity and size of the system under consideration. With the fast-moving market of computational technologies, powerful computers are becoming more affordable day-by-day. For instance, with the introduction of cluster computers assembled from the regular commodity hardware, a descent parallel computer is no longer a special product.

However, from a user's perspective, to harness this growing computational power is by no means a straightforward task. A significant effort is needed to develop new computational methods and algorithms. Development of a more efficient computational tool for uncertainty quantification of large-scale complex systems is underway. A few active areas of our interest are structural dynamics and multiscale analysis. This is a newly formed research group. We have acquired one hundred-core cluster computer dedicated to our group.

d) Simplified Methods of Evaluation of Diffused Double Layer parameters

An attempt has been made to relate the potentials of interacting and non – interacting plates of homo valent ionic system. It is found that a relationship exists between the potential at any distance from the surface for non-interacting system, $\phi_{x=d}$, with the mid - plane potential of the interacting systems, ϕ_d in the form a fourth degree algebraic equation. The repulsive pressure between the diffuse plates is a function of swell pressure of the soil mass and the distance between the diffuse plates is a function of void ratio. Therefore, to establish a relation between the swell pressure and void ratio it is necessary to calculate the mid-plane potential in the diffuse part of the interacting ionic double layers. The major difficulty in these calculations is the elliptic integral of first kind involved, which relates, half space distance and mid plane potential. As, the calculation of potential at any distance from the surface in non – interacting system is quiet easy; the above equations are advantageously used and a simple procedure to find the potential – distance relationship in homo valent ionic system is proposed by eliminating the elliptic integral calculations. The accuracy of the method has been checked by comparing the potential distance relationship with that obtained using the van Olphen procedure, which involves interpolation of data of two values of mid plane potential and slope of the curve near the surface with the use of tables.

e) Ultimate bearing capacity of group of footings and anchors

Rigorous computational analyses, based on the finite element limit analysis and the slip line method, have been performed to determine the interference effect on the ultimate bearing capacity of a group of footings and anchors (Figure 30). From the developed solutions one can determine very accurately the effect of spacing of footings and anchors on their ultimate bearing/uplift capacity.

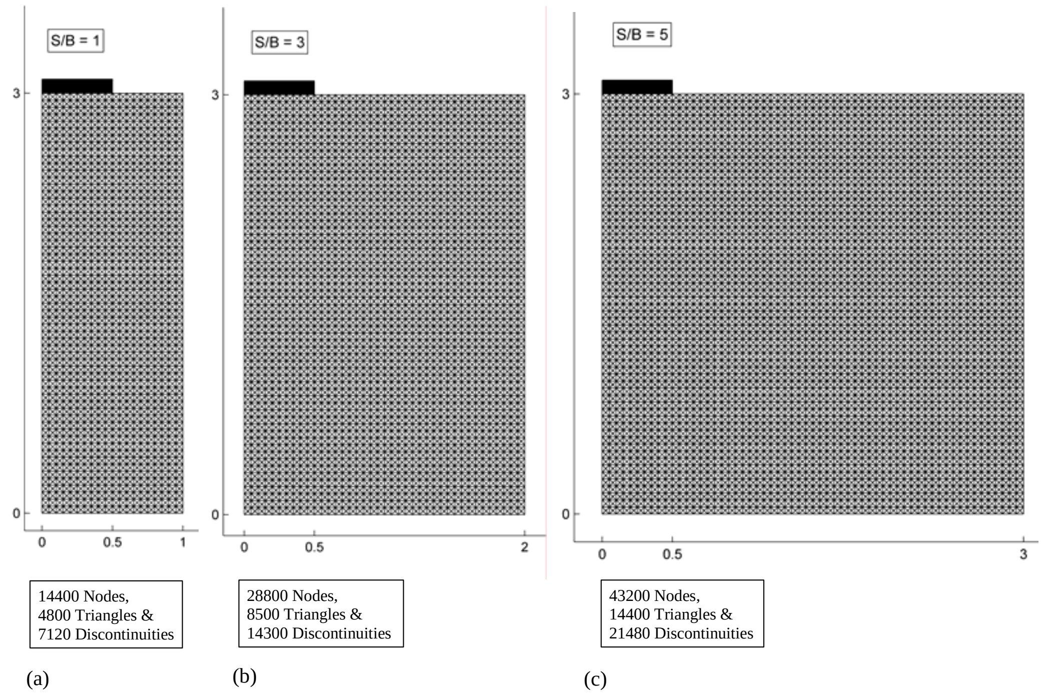
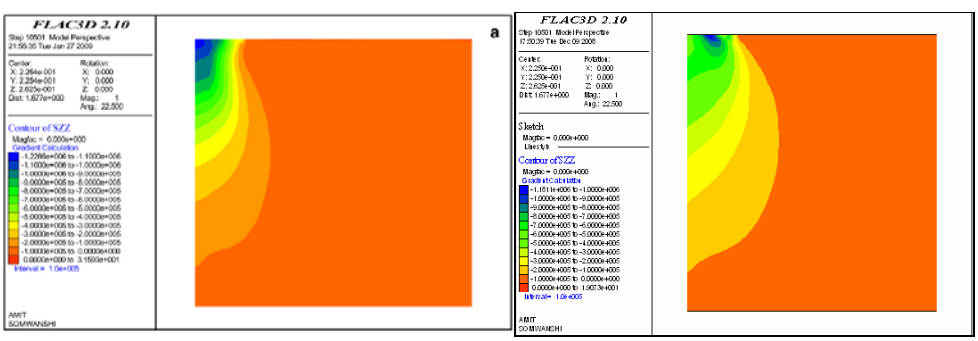


Figure 30: Finite element mesh for (a) S/B =1.0; (b) S/B =3.0 and (c) S/B =5.0

f) Numerical Simulation of geosynthetic reinforced soil structures

Numerical tools such as FLAC3D, GEOSTUDIO were used to simulate the model tests on reinforced foundation beds, retaining walls and soil nailed walls. In case of geocell reinforced foundation beds, the influence of the geometry of the geocell on the overall performance of the footing was studied through numerical parametric simulations. Simulations were also carried out on the geogrid reinforced beds to highlight the efficacy of the geocell reinforcement. Good agreement has been observed between the numerical simulations and model test results (Figures 4.31 and 4.32).



(a) **(b)**

Figure 31: Vertical stress distribution below footings on reinforced sand beds (a) planar reinforced (b) geocell reinforced

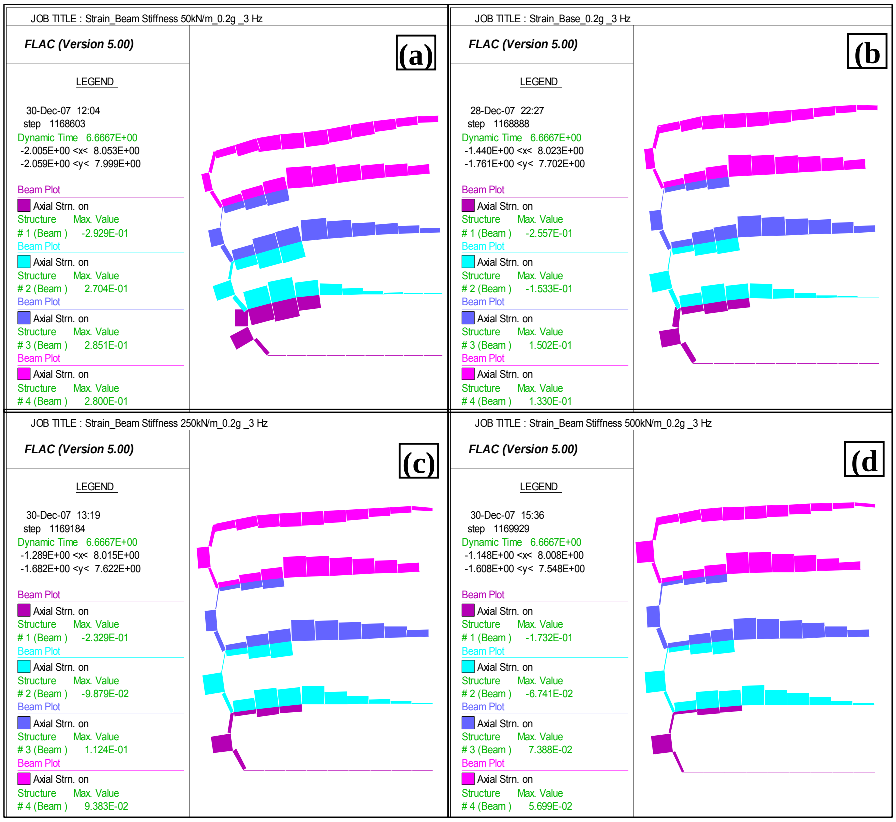


Figure 32: Axial strain distributions along the reinforcement elements in retaining wall for stiffness values: (a) 50 kN/m, (b) 150 kN/m, (c) 250 kN/m and (d) 500 kN/m

g) Finite Element Limit Analysis for Axi-symmetric problems

A new finite element limit analysis lower bound formulation has been proposed to deal with various axi-symmetric stability problems in geotechnical engineering. The proposed formulation provides very accurate solutions which are found to be very close to those reported in literature that are based on the existing three dimensional formulation. The proposed numerical formulation has been applied successfully for the different problems associated with circular footings, piles, circular anchors and circular excavations (Figure 33). This formulation has also been successfully applied for layered soil media as well.

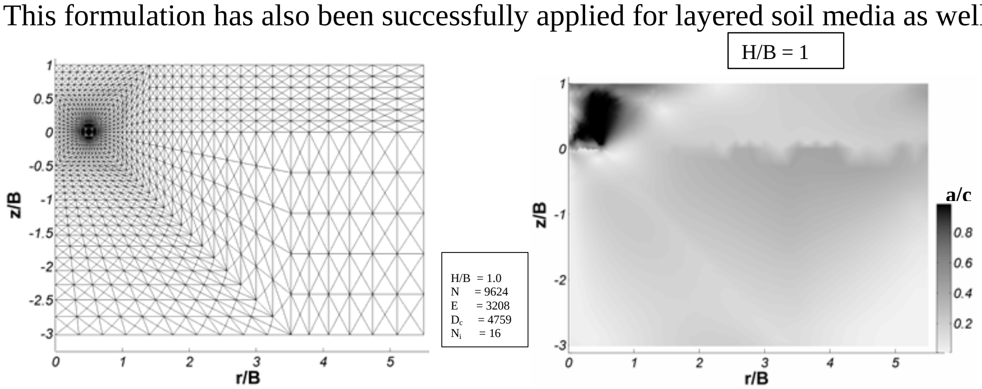


Figure 33: Finite element mesh & failure patterns for circular anchors in clays, whose cohesion increases with depth, under vertical uplift.

h) Discrete element simulation of granular soil behaviour and liquefaction

Discrete Element Modeling (DEM) technique was used to obtain microscopic information at grain scale level and an attempt has been made to describe compaction behavior, strength mobilization and shear zone formation in granular materials as a result of micro-structural changes associated with macroscopic deformations. The effect of grain size and gradation of particle sizes on the mechanical behavior of granular media is studied. In order to explain the effect of size, gradation and confining pressure on the volume change and strength behavior of coarse grained soils, numerical simulations were carried out on a wide range of sizes, gradation and confining pressure using both 2-dimensional circular disc elements and 3-dimensional spherical elements based on Discrete Element Models (DEM). The long-term goal will be to develop a constitutive model for granular materials for transfer of research results to practical application.

Numerical simulations were carried out using 2 - Dimensional assemblage of discs and 3-dimensional assemblage of spheres to address monotonic and cyclic behavior of sand from micromechanical considerations. The models were validated for both monotonic and cyclic loading conditions. Simultaneously extensive cyclic triaxial testing has been carried out to explain the liquefaction behaviour of sand from Bhuj, Ahmedabad and Assam areas. These results were compared with DEM modeling results to understand the fundamental processes at particulate level during liquefaction (Figure 34).

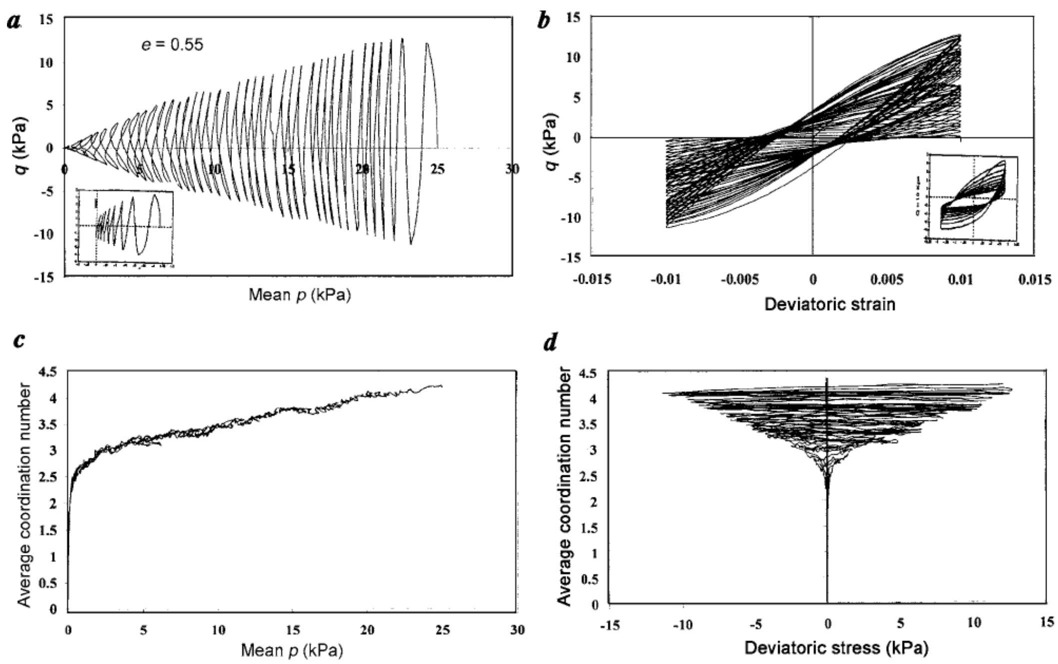


Figure 34: Results of undrained cyclic test on loose sample at 1% deviatoric strain amplitude. a) Deviator stress q versus mean p b) Deviator stress versus deviatoric strain c) Average coordination number versus mean p d) Average coordination number versus deviatoric stress.