

ABSTRACT

The boundary value problems (BVPs) of geomechanics are challenging due to the complexity in modeling soil behavior and difficulties in modeling large deformations. While traditional numerical schemes have struggled in realistically simulating geomechanical BVPs, new numerical methods – such as the material point method (MPM) – are increasingly being used to tackle these problems. However, algorithms in MPM have not yet been sufficiently developed, scrutinized, and validated. This thesis focuses on the development, verification, and validation of MPM for use in geomechanical BVPs. In particular, the thesis focuses on simulation of cone penetration tests in both controlled environments and in field conditions.

To efficiently simulate cone penetration, a silent boundary scheme, known as a cone boundary, was proposed in the generalized interpolation material point method (GIMP), a variant of MPM. The implementation of the cone boundary in GIMP was discussed, and the boundaries were validated by comparison against several benchmark problems. The cone boundaries were shown to be suitable in transmitting energy at the boundary. In addition, the implementation of traction boundaries in GIMP was analyzed. In GIMP, traction boundaries may be implemented either at the centroid of the material point, or at the edge of the material point domain. It was shown that the implementation of traction boundaries at the edge of the domain led to stress oscillations near the boundary, which were minimized when the traction boundaries were implemented at the edge of the domain.

During cone penetration, the soil near the cone-soil interface is pushed to large strains. At large strains, soils reach critical state, a state in which the soil shears at constant volume. Simulation of incompressible materials using low-order shape functions commonly used in GIMP leads to stiffer solutions and stress oscillations. To mitigate the constraints imposed by incompressibility, the non-linear B-bar method was implemented in GIMP. The modifications required for the implementation of the B-bar method in GIMP were discussed, and the efficacy of the method in mitigating incompressibility was demonstrated by analyzing several benchmark problems.

To simulate cone penetration in saturated soil, a coupled formulation was proposed in GIMP. A single material point was used to represent both the soil matrix and water. The governing equations were solved using an explicit scheme with the velocity of the soil matrix and the velocity

of water as the primary variables. The formulation was validated through problems for which analytical or numerical solutions are available.

Finally, cone penetration analyses were performed both in dry sand and saturated clays. Two bounding surface models – one for sand and one for clay – were used for accurately capturing the soil response. Cone penetration tests were performed on Ottawa 20-30 sand under a variety of loading conditions at a large calibration chamber. The penetration resistances were measured, and the displacement fields were captured using the digital image correlation technique (DIC). The cone penetration resistances predicted by MPM were within 15% of the measured values, and the displacement fields computed using MPM were similar to those captured using DIC. For saturated clays, cone penetration test results reported in the literature for a Boston Blue Clay (BBC) test site were used. The simulated cone resistance of 650 kPa lied within the CPT resistance range of 580-730 kPa reported in the field. The results demonstrate the capability of MPM in simulating cone penetration in both sands and clays provided that sufficiently accurate algorithms and advanced constitutive models capable of reproducing realistic soil behavior are used in the analyses.