Computers and Geotechnics 65 (2015) 104–114

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo

Review

Large deformation finite element analyses in geotechnical engineering

Dong Wang [a,*,1], Britta Bienen [a,1], Majid Nazem [b], Yinghui Tian [a,1], Jingbin Zheng [a,1], Tim Pucker [c], Mark F. Randolph [a,1]

[a] Centre for Offshore Foundation Systems and ARC CoE for Geotechnical Science and Engineering, The University of Western Australia, 35 Stirling Hwy, Crawley, WA 6009, Australia
[b] ARC CoE for Geotechnical Science and Engineering, The University of Newcastle, Callaghan, NSW 2308, Australia
[c] IMS Ingenieurgesellschaft mbH , A company in the Ramboll Group, Stadtdeich 7, 20097 Hamburg, Germany

ARTICLE INFO

Article history:
Received 15 September 2014
Received in revised form 14 November 2014
Accepted 11 December 2014

Keywords:
Finite element method
Large deformation
Arbitrary Lagrangian–Eulerian
Eulerian method
Penetrometers
Consolidation
Dynamic

ABSTRACT

Geotechnical applications often involve large displacements of structural elements, such as penetrometers or footings, in soil. Three numerical analysis approaches capable of accounting for large deformations are investigated here: the implicit remeshing and interpolation technique by small strain (RITSS), an efficient Arbitrary Lagrangian–Eulerian (EALE) implicit method and the Coupled Eulerian–Lagrangian (CEL) approach available as part of commercial software. The theoretical basis and implementation of the methods are discussed before their relative performance is evaluated through four benchmark cases covering static, dynamic and coupled problems in geotechnical engineering. Available established analytical and numerical results are also provided for comparison purpose. The advantages and limitation of the different approaches are highlighted. The RITSS and EALE predict comparable results in all cases, demonstrating the robustness of both in-house codes. Employing implicit integration scheme, RITSS and EALE have stable convergence although their computational efficiency may be low for high-speed problems. The CEL is commercially available, but user expertise on element size, critical step time and critical velocity for quasi-static analysis is required. Additionally, mesh-independency is not satisfactorily achieved in the CEL analysis for the dynamic case.

Contents

* Corresponding author. Tel.: +61 8 6488 3447; fax: +61 8 6488 1044.
E-mail addresses: dong.wang@uwa.edu.au (D. Wang), britta.bienen@uwa.edu.au (B. Bienen), majidreza.nazem@newcastle.edu.au (M. Nazem), yinghui.tian@uwa.edu.au (Y. Tian), 21102353@student.uwa.edu.au (J. Zheng), t.pucker@ims-ing.de (T. Pucker), mark.randolph@uwa.edu.au (M.F. Randolph).
[1] Fax: +61 8 6488 1044.

http://dx.doi.org/10.1016/j.compgeo.2014.12.005
0266-352X/

1. Introduction

Large deformation analysis is one of the most challenging topics in computational geomechanics, particularly in problems involving complicated structure–soil interaction. A qualified large deformation approach must quantify the geometric evolvement induced by changes in the surface profile and distortion of separate soil layers. The Total Lagrangian (TL) and the Update Lagrangian (UL) finite element (FE) approaches may be the most popular numerical methods in geotechnical engineering. However, the calculation must stop even if only few elements within the mesh become seriously distorted.

To capture large deformation phenomena that occur frequently in geotechnical practice, the traditional numerical approaches established within Lagrangian framework are replaced by, for example, those based on the framework of Arbitrary Lagrangian–Eulerian (ALE). Depending on the discretisation of materials, the ALE FE approaches focusing on geotechnical applications are divided into two categories: mesh-based methods such as in van den Berg et al. [40], Hu and Randolph [13], Susila and Hryciw [33] and Sheng et al. [30], which are the concern of this paper; and particle-based methods such as material point method [32,4]. In the mesh-based ALE approach with the operator-split technique, each incremental step includes a Lagrangian phase and an Eulerian phase. The Lagrangian calculation is conducted on the deformable mesh, and then the deformed mesh is updated by adjusting the positions of nodes but maintaining the topology, or is replaced via mesh regeneration. Subsequently, the field variables (e.g. stresses and material properties) are mapped from the old mesh to the new mesh, representing Eulerian flow through the mesh. Compared with static analysis, two more field variables, nodal velocities and accelerations, need to be mapped in a dynamic analysis. For coupled analysis of fully saturated soils, effective stresses and excess pore pressure, rather than total stresses, are mapped.

Among a variety of ALE approaches, three FE methods widely used in research and industry for analysis of geotechnical engineering problems are discussed in this paper: the remeshing and interpolation technique by small strain (RITSS) developed at the University of Western Australia, an efficient ALE (termed EALE) approach developed at the University of Newcastle and the Coupled Eulerian–Lagrangian (CEL) approach available in the commercial software Abaqus/Explicit. It is recognised that other large deformation FE approaches exist. However, the paper is not intended to detail the theoretical formulation of different large deformation methods. Instead, its concern is to provide an insight into the large deformation algorithms by discussing the advantages and disadvantages of the three approaches.

(1) The RITSS approach was originally presented by Hu and Randolph [13], in which the deformed soil is remeshed periodically and Lagrangian calculation is implemented through an implicit time integration scheme. The advantage of RITSS is that the remeshing and interpolation strategy can be coupled with any standard FE program, such as the locally developed program AFENA [7] and the commercial package Abaqus/Standard, through user-written interface codes. The potential of the approach has been highlighted by varied two-dimensional (2D) and three-dimensional (3D) applications of monotonic and cyclic penetration of penetrometers [19,52], penetration of spudcan foundations for mobile jack-up rigs [16,17,51], lateral buckling of pipelines [49,8] and uplift capacity and keying of mooring anchors [31,43–45,47,38,39]. More recently, RITSS was extended from static to dynamic analyses [48].
(2) The EALE approach is based on the operator split technique proposed by Benson [2], and tailored to geomechanics problems by Nazem et al. [20] in the in-house software SNAC. This method is a well-known variant of r-adaptive FE methods, which have been designed to eliminate possible mesh distortion by changing and optimising the location of nodal points without modifying the topology of the mesh. The EALE approach has been extended to the solution of consolidation problems [21], as well as to the dynamic analysis of a wide range of geotechnical problems [22,24,29].
(3) In the CEL method the element nodes move temporarily with the material during a Lagrangian calculation phase, which is followed by mapping to a spatially 'fixed' Eulerian mesh [3,10]. The calculation in the Lagrangian phase is conducted with an explicit integration scheme. In contrast to RITSS and EALE, an element in CEL may be occupied by multiple materials fully or partially, with the material interface and boundaries approximated by volume fractions of each material in the element. The CEL method has been used by a number of researchers to investigate the penetration of spudcan foundations in various soil stratigraphies [27,35,36,25,12] and uplift capacity of rectangular plates [9]. The comparatively rigid structural part (i.e. spudcan, anchor or similar) is usually modelled as a Lagrangian body and the soils as Eulerian materials. A 'general contact' algorithm by means of an enhanced immersed boundary method describes frictional contact between Lagrangian and Eulerian materials. Advanced soil constitutive models, such as a hypoplastic model for sand, a visco-hypoplastic model for clay and a modified Tresca model considering strain softening and rate-dependency of clay, have been incorporated into the CEL [27,26,12]. To date, CEL is limited to total stress analysis, although it can be modified to obtain pore pressures under undrained conditions [50].

The purpose of this paper is to assess the performance and limitations of the RITSS, EALE and CEL approaches through four deliberately-chosen benchmark cases covering static, consolidation and dynamic geotechnical applications. The analytical and numerical results, where possible, are also supplemented for comparison purposes.

2. Theoretical backgrounds of RITSS, EALE and CEL

All three approaches are classified as operator split in computational mechanics, i.e. a Lagrangian phase is followed by an Eulerian/convection phase [2]. However, the implementation of each individual approach is facilitated by specific time integration schemes for the governing equations, remeshing strategy and mapping technique (see Table 1), which results in certain advantages and disadvantages of each approach for particular problems.