Computers and Geotechnics 54 (2013) 192–201

Contents lists available at ScienceDirect

Computers and Geotechnics

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

A dynamic large deformation finite element method based on mesh regeneration

D. Wang *, M.F. Randolph, D.J. White

Centre for Offshore Foundation Systems, The University of Western Australia, Australia

ARTICLE INFO

Article history:
Received 8 March 2013
Received in revised form 5 July 2013
Accepted 6 July 2013
Available online 6 August 2013

Keywords:
Large deformation
Finite element method
Clays
Penetration
Landslides
Footing

ABSTRACT

In this paper, a large deformation finite element (LDFE) approach termed 'remeshing and interpolation technique with small strain (RITSS)' is extended from static to dynamic soil-structure interaction applications. In addition, a technique termed 'element addition' is developed to improve the computational efficiency of both static and dynamic LDFE analyses that involve moving boundaries. The RITSS approach is based on frequent mesh generation to avoid element distortion. In dynamic RITSS, the field variables mapped from the old to the new mesh involve not only the stresses and material properties, but also the nodal velocities and accelerations. Using the element addition technique, new soil elements are attached to the domain boundaries periodically when the soil near the boundaries becomes affected by large displacements of the structure. The procedures of this Abaqus-based dynamic LDFE analysis and element addition technique are detailed, and the robustness of the techniques is validated and assessed through three example analyses: penetration of a flat footing into a half-space and movement of rigid and deformable landslides down slopes.

1. Introduction

Many applications in geotechnical engineering involve large movements of foundations, anchors or other elements relative to the soil. These include cone penetration, lateral buckling of partially-embedded pipelines, rotation and translation of deep anchors and run-out of landslides. Current large deformation numerical methods based on continuum mechanics can be broadly divided into two categories: finite element (FE) methods and meshless methods. Most large deformation finite element (LDFE) methods were established within the framework of a 'decoupled' arbitrary Lagrangian–Eulerian (ALE) approach to overcome mesh distortion problems. In ALE FE methods the mesh displacements and material displacements are not required to be solved simultaneously [1]. Specific applications of the ALE approach to geomechanics problems have been reported by Di et al. [4] and Nazem et al. [13], Nazem et al. [12]. Recently, Kardani et al. [8] incorporated the h-adaptive technique into the ALE approach, to improve the numerical accuracy by continuously refining the mesh in the zone of concern.

This paper describes an extension of the LDFE approach known as 'remeshing and interpolation technique with small strain' (RITSS), which has been widely used in offshore geotechnical applications [7]. Previous studies have considered shallow and deep foundations [16,21,22,19,23], penetrometers [26,27] and pipelines [24]. Essentially, the RITSS approach can also be regarded as a special decoupled ALE method. The overall scheme of the RITSS approach is to divide the displacements of the structural element into typically dozens to thousands of incremental steps. The displacements of the element in each step must be small enough to avoid gross distortion of the soil element. The Lagrangian calculation is thus performed in each step, followed by re-meshing of the deformed geometry and 'convection' of the stresses and material properties from the old mesh to the new mesh. In the RITSS approach, quadratic elements are used and it is not mandatory to retain the original mesh topology during re-meshing. A distinct advantage of the RITSS approach is that it can be coupled with most FE programs. Existing applications of the RITSS method have been built around locally developed codes such as AFENA [2] and the commercial package Abaqus.

The RITSS approach was initially proposed by Hu and Randolph [7]. Several important advances achieved during the last decade include partial remeshing techniques, expansion from two-dimensional (2D) to three-dimensional (3D) applications and implementation in coupled analysis as summarized by Randolph et al. [15]. Also, the soil constitutive model incorporated into the LDFE analyses has evolved from the simple elastic-perfectly plastic model to more complex ones, such as the modified Cam-Clay model for coupled analysis [20] and a strain-softening rate-dependent

* Corresponding author. Address: Centre for Offshore Foundation Systems, The University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia. Tel.: +61 8 6488 3447; fax: +61 8 6488 1044.

E-mail addresses: dong.wang@uwa.edu.au (D. Wang), mark.randolph@uwa.edu.au (M.F. Randolph), david.white@uwa.edu.au (D.J. White).

0266-352X/$ - see front matter
http://dx.doi.org/10.1016/j.compgeo.2013.07.005

Tresca model for total stress analysis [27,24]. The robustness of the RITSS approach has been fully verified by comparison with small strain FE methods, plasticity limit analysis solutions and experimental model tests. However, the previous RITSS applications were focused on static problems, neglecting inertial effects. Inertia may be critical in capturing the responses of soils in medium- and high-velocity processes, which include subaerial or submarine landslides, the installation of deep penetrating anchors and post-liquefaction spreading of embankments.

In this paper, an Abaqus-based RITSS approach that can be applied to dynamic geotechnical problems is presented. The approach is validated through comparison with solutions from other LDFE approaches and simplified analysis. All of the benchmark studies were limited to plane strain conditions, but the proposed strategy is also appropriate for 3D RITSS implementations and can be coupled with most standard FE packages. An element addition technique is also developed to reduce the computational effort in dynamic problems. The element addition technique is aimed at structural elements or soil masses undergoing monotonic movement involving inertial forces, but is not intended for dynamic analyses related to seismic loading.

2. Dynamic ritss approach

2.1. Governing equations and time integration

The dynamic equilibrium equation is expressed as

$$M\ddot{u} + C\dot{u} + F_{\text{int}} = F_{ext} \quad (1)$$

where M and C represent the mass and damping matrices, respectively, and u and $\dot{u}$ are the acceleration and velocity vectors. The internal force vector F_{int} depends on the current stress vector σ. F_{ext} is the external force vector, determined by the dynamic or sustained loads applied.

For each step of the dynamic RITSS analysis, Eq. (1) is solved using an implicit time integration scheme proposed by Hilber et al. [6]. This integration scheme is actually a generalised Newmark operator with controllable numerical damping. The numerical damping is to filter out high-frequency noise induced by the inability of the spatial discretisation to model high-frequency waves. The acceleration, velocity and displacements at time $(t + \Delta t)$ are calculated as [3]

$$M\ddot{u}^{t+\Delta t} + (1+\alpha)\left(Cu^{t+\Delta t} + F_{\text{int}}^{t+\Delta t}\right) - \alpha\left(Cu^{t} + F_{\text{int}}^{t}\right) = (1+\alpha)F_{ext}^{t+\Delta t} - \alpha F_{ext}^{t} \quad (2)$$

$$\dot{u}^{t+\Delta t} = \dot{u}^{t} + \Delta t[(1-\theta)\ddot{u}^{t} + \theta\ddot{u}^{t+\Delta t}] \quad (3)$$

$$u^{t+\Delta t} = u^{t} + \Delta t\dot{u}^{t} + \Delta t^2[(0.5-\beta)u^{t} + \beta u^{t+\Delta t}] \quad (4)$$

where Δt is the time step and α, θ and β are integration parameters. The integration scheme through Eqs. (2)–(4) has second-order accuracy and unconditional stability when $-1/3 < \alpha < 0$, $\theta = 0.5 - \alpha$ and $\beta = (1 - \alpha^2)/4$. The parameter α, indicating the numerical damping introduced, was taken as -0.05 in the RITSS analyses.

The definitions of strains and stresses follow finite strain theory, to eliminate unrealistic strains induced by rigid body rotation and also to ensure rotation of the stresses with the material. In the dynamic RITSS approach an updated Lagrangian (UL) formulation is implemented using the above implicit scheme (Eqs. (2)–(4)) in each step. Correspondingly, the strains and stresses on the deformed configuration are measured with the rate of deformation and Cauchy stress, which are work conjugate. These measurements are appropriate and applicable for the elasto-plastic constitutive models that are most widely used in geotechnical numerical studies. The Jaumann rate is selected as the objective stress rate [3]. 'Small strain' in the term RITSS indicates that compared with large deformations during the entire response, the soil deformation in each step is small. As such, it is not strictly necessary to adopt the finite strain (UL) formulation for the increments between remeshing stages. However, the authors have generally adopted the UL formulation as incorporating RITSS in Abaqus (e.g. [19,24].

2.2. Procedure of dynamic large deformation analysis

In contrast to conventional small strain FE methods based on purely Lagrangian algorithms, the RITSS approach features mesh regeneration and projection of field variables. The field variables in the static total stress RITSS approach consist of the stresses and material properties. The field variables are recovered from the old integration points to each element node, and are then interpolated onto each new integration point for the next incremental solution step. The Superconvergent Patch Recovery (SPR, [28] was selected to recover field variable within a patch of elements to individual nodes:

$$V^{*} = Pa \quad (5)$$

where V^{*} represents a field variable recovered, P is a polynomial expansion and vector a comprises a finite number of unknown parameters. For 2D quadratic elements, P is written as

$$P = (1 \quad x \quad y \quad x^2 \quad y^2 \quad xy) \quad (6)$$

For an element patch with total n sampling points, the error of the recovered field variable is minimized

$$\Pi = \sum_{k=1}^{n}(\hat{V} - Pa)^2 \quad (7)$$

$$\frac{\partial \Pi}{\partial a} = 0 \quad (8)$$

where $\hat{V}$ is the FE solution at the sampling point. After the parameter vector a is deduced from Eq. (8), it is substituted into Eq. (5) to obtain the field variable at the element node.

The soil was meshed with quadratic 6-noded triangular elements. The integration points of the triangular elements were empirically found to be the optimal sampling points which exhibit one order higher convergence than for other positions. In our previous static simulations of pipe-soil interaction and plate anchor keying, the quality of SPR for triangular elements has already been validated [24,19].

The material properties extrapolated include, at least, material density and state variables for history-dependent constitutive relationships. Some material properties in static analyses might be defined as a function of the notional time period, for instance, the shear strain rate in a rate-dependent constitutive model [26,24]. However, the notional time is not real time and the inertial component in Eq. (1) is not considered in the static RITSS approach.

In the dynamic RITSS approach, two additional field variables – the nodal velocities and accelerations – need to be mapped between meshes. The velocities and accelerations at each new element node are interpolated from the deformed old element within which the new node falls

$$\dot{u}_p = N_i\dot{u}_i, \quad \ddot{u}_p = N_i\ddot{u}_i \quad (9)$$

where N_i represents the shape functions of the old element, and $\dot{u}_i$ and u_i are the nodal velocity and acceleration vectors, respectively. The subscript 'p' indicates the projected field variables. The projected velocities and accelerations are transferred into Abaqus/Standard as user-specified initial boundary conditions.

Ideally, the projected field variables, velocities and accelerations at nodes and stresses and material parameters at integration