Journal of Rock Mechanics and Geotechnical Engineering 10 (2018) 259–279

Contents lists available at ScienceDirect

Journal of Rock Mechanics and Geotechnical Engineering

journal homepage: www.rockgeotech.org

Full Length Article

Axisymmetric alternating direction explicit scheme for efficient coupled simulation of hydro-mechanical interaction in geotechnical engineering—Application to circular footing and deep tunnel in saturated ground

Simon Heru Prassetyo [a,b,*], Marte Gutierrez [a]

[a] Department of Civil and Environmental Engineering, Colorado School of Mines, Golden, USA
[b] Mining Engineering Program, Institut Teknologi Bandung, Bandung, Indonesia

ARTICLE INFO

Article history:
Received 10 July 2017
Received in revised form
14 August 2017
Accepted 18 September 2017
Available online 31 January 2018

Keywords:
Hydro-mechanical (H-M) interaction
Explicit coupling technique
Alternating direction explicit (ADE) scheme
High-order finite difference (FD)
Non-uniform grid
Axisymmetric consolidation
Circular footing
Deep tunnel in saturated ground

ABSTRACT

Explicit solution techniques have been widely used in geotechnical engineering for simulating the coupled hydro-mechanical (H-M) interaction of fluid flow and deformation induced by structures built above and under saturated ground, i.e. circular footing and deep tunnel. However, the technique is only conditionally stable and requires small time steps, portending its inefficiency for simulating large-scale H-M problems. To improve its efficiency, the unconditionally stable alternating direction explicit (ADE) scheme could be used to solve the flow problem. The standard ADE scheme, however, is only moderately accurate and is restricted to uniform grids and plane strain flow conditions. This paper aims to remove these drawbacks by developing a novel high-order ADE scheme capable of solving flow problems in non-uniform grids and under axisymmetric conditions. The new scheme is derived by performing a fourth-order finite difference (FD) approximation to the spatial derivatives of the axisymmetric fluid–diffusion equation in a non-uniform grid configuration. The implicit Crank-Nicolson technique is then applied to the resulting approximation, and the subsequent equation is split into two alternating direction sweeps, giving rise to a new axisymmetric ADE scheme. The pore pressure solutions from the new scheme are then sequentially coupled with an existing geomechanical simulator in the computer code fast Lagrangian analysis of continua (FLAC). This coupling procedure is called the sequentially-explicit coupling technique based on the fourth-order axisymmetric ADE scheme or SEA-4-AXI. Application of SEA-4-AXI for solving axisymmetric consolidation of a circular footing and of advancing tunnel in deep saturated ground shows that SEA-4-AXI reduces computer runtime up to 42%–50% that of FLAC's basic scheme without numerical instability. In addition, it produces high numerical accuracy of the H-M solutions with average percentage difference of only 0.5%–1.8%.

1. Introduction

Biot's theory of poroelasticity (Biot, 1941) has gained new prominence in geotechnical engineering to understand the coupled response of fluid flow and deformation in deformable porous media (i.e. soils and rocks). The most common examples of this coupled hydro-mechanical (H-M) interaction are consolidation and subsidence induced by fluid extraction from underground formations (e.g. oil and gas from hydrocarbon reservoirs and water from aquifers). In these examples, the transient fluid flow affects deformation in the ground and vice versa (Wang, 2000; Gutierrez and Lewis, 2002; Neuzil, 2003). Thus, consideration of this H–M interaction is essential for the safe design of structures built above or in saturated ground such as circular footing and deep tunnel.

Among various techniques to solve the coupled H-M equations, explicit technique is the most attractive one to be used (Minkoff et al., 2003; Dean et al., 2006). The technique not only is simple to be implemented, but also requires less time in building the separate mechanical and fluid flow codes for solving the coupled Biot's equations that govern the response of the fluid and the porous medium. Unfortunately, explicit techniques come at a price: they are only conditionally stable. The nature of an explicit

---

[*] Corresponding author.
E-mail address: simon@mining.itb.ac.id (S.H. Prassetyo).
Peer review under responsibility of Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.

https://doi.org/10.1016/j.jrmge.2017.09.010

technique requires that small time step sizes must be used to maintain numerical stability, placing a strong limitation on the technique. Consequently, the efficiency of computer runtime for an explicit-type coupling approach cannot be fully exploited for large-scale and long-term H-M simulations that may need enormously long computation time. For example, the H-M response of tunneling in low-permeability ground may need a consolidation time up to 250 years to reach the steady-state pore pressure distribution (Prassetyo and Gutierrez, 2016a, b).

One of the most widely used explicit finite difference (FD) codes for H-M simulation in geotechnical engineering is the fast Lagrangian analysis of continua (FLAC) developed by Itasca (2011a). It is also conditionally stable. The time step size used for its flow calculation must be lower than a critical value in order that the pore pressure behavior remains stable and monotonic (Itasca, 2011b). Unlike the fluid flow effect that takes place over a considerable amount of time, the geomechanical calculation in FLAC is not of particular concern because the response occurs almost instantaneously particularly for static geomechanical problems.

2. Need for an efficient explicit coupling technique

To improve the efficiency of an explicit coupling technique, one proposed method is to use an unconditionally stable fluid flow scheme that can be sequentially coupled with an existing geomechanical simulator such as FLAC. The alternating direction explicit (ADE) is one of such schemes. In an ADE scheme, two explicit FD equations are executed simultaneously in two physical directions: one in a forward sweep and the other in a reverse sweep (see Fig. 1).

To obtain the mathematical sense of how the ADE scheme works, the following diffusion equation is considered:

$$\frac{\partial p}{\partial t}=\frac{\partial^2 p}{\partial x^2}+\frac{\partial^2 p}{\partial y^2} \tag{1}$$

where p is the pore pressure.

As presented in Barakat and Clark (1966), to solve Eq. (1), the ADE scheme executes two explicit FD equations in a forward sweep (Eq. (2)) and in a reverse sweep (Eq. (3)):

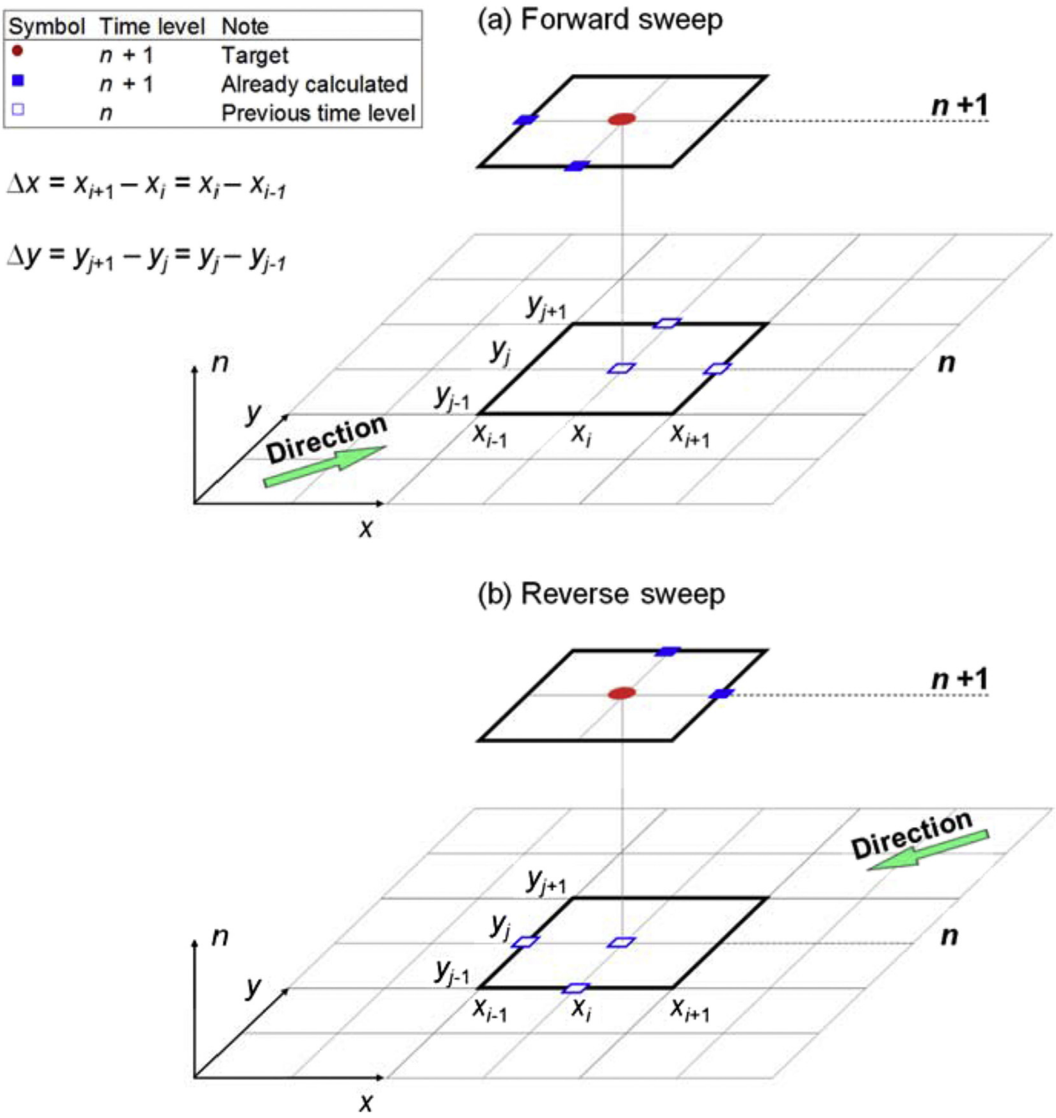

Fig. 1. Illustration of (a) the forward and (b) the reverse sweeps of the standard plane strain ADE scheme.