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Novel adaptive time stepping method and its application to soil seismic liquefaction analysis

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ABSTRACT

In solid–fluid coupled and dynamic analysis, the temporal discretization error related to the time step size is unavoidable. To improve the calculation efficiency, a novel adaptive time stepping procedure based on a finite element and finite difference (FEM–FDM) coupled method is proposed for soil seismic liquefaction analysis. The core concept of this adaptive stepping method is the mixed displacement and pore water pressure error estimation, which is obtained by an embedded error estimator, and a time stepping strategy, which is operated according to the relation between the current mixed error and the prescribed error tolerance. Two numerical examples were performed to validate the proposed method. It is shown that under the same condition of mesh size and other numerical parameters, the time step size obviously affects the calculation results; using adaptive stepping method is economical, robust and has the same degree of accuracy as compared with the fixed stepping method in the soil earthquake liquefaction analysis.

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1. Introduction

Liquefaction is defined as the transformation of a granular material from a solid to a liquefied state owing to increased pore water pressure and reduced effective stress [1]. Intense dynamic loads such as seismic load and blast load are known to induce soil liquefaction, which leading to a reduction in soil strength and damage to structures. In the last century, major earthquakes such as Niigata earthquake, Japan, in 1964 and the Wenchuan earthquake, China, in 2008 have already caused considerable damage [2,3]. Field investigations have revealed many types of damage caused by soil liquefaction such as embankment settlement [4,5], pile break-off [6,7], and the uplifting of underground structures. In this regard, the 1985 report of the National Research Council (NRC) has become a worldwide reference for liquefaction assessment [8,9]. In addition to field investigations, empirical and analytical methods [10,11], and laboratory tests [7,12], numerical methods are proving an effective approach for predicting and investigating soil liquefaction. With improvements in computational techniques, huge models with a large number of elements and nodes are being built and analyzed using the finite element method. Therefore, the accuracy and efficiency of dynamic numerical analysis become important research issues, and accordingly, determining numerical errors and adjusting the stepping and meshing adaptively are issues that have attracted considerable attention in recent decades.

The numerical discretization error is mainly from two sources: spatial and temporal discretization. The spatial discretization error can be reduced by an adaptive mesh refinement method [13]. In our previous research [14–15], an effective spatial discretization error estimator was presented and the concerned area mesh was successfully refined by the adaptive meshing methods. In the paper [16], a galerkin mesh free method was proposed to deal with the mesh distort problem. In this paper, we develop the FEM–FDM from the other hand, the temporal discretization error estimation and adaptive time stepping method.

For the temporal discretization, especially one with irregular loading conditions, it is inefficient to use a constant time step in the entire process. Therefore, in the temporal domain, an adaptive time stepping method is required. From the previous studies, the adaptive time stepping method is widely used in the structural engineering [17], fluid flow analysis [18–21], and soil consolidation analysis [22,23], but relatively few studies have focused on soil dynamic analysis using an adaptive time stepping method. Exactly, for soil dynamic analysis, it is a time consuming process due to the time-history analysis and the limitation of time step size. Sometimes, constant time stepping method is inefficient and inaccuracy, especially for the explicit scheme. Therefore, implementing the adaptive time stepping procedure into the numerical scheme is significant and valuable.

To better understand the adaptive time stepping method, some traditional time integration methods are reviewed firstly. The most

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commonly used are Difference method, Newmark method [24], Wilson-θ method [25], Generalized-α method [26,27] and so on. In this paper, we will focus on the Newmark method. Many studies have already modified the Newmark method itself [28–31], whereas some others attempted to estimate the temporal error and perform adaptive calculations. In 1991, Zienkiewicz [32] proposed a simple local error estimator by comparing the Newmark integration solution and the exact solution from the Taylor expansion. Zeng [33], Li [34] and Wiberg [35] modified Zienkiewicz's method and modeled a single degree of freedom. Hulbert [17] developed an automatic time step control method for structural dynamic analysis. In subsequent decades, Zienkiewicz's method, Zeng's method and Hublert's method were extensively used. In the reference [36], it was well explained the posteriori error and compared the previous stepping methods. In this study, Zeng's method was employed and modified. Before that, the study [37] have applied Zeng's method to the scaled boundary finite element method (SBFEM). The detail description of Zeng's method can be found in the relevant references [33,37].

Most of the previous error estimators are established just for solid displacement error estimation. In our study, for the saturated soil liquefaction analysis, we have to take one step further from Zeng's method by combining solid node displacement error and

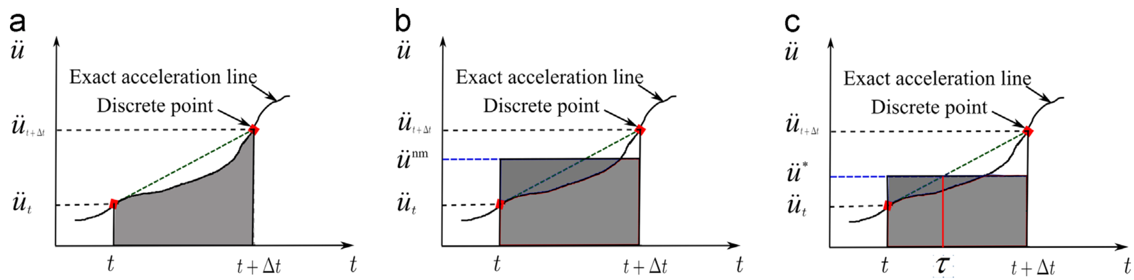

Fig. 1. Newmark discretization error estimation (a) exact integration (b) Newmark integration (c) more accurate integration.

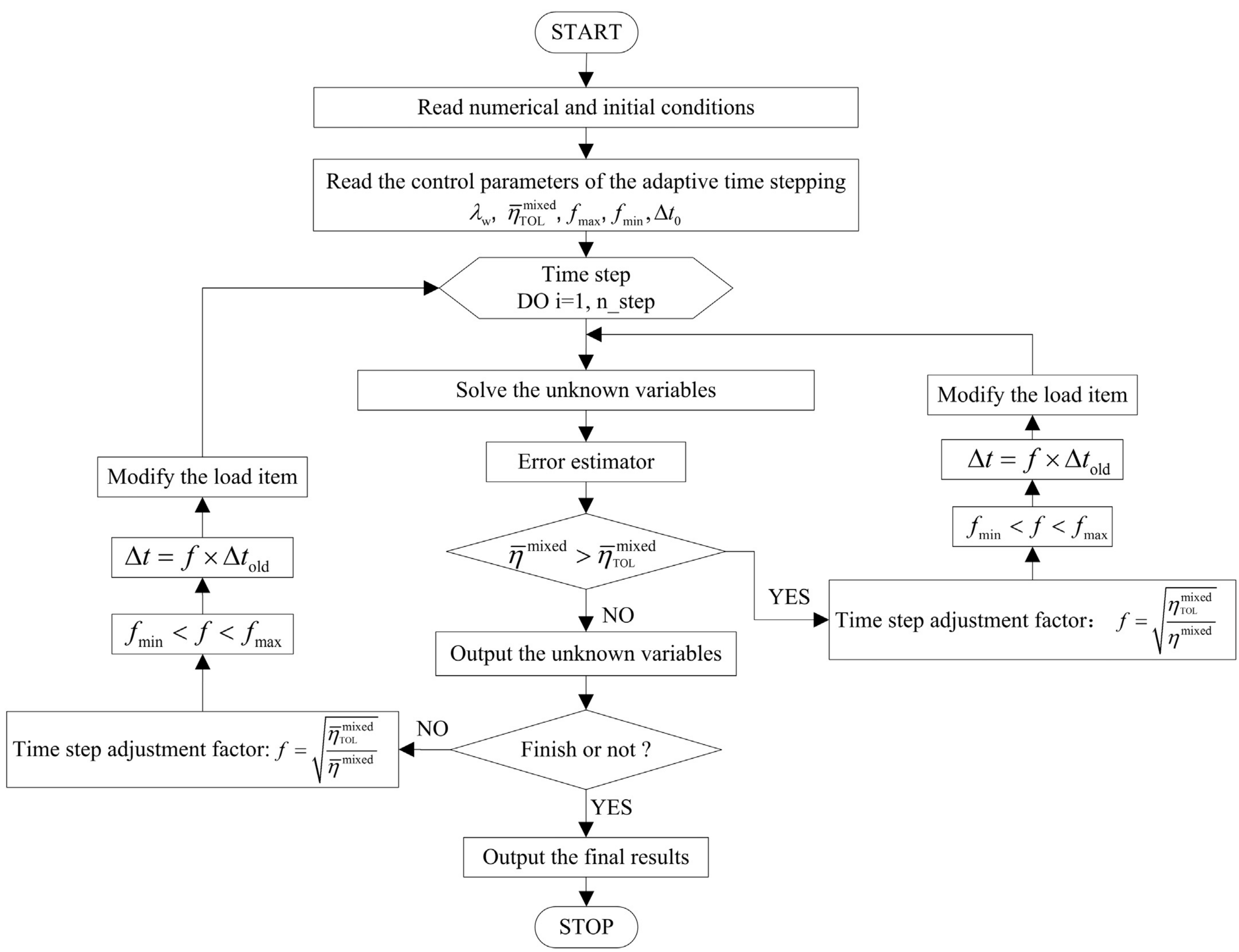

Fig. 2. The flowchart of the adaptive time stepping procedure.

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