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ScienceDirect

Procedia Engineering 199 (2017) 316–321

Procedia Engineering

www.elsevier.com/locate/procedia

X International Conference on Structural Dynamics, EURODYN 2017

Nonlinear Seismic Dam and Foundation Analysis Using Explicit Newmark Integration Method with Static Condensation

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Abstract

Engineers use the explicit Newmark integration method to analyze nonlinear dynamic problems. Instead of using computationally expensive global matrix assembly and factorization, the explicit integration method performs computations at element level which is computationally efficient, easily parallelizable, and does not require equilibrium iterations in case of nonlinear analysis. On the other hand, the explicit schema might require much smaller time steps compared to implicit integration alternative especially for models with high stiffness and low mass density. A problem type that might suffer from such a disadvantage is the seismic analysis of dams and their foundation. In these type of problems, the foundation is usually assumed massless in order to model the wave propagation realistically. For this purpose the foundation is modeled with zero or very small mass density which makes the use of explicit integration method almost impossible. Modeling the foundation with zero mass would result in indefinite solutions and modeling the foundation with very small mass density would result in very small time steps, and make the analysis computationally inefficient. In this study, static condensation method is utilized to reduce the full stiffness matrix of the foundation to the degrees of freedom at the dam-foundation interface. This way the foundation can be modeled with zero mass and integrated by the explicit Newmark integration method. Thus, an explicit integration algorithm with static condensation was implemented on a previously developed high performance parallel finite element analysis framework and tested on a 32 cores high performance computing system. The efficiency and accuracy of the proposed approach was examined by performing nonlinear time history analysis on several 3D dam and foundation models with different mesh densities.

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1877-7058 © 2017 The Authors. Published by Elsevier Ltd.
Peer-review under responsibility of the organizing committee of EURODYN 2017.
10.1016/j.proeng.2017.09.055

Keywords: Explicit Newmark Integration; Static Condensation; Nonlinear Dynamic Analysis; 3D Dam and Foundation Analysis

1. Introduction

Modeling the soil-structure interaction realistically requires considering the contribution of the foundation mass and the radiation boundaries in a finite element analysis solution. Consequently, seismic analysis of the dams have to be conducted modeling the foundation as well. For modeling the wave propagation effects exactly, costly elements like Perfectly Matching Layers (PML) or boundary elements [1] [2] can be used. However, industry mostly relies on approximate boundaries like the Lysmer-Kuhlemeyer around the foundation or the massless foundation approximation given the time constraints and computational demands for the seismic analysis of such systems. Moreover, rigorous methods work in the frequency domain, limiting their application to the prediction of elastic demands on these systems.

Dam-foundation-reservoir interaction is perhaps the most typical problem in civil engineering requiring the solution of a large domain for transient loading. For such systems, Explicit Newmark integration method is the preferred tool due to being computationally efficient and easily parallelizable. The explicit integration demands very small time steps: the computational demands, often higher than the implicit methods, are alleviated with parallel computation. With the parallelization of the common desktop CPUs, explicit solution is currently a viable alternative to implicit solutions given the lack of iterations as well as the establishment of a global stiffness matrix. The explicit integration is conditionally stable and the stability limit is based on the highest natural frequency of the structural model.

In contrast to the implicit solution, the inclusion of the massless foundation assumption in an explicit solution algorithm leads to stability problems. Zero density makes explicit solutions mathematically unstable. This problem can be handled by assigning a spurious miniscule density to these elements (different than zero), however, such an approximation leads to the requirement for very small time increments in order to satisfy the stability condition on the solution. In this study, a condensation algorithm was implemented to the high performance finite element analysis platform, Panthalassa [3], in order to address this problem for the explicit Newmark solution scheme. By utilizing static condensation, the full stiffness matrix of the foundation was reduced to the degrees of freedom at the dam-foundation interface. This way, the massless foundation was integrated by using explicit Newmark method. The proposed method was verified for a large dam model by comparing the implicit and explicit Newmark solutions. Additionally, the scalability of the discussed technique was also covered. While the focus of this work was on a dam system, the proposed methodology can also be applied for systems with zones of very small mass for addressing the stability problems of transient solutions.

2. Implementation of Static Condensation Algorithm

Nonlinear dynamic analysis was implemented using an explicit version of the Newmark dynamic integration method [4]. This version of the algorithm was first implemented by Hughes and Liu [5]. Explicit Newmark algorithm is based on approximation of the fundamental dynamic equation (Equation 1) by the central difference formulas.

$$M\ddot{u} + C\dot{u} + Ku = F^{Ext} \tag{1}$$

Equation 1, known as the fundamental dynamic equation, relates the dynamic external forces ($\boldsymbol{F^{Ext}}$) to the displacement ($\boldsymbol{u}$), the velocity ($\dot{\boldsymbol{u}}$) and the acceleration ($\ddot{\boldsymbol{u}}$) of the system. $\boldsymbol{M}$ is the mass, $\boldsymbol{C}$ is the damping and $\boldsymbol{K}$ is the stiffness matrices of the system. Discretization of this equation by the central difference equation results in Equation 2 [6]:

$$\frac{1}{\Delta t^2} M u_{n+1} = F^{Ext} - F^{Int} + \left[\frac{2}{\Delta t^2} M - \frac{1}{\Delta \mathrm{t}} C\right] u_n - \left[\frac{1}{\Delta t^2} M - \frac{1}{\Delta \mathrm{t}} C\right] u_{n-1} \tag{2}$$