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

Utku Albostan[a,b,*], Tunc Bahcecioglu[b], Yalin Arici[c], Ozgur Kurc[c]

[a]*Research Assistant, Department of Civil Engineering METU, Ankara 06800, Turkey*
[b]*PhD.candidate, Department of Civil Engineering METU, Ankara 06800, Turkey*
[c]*Assoc. Prof. Dr., Department of Civil Engineering METU, Ankara 06800, Turkey*

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.

* Corresponding author. Tel.: +90-312-210-54-08; fax: +90-312-210-54-01.
E-mail address: albostan@metu.edu.tr

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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]:

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

The left-hand side of the equation is only dependent on the mass matrix and if diagonal element mass matrices are used, the need to factorize the global mass matrix is eliminated. This enables easy and efficient parallelization of Equation 2 as there is no coupling between the computations for each element. In the parallel implementation, the elements are partitioned among the available number of threads, usually the number of cores of the system. The computation for the displacements of the degrees of freedom of the elements are conducted in the assigned thread. The computation is uncoupled; however, the assignment of the final displacement value is not, given a degree of freedom can be related to the elements assigned to different threads. In order to avoid race conditions, the final displacement assignment is done with an atomic sum operation.

This approach has one drawback: If the mass of a degrees of freedom is zero or close to zero, displacement computed from Equation 2 becomes infinite or close to infinite. This makes the modelling of the foundation impossible as the mass of the foundation should be close to zero or zero for this specific type of problem. In order to solve this problem, the foundation is assumed to be linear, its mass is omitted and its stiffness is condensed out to the bottom area of the dam.

During the condensation procedure, degrees of freedom of the foundation are separated into two parts: the ones correspond to the boundary with the dam, the boundary degrees of freedom and the others defined as internal ones.

$$\begin{bmatrix} K_{rr} & K_{rc} \\ K_{cr} & K_{cc} \end{bmatrix} \begin{Bmatrix} u_r \\ u_c \end{Bmatrix} = \begin{Bmatrix} F_r^{EXT} \\ F_c^{EXT} \end{Bmatrix} \tag{3}$$

Equation 3 presents the static force equilibrium for the separated degrees of freedom. Symbol $\boldsymbol{r}$ is used to define quantities corresponding to boundary degrees of freedom and $\boldsymbol{c}$ is used for the interior ones. The bottom part of Equation 3 is solved for $\{\boldsymbol{u_c}\}$ (Equation 4) and is substituted to the upper portion (Equation 5).

$$\{u_c\} = -[K_{cc}]^{-1}([K_{cr}]\{u_r\} - \{F_c^{EXT}\} \tag{4}$$

$$([K_{rr}] - [K_{rc}][K_{cc}]^{-1}[K_{cr}])\,\{u_r\} = \{F_r^{EXT}\} - [K_{rc}][K_{cc}]^{-1}\{F_c^{EXT}\} \tag{5}$$

The left part of the Equation 5 that is related to stiffness of the system is known as the condensed stiffness matrix and is used to condense internal stiffness matrix of the foundation to boundary degrees of the freedom. This matrix is also known as the Schur matrix. Similarly, the right hand side of the equation relates the external forces on the internal degrees of freedom to the ones on the boundary. In order calculate the condensed stiffness matrix and the external forces on the boundary, Schur computation functions from the MUMPS Library [7] was utilized. Condensed stiffness matrix is multiplied with a coefficient to compute the condense damping of the foundation at the boundary nodes. Condensed stiffness, condensed damping, and external forces are then inserted into Equation 2 and the non-linear dynamic algorithm is executed without the internal degrees of freedom of the foundation.

The size of the condensed matrices of foundation are equal to the number of degrees of freedom on the boundary between the dam and the foundation and quite large compared to the finite elements used to discretize the dam. In order to keep the computational balance of the parallel implementation, as the processing of the condensed stiffness would take more time than processing an element of the dam, the condensed stiffness matrix is treated separately with respect to the other elements on the dam. After the first step, where each thread worked on the Equation 2 for each finite element on the dam body, at the second step, all threads contribute to the computation of Equation 2 for the condensed stiffness matrix of the foundation. Since the condensed stiffness matrix is a full matrix, the matrix operations are performed by utilizing the parallel dense matrix operations from the Eigen library [8].

3. Validation of the Proposed Method

In this study, 3D modeling of an 80m high gravity dam system and its foundation were conducted for the validation of the proposed method. For this purpose, a model comprised approximately of 7000 elements was created. Both the dam body and the foundation were modeled with elastic material models whose properties as presented in the table given below. The full model of the dam-foundation system is presented in Figure 1 (a). The dam body is shown in Figure 1(b).

Table 1 Material Properties

	Dam Body	Foundation
Elastic Modulus (GPa)	20	10.8
Poisson Ratio	0.20	0.25
Density (kg/m3)	2400	0

In the analyses, the damping ratio of the dam body was assumed at a typical value of 5%. The Rayleigh damping approach was used to model the damping in the system. The ground motion time history displayed in Figure 1(c) was applied to the model by multiplying the ground acceleration with the mass matrix of the dam body and computing the external forces on each node. For the purposes of this simulation, the self-weight of the dam body was ignored. Time step for the explicit scheme was taken as 0.00005 seconds in order to satisfy the stability condition. The solution to the massless foundation model, as given above, consists of two steps. At the first step, the degrees of freedom of the foundation were condensed out and the corresponding elements were removed from the model. Then, the stiffness coefficients of the foundation were added to the dam stiffness matrix (Figure 1(b)).

The proposed methodology was validated by comparing the results to an implicit solution which was conducted on the general purpose finite element software DIANA [9]. An identical model, with the dam body and the foundation was solved in DIANA with the same loading with a 0.005 second time step. DIANA uses an implicit solution scheme, thus having zero diagonal values in mass matrix does not cause any mathematically undefined conditions. Hence, the foundation and dam body was considered together for the DIANA model (Figure 1(a)) and the tip displacement was computed and compared to the explicit solution. The comparison of the displacement time histories are presented in Figure 2. The results from DIANA and Panthalassa modified with the proposed methodology compare very well as shown in the figure.

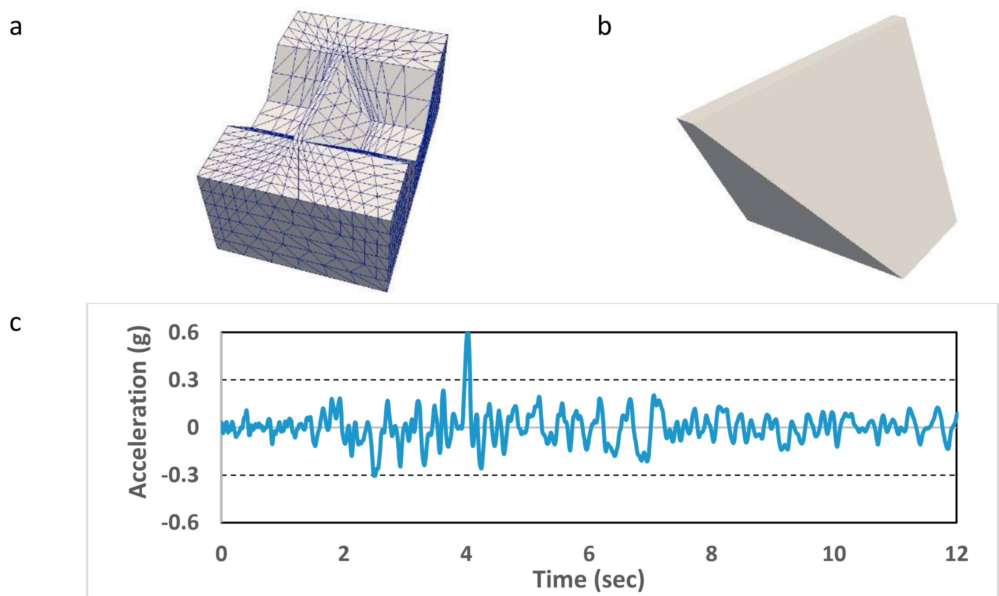


Fig. 1. (a) Full Dam Model; (b) Condensed Dam Model; (c) Applied Ground Acceleration.

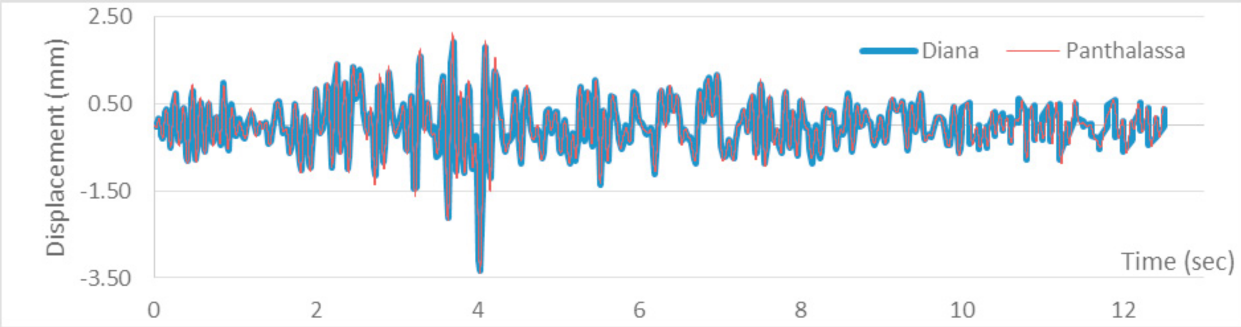
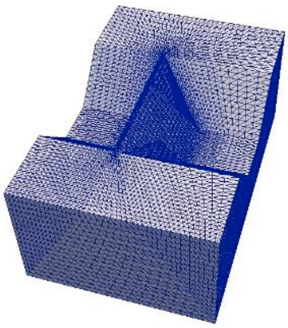


Fig. 2. Top Displacement Time History

4. Scalability of the Proposed Methodology

In addition to validation, scalability of the proposed method for nonlinear solutions was investigated. For this purpose, the same dam and its foundation were modeled with smaller element size by utilizing 600000 linear tetrahedral elements. The new model and its properties are presented in Figure 3. Since the model was comprised of elements much smaller in size, the time step was reduced to 0.000025 seconds for the solution corresponding to 500,000 steps for the solution of the full ground motion. The scalability was investigated using the speed of the solutions for the first 1.25 seconds period of the ground motion (50,000 steps). This model comprised of 106k elements was solved by using the proposed condensation technique on an AMD 6380 multi-threaded computer system with 2 x 16 CPU cores, 64 GB and Windows Server 2008 R2 operating system. The scalability was tested for 4, 8, 16 and 32 cores. The duration of the solution and the corresponding speed-ups in the algorithm for the plots are presented in Figure 4.



# of Nodes	
106447	
# of Elements	
Foundation:	235088
Dam:	373116
Total:	608204

Fig. 3. 106k Dam Model and Its Properties.

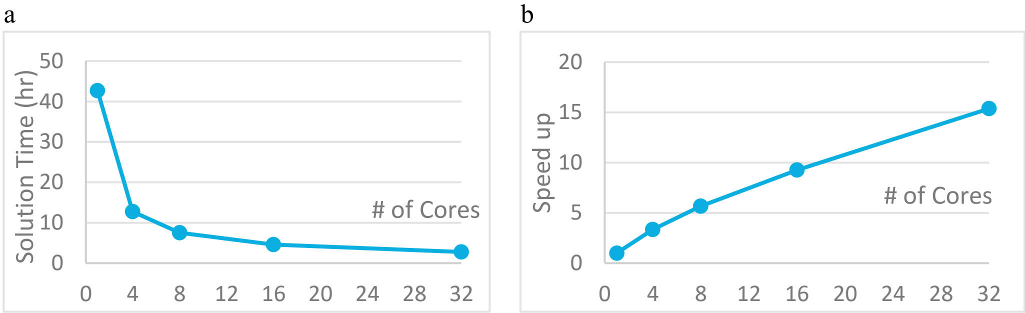


Fig. 4. (a) Analysis Times Plot; (b) Speed up Plot.

The dramatic increase in the speed by the utilization of more cores is shown in Figure 4. The solution time for a 300000 DOF 600K element finite element model dropped to about 1 hour per 1 second of the time history analysis. The scaling of the presented methodology was almost linear as shown in Figure 4b. With the inclusion of more processors 3-4 hours solution times for large systems such as these are attainable. It should be noted the size of the global stiffness matrix for such systems renders the problem virtually unsolvable using the implicit integration technique.

5. Conclusion

In this study, utilization of the static condensation technique within the explicit Newmark solution was proposed in the context of the solution of the dam-reservoir-structure interaction problem with a massless foundation assumption. The transient analysis of a selected dam-foundation model was conducted in order to validate the proposed methodology. The solution was compared to an implicit counterpart and validated. The scaling performance was investigated and good performance was verified. It was verified that the static condensation method can be used within the explicit nonlinear solution algorithms for dam structures making the typical massless foundation approach possible. Moreover, with the allocation of decent computational power, nonlinear time history solution of large models with significant mesh density becomes a possibility with a reasonable execution time. The proposed methodology can also be used for other systems in which the contrast of mass density among different parts of the system is very different, leading to problems in the determination of a feasible time increment for the explicit integration.

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