Simulation of Earthquake Liquefaction Response on Parallel Computers

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INTRODUCTION

Simulations of earthquake responses and liquefaction effects generally involve coupling solid and fluid phases, and often require the incorporation of soil plasticity models. Large-scale earthquake simulations are not feasible on most current single processor computers. Utilization of parallel computers, which combine the resources of multiple processing and memory units, can potentially reduce the solution time significantly. Furthermore, parallel computing allows analysis of large and complex models that may not fit into a single processing unit. Application software, such as finite element programs, must be re-designed in order to take full advantage of parallel computing.

This joint research effort between Stanford University and University of California at San Diego explores the implementation of a geomechanics nonlinear finite element program on distributed memory parallel computers. The research focuses on the development of a parallel version of a nonlinear finite element program, CYCLIC, for the simulation of earthquake ground response and liquefaction effects. The objective is to extend the computational capabilities of the finite element program to simulate large-scale systems, and to broaden the scope of its applications to seismic ground-foundation interaction problems.

PARCYCLIC

The parallel finite element program, ParCYCLIC, is implemented based on a sequential geomechanics nonlinear finite element program, CYCLIC, which has been developed to analyze cyclic mobility and liquefaction problems (Parra 1996; Yang et al. 2003). CYCLIC is based on small-deformation theory, which does not account for nonlinearity effects due to finite deformation or rotation. Extensive calibration of CYCLIC has been conducted with results from experiments and full-scale response of earthquake simulations involving ground liquefaction. For the liquefaction model currently employed, emphasis is placed on controlling the magnitude of cycle-by-cycle permanent shear strain accumulation in clean medium-dense sands. Following the classical plasticity formulation, it is assumed that material elasticity is linear and isotropic, and that nonlinearity and anisotropy are the results of plasticity. The selected yield function forms a conical surface in stress space with its apex along the hydrostatic axis, as shown in Figure 1. During shear loading, the soil contractive/dilative behavior is handled by a non-associative flow rule (Parra 1996) so as to achieve appropriate interaction between shear and volumetric response.

The computational procedure of the developed ParCYCLIC program is illustrated in Figure 2. The procedure can be divided into three distinct phases, namely: preprocessing and input phase, nonlinear solution phase, and output and postprocessing phase. In the nonlinear solution phase, modified Newton-Raphson algorithm is employed, that the stiffness matrix at

each iteration step uses the same tangential stiffness from the initial step of the increment. Although this modified iterative approach will typically require more steps per load increment compared with full Newton-Raphson scheme, substantial savings can be realized as a result of not having to assemble and factorize a new global stiffness matrix during each iteration step. As shown in Figure 2, if the solution is not converged after a certain number of iterations (e.g., 10 iterations) within a particular time step, the time step will be split into two to expedite convergence.

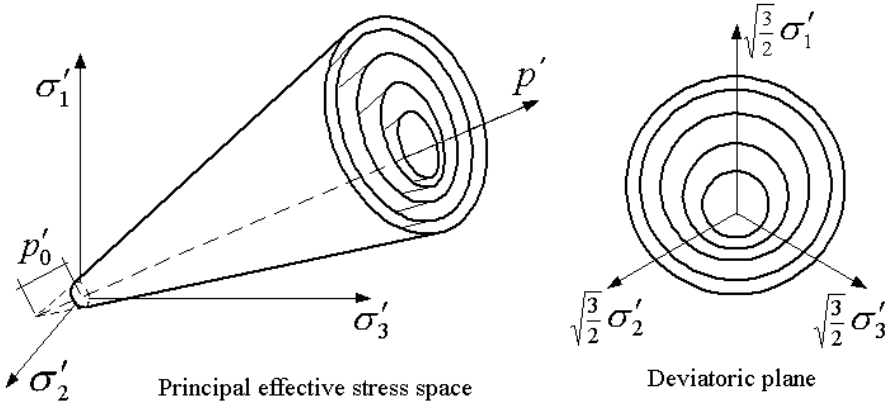

Figure 1 – Conical yield surface in principal stress space and deviatoric plane

PARALLEL PROCESSING

Programming models required to take advantage of parallel programming are significantly different from the traditional paradigm for a serial program (Mackay 1992). To achieve high efficiency for parallel applications, it is important to keep all participating processors busy performing useful computations and to minimize communications among the processors.

One common approach in developing application software for distributed memory parallel computers is to use the single-program-multiple-data (SPMD) paradigm. In this parallel programming paradigm, all processors are assigned the same program code but run with different data sets comprising the problem. Each processor of the parallel machine solves a partitioned domain, and data communications among sub-domains are performed through message passing. In the implementation of ParCYCLIC, METIS (Karypis and Kumar 1998) routines are applied to decompose the finite element domain. The algorithms in METIS are based on multilevel graph partitioning (Karypis and Kumar 1998), which is an efficient and popular domain decomposition approach.

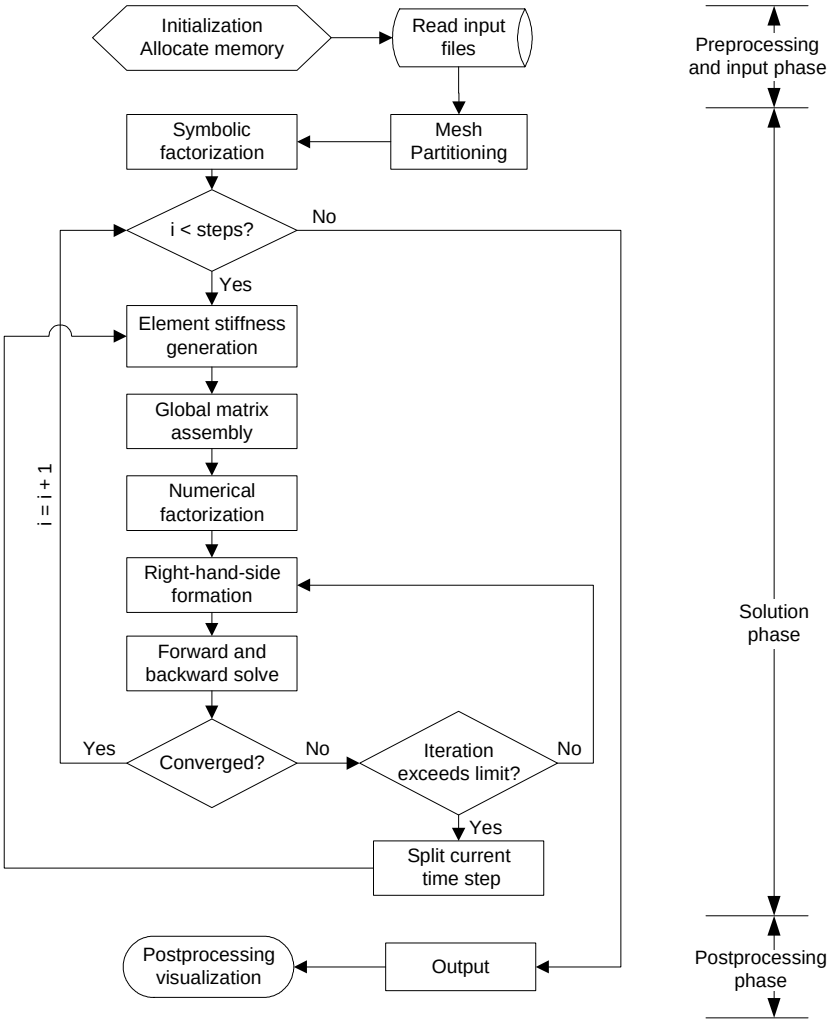

Figure 2 – Flowchart of ParCYCLIC computational procedures

After the domain partitioning, symbolic factorization is performed to set up the data structure for storing global stiffness matrix. The assembly of the global matrix from the element stiffness matrices is one of the most natural tasks for parallel implementation. Since each element stiffness matrix can be generated independently of the other element stiffness matrices, each processor can work independently on the elements assigned to it. Once the processor assignment and the assembly of the global stiffness matrix are completed, numerical solution of the global system of linear equations can proceed. A parallel row-oriented sparse solver (Mackay and Law 1993) is adopted in ParCYCLIC for performing the numerical calculation. The parallel numerical factorization procedure is divided into two phases. In the first phase, each processor independently factorizes certain portions of the matrix that assigned to a single processor. In the second phase, other portions of the matrix shared by more than one processor are factored. Following the parallel factorization, the parallel forward and backward solution phases proceed to compute the solution to the global system of equations.

The inter-process communication of ParCYCLIC is implemented using MPI (Snir and Gropp 1998). MPI (Message Passing Interface) is a specification of a standard library for message passing that was defined by the MPI Forum, a broadly based group of parallel computer vendors, library developers, and applications specialists. The strength of MPI is its portability, which makes it suitable to write programs to run on a wide range of parallel computers and workstation clusters. For ParCYCLIC, during the global matrix assembly and matrix factorization phases, most of the communications are point-to-point messages; while in the forward and backward solution phase, most of the communications are broadcast messages.

PARALLEL PERFORMANCE

The performance of ParCYCLIC is tested on the Blue Horizon machine at San Diego Supercomputer Center. Blue Horizon is an IBM Scalable POWERparallel (SP) machine, which has 144 compute nodes, each with eight POWER3 RISC-based processors and with 4 GBytes of memory. Each processor on the node has equal shared access to the memory. The performance of ParCYCLIC is evaluated by using a three-dimensional soil-pile interaction model, as shown in Figure 3. In this model, a 3x3 pile group, embedded in a fully saturated soil foundation with three stratums (liquefiable soil as middle layer), is subjected to earthquake excitation along the X direction at the base. As shown in Figure 3, only half of the model is used due to its geometrical symmetry.

Table 1 summarizes the timing results of the nonlinear analysis for one time step. The results for the solution phase and the total execution time (which includes the sequential phases such as input, domain decomposition, output and postprocessing steps) are also illustrated in Figure 4. Note that the results for one processor are not available because the model is too large to fit into the memory of a single processor. The performance results demonstrate excellent parallel speedup on the solution phase for the model. The results also show that the ParCYCLIC program is scalable to a large number of processors, e.g., 64 or more.

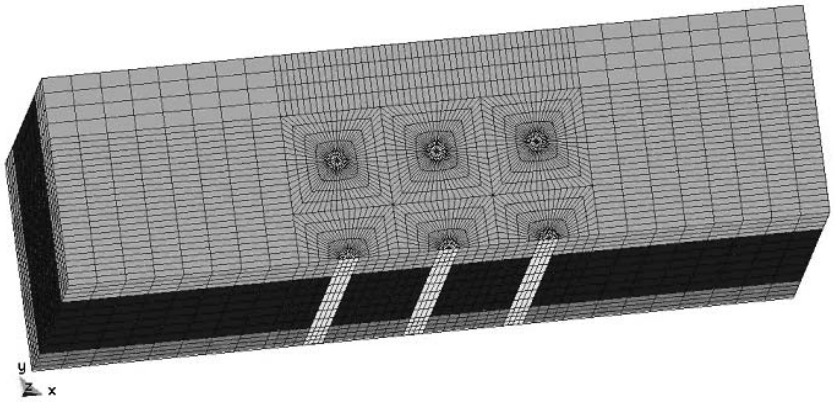

Figure 3 – A soil-pile interaction finite element model

Table 1 – Solution times for the soil-pile interaction model (time in seconds)

(130,020 equations; 29,120 elements; 96,845,738 non-zeros in factor L)				
Number of processors	LDL^T factorization	Forward and backward solve	Solution phase	Total execution time
2	332.67	1.41	370.42	455.91
4	166.81	0.78	187.72	286.97
8	85.20	0.45	97.71	186.67
16	50.73	0.29	59.39	147.55
32	27.80	0.23	34.61	124.30
64	18.41	0.26	24.40	116.21

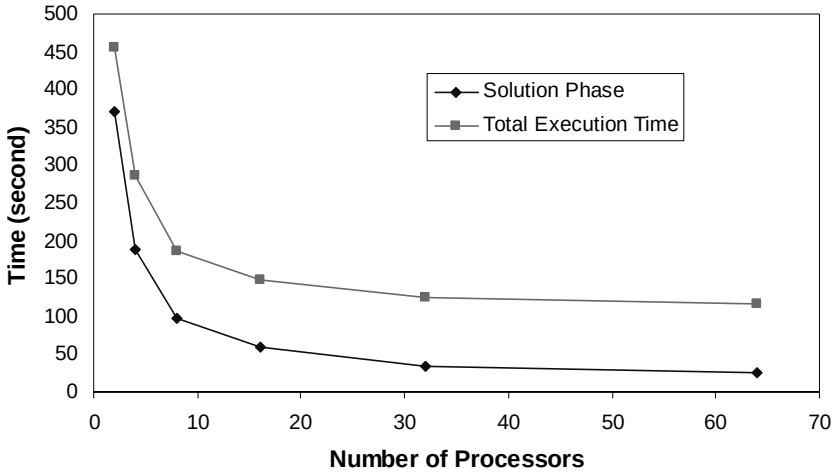

Figure 4 – Solution times for the soil-pile interaction model

CONCLUSIONS

This article presents the analysis and solution strategies employed in ParCYCLIC, a parallel nonlinear finite element program for the simulations of earthquake site response and liquefaction. In ParCYCLIC, finite elements are employed within an incremental plasticity coupled solid-fluid formulation. A constitutive model developed for the simulation of liquefaction-induced deformations is a main component of this analysis framework. Large-scale experimental results for 3-D geotechnical simulations are presented to demonstrate the performance of ParCYCLIC. It is shown that ParCYCLIC can be used to simulate large-scale problems, which would otherwise be infeasible using single-processor computers due to the limited memory sizes. Furthermore, the results show that the ParCYCLIC program is scalable to a large number of processors. Research continues to optimize the program to further reduce the total solution time and to apply the finite element program for large-scale simulation of ground-foundation interaction problems.

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