

NUMERICAL ANALYSIS STRATEGY FOR SOLVING THE LARGE SCALE AND COMPLEX CIVIL ENGINEERING STRUCTURES PROBLEMS

Jafril Tanjung¹, Makoto Kawamura² and Harpito³

¹Civil Engineering Department, Andalas University, Padang, Indonesia

²Architecture and Civil Engineering Department, Toyohashi University of Technology, Japan

³Graduate Student, Graduate School of Civil Engineering, Andalas University, Indonesia

Email: jafrihtanjung@ft.unand.ac.id, kawamura@ace.tut.ac.jp, harpito82@gmail.com

ABSTRACT

As the results of the last two decade of the earthquake disaster causes damage of the port facilities, new analysis method, so called seismic performance-based design method, is introduced in technical standards for civil engineering structures to access seismic performance of structures beyond the limit of force-balance responses. The implementation this method, however, requires an effective stress analysis by using finite element technique to capture their interaction, including the effect of pore water pressure when subjected to high ground motion. In many cases, analysis using a finite element approximation leads to the large number of unknowns, especially in three-dimensional nonlinear dynamic case; requires long computing time and large computer memory. The analyses using the conventional single processor machine very often exceed the available computer capacity. This study is concerned in parallel computation finite element analysis to overcome its limitation when analyze the large scale and complex civil engineering structures problems such as seismic performance analysis of the waterfront structures.

KEY WORDS: Seismic Performance-Based Design, Parallel Computation, Nonlinear Finite Element, Domain Decomposition Method and Earthquake Engineering

1. INTRODUCTION

The gravity type of concrete caisson quay wall constructed as waterfront structures in the port area are one of the typical complexity example of the civil engineering structures problem which requires the comprehensive consideration on their designing processes, particularly when the quay wall is designed for the port in high risk seismic area. For seismic resistance design, the quay wall structure is conventionally evaluated by using the pseudo-static design method (Ichii, 2004; Nozu et. al, 2004).

In the pseudo-static approach, the stability of caisson quay walls is evaluated with respect to sliding, overturning, and loss of bearing capacity. When reach their limit state under strong shaking, the instability with respect to overturning is much more serious rather than for sliding because tilting of the wall, if excessive, will lead to collapse. Thus a higher safety factor is assigned for overturning than for sliding and

loss of bearing capacity (Ministry of Transport, Japan, 1999, after Nozu et. al, 2004).

In designing procedures, the earth pressure due to backfill layer behind the wall is estimated following the equation proposed by Mononobe-Okabe (Mononobe, 1924; Okabe, 1924). During earthquake shaking, the sea water in front of the quay wall exerts the cyclic dynamic loading on the quay wall; the critical mode occurs during the phase when suction pressure is applied on the quay wall. The design load caused by sea water wave can be approximated by Westergaard equation (Westergaard, 1933) as is schematically shown in Figure 1. A brief explanation about the design procedure for the quay wall structure in high seismic area is well documented by Nozu et. al (2004).

As the results of the last two decade of the earthquake disaster causes damaged of the port facilities, the new analysis method is introduced in technical standards for civil engineering

structures to access seismic performance of structures beyond the limit of force-balance responses. A need was recognized for the performance-based design method, in which seismic performance of a structure beyond the limit of force-balance is evaluated instead requiring that the limit of equilibrium not be exceeded. In order to implementation the

performance-based design method, an effective stress analysis is required. The analysis will involve the soil-structure interaction wherein the response of the foundation and backfill soils is incorporated in the computation of the wall structure response. The finite element method is widely known as tool to conduct such kind of the effective-stress analysis.

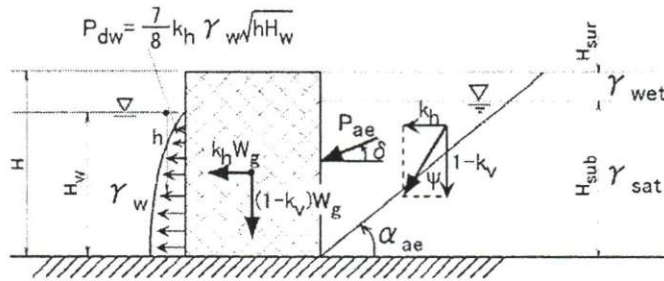


Figure 1. Seismic Actions on Quay Wall Structure in Pseudo-static Analysis (Nozu, et al, 2004)

In general, the soil layers are composed of the soil grains, pore water and/or pore air. When the soil layers are saturated, the soil skeletons are fulfilled by pore water and behave two-phase system coupling of the skeleton and the pore water. The soil skeletons and the pore water interacts each other (Hilton, 1981, Lewis, 1984). Analysis of the saturated soil layers considering the coupled system of the soil skeleton and the pore water gives more realistic results compared with homogenous equivalent solid assumption. Analysis using a finite element approximation leads to the large number of unknowns, especially in three-dimensional nonlinear dynamic case; the analysis requires long computing time and large computer memory. The analyses using the conventional single processor machine very often exceed the available computer capacity. With advent of the computer technology, analyzing a single large-scale problem using several processors concurrently becomes possible (Baker, 1987, Kumar, 1994). This type of works is called parallel computing. Each processor may calculate the different domain and/or different formulations. The processors are allowed to communicate each other if required.

Indeed, analytical study using a multiprocessors machine needs a special treatment to allocate the tasks onto different available processors. For this purpose, the domain decomposition method,

DDM, has been frequently used in the finite element method. In the DDM a whole of analysis domain is separated into several non-overlapping subdomains. These subdomains are assigned to the individual processor and the problem is solved in parallel manner. The analytical study discussed in this paper is the application of the parallel algorithm in the nonlinear dynamic finite element analysis to solve the large-scale and complex civil engineering structure as was previously described, i.e. to overcome the limitation of the conventional serial method.

2. THREE DIMENSIONAL DYNAMIC NONLINEAR PARALLEL FEM

The three-dimensional nonlinear parallel finite element algorithm in this study was developed based on the domain decomposition method following study by Tallec (1997), Papadrakakis (1997), and Farhat and Raux (1991). The DDM is applied to separate a whole the interest analysis domain into several non-overlapping subdomains. In order to enforce the continuity condition on the subdomain interfaces, i.e. the summation of the unknowns on the interfaces are equal to zero, a traction force was used. As the result, a boundary value problem then can be converted into an interface problem as is formulated in Eq. (1). The equation (1) was obtained by applying the weighted residual

method onto governing equation of motion and its continuity condition, while Galerkin method was used to spatial discretization the equation of motion (Zienkiewicz and Taylor, 1991, Hughes, 1996). The spatial discretization the equation of motion, furthermore, was integrated in time by using Hilber- α method to obtain its dynamic response (Hugher, 1996).

$$\sum_{s=1}^{Ns} \left[\mathbf{B}^{(s)} \hat{\mathbf{K}}_{T_n}^{(s)-1} \mathbf{B}^{(s)T} \right]^{(k)} \Delta \lambda_n = \sum_{s=1}^{Ns} \left[\mathbf{B}^{(s)} \hat{\mathbf{K}}_{T_n}^{(s)-1} \right]^{(k)} \Delta \mathbf{R}_n^{(s)} \quad (1)$$

with respect to continuity condition

$$\sum_{s=1}^{Ns} \mathbf{B}^{(s)} \Delta \mathbf{d}_n^{(s)} = \mathbf{0} \quad (2)$$

where

$$\hat{\mathbf{K}}_{T_n}^{(s)} = \frac{1}{\beta} \Delta t^2 \mathbf{M}^{(s)} + \frac{\bar{\gamma}}{\beta} \Delta t \mathbf{D}_{n-1}^{(s)} + \mathbf{K}_{T_{n-1}}^{(s)} \quad (3)$$

$$\Delta \mathbf{R}_n^{(s)} = \hat{\mathbf{F}}_n^{(s)} - \sum_{j=1}^{k-1} \left(\hat{\mathbf{K}}_{T_n}^{(s)} \right)^{(j)} \Delta \mathbf{d}_n^{(s)} \quad (4)$$

$$\Delta \hat{\mathbf{F}}_n^{(s)} = \left(\mathbf{F}_n^{(s)} - \mathbf{F}_{n-1}^{(s)} \right) + \left(\frac{1}{\beta} \Delta t \mathbf{M}^{(s)} + \frac{\bar{\gamma}}{\beta} \Delta t \mathbf{D}_{n-1}^{(s)} \right) \dot{\mathbf{d}}_{n-1}^{(s)} + \left(\frac{1}{2\beta} \Delta t^2 \mathbf{M}^{(s)} + \left(\frac{\bar{\gamma}}{2\beta} - 1 \right) \Delta t \mathbf{D}_{n-1}^{(s)} \right) \ddot{\mathbf{d}}_{n-1}^{(s)} \quad (5)$$

For the above equations, the time integration parameters are defined as follows,

$$\frac{1}{3} \leq \bar{\alpha} \leq 0; \bar{\gamma} = \frac{1-2\bar{\alpha}}{2}; \bar{\beta} = \frac{(1-\bar{\alpha})^2}{4} \quad (6)$$

The notations $\mathbf{M}^{(s)}$, $\mathbf{D}^{(s)}$ and $\mathbf{K}^{(s)}$ are the mass, damping and stiffness matrices for each subdomain. \mathbf{K}_T is the tangent stiffness matrix, which depends on the effective stress history of the soil grains parts. Obviously, there are three unknowns which have to be solved in the Eqs. (1) and (2), i.e. $\mathbf{K}_{T_n}^{(s)}$, $^{(k)}\Delta \lambda_n$ and $^{(k)}\Delta \mathbf{d}_n^{(s)}$. For a given of increment external seismic force, Eq. (1) may be solved by using an iterative solver of the Conjugate Gradient (CG) algorithm.

To capture a nonlinear behavior of the soil layer, an appropriate material constitutive model for the soil grains, which able to represent the nonlinear stress-strain relationship and the loading-unloading hysteresis loop, may be

represented by a simplified bounding surface plasticity model. The model allows the change of plastic strain during cyclic loading is evaluated according to relative position of the current stress point on the loading surface inside the bounding surface. The model is applicable for both of clays and sands by unifying the parameters in the single frame of a constitutive model as was successfully applied by Kawamura and Tanjung (2001), Kawamura and Tanjung (2002), Tanjung (2010b), Tanjung and Kawamura (2012) to investigate the interaction problem in civil engineering structures. A complete formulation for this dynamic nonlinear parallel finite element analysis has been documented by Tanjung (2010a).

3. PARALLEL COMPUTATIONAL STRATEGY

To achieve an efficient parallel algorithm, two following conditions should be considered, i.e. load works balancing and interprocessor communication. The works in each processor should be balanced as possible and the interprocessor communication should be as less as possible. In order to reach these conditions, the parallel algorithm should be designed to be mostly work in subdomain basis without interprocessor communication. For this purpose, the algorithm was implemented as a single program multiple data, SPMD, programming model. The interprocessor is only required when solving the interface problem.

In the SPMD programming model, most of finite element computations may be conducted in subdomain basis likely conventional serial programming, i.e. independently analyze each subdomain. Therefore, the computations can be assigned into individual processor in the multiprocessors machine; each processor will conducts identical works which is related to their subdomain input data, in parallel manner. Since each processor conducts the identical works, we only need to develop a single algorithm flow as the usual finite element analysis. The algorithm may be executed in the assigned processor. A special treatment is only required to manage the algorithm for performing the computations with respect to the different input data – related to the different properties of the subdomains – on the different processors.

Indeed, the interface problem as is written in Eq. (1) identical to a minimizing problem respect to continuity condition given in Eq. (2). A conjugate gradient, CG, method has been known as a powerful iterative algorithm to solve such kind of the problem (Gill, 1974). One of the features of the CG method is that the components of matrices are maintained without modification during iteration; therefore, the

algorithms make the computations become very convenient in the parallel machine since the components of the finite element matrices are constructed in the several independent individual processors. A specific algorithms of the CG method have been well documented by Gill (1974), Kawamura and Tanjung (2000), and Tanjung (2010a).

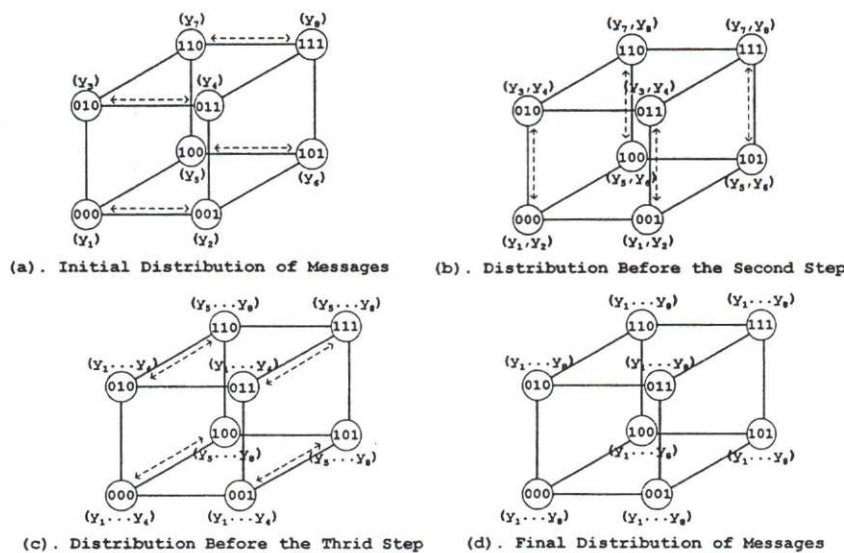


Figure 2. Interprocessor communications on 3D-hypercube (Kawamura and Tanjung, 2000)

An interprocessor communication is a critical point when develop the parallel computational, since the communication will significantly delay the calculation works during analysis. The interprocessor communication is required to exchange the data from one to other processors. A simple way to conduct the interprocessor communication is collect all subdomains contribution and directly broadcast to other subdomains. Unfortunately, this simple way will reduce rank of parallelism since each processor has to communicate to other processors. To improve this simple interprocessor communication, the authors have developed the interprocessor communication based on the hypercube networking as schematically shown in Figure 2. (Kawamura and Tanjung, 2000).

After mapping the subdomains onto the hypercube networking such that each processor is assigned into different active processor, the interprocessor communication is conducted as

follows. The interprocessor communication starts from the lowest dimension of the hypercube and then proceeds along successively higher dimensions. The processors communicate in pairs with least significant bit of their binary representations. Noting that, in the hypercube pattern each processor is only communicate with the neighbours. Each processor will hold the same result after interprocessor communication is terminated.

4. IMPROVED CG METHOD FOR RHS

When solving the nonlinearity condition by using the nonlinear solver such as Modified Newton-Raphson, the different residual dynamic loading vector has to be evaluated on each time step, while the equivalent tangential stiffness matrix remains constant. This task will repeat every time step until the analysis process is completed. This problem is known as a repeated right hand side, RHS problem. The direct solver

processes, such as the Gauss elimination families (Watkins, 1991), shows a clear advantage over the iterative. Once the equivalent tangential stiffness matrix has been factorized, the solution for the repeated loading vector can be obtained by forward and backward substitutions. These processes are relatively inexpensive compared with the iterative solver which requires a restart processes from every scratch of the iterative processes for each repeated loading.

Farhat (1994) has proposed a method to overcome the drawback of the iterative solver such as CG method. The method applies the re-orthogonal procedure to original conjugate gradient algorithms. In this method the overall problem is basically reformulated as a series of consecutive minimizing problem over AI-orthogonal and the supplementary subspaces and tailored to the conjugate gradient method via projection of the agglomerated Krylov space associated with the previous right-hand side problem.

Table 1 Parallel Computation Indicators

Scale of Model	Increment of Memory (%)	Increment of Executing Time (%)	
		Linear	Nonlinear
1	0.000	0.000	0.000
2	0.068	6.635	0.916
4	0.222	13.884	4.110
8	0.506	16.084	10.446
16	1.143	18.210	13.144

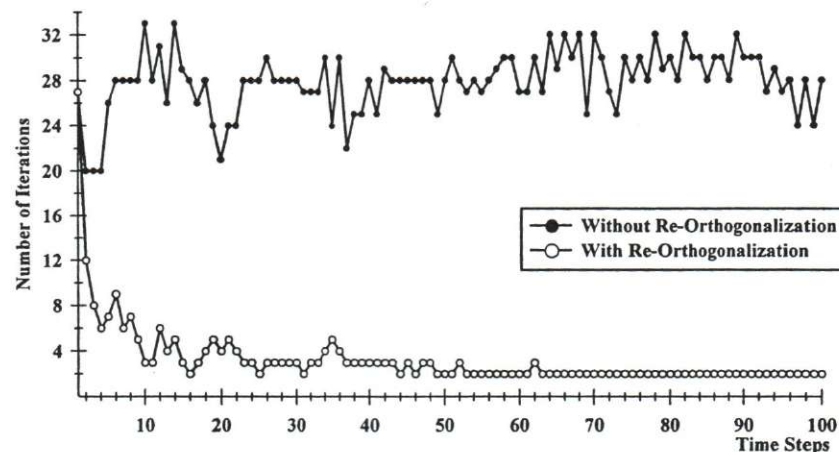


Figure 3. Comparison of the Reorthogonalization to Original Conjugate Gradient Algorithms

5. PERFORMANCE

To evaluate the performance of the nonlinear parallel computation, series of the analysis were carried out and result is shown in Table 1. In the series of the analysis the results for nonlinear responses of the soil materials are compared with those of linear response of the soil material. In both of the linear and the nonlinear cases the model size and the number of processors are increased and keeping the specified number of elements assigned to one processor. The subdomain for each processor is composed of 392 elements and 3072 numbers of degrees of

freedom. The executing time and the computer memory requirement were recorded and to be investigated as the indicators of the parallel computation. These indicator values were recorded after the first step of the dynamic analysis. The execution time is sum of the elapsed time for the calculation processes in each processor and the interprocessor communications. For the nonlinear case, the model scaled 16 times to the original one gives the increment of the executing time and the computer memory requirement are 13.1% and 1.1%. The increment of the executing time for

the linear case is 18.2%. These results suggest that the performance of the parallel computation is very efficient and more effective for nonlinear analysis rather than for the linear case.

To clearly show the robustness of improvement of the conjugate gradient method by using the reorthogonalization procedures for solving the repeated right hand side problem, a simple model of saturated soil layer has been analyzed. The model consists of 64 elements, partitioned into 4 subdomains and solved using 4 processors. The model analyzed in 100 time steps. The converged number of iteration of the conjugate gradient algorithms was recorded in each time step. Comparison of number of iteration for convergence in these algorithms with and without reorthogonalization procedures is plotted in the Figure 3. As it is expected, the number of iterations of the improved conjugate gradient method in each time step is significantly reduced.

The nonlinear parallel finite element method described in this paper has been successfully applied to simulate the experimental work and evaluate the damaged of the port of Kobe during Kobe earthquake, 1995 as are well documented in Kawamura and Tanjung (2001), Kawamura and Tanjung (2002), Tanjung (2010b) and Tanjung and Kawamura (2012). In these analysis works, the parallel computation was developed by using FOTRAN-77 and was conducted in SGI Origin 2000 machine.

6. CONCLUSION

The three-dimensional nonlinear parallel finite element procedures have been discussed in this paper to facilitate the analysis tool for solving the large scale and complex civil engineering structures problems. The performance and its applications were also briefly explained. Although the analysis works were done in super computer machine, i.e. SGI Origin 2000, the algorithm described in this paper still applicable in distributed personal computer machine, since most of computations can be independently conducted in different machine.

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