A Serial Domain Decomposition Method for Discrete Element Method Simulation of Soil–Wheel Interactions

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ABSTRACT

We applied a serial domain decomposition method (DDM) to our two-dimensional discrete element method (DEM) program and investigated the effectiveness of DDM in terms of computer hardware. The developed program could obtain sufficiently accurate results for wheel slip, traction, and gross traction, comparable to DEM without serial DDM. We also confirmed that the soil deformation field under the wheel for DEM with serial DDM was similar to that for DEM without DDM. Moreover, the increased sub-domain loop was effective in reducing computational time in the case of serial DDM. Since each sub-domain loop contains the time integration and coordinate update routine, further optimization of memory usage in our serial DDM may be possible, which would allow large-scale three-dimensional DEM analysis on an economical desktop PC system.

Keywords: computational mechanics, soil–wheel system, contact interaction, DEM, domain decomposition method, serial analysis, lugged wheel, elapsed time, Japan

1. INTRODUCTION

The discrete (or distinct) element method (DEM) has been applied to various dynamic problems, not only in granular mechanics, but also in soil-related interaction problems often encountered in terramechanics. In principle, DEM can express a localized slip zone, or shear lines, which are often observed at soil–wheel or soil–machine interfaces (Oida and Momozu, 2002; Soni and Salokhe, 2006; Tanaka et al., 2007). However, a well-known inherent shortcoming is the computational time required for contact check and reaction calculations on all elements, because of the number of small time steps in explicit time integration for equations of motion in the DEM. DEM has, therefore, been applied to soil–tire interactions problems (Fujii, 2003; Nakashima et al., 2007) while trying to reduce the time-consuming DEM region by coupling DEM with the finite element method (FEM) (Nakashima et al., 2004a) or by introducing parallel processing (Nakashima et al., 2004b).

As computer technology has developed, large-scale analysis with high solution accuracy using a desktop PC system has become a current topic of interest. For example, the domain decomposition method (DDM) has been applied to parallel processing of DEM with message passing interface (MPI) for soil-cutting problems (Horner et al., 2001). In these cases, massive assemblies of discrete elements (DEs), as large as 10 million particles, are spatially divided into sub-domains, and parallel processing is applied for each domain using a supercomputer system. For effective parallel processing with MPI, computer hardware and software must be well prepared and computational loads should be evenly distributed among CPUs, while the data communication process must be optimized. For massive scale analysis, the proportion of load imbalance caused by the movement of a soil-engaged tool was assumed to be insignificant, although the relationship between the total number of processors and the time steps per second did not show a clear linear relationship (Horner et al., 2001). In DEM analysis of soil–wheel interaction, a wheel is usually considered to run over soil, which is modeled as an assembly of DEs. The long travel distance of the wheel may degrade the load balancing of nodes in DDM with relatively small numbers of total elements under a desktop PC system. Therefore, decreased effectiveness will be more likely when parallel DDM is applied to DEM for interaction analysis.

Since domain decomposition reduces the maximum size of arrays for global variables in the program, it is expected that the time-consuming DEM with massive memory usage might make the computation more economical with the use of divided memory. Thus, it may be useful to apply DDM (specifically, serial processing of DDM) to DEM. Using a notebook PC, it has been demonstrated that a serial application of DDM to DEM may be possible in executing a three-dimensional DEM program with optimum use of limited on-board memory (Sakaguchi, 2004). Since our project has focused mainly on DEM simulations of interaction problems in terramechanics using a desktop PC, it is quite interesting to investigate the applicability of a serial DDM to our two-dimensional DEM program in preparation for a three-dimensional DEM on a desktop PC system. Therefore, the objective of this study was to evaluate the use of a serial DDM for soil–wheel interaction studies and check the accuracy of analysis and economical use of computer hardware resources and computational time.

2. INTRODUCTION OF DDM

2.1 Perspectives from Original DEM Simulation

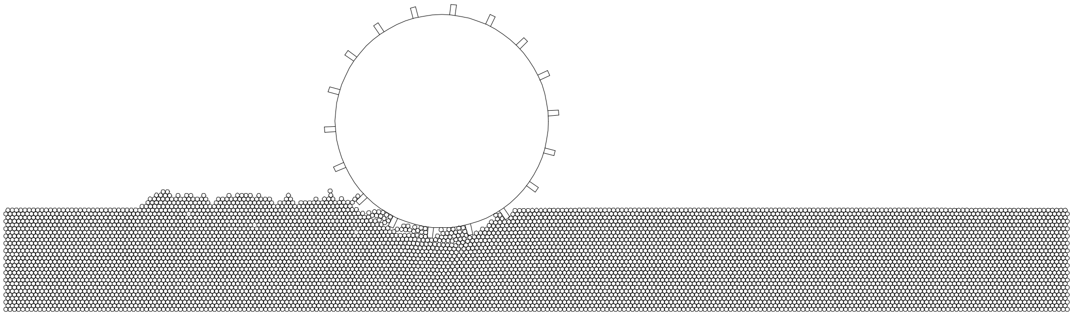

Figure 1. Example of a DEM simulation result.

A DEM simulation result for the performance of a lugged wheel on soil is shown in Fig. 1. The wheel was modeled by one DE, and lugs on the wheel surface are expressed by virtually distributed DEs at each lug (Fujii et al., 2002; Fujii, 2003).

In the simulation, a wheel travels over a soil surface with slip, corresponding to the given drawbar pull and load conditions. Therefore, a change in the travel distance resulting from wheel slip based on the given loading conditions is unavoidable.

2.2 DDM

Two types of DDM exist: with overlapping boundaries and with non-overlapping boundaries (Yagawa et al., 1998). For DEM analysis, a spatially non-overlapping DDM can be directly incorporated when the contact reaction is the sole information that should be transmitted between neighboring domains, and the contact reaction is then calculated.

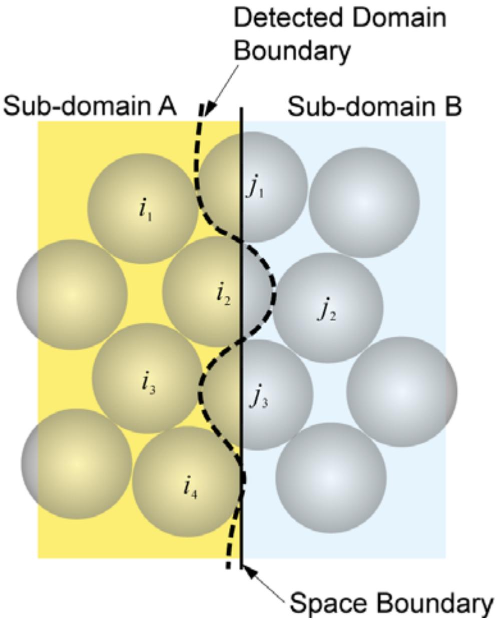

Figure 2. Boundary expression of DDM in DEM.

Figure 2 shows a schematic diagram of neighboring sub-domains at a DDM boundary and the relevant DEs. The real shape of the domain boundary may not be flat because of the particulate nature of DEs. For sub-domain, elements that form the detected boundary are expressed as i_n, where n = 1 to 4. In calculating the contact reaction on an element, for example, i_2 at the detected boundary, a reaction contribution from elements j_k (where k = 1 to 3) that contact i_2 and belong to an adjacent sub-domain B should be added. Moreover, all the reactions acting on j_k (where k = 1 to 3) in sub-domain B should be stored in the memory for contact evaluation at element i_2 in order to prepare for successive computation in sub-domain B.

2.3 DDM in Soil–wheel Interaction Analysis

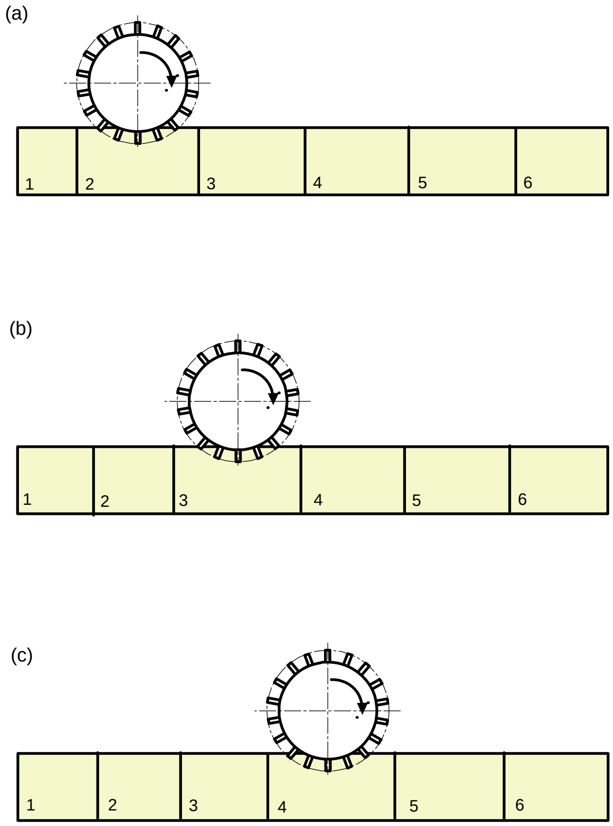

Figure 3. Update of sub-domain divisions for soil–wheel system.

In target soil–wheel interaction problems, a rigid wheel travels over the soil surface (Fig. 1). Since our simulation aims for an analysis over a wide range of wheel travel with wheel slip, and soil–wheel contact can easily be processed within the same algorithm for DEM contact, an update of sub-domain division (Fig. 3) is introduced, which redefines and updates the pre-assigned sub-domain division based on the updated location of the running wheel. Moreover, the total number of domain divisions should be decided based on the target length of the soil bin and the size of wheel under investigation. Thus, the sub-domain to which the wheel and the soil under it belong is allotted one domain, e. g., sub-domain 3 in Fig. 3(b), and other sub-domains, such as 1 and 2 at the left of wheel and from 4 to 6 at the right of wheel, for the soil are divided as evenly as possible, depending on the wheel's location on the soil surface for a given time step.

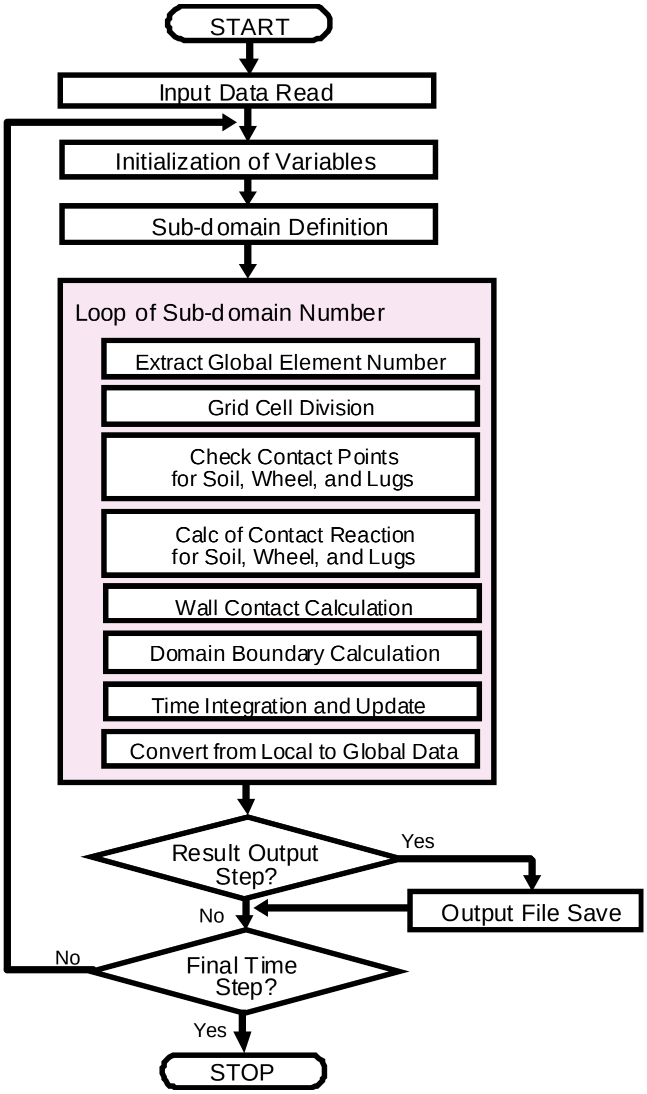

Figure 4. Program flow of DDM.

3. IMPLEMENTATION OF SERIAL DDM

The original two-dimensional DEM program developed by Fujii et al. (2002) was modified and optimized to implement serial DDM. A schematic flowchart of the modified program is summarized in Fig. 4. The sub-domain definition is updated once the horizontal distance covered by the running wheel exceeds the pre-assigned DDM boundary location. With the update of sub-domain definition, the correspondence between global DEs and the local DEs counted in each sub-domain was calculated, and this information was stored. Note that the loop of the sub-domain number applies not only to contact check and reaction calculations but also to domain boundary contact calculation, time integration, coordinate update, and conversion from local to global data for both coordinates and reactions for the preparation of the result file.

At domain boundaries, contact reaction calculation is performed between elements in the current sub-domain and elements in the next sub-domain. Once contact between elements is detected at a domain boundary, we can apply the same routine of reaction calculation as in a conventional DEM.

4. NUMERICAL VERIFICATION

4.1 Description of Numerical Experiments

The DEM program with a serial DDM was verified by using the input data used for conventional DEM analysis, where the results of DEM were compared with the experimental results, and sufficient accuracy could be obtained (Fujii, 2003; Nakashima et al., 2007). Table 1 shows the wheel parameters used in the numerical experiment. The values used for parameters such as spring constant, damping coefficient, and elemental density were the same as those of previous studies (Fujii, 2003; Nakashima et al., 2007). It is noted that soil DEs had a uniform diameter of about 4 mm, as the main objective was the development of an algorithm for serial DDM and it was easier to perform the analysis using the same data files as the previous DEM. The total number of soil DEs was 6986, and 45-sec wheel travel was simulated.

Table 1. Wheel parameters for DEM simulation.

Wheel Diameter (cm)	20
Wheel Width (cm)	10
Lug Height (cm)	1
Number of Lugs	18
Vertical Wheel Load (N)	19.6
Angular Velocity (rad/s)	0.138
Drawbar Load (N)	10

Table 2. Specifications of PC used for DEM simulation.

Product Name	Apple MacPro
CPU (X2)	Intel Quad-Core Xeon
CPU Clock	3 GHz
Main Memory	8 GB 667 MHz DDR2 FB-DIMM
OS	MacOS 10.5.2
Compiler	Intel Fortran Compiler 10.1

4.2 Description of PC System

A desktop PC system with two multi-core CPUs was used in the numerical experiments. The main specifications of the system are listed in Table 2. Two programs, one for conventional DEM and the other for DEM with serial DDM, were written in Fortran90, based on our previous C program for soil–wheel interaction analysis, and were compiled using Intel's Fortran Compiler. The compiler's automatic vectorization option was used when compiling the program to obtain faster execution speed.

5. RESULTS AND DISCUSSION

5.1 Comparison of Analysis with and without Serial DDM

First, the simulation accuracy was checked before and after the introduction of DDM to the DEM analysis. The average wheel slip, net traction, and gross traction obtained from the analysis are summarized in Table 3. It is clear that all the results with serial DDM are almost the same as those from the conventional DEM analysis without DDM.

Table 3. Wheel performance in DEM simulations with and without DDM.

	With DDM	Without DDM
Wheel Slip	0.730	0.736
Net Traction (N)	9.952	9.968
Gross Traction (N	12.721	12.697

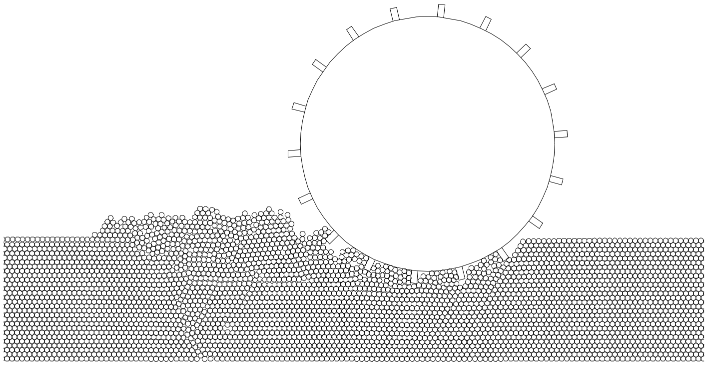

Figure 5. Deformation of soil under wheel for DEM without DDM.

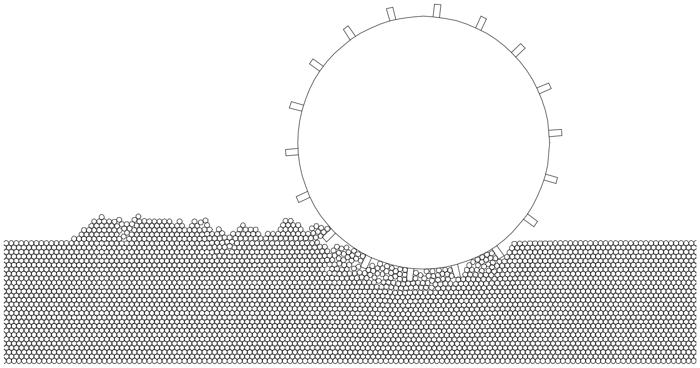

Figure 6. Deformation of soil under wheel for DEM with DDM.

The resulting deformation field under the wheel is shown in Fig. 5 for DEM without serial DDM and in Fig. 6 with DDM. Again, similar soil behavior can be seen in both Figures 5 and 6. However, it is obvious that parts of some soil elements behave differently in the case with DDM (Fig. 6). The difference may arise from the difference in stress state within the soil before and after the new definition of domain decomposition, since strict updating of the stress field is not included in the current DDM.

5.2 Computational Time and Memory Capacity

The total elapsed time for the current DEM with serial DDM was 6287 s, while that for the conventional DEM was 6844 s. The serial DDM's shorter time might be attributed to a redesign of procedures based on the sub-domain loop, in which the reduction of small element-based loops was modified into one large sub-domain-based loop. Thus, the generation of large procedures in the sub-domain loop was accelerated with vectorized computation, although some preparatory processes for sub-domain calculation were added in the serial DDM program.

Since each sub-domain loop contains time integration and coordinate updates, as shown in Fig. 4, we expect to reduce the working memory size for DEM, whose computation is independently allotted in each sub-domain, by storing necessary information about coordinates and reactions along with the domain boundary elemental information. Currently, completion of the serial DDM algorithm is the main target, and therefore, the aggressive reduction of required memory capacity in each sub-domain has not yet been implemented. This modification will be necessary for the realization of large-scale three-dimensional DEM analysis on a desktop PC system.

6. CONCLUSION

We applied serial DDM to our two-dimensional DEM program and investigated the effectiveness of DDM in terms of computer hardware. The resulting program gave sufficiently accurate results for wheel slip, traction, and gross traction, comparable to DEM without serial DDM. We also confirmed that the soil deformation field under the wheel for DEM with serial DDM was similar to that for DEM without DDM. Moreover, the increased sub-domain loop was effective in reducing computational time in the case of serial DDM. Since each sub-domain loop contains the time integration and coordinate update routine, further optimization of memory usage in our serial DDM may be possible, which would allow large-scale three-dimensional DEM analysis on an economical desktop PC system.

7. ACKNOWLEDGMENTS

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