# Parallel computations for fluid-structure interaction problems in civil engineering using multiphase modeling

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**Abstract.**

The applicability of a parallelized multiphase-computational method (MICS), proposed by Ushijima et al. (2008), was demonstrated through the several numerical experiments associated with fluid-solid interactions, which have been difficult to deal with by the usual computational methods. The MICS is based on an incompressible one-fluid model in multiphase flows, in which the governing equations were solved with a finite volume method including some improved numerical procedures: the implicit C-ISMAC method in which higher-order TVD schemes can be implemented, the pressure computational method C-HSMAC method that can control the accuracy of incompressibility, as well as the parallelized procedures based on a 3D domain decomposition method with flat MPI. Some results of numerical experiments related to fluid-solid and solid-solid interactions will be shown in this paper.

**Keywords:** Parallel computation, Fluid-solid interaction, Multiphase modeling

## 1. Introduction

It is important to predict fluid-solid interaction problems in civil engineering, e.g., transportation of tsunami debris and movements of sand particles due to flows. Thus, many computational methods have been proposed in preceding studies. The computational method ”MICS” (Multiphase Incompressible flow solver with Collocated grid System) [1], was also developed in order to deal with such problems in three dimensions. In the MICS, shapes of solids are represented by multiple tetrahedron elements and fluid forces acting on solids are calculated using these elements. Therefore, the MICS enables us to more accurately predict mechanical interactions between flows and arbitrarily shaped solids than other similar numerical models [2, 3] that deal with solids as aggregates of spheres, since volumes, inertia tensors and physical properties of solids are estimated from tetrahedron elements with high accuracy.

The MICS is a powerful method for complicated fluid-structure interaction problems, on the other hand, computational costs largely increase when the spatial scale and the number of solid objects become large. Recently, the MICS was parallelized on the basis of a 3D domain decomposition method and applied to actual problems in civil engineering that contain many solid objects [6, 7]. In this paper, numerical experiments are conducted for the transportation of many floating objects by dam-break flows and movements of sand particles due to overflows from a weir in order to confirm applicabilities of the MICS. All computations were conducted on the supercomputer system of Kyoto University.

## 2. Computational method

The MICS [1] is based on an incompressible one-fluid model in multiphase flows. The cell-averaged governing equations for multiphase fields are solved with a finite volume method (FVM) and some improved numerical procedures, e.g. the implicit C-ISMAC method [1] that enables us to implement higher-order TVD schemes [4] for calculations of advection terms, the C-HSMAC method [1] that can control the accuracy of incompressibility in the pressure calculation stage.

In the MICS, shapes of solids are represented with multiple tetrahedron elements and the physical properties of solids, such as volume, mass and inertial tensors, are estimated using these elements. The fluid forces acting on the solids are calculated by the volume integral of the pressure and viscous terms of the momentum equations for multiphase fields. In addition, the contact detection spheres (CDSs) are placed near the solid surfaces and contact forces are calculated using the CDSs. Therefore, the MICS enables us to easily treat collisions among arbitrarily shaped solids.

Numerical procedures of the MICS are parallelized based on a 3D domain decomposition method using flat MPI. In particular, the solid data are divided into common and send-receive data as shown in **Tab. 1**. The common data are shared among all processes and only send-receive data are communicated among neighbor processes as shown in **Fig. 1** in order to reduce the memory for solid data in each process.

Table 1: Type of solid data

| | |
|---|---|
| Common data | shape and type number, posture location<br>information of tetrahedron, mass, density<br>tensor of inertia, DEM parameter etc. |
| Send-receive data | object number, shape and type information of object<br>nodal coordinate, center of gravity<br>barycentric velocity, angular velocity<br>quaternion, fluid force, contact force etc. |

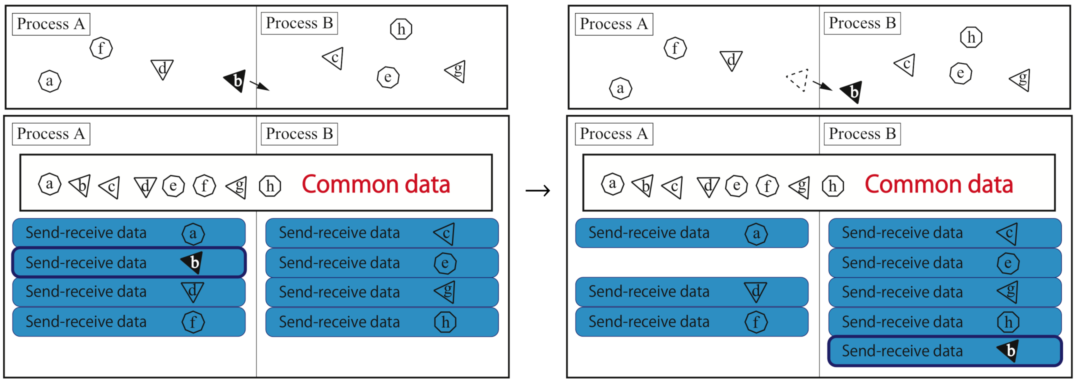


Figure 1: Treatment of solid information (solid *b* moves from Process *A* to Process *B*)

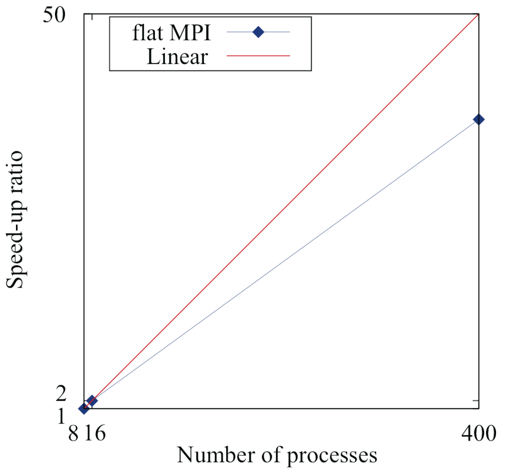


Figure 2: Speed-up ratios on the basis of 8 processes [5]

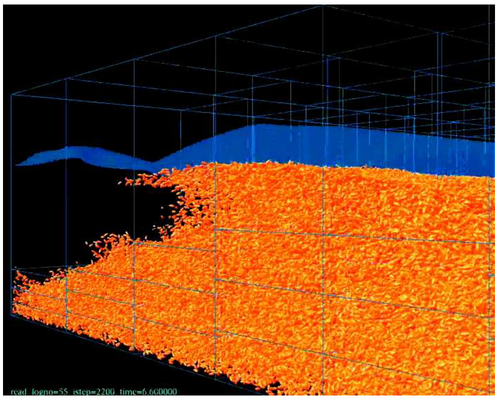


Figure 3: Numerical experiment for 1,000,000 spheroids transported by free-surface flow [7]

In preceding studies, the MICS was applied to various fluid-solid interaction problems that contain many moving solid objects. For example, Aoki et al. [5] conducted numerical experiments for the transportation of 240 vehicles among debris control structures caused by tsunami flows and the efficiency of the parallel computations was discussed. **Figure 2** shows the speed-up ratios on the basis of 8 processes on the supercomputer system of Kyoto University, System A (Camphor). As shown in **Fig. 2**, about 37 times speed-up ratio was obtained on basis of 8 processes in this application. Yagyu et al. [6] calculated movements of about 30,000 sand particles due the impact of a water drop using the MICS. Through comparisons with experimental data regarding a volume of the hole arisen by the impact of the water-drop that has different momentums, the validity of the MICS was confirmed. In addition, numerical experiments were conducted by Maruyama et al. [7] for 1,000,000 spheroids transported by free-surface flows using the techniques for improving the load-balance in case that nonuniform distributions of solids arise in the computational area as shown in **Fig. 3**.

# 3. Applications

## 3.1. Transportation of many floating objects by dam-break flows

The MICS was applied to the transportation of 175 floating objects among static structures due to dam-break flows as shown in **Fig. 4**. The floating objects and static structures are rectangle solids (12 [cm] × 5 [cm] × 5 [cm]) and cubes (40 [cm] × 40 [cm] × 40 [cm]) respectively. Each of the floating objects is represented with 490 tetrahedron elements. The different distances among the static structures were considered and numerical experiments were conducted for three cases. The number of computational cells and parallel processes are 840 × 480 × 60 (= 24,192,000) and 28 × 16 × 3 (= 896) respectively. In addition, all computations were conducted on the supercomputer system of Kyoto University, System D (Magnolia).

As a result of the computations, floating objects are transported by dam-break flows colliding with each other and the static structures as shown in **Fig. 5**. **Figure 6** shows distributions of floating objects near the static structures predicted in different distances among static structures. The number of objects trapped in front of the static structures became large when distances among the structures were small as shown in **Fig. 6**. These results show that the MICS can be applied to the transportation of tsunami debris in coastal cities.

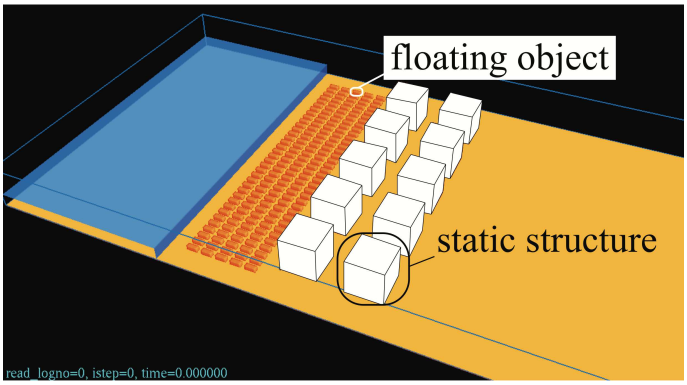
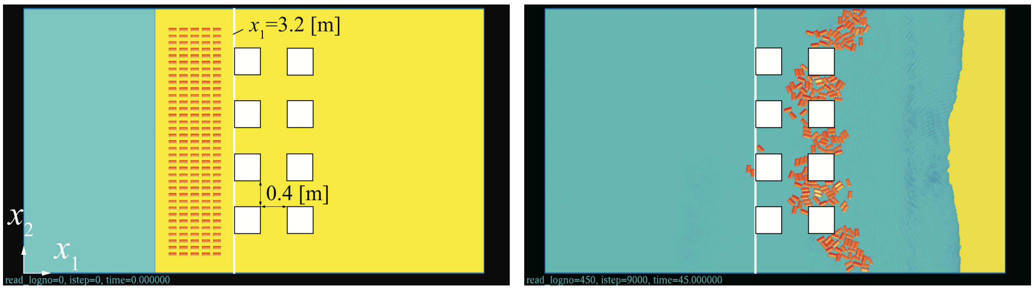
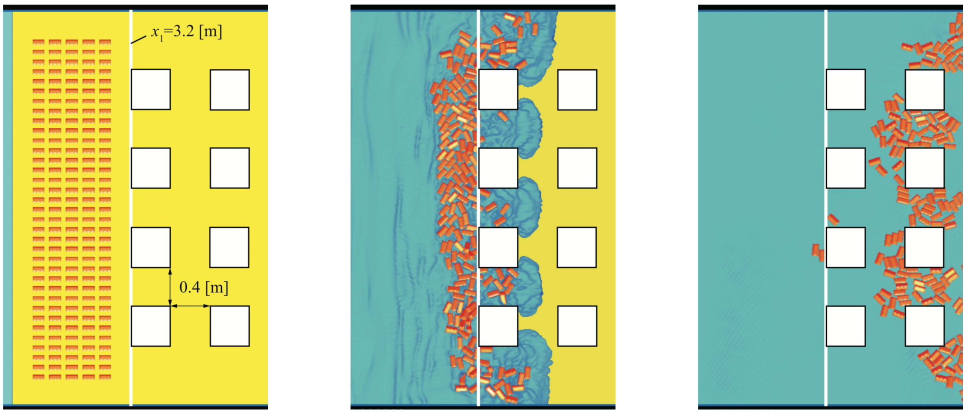


Figure 4: Calculation area contains floating objects and static structures



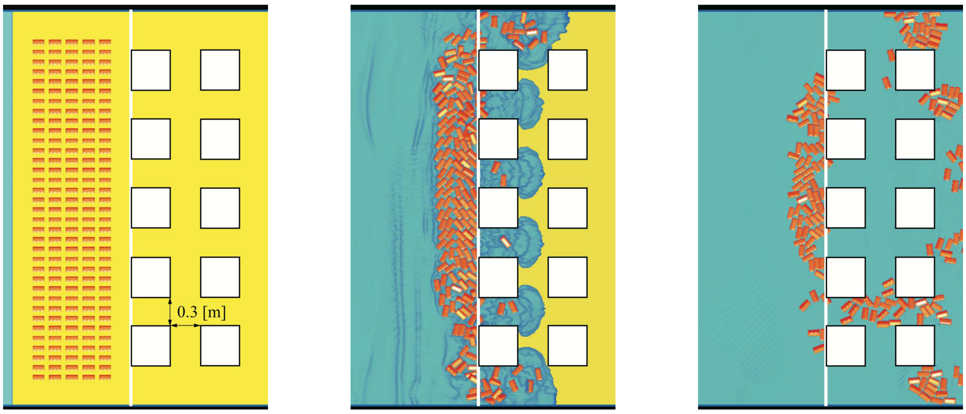
$t$ = 0.0 [s] $t$ = 4.0 [s]

Figure 5: Floating objects transported by dam-break flows



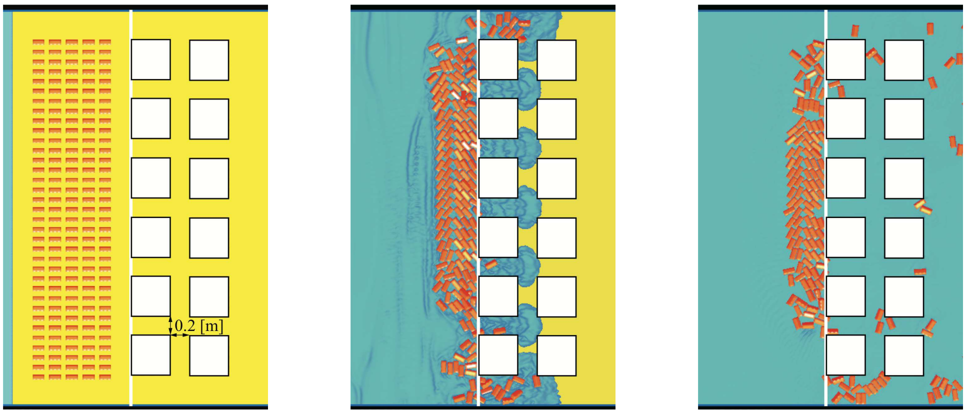
$t$ = 0.0 [s] $t$ = 4.0 [s] $t$ = 45.0 [s]

(a) Case 1 (distances between static structures are 0.4 [m])



$t$ = 0.0 [s] $t$ = 4.0 [s] $t$ = 45.0 [s]

(b) Case 2 (distances between static structures are 0.3 [m])



$t$ = 0.0 [s] $t$ = 4.0 [s] $t$ = 45.0 [s]

(c) Case 3 (distances between static structures are 0.2 [m])

Figure 6: Distributions of floating objects near the static structures

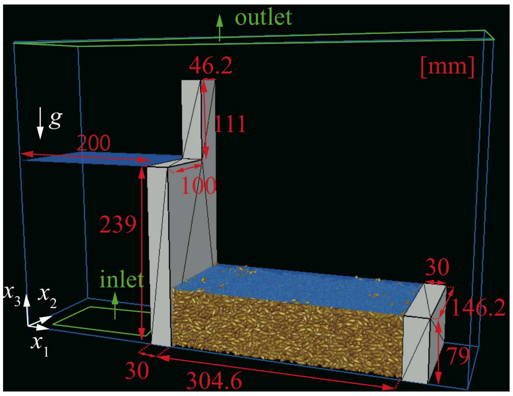


Figure 7: Calculation area for movements of sand particles due to overflows from weir (unit: [mm])

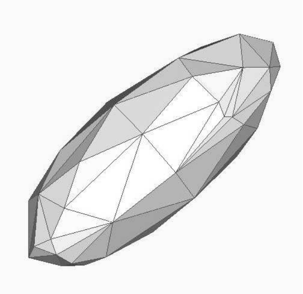


Figure 8: Sand particle represented with 121 tetrahedron elements

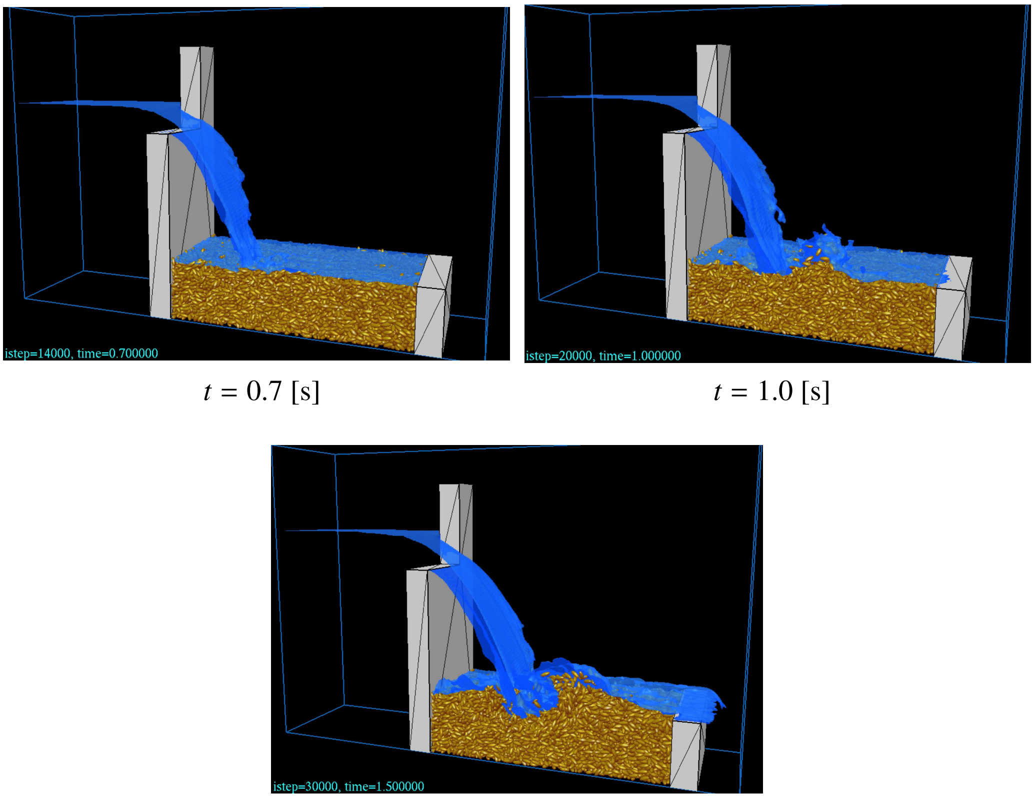
### 3.2. Movements of sand particles due to overflows from weir

The numerical experiments were conducted for movements of 14,400 sand particles due to overflows from a weir as shown in **Fig. 7**. The sand particles are spheroids and their long and short diameters are 12.2 [mm] and 5.0 [mm] respectively. In addition, each of the sand particles are represented with 121 tetrahedron elements as shown in **Fig. 8**. The inlet condition is imposed on the bottom of calculation area as shown in **Fig. 7**. The inflow rate is $1.8 \times 10^{-3}$ [m$^3$/s] and the inflow is stopped at $t = 1.5$ [s]. The number of computational cells and parallel processes are 392×96×260 (= 9,784,320) and 14×8×2 (= 224) respectively. The computation was conducted with the supercomputer system of Kyoto University, System D (Magnolia).

**Figure 9** shows predicted three-dimensional movements of sand particles due to overflows from the weir. **Figure 10** shows the local scour behind the weir caused by the overflows. As shown in **Fig. 9** and **Fig. 10**, complicated movements of many sand particles were calculated, e.g. detachment from the sand bed and deposition. As a result of such movements of sand particles, the local scour arose behind the weir same as preceding similar experiments [8].

## 4. Conclusions

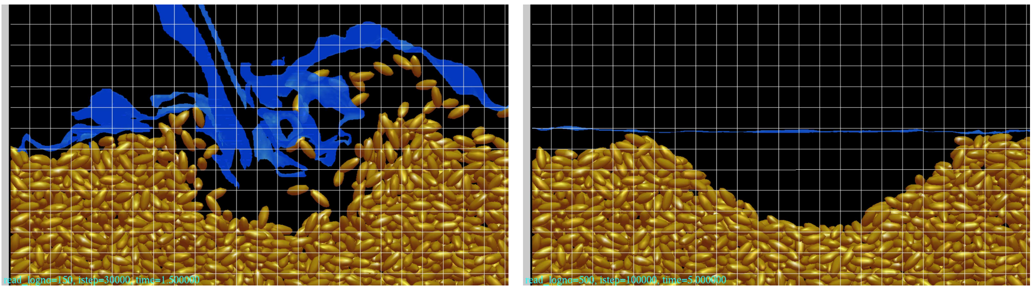
In this paper, 3D parallel computational method, MICS, was applied to fluid-solid interaction problems in civil engineering that contain many solid objects. As a result of the numerical experiments for transportations of many floating objects by dam-break flows and movements of sand particles due to overflows from the weir, it is concluded that the MICS enables us to predict three-dimensional motions of many solid objects included in the flows by using parallel computations and the supercomputer system.



$t$ = 0.7 [s] $t$ = 1.0 [s]

$t$ = 1.5 [s]

Figure 9: Movements of sand particles due to overflows from weir



$t$ = 1.5 [s] $t$ = 5.0 [s]

(Sand particles are drawn within 0 [mm] $\leq x_2 \leq$ 14.6 [mm])

Figure 10: Local scour behind weir

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