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A COMPACTION PROCESS OF WAVE DISSIPATING BLOCKS DUE TO HIGH WAVES SIMULATED BY 3D LAGRANGIAN MODEL

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ABSTRACT

A compaction-process of blocks which is one of a subsidence mechanism of wave dissipating blocks has been investigated by an experiment and a numerical simulation. The experiment was conducted in wave flume with piston-type wave generator. The 1/100 scale model of 80t type tetrapod® block was used as a wave-dissipating block. On the other hand, numerical simulation was performed under the same condition as the experiment using the block model based on the three-dimensional distinct element method with the passively-moving-solid model. Influence of the subsidence of blocks on the mound topology of blocks will be described from a comparison between the experiment and the numerical simulation.

Keywords: Wave dissipating block, 3D distinct element method, Passively-moving-solid model, Hydraulic model experiment

1. INTRODUCTION

A seawall covered with wave-dissipating blocks, which attenuate wave over topping and decrease reflected wave, is one of the protection facilities of harbour, and also is widely used around coastal zone facing open sea. There are many reports of coastal disaster about subsidence of wave-dissipating blocks in front of a caisson. The subsidence of blocks are caused as follows: 1)liquefaction of sea bed around bottom of the wave-dissipating blocks (e.g. Zen *et al*., 1990), 2)scouring at toe of wave-dissipating blocks (e.g. Suzuki *et al*., 2002), and 3)compaction of wave-dissipating blocks due to a change of engagement between blocks. Although an occurrence of a clear liquefaction is not confirmed from a measurement of pore water pressure on site, significant subsidence of blocks after a storm was reported in recent studies (e.g. Sassa *et al*., 2003 and Takayama *et al*., 2004). Furthermore, Gotoh *et al*. (2005) shows that irregular disposition of blocks is a great influence on a compaction of blocks from the numerical simulation by using the three dimensional block model (Gotoh *et al*., 2002) based on the distinct element method (Cundall *et al*., 1979).

In the present study, to show the relation between the subsidence and compaction of blocks, the experiment by using a wave flume and the numerical simulation by using the three dimensional block model based on the distinct element method have been performed. In the experiment, we have confirmed the subsidence of blocks due to compaction, and we have shown the influence of the geometric feature of bed on the subsidence of blocks. On the other hand, the internal structure of blocks, measurement of which is difficult in the experiment, has been investigated computationally from the viewpoint of inter-block force.

2. SIMULATION MODEL

2.1 Block model

The model of the compaction process of the wave-dissipating blocks is described by the three dimensional distinct element method, or the 3D-DEM, proposed by Gotoh *et al.* (2002) to calculate interactions between contacting blocks explicitly. Present model is the extension of the movable bed simulator, or the MBS, proposed by Gotoh *et al.* (1997). The 2D-DEM code is the lagrangian model of the motion of sediment particles in turbulent flow in considerartion of inter particle collision. In the distinct element method, block/block and block/wall interactions are modeled by the spring and dashpot system assumed at every contacting point with other blocks or wall. The wave-dissipating block is constituted by spherical elements. The motion of each block element is tracked by the translational and rotational equations as follows:

$$\frac{d^2 \boldsymbol{x}_i}{dt^2} = \frac{\boldsymbol{F}_{pint} + \boldsymbol{F}_{wave}}{M_i} + \boldsymbol{g} \tag{1}$$

$$\frac{d^2 \boldsymbol{\phi}_i}{dt^2} = \frac{\boldsymbol{T}_{p\,\mathrm{int}}}{I_i} \tag{2}$$

$$M_i = \frac{\sigma \pi d_i^3}{6}\,;\, I_i = \frac{\sigma \pi d_i^5}{60} \tag{3}$$

in which, $\boldsymbol{x}_i$, $\boldsymbol{\phi}_i$=location and rotational angle on the global coordinate $\boldsymbol{x}$; $\boldsymbol{F}_{pint}$=element/element interaction force vector on the global coordinate $\boldsymbol{x}$; $\boldsymbol{F}_{wave}$=force vector caused by wave pressure; M_i=mass of element; $\boldsymbol{T}_{pint}$=torque on the global coordinate; I_i=moment of inertia of element; σ=specific density of element; and d_i=diameter of element. The contact force between each contacting elements is modeled by arranging the voigt model, or a spring-dashpot system, both of the normal and the two tangential axes of the local coordinate formed on the contacting plane of elements. The model constants (k_n, k_s=normal and tangential components of spring constants respectively; and c_n, c_s=normal and tangential components damping coefficients respectively) are determined with following the optimization procedure proposed by Gotoh *et al.* (2001) as follows: k_n=9.47×10^6 N/m, k_s=3.64×10^6 N/m, c_n=3.58×10^5 Ns/m, c_s=2.22×10^5 Ns/m. In this simulation, the torque of the rotational motion of element around normal axis of contact plane between elements is not taken into consideration.

The wave-dissipating block of tetrapod® type is formed by overlapping 32 spheres, diameter of which is 2.0m, in consideration of the geometric shape of the tetrapod® as shown in Figure 1. The motion of block is tracked by using the passively-moving-solid model proposed by Koshizuka *et al.* (1998). First block is tracked by the distinct element method with no rigid connection among each element of block. As a result, the relative position of each element of block changes. So, correcting calculation is given to the block elements to keep initial relative position of each element of block. The relative position of each block is corrected in the following way. The translational and rotational velocity vectors $\boldsymbol{T}$ and $\boldsymbol{R}$ of each block is calculated as follows:

$$\boldsymbol{T} = \frac{1}{N}\sum_{i=1}^{N} \boldsymbol{u}_i \tag{4}$$

$$\boldsymbol{R} = \frac{1}{I}\sum_{i=1}^{N} (\boldsymbol{r}_i - \boldsymbol{r}_g) \times \boldsymbol{u}_i \tag{5}$$

in which, N=number of block elements; and $\boldsymbol{u}_i$=velocity vector of block element i. The gravity center $\boldsymbol{r}_g$ and the inertia tensor I of block is given by

$$\boldsymbol{r}_g = \frac{1}{N}\sum_{i=1}^{N}\boldsymbol{r}_i \quad ; \quad I = \sum_{i=1}^{N}\left|\boldsymbol{r}_i - \boldsymbol{r}_g\right|^2 \tag{6}$$

Then, to satisfy motion as a rigid body the velocity vectors of block elements are replaced by velocity vector $\boldsymbol{u}_{Bi}$ as follows:

$$\boldsymbol{u}_{Bi} = \boldsymbol{T} + (\boldsymbol{r}_i - \boldsymbol{r}_g) \times \boldsymbol{R} \tag{7}$$

$$\boldsymbol{r}_i(t + \Delta t) = \boldsymbol{r}_i(t) + \boldsymbol{u}_{Bi}\,\Delta t \tag{8}$$

By applying the above mentioned velocity-vector-correction procedure to the block elements, the motion of block can be tracked.

Each wave-dissipating block
consists of 32 elements.

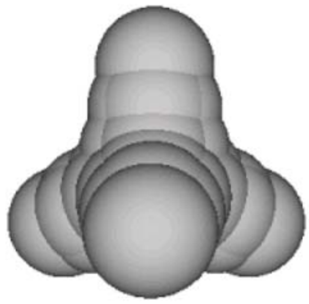

Figure 1 Model of wave-dissipating block

2.2 Modelling of driving force due to wave

To evaluate dynamic wave force acting on blocks precisely, an analysis of local flow field around blocks by using full three dimensional free-surface flow model is required. However, computational load of this kind of model is extremely high. In the present study, with focusing on block dynamics, evaluation of flow field was treated simply. The peak wave pressure in the horizontal direction acting on each block is calculated by using Goda's formula (Goda, 1973) of wave pressure. The wave pressure acting on each block element is evaluated by the product of the value of Goda's formula (Goda, 1973) and area of sphere projected on the onshore direction. The wave pressure acts on center of the spherical elements. By the way, in the present study, each block was composed of overlapping 32 spherical elements. Hence, if wave pressure is given to all components of each block, the wave pressure acting on each block is overestimated. Besides, wave pressure does not act directly on inside blocks covered with other blocks. In consideration of these facts, wave pressure acts on only the outside of the blocks, which are in most offshore side. Time-dependent pattern of wave pressure acting on the block is given simply as an alternative repetition of 1.0s-loading and 4.0s-unloading by using a impulse wave of 5.0s wave period shown in Figure 2. We paid attention to keep enough period of unloading phase as motion of block does not affect next loading phase.

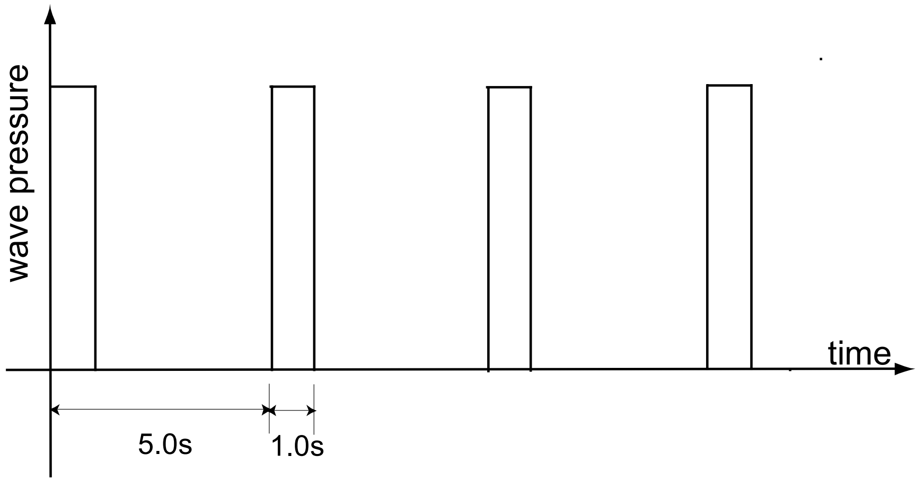

Figure 2 Pattern of wave pressure

3. EXPERIMENTAL CODITION

The experiment is conducted by the wave flume, which is 16.0m in length, 0.5m in width, 0.8m in depth, with piston-type wave generator. A model of a seawall covered with wave dissipating blocks is formed with about 200 pieces of the 1/100 scale model of 80t-type tetrapod® blocks set in front of bricks as a model of caisson, which is placed in about 12.0m from the wave making paddle shown in Figure 3.

The blocks are arranged in the two-layer arrangement type in the horizontal direction in consideration of as dense arrangement of blocks as possible. The blocks are arranged on 15 sheets (3×5: 3 sheets in *x*-axis, 5 sheets in *y*-axis) of the glass boards, each glass board is formed by gluing 25 (5×5) glass beads. Each glass bead is 2.5 in specific density and 2.0cm in diameter. In addition, the glass boards are on the uneven bed made by the acrylic resin board 0.6cm in thickness. The 1/100 model is made with following the Froude similarity. The experiment is performed in the condition as follows: 0.17m in water depth, 1.2s in wave period, and 0.1m wave height. The subsidence process is recorded by using a digital video camera from three directions: side, front, and top of the wave flume.

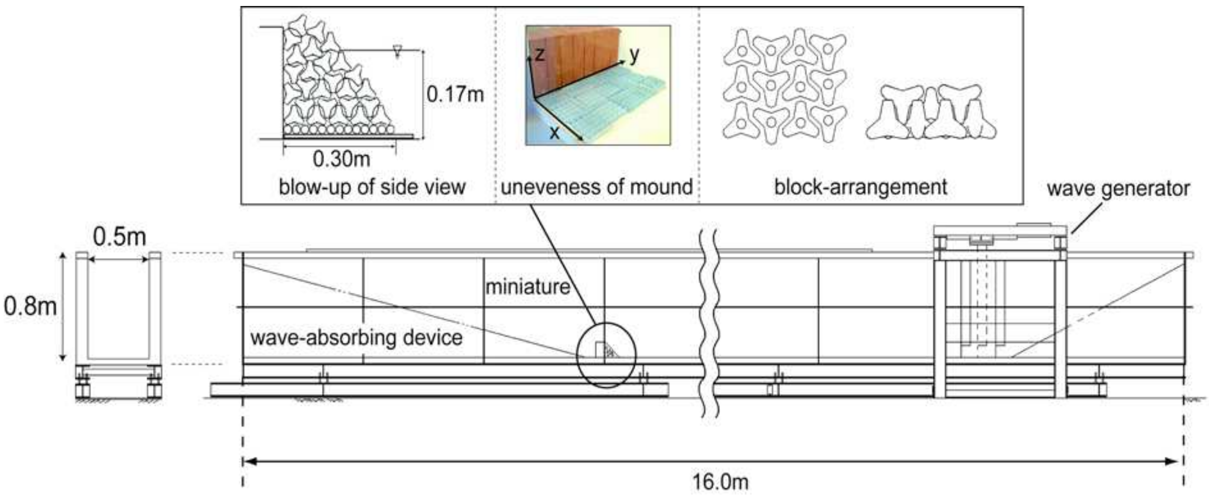

Figure 3 Schematic diagram of wave flume and experimental set up

4. COMPACTION PROCESS OF BLOCKS

4.1 Comparison between experiment and simulation

The compaction process of blocks due to acting waves in the experiment and the simulation are shown in Figure 4. The tendency of subsidence is confirmed from the difference of relative displacement of blocks between initial condition and after acting 10 waves in both of the experiment and the simulation. A slightly large subsidence in the simulation shown in comparison with the experimental result. The reason is that we can arrange blocks tightly one by one in the experiment, on the other hand, such operation is impossible in the simulation. Hence, interlocking blocks in the simulation is looser slightly than the experiment. For that reason, a slightly large subsidence can be shown in the simulation. A remarkable subsidence around the top of the blocks is found. The reason should be that the dead load of blocks which contributes as a resistance of block motion, in upper layer is smaller than that on the middle and bottom of the blocks. In the experiment, the fallen block can be found. The fallen block after acting waves is circled in the figure of the initial condition of the experiment. In the figure of the top view, the movement of blocks in the direction of *x*-axis is shown. The movement of the blocks around the top layer toward the negative direction of *x*-axis is shown clearly from the relative displacement of blocks from the dashed line of *x*=5.0cm between initial and after 10 waves conditions. A good agreement between the experiment and the simulation is understood from the movement of the white blocks located on the dashed line.

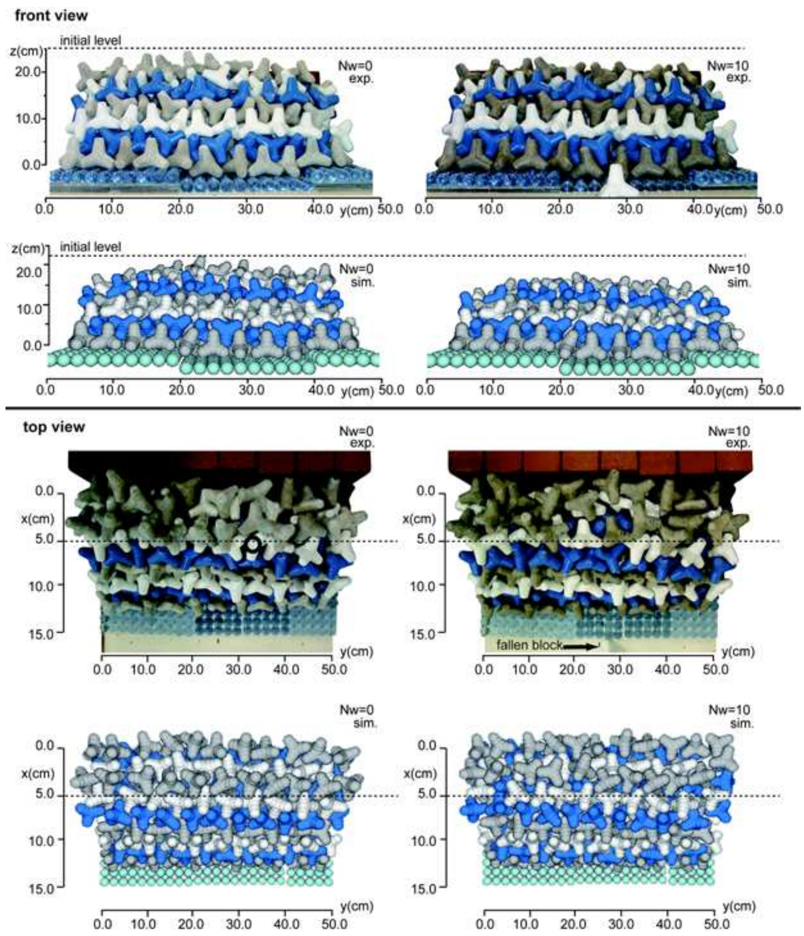

Figure 4 Compaction process of blocks (upper: front view, lower: top view)

Figure 5 shows the time series of subsidence observed in blocks around crest height at every wave period. Although about 5% difference in the subsidence is found at 10th period, good agreement between the experiment and the simulation such as the tendency of gradual subsidence of blocks is shown as follows: sudden subsidence in initial periods, stagnation process of subsidence from the 3rd- to the 5th-periond, and then sudden subsidence again from the 5th- to the 7th-period. The good performance of the present simulation code is demonstrated.

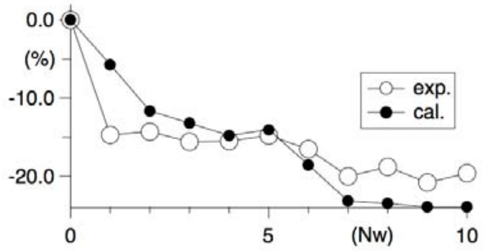

Figure 5 Time series of settlement

4.2 Internal structure of blocks

To examine the moving process of blocks under the condition of subsidence, the displacement of blocks layers as targets shown in Figure 6. And the displacement of blocks after 10 waves action is given in Figure 7; the center of gravity of each block was plotted. The movement of each block in the 1st-layer, or around the top of blocks, shows spatially non-uniform movement. Especially, the significant movement of blocks is shown around x=20.0-30.0cm. Although the same kind of movement of blocks as the experiment is found in the simulation, the spatially non-uniform movement of each block can not be clearly confirmed. The remarkable movement of blocks around the sidewall of the wave flume is not shown in the experiment, while the blocks arranged around the sidewall shows significant movement in the simulation. The discrepancy may be caused by the different way of the arrangement of the blocks. In the experiment, each block is arranged one by one tightly contacting with neighbouring blocks. Hence, blocks arranged around sidewall are especially tightly, and are restricted to active movement by neighbouring blocks. On the other hand, the interlocking of the initial arrangement between block/block and block/wall is not enough in the simulation. In addition, the tendency of irregular movement of blocks is shown in the experiment because the blocks were arranged with the slight irregularity according to the position of neighbouring blocks. While, because the blocks are arranged regularly in the simulation, the tendency of regular movement of blocks would be shown comparatively. The movement of the 2nd-layer is smaller than that of the 1st-layer in the experiment. This would be the reason why the dead load of blocks in the 2nd-layer is larger than that of the 1st-layer, the blocks around the 2nd-layer is in difficult condition to move in comparison with the blocks in the 1st-layer. Furthermore, the influence of the uneven bed form on regularity of block-arrangement at each layer increases gradually from the bottom to the top of blocks; that is to say the influence of the uneven bed form on the blocks around the 2nd-layer is less than that the 1st-layer, and also the arrangement of blocks are more regular in comparison with the 1st-layer. Therefore, the structure of blocks around the 2nd-layer would be more steady than that of the 1st-layer. On the other hand, in the simulation, the blocks around the 2nd-layer would be pushed regularly by the acing waves toward the negative direction of x-axis on the whole, because the engagement between neighboring blocks is not enough due to the regular arrangement of blocks. In addition, the significant movement of blocks after acting waves around the bottom of the blocks was not found in both the experiment and the simulation.

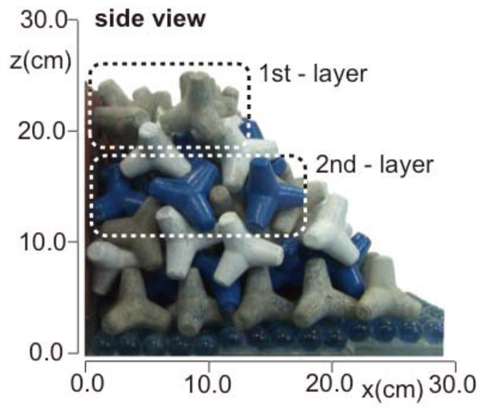

Figure 6 Illustration of block layer

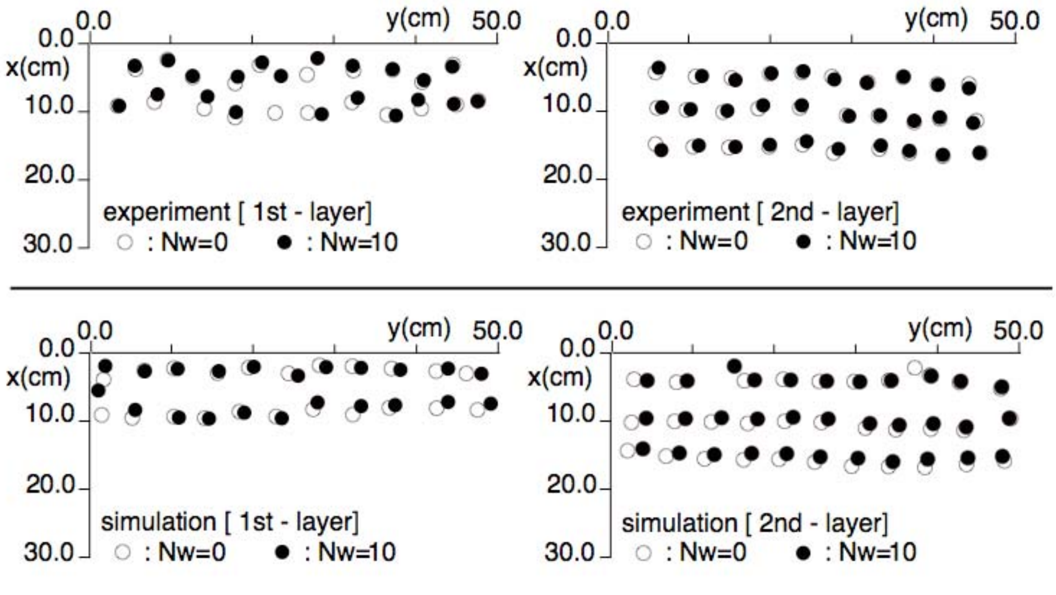

Figure 7 Movement of blocks in each layer

The investigation of the force between blocks is important for understanding the internal structure of blocks. The measurement of force between blocks is difficult in the experiment, while the evaluation of that is easy in the simulation. The force between blocks at each acting wave is shown in Figure 8. The force between blocks is represented as the cylinder, the axis direction of cylinder is the direction of acting force and the force is in proportion to the diameter of the cylinder. Although the remarkable force between blocks due to the change of the block arrangement is shown around the top of the blocks in the vicinity of the area (x, y, z)=(10.0cm, 0.0cm, 20.0cm), the inside of the block mound does not shows the significant concentration of force between blocks at the 1st-period. The remarkable force between internal blocks would not be shown at this stage, because the interlocking blocks are in loose. However, at the 5th-period when the compaction process of blocks is found as the time series of subsidence of blocks shown in Figure 5, the wave force would lead to the concentration of force between the blocks inside the block mound. The same tendency such as the concentration of force between inside blocks is shown more clearly at the 10th-period. In addition, this significant concentration between blocks is shown around the x=5.0-15.0cm, y=30.0-40.0cm where unevenness level of the bottom bed is large. From this fact, the large unevenness of bottom bed would lead to a damage of broken leg of blocks. And the phenomenon of this kind of the concentration between blocks is promoted by the unevenness of bottom formed by the sand outflow due to suction, too. Hence a control of the unevenness of the bottom bed is important for the prevention of the subsidence of blocks.

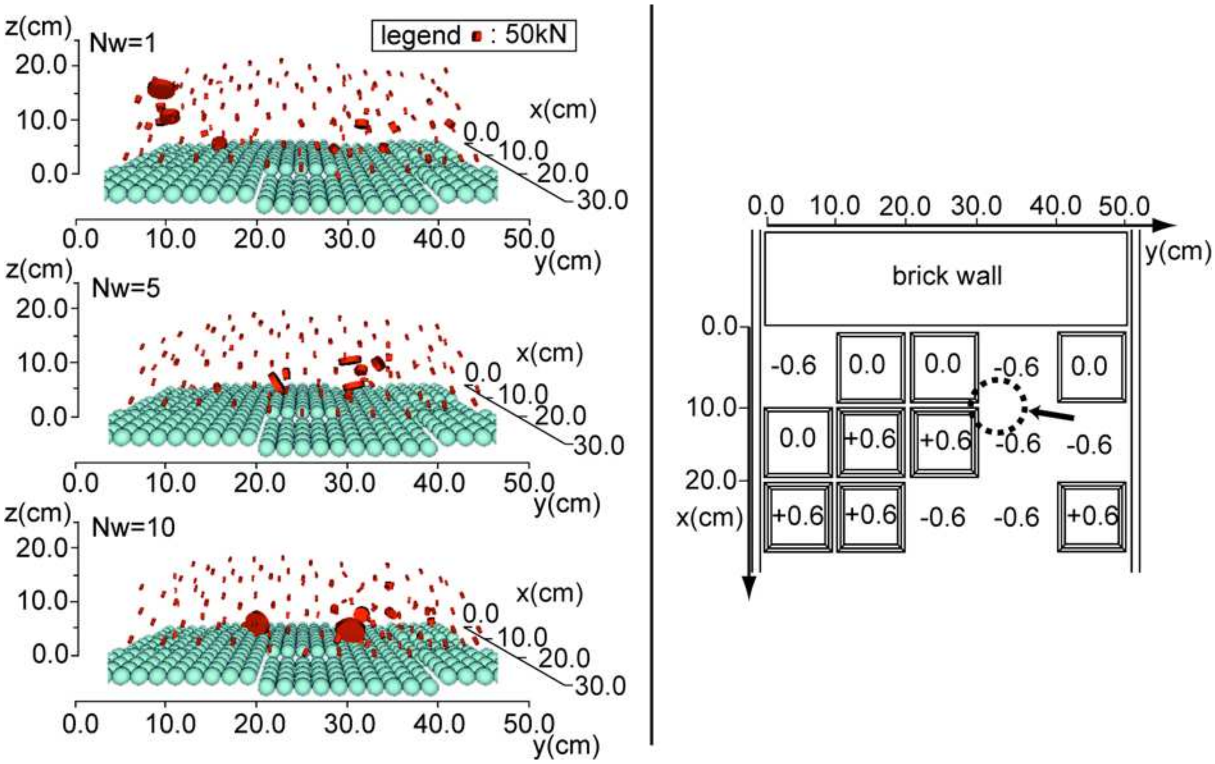

Figure 8 Inter block force vector and unevenness of mound

5. CONCLUSION

In this study, the compaction process of blocks due to acting waves was experimentally and numerically investigated in detail. The good agreement of the tendency of the gradual subsiding process of the blocks was found in both of the experiment and the numerical simulation. The slight difference of the characteristics of the movement of blocks between the experiment and the numerical simulation was investigated in detail from the viewpoint of interlocking blocks. Furthermore, the influence of the unevenness of the bottom bed on the concentration between blocks and the characteristic of the movement of the inside blocks were investigated.

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