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Ice load on floating structure simulated with dilated polyhedral discrete element method in broken ice field

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ABSTRACT

The discrete element method with dilated polyhedral elements is developed to simulate the interaction between ice floes and the floating structure. The 2D-Voronoi tessellation algorithm is adopted to generate polyhedral ice floes with a given ice thickness in broken ice field. According to the Minkowski sum theory, the dilated polyhedron is constructed via sweeping a sphere on the surface of a basic polyhedron. The Hertzian contact model and its simplified form are then adopted to determine the contact force between dilated elements due to the round profile of the element. Meanwhile, the buoyancy and buoyancy moment, the drag force and drag moment on ice floes are calculated by meshing every polyhedral element as tetrahedrons. The floating structure *Kulluk*, which operates in the Arctic, is modeled as a rigid body restricted by mooring lines with the linear stiffness. The structure motion is calculated with six degrees of freedom in terms of the ice contact force, the buoyancy, the drag force of current, and the mooring force. Under different ice thickness and concentration, the ice load on the floating structure is reasonably compared with the field data. General influences of different ice conditions are analyzed to provide operational principles in engineering.

1. Introduction

The sphere in 3D has been adopted in discrete element method (DEM) since its contact detection and force model are simple and efficient. The bonding model of the sphere element was developed systematically for applications in engineering [1]. However, the sphere element has drawbacks in describing the complex shape of the granular matter, and scale parameters would influence the result seriously [2]. Considering the disadvantages of the sphere element, non-spherical particle element including the clump element consisted of several bonded spheres is developed in DEM [3–5], especially the polyhedron-based DEM which is widely used in the geological evolution and the geotechnical engineering due to the realistic geometric shape [6–8].

It is well known that the computation time of the polyhedron-based DEM is mainly cost in the contact detection which includes the calculation of the contact point and the overlap between contacted polyhedrons [9,10]. The Common-plane (CP) algorithm is one of the most famous and important methods [11]. The fast common plane (FCP) [12] and the shortest link method (SLM) [13] were developed based on the CP. However, the efficiency of such CP-based methods greatly depends on the choice of the initial point/section and the number of iterations is highly uncertain [14], especially when the objective polyhedron or the contact pattern is excessively special in 3D space. Meanwhile, the determinations of the contact point and the normal direction are different in different detection methods, especially for the singularity in the corner–corner contact pattern [15]. The digital method costs a huge computational memory [16], and the ODDS (Orientation Discretization Database Solution) approach is not suitable for the particles with many different shapes [17]. On the other hand, the contact force of polyhedrons is mostly determined by a product function between a constant stiffness and the overlap [13,18]. Usually the stiffness is determined by experience and without physical reasons. Thus, such solutions of the contact force are short of mechanical bases and just for a heuristic simulation for now.

The Minkowski sum is adopted to generate the dilated polyhedron with the tunable grain roundness which can make the contact detection more efficient [19,20]. The finite wall method [21] and the shrunken edge algorithm [22] applied in the contact detection were developed with the homologous morphology concept. The dilated flat disk was introduced to simulate the ice motion with the Minkowski sum [23,24]. This method for the polyhedron/polygon element in DEM was initially and systematically introduced by

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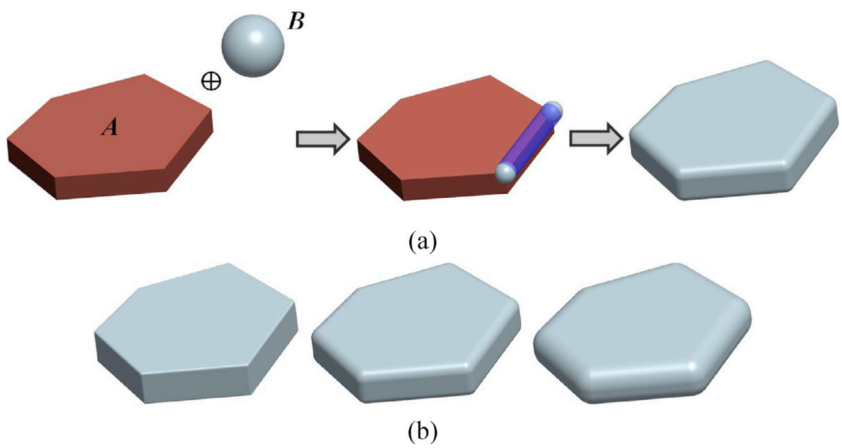

Fig. 1. Dilated polyhedron generation: (a) dilated polyhedron by the Minkowski sum of a polyhedron and a sphere; (b) different shapes of dilated polyhedron with different dilated radii.

Pournin and Lionel [25], and then developed by Alonso [26] and Galindo-Torres [27]. The singularity of the corner contact and the choice of the contact point are solved credibly by this means. Furthermore, the bonding model for the breaking process and the LBM (Lattice Boltzmann Methods)-DEM coupled model have been established by the dilated polyhedral element [28,29]. The dilated polyhedron has extensive applications in engineering.

The discrete element method is applied in the sea ice simulation to represent the granular characteristics of the sea ice [30–33]. The fracture of ice is also simulated by DEM based on continuum theory and bonding model [34–36]. The discrete element method is an important method to simulate the ice collision, pile-up, and dynamic ice loads on the structure. The station keeping in the broken ice cover is modeled with DEM and vortex element method to concern the complex hydrodynamics on the structure and ice floes [37]. The ice load on floating structure from the level ice and ice floes is simulated by 2D Particle-In-Cell method [38] or ice fracture theory [39]. However, a real 3D scaled DEM simulation for the interaction between ice floes and the floating structure is still demanded to analyze the ice load in engineering and the practical operations.

In this paper the dilated polyhedral DEM is developed including the element construction, the contact force model and the contact detection method. The multiprocessing parallel technology OpenMP (Open Multi-Processing) is utilized to improve the computational efficiency. The interaction between sea ice floes and the floating structure *Kulluk* is simulated to determine the ice load. The simulation results are validated against field data.

2. Initialization of ice element

The dilated polyhedron is constructed by the Minkowski sum of a sphere and a randomly-shaped convex polyhedron. Vertices and edges are turned to be spheres and cylinders in the dilated polyhedron. Meanwhile, the 2D-Voronoi tessellation algorithm is employed for the random distribution of the floe size and shape. Hence, the elements representing ice floes are generated by stretching polygons from the 2D-Voronoi diagram at vertical direction.

2.1. Generation of dilated polyhedron

The Minkowski sum of a polyhedron A in 3D space and a sphere B is defined by [19]

$$A \oplus B = \left\{ \vec{x} + \vec{y} | \vec{x} \in A, \vec{y} \in B \right\} \tag{1}$$

where the operator $\oplus$ means sweeping one set around the profile of the other. A dilated polyhedron is constructed by the Minkowski sum of a basic polyhedron and a sphere. The outcome is a larger 3D geometric shape with smooth corners and edges, as shown in Fig. 1. Different shapes of dilated polyhedron can be generated by different shapes of basic polyhedron and different sphere radii (dilated radii).

Normally, the overlap between polyhedrons in contact required in the contact force model cannot be obtained efficiently. The contact detection of two spheres is more efficient than that of two polyhedrons, and therefore the overlap is easier to be determined owing to the simple geometry parameters of the sphere. A dilated polyhedron could be regarded as a polyhedron enwrapped by countless spheres according to the definition of Minkowski sum. Hence, the contact detection of dilated polyhedrons can be converted into the contact detection of spheres. In fact, the contact detection of polyhedrons including vertex-vertex, vertex-edge, vertex-face, edge–edge and edge-face are converted into: sphere-sphere, sphere-cylinder, sphere-face, cylinder–cylinder and cylinder-face between dilated polyhedrons. The efficiency of contact detection is improved by the Minkowski sum apparently.

2.2. Generation of broken ice field with Voronoi tessellation

The random distribution of floes including shape, size and ice concentration is important to the numerical simulation [40,41]. The 2D-Voronoi tessellation algorithm is employed to divide a domain into random shape of polygons called 2D-Voronoi diagram (also called 2D-Voronoi cell) [42]. This diagram is based on some random points called Voronoi points in the domain. Firstly the Voronoi points are connected to be Delaunay triangles which are unique if the points are settled. The perpendicular bisectors of every triangle segments are then drawn until convex and closed polygons are formed. Fig. 2(a) shows 200 Voronoi points and the outcome of the Voronoi tessellation algorithm while the rectangle boundary is concerned.

The ice concentration can be decided directly. If the broken ice area is $S = l \cdot w$, where l and w are the length and width of this region, the pure ice area S' under the ice concentration c can be computed as $S' = l \cdot w \cdot c = \left(l \cdot \sqrt{c}\right) \cdot \left(w \cdot \sqrt{c}\right) = l' \cdot w'$, where l' and w' are the length and width of this new area. Then the Voronoi polygons would be created on the new area S'. The position of each polygon can be rearranged according to the ratios of S' to S. Ultimately the polygon will be rearranged on the entire region with the objective ice concentration. Fig. 2(b) shows the example of a broken ice field with ice concentration of 60%.

The distribution of the floe shape and size cannot be controlled directly. The shape and size distribution is influenced by the distri-