RMIB FOR MODELING ICE-STRUCTURE INTERACTIONS IN BROKEN AND UNBROKEN SEA ICE FIELDS (EFFICIENT GPGPU SIMULATION)

O.L. Konovalov
Belarusian State University, Minsk, Belarus

Introduction

In this thesis, we investigate the computationally efficient approach to coupled simulate the processes of failure both a continues ice fields and a broken ice dynamic, caused by moving ice-breaking ships. Simulations of ice–structure interaction need to consider a complicated process (figure 1) including: fragmentation of ice field; formation and motion of ice blocks; interactions between the blocks; interactions between the blocks and the structure.

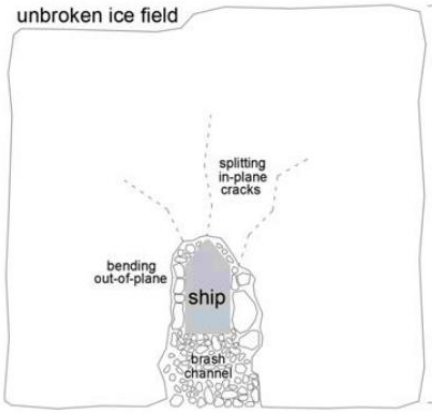


Figure 1. Ice-structure interaction process

Due to the discrete nature of broken ice, the Discrete Element Method (DEM) plays a central role in the development of numerical simulation programmers for ships traveling through broken ice. The classical DEM adopts an explicit scheme using rigid blocks and is usually referred to as the Smooth Discrete Element Method (SDEM). The contact detection (figure 2) on the fly is the most important issues in SDEM, and many researchers think that this “meshless” (ability of detection new contacts during the calculation procedure) is main feature of SDEM methods.

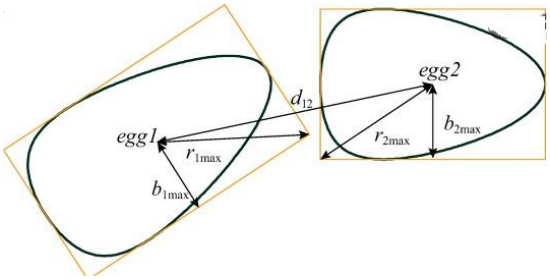


Figure 2. Contact detection scheme

From other side the collision detection is the most time-consuming step in

DEM. In worst case the complexity of contact detection is **O(N2)**, where N is number of particles. There are many contact detection algorithms, which target is saving computing time and memory space, however this step is one of the most time consuming step of DEM.

From other side, for the simulations of fracture of continuous icefields, the bond based Discrete Element Method (BDEM) is used[1]. Bond DEM use stable bond's structure and there are not need the collision detection calculation step.

Typical example of bond DEM is real multidimensional internal bond (RMIB) approach that provide proper result of failure of continuous geostrsata. Physical correct crack propagation in RMIB arrive by very small time step that is proportional to value of relation of smallest bond length to sonic velocity for modeling material. Such small simulation time step request the special acceleration mechanism. For example massif parallelism approach based on GPGPU calculation. The BMIB is light applicable to GPGPU due to stable bond grid structure.

For coupled simulate the processes of failure (both a continues ice fields and a broken ice) there are as usually used both described above schemes, as SDEM, as bound DEM.

The main idea of presented in this thesis approach is to use one bond DEM computation scheme for both simulation. For this purpose, we provide to separate bond structure on two parts: stable and dynamic. The stable part are placed on GPU memory all time of computation, and the dynamics bonds are periodically reloaded between CPU<=>GPU.

The main assumption of presented approach is that size of scope of dynamic bonds is enough small and frequency of dynamic bond recalculation is enough low. If above assumption will be true, then we should also provide of correctness of proposed computational approach.

So, the contents of our thesis is following: we described our specific "one layer" bond DEM and perform number of numerical experiments to estimate size increase of dynamic bonds, frequency of CPU<=>GPU exchange and correctness of proposed computational scheme.

1. One layer ice RMIB

Historically the first approach for modeling the crack propagation in elastic rock environment was LS (Lattice Spring) [2]. The next step was the VIB (Virtual Internal Bonds) model, where a continuous medium are determined as discretized model of microstructural relationships. The improved model of VMIB (Virtual Multidimensional Internal Bonds) was proposed by Zhang [3]. In

VMIB model bonds are broken down into components: normal and tangential forces are considered separately. At the current time, Zhao proposed the RMIB (Real Multidimensional Internal Bonds) model[4], where the bonds are determined by the contact of the particles in some packaging of the simulated medium. Take into account that RMIB provide good results in simulation of failure of continuous geostrsata, we design to based our ice DEM model on this approach. It should be pointed that some authors already used bond based DEM for the simulations of fracture of continuous icefields.

In RMIB model, each bond contains two springs: a normal spring and a shear spring where, k_n and k_s are respectively the normal and shear stiffness of bond. The deformation vector u_{ij} of the bond, that connected particles i and j, decomposes into a normal u^n and a shear u^s_{ij} components. The normal and shear forces acting on the particle are: $F^n_{ij} = k_n * u^n_{ij}$, $F^s_{ij} = k_s * u^s_{ij}$. If the bond's deformation reaches the critical value (i.e. $u_{ij} > \delta_0$), the bond goes to the broken state. In this state, the normal spring still elastically works on compression, but does not exert a tensile strength. The forces, that arise when the shear spring is deformed, should be are decreased and works as friction forces.

In RMIB theory, the relationship between properties of discretized 3D model k_n, k_s and properties of continuous 3D model **E**, **ν** is given by equations:

$$k_n = \frac{3E}{\alpha^{3D}(1-2\nu)} \qquad (1)$$

$$k_s = \frac{3(1-4\nu)E}{\alpha^{3D}(1+\nu)(1-2\nu)} \qquad (2)$$

$$\alpha^{3D} = \frac{\sum l_i^2}{V} \qquad (3)$$

here **E**, **ν**, V, l are respectively the Young's modulus, Poisson ratio, volume of modeled media and average bond length.

For the shear spring, the relative shear displacement between two particles can be obtained simply as $u^s_{ij} = u^n_{ij} - u_{ij}$ like in some conventional lattice spring models. However, the shearing force calculated in this way is not rotationally invariant. To overcome the problem, Zhao has proposed a local strain based method [4]. In this method, the local strain of one particle is evaluated by a least square scheme, which only uses the displacement of itself and other particles, which have intact bonds with the particle. Based on above neighbor information the inverse of global transformation's matrix can be calculated. Unfortunately, in a practical simulation, the inverse of transformation's matrix may not exist in some conditions[4].

Our main assumption is that initial structure of ice bond structure is two dimensional Steiner constrained Delaunay triangulation (Steiner CDT). This bond grid structure we will name "**initial structure**". Therefore, the center of elements will be associates with triangulation vertices. It means that our ice model is "one layer". It means also that particle size is correlate with ice thickness. For each elements form the initial structure, we can define local manifold neighborhood (LMN) – the set of triangles adjusted with appropriate triangulation vertex (see figure 3).

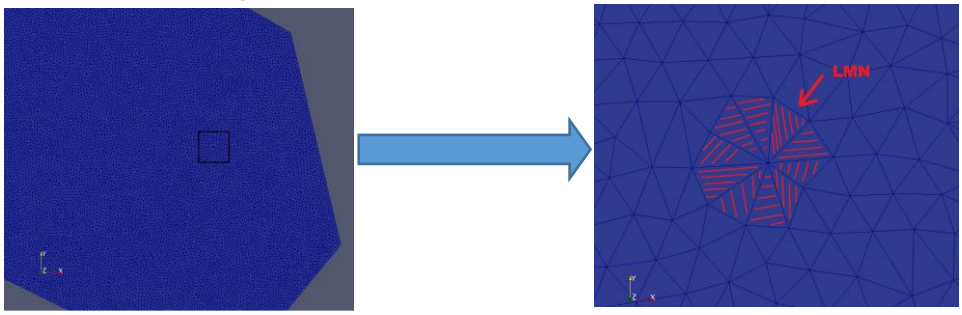


Figure 3. The set of triangles adjusted with appropriate triangulation vertex

The usage of Delaunay triangulation as bond structure give as some benefits. The first benefit of defined above structure is that under plane normal forces it provide 0.33 Poison ratio without usage of share forces. The second benefit is that we can use average normal of LMN as local appreciation of ice surface normal in center of DE. Let $\mathbf{a_i}$ is average LMN normal of particle **i**. We will calculate $\boldsymbol{u^n}$ as projection $\boldsymbol{u_{ij}}$ on plane with normal $\mathbf{a_i}$ and we will calculate $\boldsymbol{u^s_{ij}}$ as projection $\boldsymbol{u_{ij}}$ on vector $\mathbf{a_i}$. So, the interaction forces at the contact interface between two particles i and j (F ij) are obtained from the normal ($F_{ij}^n = k_n * \boldsymbol{u^n_{ij}}$) and tangential ($F_{ij}^s = k_s * \boldsymbol{u^s_{ij}}$) components.

2. Dynamic bonds structure and effective re-meshing algorithm.

If during simulation moving ice-breaking ships process the initial 2d bond structure is "lose" thee Delaunay properties, then we force recalculate bond's structure. The Delaunay lemma give as the way to recognize this "loses" effectively due to control only local Delaunay property (figure 4). It give as possibility to move this control on GPU level. The cost of above solution is additional global memory to store cells and neighborhood.

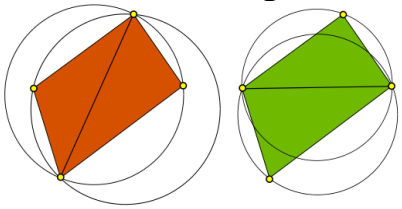


Figure 4. Local Delaunay property control

If this re-meshing will be perform on CPU then we need periodically reloading new bond structure between CPU and GPU memory and it can destroy all GPGPU advantages. To avoid this we propose divide bond structure on two parts static and dynamic.

We have propose the following algorithm to calculate above “dynamic 3d bond structure”. We will perform three dimensional Delaunay triangulation (DT) over “extended simplicial complex”. This “extended” complex includes initial CDT triangulation and two additions “bounding” points. One of them place below and other place under of ice field to provide 3d convex hull included elements of initial 2D bond structure. Than we remove from resulting DT the all edges that already presented in initial structure of bonds and edges adjusted with two “extended” bounding points. The scope of residual edges will be the required dynamic bond structure. The complexity of three dimensional Delaunay triangulation is ***N*log(N)***. Therefore, we receive main benefit of our approach:

O(N*log(N)) instead ***O(N2).***

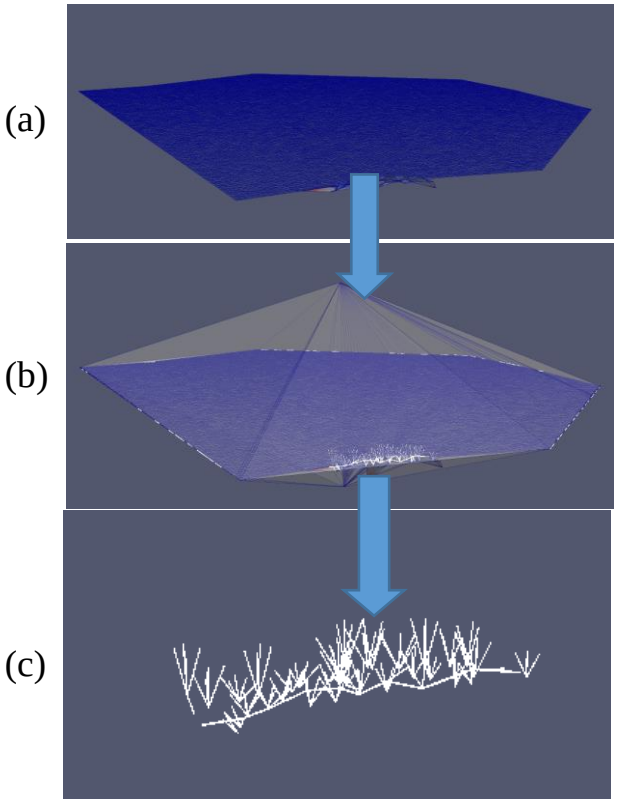


Figure 4. Dynamic 3D bond stucture calculation algorithm

The figure 4 illustrate described above algorithm. On subfigure “a” we see the current stage of our “one layer ice” model. On subfigure “b” we see three dimensional Delaunay triangulation over “extended” complex includes initial CDT triangulation and two additions “bounding” points. On subfigure “c” we see the new detected dynamic bonds structure.

During bond DEM calculation pipeline, we will use both bond schemes and “static” and “dynamic”. Therefore, size of “dynamic structure” are critical for proposed approach. We will be investigate this value experimentally.

3. Numeric simulation

3.1 Ice cakes and floe-ice fractures by spherical body.

In this section we study the interaction between an ice-breaking ship and separate ice floes. The simulated system consists of a digital model of a theoretical ship bow advancing with a constant speed in one direction towards the modeled ice floe. Thus, the numerical simulation is of a Single Degree of Freedom (SDF) motion. This simulations are described by two elements: the ship bow and the modeled ice floe. The ship bow is considered as a solid with imposed motion and represent be analytical sphere body, whereas the ice floe is composed by an arrangement of bonded Voronoy particles.

In Table 1 the computational parameters for the ice material, the computational parameters for the ship bow and the numerical computational parameters are listed.

Table 1. Material’s property and ship bow geometry

Definitions	Values	Units
Ice cover size	150 x 300	m
Ice thickness	0.3	m
Sphere radius	25	m
Sphere velocity	0.5	m/s
Sphere/water elevation	0.5	m
Density of ice	920	kg/m3
Young Modulus of ice	1e+9	Pa
Poisson ratio of ice	0.33	
Ice-ice (static) friction	0.05	
Ice-bow (static) friction	0.25	
Young Modulus of ship bow	20e+9	Pa
Time step	1.0e-5	s
Simulation time	70	s
Calculation time	2	hour

Motion scheme and boundary conditions present on figure 5. The white ray show us the direction of ship movement. The red areas define the boundary condition on ice floe with zero velocity.

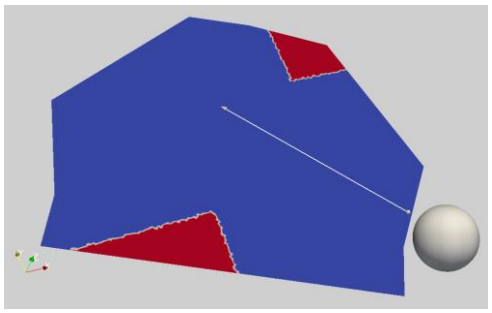
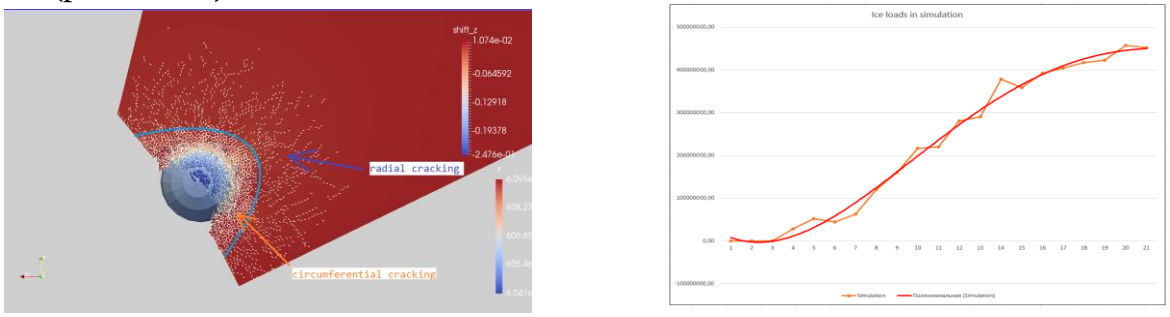


Figure 5. Boundary conditions

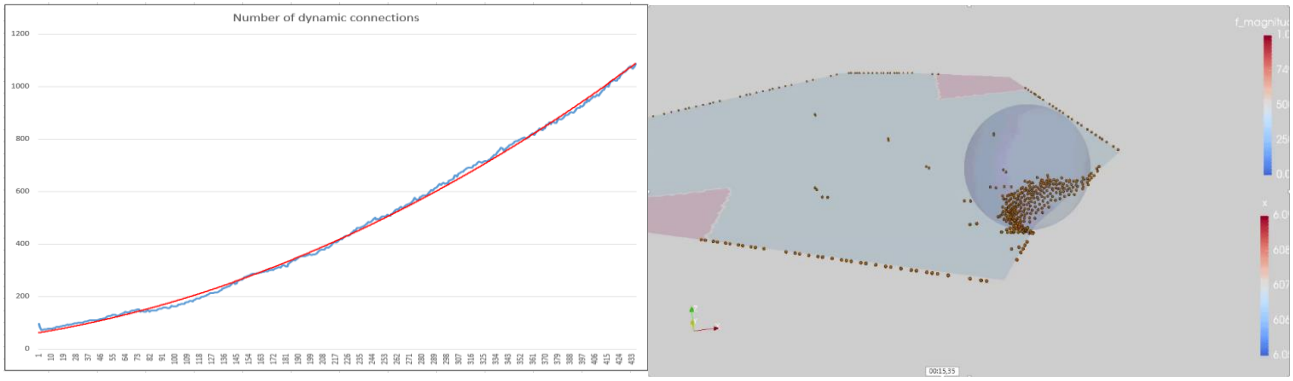
The simulation process reproduce as “radial” as “circumferential” cracks (picture 6a) and also demonstrate the suitable ice loads on the spherical ship bow (picture 6b).



(a) (b)

Figure 6. Crack propagation process

However, the main our goal was investigate the increasing of size of “dynamic structure”. This increasing presented on subpicture 7a. On subpicture 7b present the placement of dynamic bonds. We see that rate of increasing of “dynamic size” is enough low. Especially in comparison with size of “static” bond’s structure, that is near 50000 bonds. We see that maximum number of dynamic bonds is less then 3% of number of static bonds.



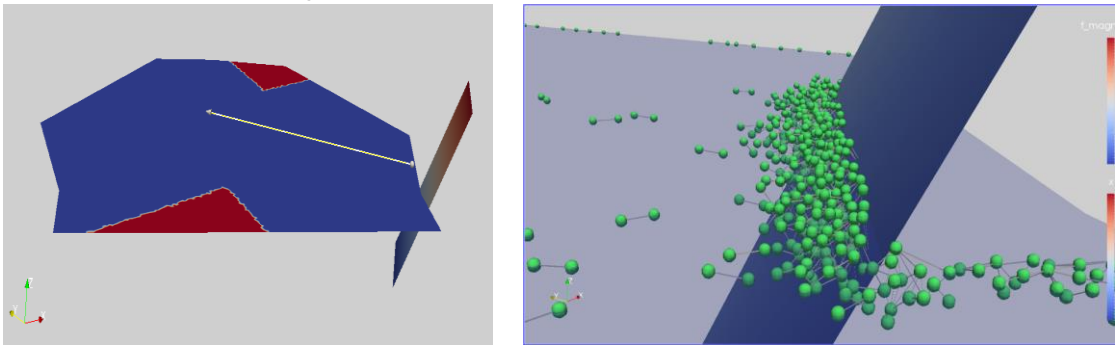
(a) **(b)**

Figure 7.Dynamic structure size increase

3.2 Inclined plane.

The next simulation is well-known problem - the horizontal ice load applied on the inclined plane. We changed movement scheme in comparison with classical approach. Plane moved instead ice floes. Ice floes is under

boundary conditions present on picture 8a. The white ray show us the direction of inclined plane movement. The red areas define the ice floes boundary condition with zero velocity.



(a) (b)

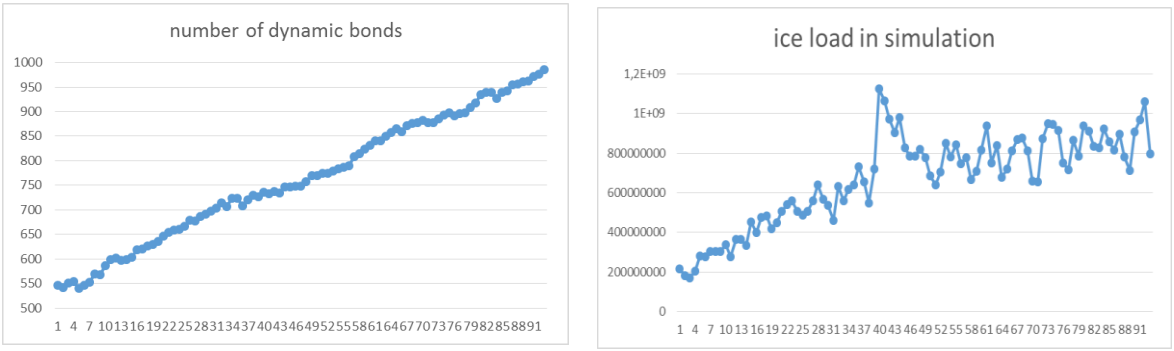
Figure 8. Boundary conditions for the case of the horizontal ice load applied on the inclined plane

In Table 2 the computational parameters for the ice material, the computational parameters for the inclined plane and the numerical computational parameters are listed.

Table 2. Material's property and inclined plane geometry.

Definitions	Values	Units
Ice cover size	150 x 300	m
Ice thickness	0.3	m
Plane width	20	m
Plane velocity	0.5	m/s
Density of ice	920	kg/m3
Young Modulus of ice	1e+9	Pa
Poisson ratio of ice	0.33	
Ice-ice (static) friction	0.05	
Ice-structure (static) friction	0.25	
Young Modulus of structure	20e+9	Pa
Time step	1.0e-5	s
Simulation time	70	s
Calculation time	2	hour

The simulation process reproduce the "typical" behavior of ice load for inclined plane simulation [5] (picture 9b).



(a) (b)

Figure 9. Number pf dynamic bond and ice load in similation

However, the main our goal was investigate the increasing of size of

“dynamic structure”. This increasing presented on subpicture 9a. On subpicture 8b present the placement of dynamic bonds. We see that rate of increasing of “dynamic size” is enough low. Especially in comparison with size of “static” bond’s structure, that is near 50000 bonds. We see that maximum number of dynamic bonds is less then 2% of number of static bonds/

Conclusion

We try here very briefly describe the idea of “dynamic bonds” for BDEM approach. As example of BDEM we use here RMIB. The applicability of above idea is the case when global part of simulated structure is more less stable and sufficient movements of particles take place in local part of simulated structure. In this case, we propose to use BDEM approach that is well GPGPU applicable. But in any case some bonds will be changed during simulation process. To avoid extensive CPU <=> GPU intercommunication we propose separate bonds on “stable” and “dynamics” parts. The another features of our approach is use Delaunay triangulation instead contact detection algorithms. Of course described approach is rather than universal, bat in some case they can give us the way for real simulation of complex problems.

References

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