Breaking Cobalt-Rich Crust Based on Cellular Automata Model

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ABSTRACT

Based on the analysis of fracturing mechanism of pulsed high-voltage, the distribution of electric field in cobalt-rich crusts was calculated by Laplace differential equation. A new cellular automata model of breaking cobalt-rich crusts was proposed according to traditional theory of cellular automata. The process of breaking deep-sea cobalt-rich crusts was simulated by this proposed model, and some of conclusions are similar to others' breaking rock experimental results in distilled water. The simulation shows: When coefficient η decreases, the number of breaking fragments increases, on the other hand, when η increases, the number of fragments decreases. The higher E_c of cobalt-rich crusts, the fewer pieces of it after voltage discharging, on the contrary, the more selecting points, the more pieces of cobalt-rich crusts after simulation.

KEYWORDS: Cobalt-Rich Crusts; high-voltage; simulation; cellular automata; fracture mechanism

INTRODUCTION

Cobalt-Rich Crusts(CRC) is a kind of mineral distributed abundantly on the top and flank of seamounts, ridges, plateaus and sea hill at a depth of 1000~3500m in the South and Middle of the Pacific Ocean, and the thickness of CRC is about 20~240mm[1] ,Since the 90s of last century humans began in the study of exploiting CRC from deep-sea basing on experience of mining manganese, and the difficulties are how to strip down the upper thin layer of cobalt-rich crusts from substrate. On the basis of experiment, the American, Japanese and Russian scholars had put forward the mining method of spiral roller[2].College of mechanical and electrical engineering of Central South University had designed spiral cutting platform of vibration and conducted many researches on breaking method, mechanical properties, collection of minerals, energy consumption and simulation[3-4].In short, the breaking way of deep-sea cobalt-rich crusts still stay in mechanical and hydraulic breaking methods, which are unavoidable to add a lot of waste rocks in the process of mining. Our project teams had designed a high-voltage discharging equipment of breaking deep-sea solid mineral which had be authorized by national patent management department[5].

Pulsed high-voltage is applied in many industries, such as in fractal researching[6], in biological sterilization[7],in wastewater treatment[8],in rock drilling[9] et al. But in deep-sea mining industry, only Japanese scholars Wang et al[10] had preliminary researched on breaking cobalt-rich crusts in the lab, both at home and abroad were not found in other reports. For breaking model of pulsed high-voltage, Russian scholars Burkin[11] et al had proposed a breaking rock model based on the plastic deformation of the solid and the liquid medium. The model is based on energy to discuss breaking rock by the plasma channel, and the process of energy conversion is very complex, so the quantitative comparison is quite difficult. Because ratio of energy loss for different ores is not the same, the model is difficult relatively to be used to practice.

A cellular automata model of breaking cobalt-rich crusts was proposed basing on discharging probability function [12].The model had used discharging probability function to calculate the breaking probability of cobalt-rich crusts. The crushing process had been simulated on the basis on cellular automation model. Some simulating results are close to the experimental results in pure water in other’s research, which indirectly proves the credibility of the proposed model. Some guidance was provided by these simulation results for further study of the breaking cobalt-rich crusts and designing samples of breaking deep-sea solid minerals by plasma channel.

BREAKING MODEL OF COBALT-RICH CRUSTS

Simplified physical model of pulsed high-voltage breaking cobalt-rich crusts

The basic parameters of pulsed high-voltage are as follows: The output voltage is 0～50kV,The frequency is 0～200Hz,The rising time of pulse is 40～200ns.High voltage is loaded on the positive crushing electrode and zero voltage is added on the zero electrode. The two electrodes are placed directly on the seafloor cobalt-rich crusts, which will produce plasma channel in the cobalt-rich crusts. The breaking effects, breaking paths and particle size of fragments are compared by changing voltage of two electrodes in the simulation, at the same time, the parameters of discharging voltage, structure of electrodes and distance of two electrodes are adjusted according to optimizing results.

Breaking probability calculation

The pulsed voltage was loaded to the two electrodes, and the time-varying electric field was formed in the cobalt-rich crusts at same time. When the strength of electric field in the cobalt-rich exceeds its limit in some points, the cobalt-rich crusts will be broken by electric field. Therefore, it is necessary to mesh cobalt-rich crusts to study fragmental rules of every meshed point. Theoretically speaking, under the conditions of applied electric field, every given grid point of cobalt-rich crusts has a breaking probability. The developing probability function of WZ model[12] was used to calculate the breaking probability. From physical meaning, the developing probability function of WZ model is just the breaking probability of grid point of cobalt-rich crusts.

$$p_{i,j} = \begin{cases} \left|E_{i,j}\right|^{\eta} / \sum \left|E_{i,j}\right|^{\eta} & \left|E_{i,j}\right| > E_c \\ 0 & \left|E_{i,j}\right| < E_c \end{cases} \tag{1}$$

where $p_{i,j}$ is the breaking probability of point (i,j); $E_{i,j}$ is the strength of electric field of point(i,j); $\sum \left|E_{i,j}\right|^{\eta}$ is the algebraic sum of strength of electric field in the directions of all possible breaking paths; E_c is the limit of strength of electric field for cobalt-rich crusts. When the strength of electric field at the point is higher than E_c, the point of cobalt-rich crusts will be broken, η is the parameter of breaking probability. For different minerals, the value of η may be completely different, even the same mineral may not be the same. Sometime the value needs to be determined through experiments and simulation.

The potential of the space points can be calculated by the Laplasse equation and the spatial potential of Laplace equation is as follow:

$$\nabla^2 \varphi = 0 \tag{2}$$

The finite element method and finite different method are used to calculate for the formula 2.For simplicity, the finite difference method was chosen to solve this issue. For analysis of electric field of two dimensions, the formula 2 can be discretized by following differential equation：

$$\varphi_{i,j} = \frac{1}{4}\left(\varphi_{i,j-1} + \varphi_{i-1,j} + \varphi_{i,j+1} + \varphi_{i+1,j}\right) \tag{3}$$

The corresponding boundary conditions were added to the differential equation, and iterative method was chosen to calculate potential of a specified grid point, and the size of strength of electric field can be calculated by potential difference and distance. Before calculation, the initial values of the two-dimensional plane are defined as follows: The horizontal division between the two electrodes is divided into 200 grids, and the vertical part is divided into 100 grids. The value of E_c cannot be calculated by theoretical method, and taking into account the strength of the similar rock, E_c is assumed to be 1.8e6v/m, and E_s is $0.9 \cdot 10^6$v/m (the half value of E_c), the maximum of voltage between two electrodes is 50kv.

THE APPLICATION OF CELLULAR AUTOMATON THEORY IN DEEP-SEA MINING

The cellular automaton model of breaking cobalt-rich crusts in deep-sea

According to the conditions of breaking cobalt-rich crusts by pulsed high-voltage, a new evolution of cellular automata model for breaking deep-sea solid mineral was proposed. Cellular automaton is composed of four parts: the cells, the states of the cells, the neighbor and the local rules[13].

$$A = (L_d, S, N, F)$$

where A is a cellular automata, and L_d is cellular space, and d is the dimension of cells, and S is the set of finite state of cells, and N is a combination of all the neighboring cells, and F is a state transition function which mapping S_n to S.

(1) Cells: A cell is called unit, which refers to the unit that is distributed in the two-dimensional discrete space. Cobalt-rich crusts in the deep-sea was chosen as researching object, which is divided into n*m grids(N is 100 and M is 200), and each mineral grid points is treated as a separate element, and its position is represented by (x_i, y_i). Usually, properties of every individual cell can be exactly the same(isotropic),or in accordance with a certain distribution to study(anisotropy).

(2) The states of cells: $\Phi(x_i, y_i, t)$ is used to represent the state of cell, which is referred to the state of point (x_i, y_i) at time t, and the cellular state includes two states.

$$\Phi(x_i, y_i, t) = \begin{cases} 0 & \text{at time } t, \text{ the cell of point}(x_i, y_i) \text{ keeps intact} \\ 1 & \text{at time } t, \text{ the cell of point}(x_i, y_i) \text{ is broken} \end{cases} \quad (4)$$

(3) Neighbor selection: For the sake of simplicity and computational easiness, the 8 neighbor model of the two dimensional cellular automaton was chosen to simulate, which is the molar type (Moore).

(4) Initialization: $P(x_i, y_i, t)$ is the breaking probability of the point (x_i, y_j) at time t, and $P(x_i, y_i, 0)$ is the breaking probability at time 0, the breaking probability can be calculated by formula 1. At time 0, the cell keeps intact and initial breaking probability is zero.

(5) Probability adjusting: When the cobalt-rich crusts are broken by high pulsed voltage, the value of η and the limit E_c of electric field should be considered. Because the plasma channel can be simplified to a circuit, the cobalt-rich crusts can be supposed to be a resistance. Therefore, it is necessary to consider the channel's internal voltage drop $E_s \cdot l$ (E_s is the electric strength, l is the

length of channel). When a new point is chosen, the potential of the new selecting point should be updated.

$$\varphi_i^{'} = \varphi_i - E_s \cdot l \tag{5}$$

where l is the distance between two the points, and φ_i is the last voltage, and $\varphi_i^{'}$ is the new voltage at new selecting point and the new formula should be added to the boundary conditions. At same time, new potential and electric strength should be recalculated, and a new breaking probability should be updated the value of last time.

(6) Selection of breaking path: The point near positive electrode or the point on the breaking path will be selected to be the starting point, and the point near the zero electrode or the point on the breaking path will be selected to be the ending point. The size of breaking probability is the main basis for choosing the breaking path. When a breaking path is finished then the next path is beginning, and the work will not be terminated until all the possible paths are chosen. When the breaking probability is equal, the random function of MATLAB is used to select breaking point. If all the neighbor points were selected, then stop this path, and select the next possible path. The simulation flow chart of the cellular automaton is shown in Figure 1.

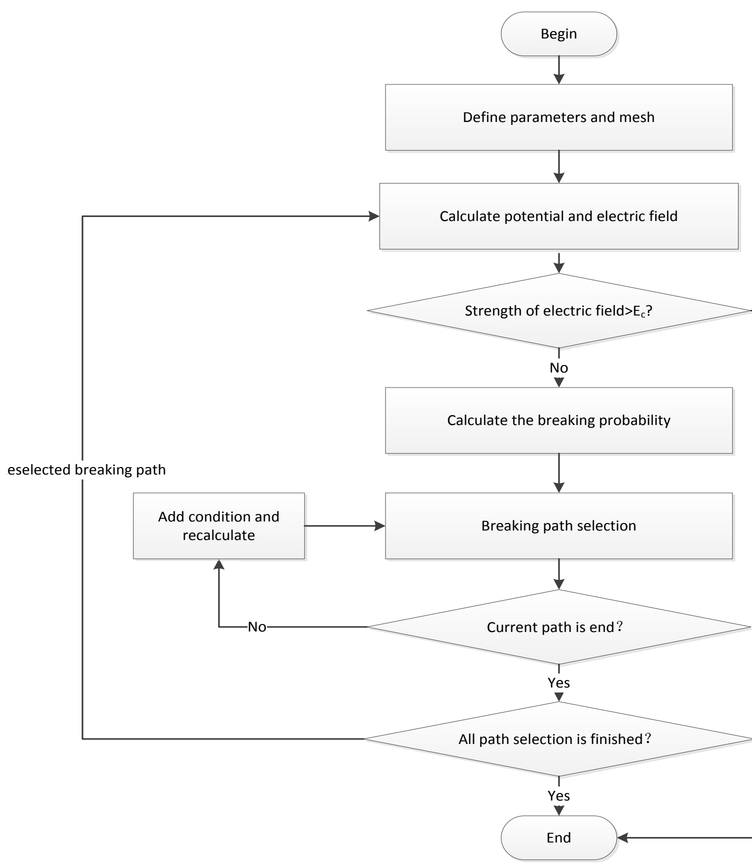


Figure 1: Cellular automata simulation flow chart for breaking cobalt-rich crusts

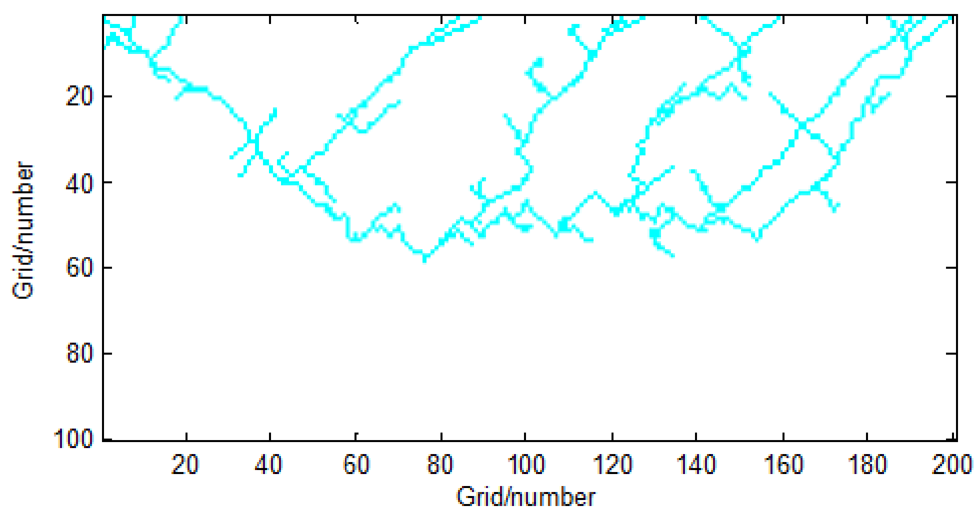
Cellular automaton of deep-sea breaking cobalt-rich crusts

The default parameters are as follows: The distance between the two electrodes is 2cm,and the period of the pulsed voltage is 100ns,and developing probability coefficient η is 1, and the value of high voltage is 50kv.In this case, the researched cobalt-rich crusts is divided into 200*100 grids, then the size of every grid is 0.01cm.In the process of simulation, the results are compared by changing only one parameter and the others keep unchanging.

The breaking effects of different developing probability coefficient η

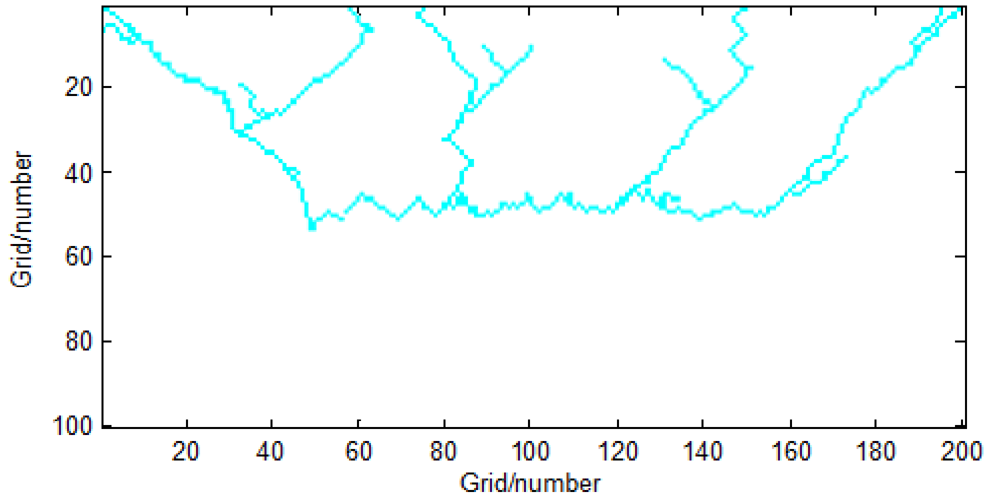
Fixed other simulation parameters, changing the value of η, the simulation results are shown in Figure 2.From Figure 2: The number of breaking pieces when η is 0.01 is more than η is 1. When η is 5,only one breaking path between positive and zero electrodes.

In short, the less η, the more pieces of fragments, and the more η, the more simple breaking paths. The value of η is the inherent characteristics of minerals, which related closely with minerals and fractal dimension. Even the same mineral, different mining area, this value may also not the same.

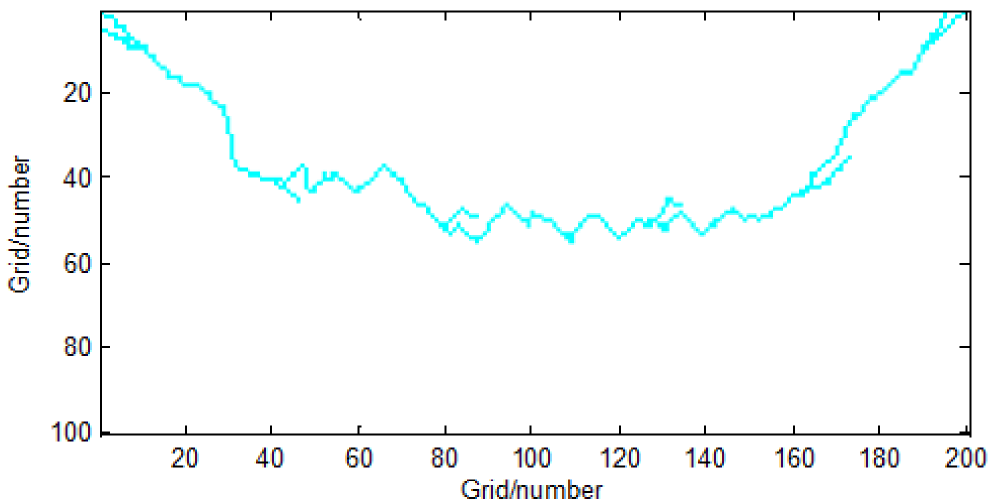


(a)η=0.01

Figure 2: *Continues on the next page*



(b)η=1



(c)η=5

Figure 2: Simulation results of breaking cobalt-rich crust under different η

The relationship between breaking depth and distance of two electrodes

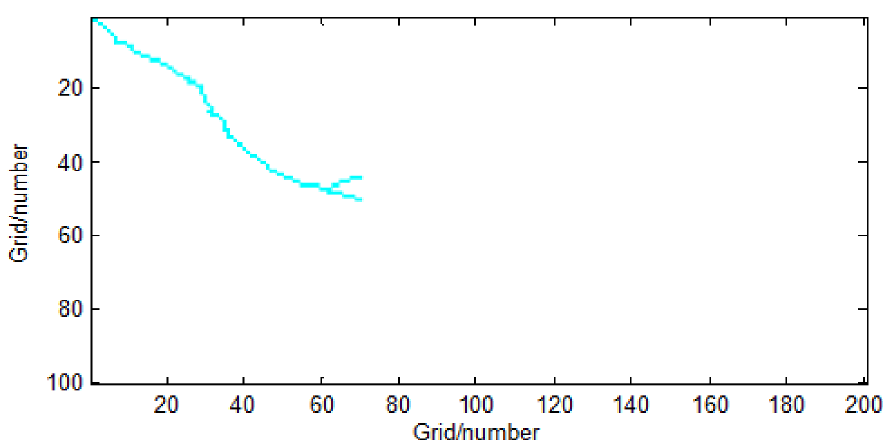
Fixed other parameters, adjusting the distance between two electrodes, the simulation results are shown in Table 1.From Table 1: The value of H/S is between 0.21~0.26, when distance of the two electrodes is 2cm,H/S value is the best. This conclusion is similar to results of breaking rock by plasma channel in pure water (H=0.318S) [14], which also indirectly proves the correctness of the model.

Table 1: Relationship between the distance of electrodes and the breaking depth of the cobalt-rich crust

Simulation sequence	Distance S(mm)	Breaking depth H(mm)	H/S
1	30	6.8	0.227
2	25	6.5	0.26
3	22	5.2	0.236
4	20	5.0	0.25
5	18	3.9	0.217
6	15	3.4	0.227
7	12	2.8	0.23
8	10	2.1	0.21
9	9	2.0	0.22

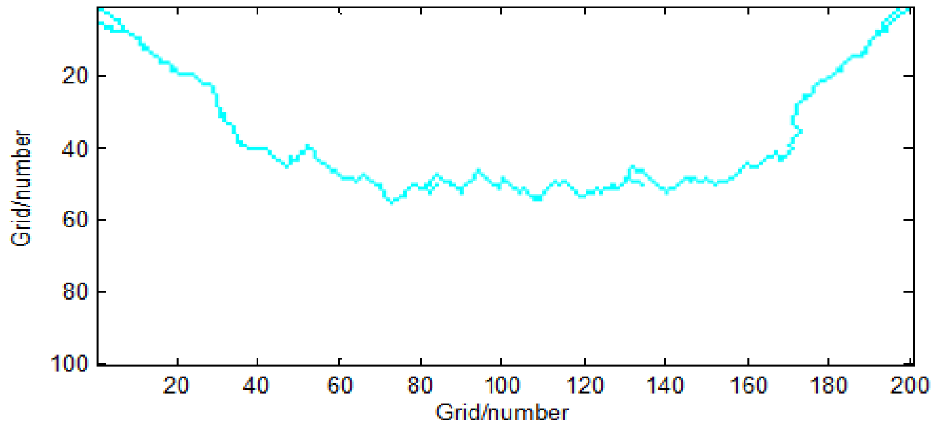
The relationship between E_c and the number of breaking fragments

Fixing other simulation condition, and changing the value of E_c, the results are shown in figure 3.From Figure 3: When E_c is 2.2e6v/m, the number of breaking paths is relatively small, and the breaking is uncompleted. When E_c is 2.0e6v/m, the number of breaking paths increased. When E_c is 1.8e6v/m, the number of breaking paths increased significantly, and achieved the full effect of breaking. In a word, the more E_c, the less break pieces of fragments, the less fractal dimensions. Conversely, the less E_c, the more breaking paths, and the pieces of fragments is also relatively increased.

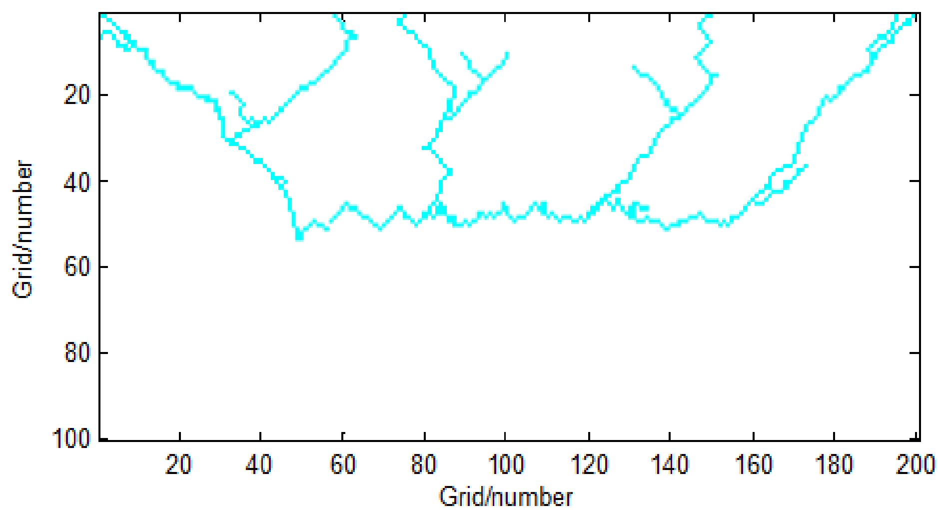


(a) E_c=2.2e6v/m

Figure 3: *Continues on the next page*



(b) E_c =2e6v/m



(c) E_c =1.8e6v/m

Figure 3: Simulation results of breaking cobalt-rich crusts under different E_c

CONCLUSIONS

All in all, a new deep-sea breaking method of cobalt-rich crusts is put forward, and a cellular automaton evolution model is proposed based on developing probability function of WZ model. Through simulation and analysis, the conclusions are as follows:1)The value of η is closely related with the number of breaking fragments and the breaking paths;2）The ratio between the breaking depth and the distance of the breaking electrodes is about 0.21～0.26,which is similar to the conclusion of the breaking rock in pure water.3) When the parameters such as voltage and distance of electrodes are not fit, the plasma channel cannot be formed in the cobalt-rich crusts. From the aspects of the particle size of fragments and the energy, it should ensure that the distance of two electrodes cannot be too close, but also ensure that the distance of two electrodes is not too far. 4) When the strength's distribution of electric field is more uniform, the number of fragments and breaking paths become more, On the contrary, the fewer pieces of breaking fragments and breaking paths.

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