Large Deformation Analyses of Concrete Caisson Quay Wall Subjected to Earthquake Loading by Using Distinct Element Method

Guixuan Wang[1] and Pei Qiang[1,2] and Xuefeng Chen[1]

[1] *The R&D Center of the Civil Engineering Technology, DaLian University, Dalian, China*
[2] *School of Civil Engineering, Harbin Institute of Technology, Harbin,China*
Email:tumuxinxi@163.com

ABSTRACT : The possibility of using distinct elements in solving large deformation seismic response of concrete caissons and backfills is discussed. A rectangular element is developed that can depict the geometry shape and the character of friction between caisson and soil. As a numerical example, seismic response of a concrete caisson quay wall is analyzed. Through numerical calculation, the course of caisson quay destroyed is repeated when earthquake happened. The method presented here can be used as a new solution to the large deformation of the caisson due to earthquake loading. The analysis results about two different models of caisson are compared in order to study effects of distinct element types on the numerical results.

KEYWORDS: rectangular element, distinct elements, caisson earthquake, large-deformation analysis

1. INTRODUCTION

Recent researches on the earthquake disaster(Jibu,1995) illustrated that concrete caisson quay tended to move toward the sea. This movement induced groundsill settlement and structure damage on the seashore so that quay is not able to be used normally. Fig.1 showed the post-earthquake deformation of caisson quay in Japanese Kobe earthquake in 1995(Jibu, 1995). During the earthquake, individual caisson's movement toward the sea reached several meters.   The traditional finite element method can not analyze this type of vibrational problem.
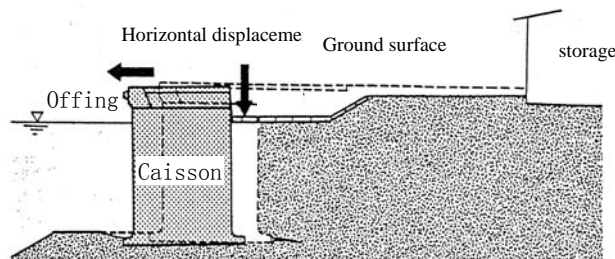

Fig.1 Earthquake-induced deformation of concrete caisson quay

Recent years, assuming sand and stone as the round or elliptic element of rigid body (SISUI, 1987; Meguro, 1988), the distinct element method were used to analyze the response of civil structures due to gravity or earthquake loadings. The distinct element method is regarded as the effective method for the large deformation of the civil structures because this method can be used to simulate the movement of the rigid body. Using the distinct element method, Meguro (1988) analyzed the concrete block body interaction with the grain body based on the link model of the round elements in Fig.2 in the case of earthquake loadings. However, the circular elements can't accurately depict the shape of the caisson so that the analysis precision is limited. In this paper, the rectangle elements that can depict the shape of caissons are developed to analyze the response of the earthquake on the caissons and filling back them. A simplified example is used to analyze the large deformation of the caisson due to earthquake loading. The comparison between the link model of the round elements and the rectangle elements influencing the results is taken. Then a proposed method is developed.
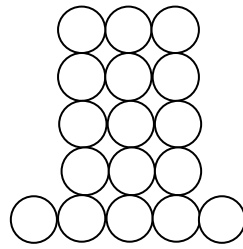
Fig. 2   Link model of circular elements

2. THE DISTINCT ELEMENT MODEL OF THE CAISSONS

2.1. Model of Caissons (Development of the Rectangle Element)

The distinct elements method is presented by Cundall (1971) to analyze the discontinuous body. This method is different from the finite element method and the boundary element method. In the distinct elements, the element is supposed as the rigid body, the interaction among the different elements is analyzed when the mechanical model is established through setting the contacting point or plane, then the deformation and movement of the elements is given out. The rigid body element was initially used to simulate the polygon. But the estimation on the contacting condition of the polygon is complicated and the computing time is long. Therefore, the rigid body element is limited in the application. In order to solve aforementioned questions, the circular element and elliptical element are presented by Sisui and Hakuno (1987), Meguro (1988) and Cundall and Strack (1979).

In this research, the circular rigid element is used to simulate the carpolite and filling back the caissons. In order to estimate whether the circular rigid element touched the caissons, Meguro (1988) utilized the link model of the round element shown in Fig.2 to simulate the body of the concrete, but his model can't adequately depict the shape of the caissons so that it is difficult that the scraggy forces acting on the surface illustrate the real forces on the caissons. The model of caissons is simplified as the rectangle rigid element shown in Fig.3 this paper. The semi-circular shape is utilized in the corner of the rectangle in order to avoid the singularity happening in the estimation of the rectangle elements touching the circular elements. The rectangle model is made of four circular elements and four boundary elements, where the boundary elements are the rigid boundary with the frictional characteristic and without mass, the circular elements which joint through the spring distribute averagely the mass of caissons. The stiffness characteristic of the structure can be assured from adjusting the spring coefficient. During the movement of caisson, the contacting mode of the caisson model elements with other elements is considered as three modes in Fig.4.
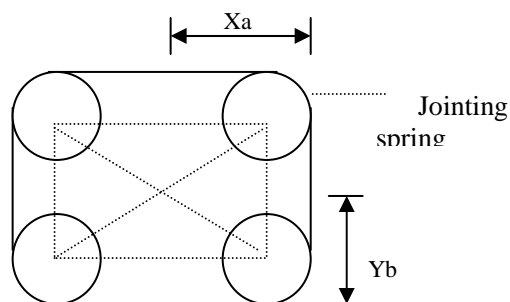

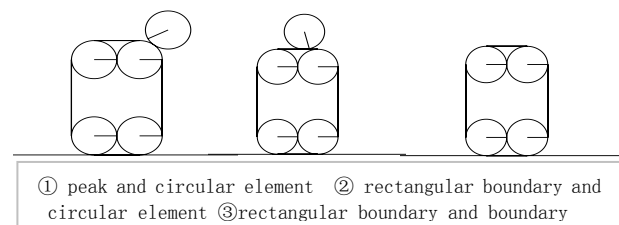Fig.3   Rectangular element model of box caisson

① peak and circular element ② rectangular boundary and circular element ③rectangular boundary and boundary

Fig.4 contact mode of box caisson model with other elements

2.1. Characteristic of the Caisson Elements

The movement of the rectangular elements is embodied through the circular elements, at the same time, the boundary elements is altered by the position of the circular elements. The circular elements averagely

distributed the geometric and mechanical characteristic of the rectangular elements. The inertial moment of the rectangular elements is expressed as:

$$I_z = \frac{1}{12} w_{rta}(X_a^2 + Y_b^2) \qquad (1)$$

Here, w_{rta} is the weight of the caisson, X_a and Y_b are respectively the half of the length and the width of rectangle in Fig.2. The rigidity obtained from Eq.(1) is averagely distributed to the four circular elements.
The forces and their moments on the circular elements and boundary elements can be gathered to the center of the rectangular elements. Then, the forces and their moments can be computed from Eq.(2) to Eq.(4).

$$F_{eX} = \sum_{i=1}^{nucnt} F_{xi} / 4 \qquad (2)$$

$$F_{ey} = \sum_{i=1}^{nucnt} F_{yi} / 4 \qquad (3)$$

$$M_e = \sum_{i=1}^{nucnt} F_{yi}[XP(1,i) - xcen]/4 + \sum_{i=1}^{nucnt} F_{xi}[XP(2,i) - ycen]/4 \qquad (4)$$

In which, XP(1,I) and XP(2,I) is respectively the horizontal and vertical coordinate of the I-th circular elements which touched the boundary of the rectangular elements in the center. F_{xi} is the total forces on the center of the I-th circular elements in the x-direction, F_{yi} is the total forces on the center of the I-th circular elements in the y-direction. nucnt is the total circular elements contacting the boundary of rectangular elements. xcen and ycen is respectively the horizontal and vertical coordinate of the rectangular elements. F_{ex}, F_{ey} is respectively the increased values of the forces in the x-direction and y-direction when the limbic parameters are simplified to the circular elements of the rectangular elements. M_e is the increased values of the force moments when the limbic parameters are simplified to the circular elements of the rectangular elements.

3. COMPUTATION FLOW OF THE LARGE DEFORMATION OF THE CAISSONS QUAY

The elements in this research used round elements except the boundary when filling soil and block are assumed as circular elements. The contact mechanical model among elements is shown in Fig. 5. The contact and movement among elements are simulated by setting the spring and damp in the tangent and normal direction(Meguro,1988). The deformation of elements is limited to contact point among elements. The frictional boundary is set between the circular elements and boundary. The moving equations of the circular elements are expressed as following:
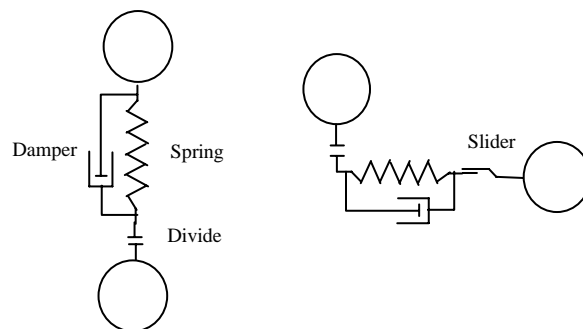

Fig.5   Mechanical model between circular elements

$$m\frac{\partial^2 x}{\partial t^2} - F_x = 0$$

$$m\frac{\partial^2 y}{\partial t^2} - F_y = 0 \qquad (5)$$

$$I \frac{\partial^2 \varphi}{\partial t^2} - M = 0$$

In which, m is the mass of the elements. I is the inertial moment of the elements. F_x and F_y is respectively the total x-directional and y-directional forces in the center of the elements. M is the total moment in the center of the elements. It is difficult to solve the all moving equations of the elements. In this paper, the moving track of each element is traced through the different method, so that the earthquake response analysis of the caissons and filling soil can be carried through. The computing flow chart about the distinct element is shown in Fig.6.
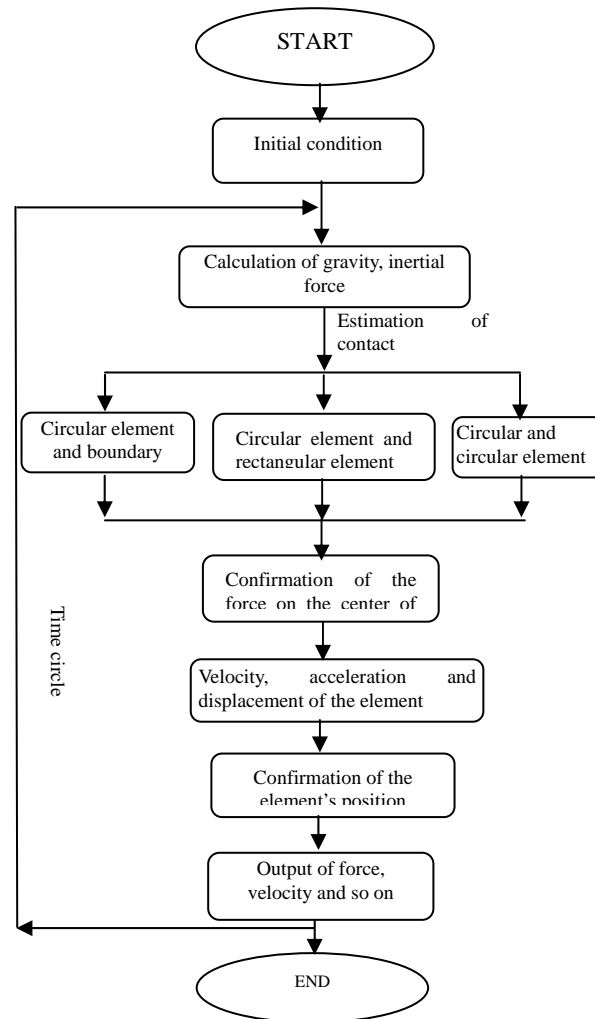

Fig.6 Analysis diagram of DEM

4. EXAMPLE FOR THE EARTHQUAKE RESPONSE OF THE LARGE DEFORMATION OF THE CAISSON QUAY

4.1. Analysis Model of the Caisson Quay

The analysis model of the caisson is shown in Fig.7. The caisson is mounted on the bedrock. The height of the caisson is same as the water surface. The jackstone back the caisson is simulated as the circular elements, whose diameter is defined through the random method. Based on the level distribution curve of the jackstone, the average diameter and the uneven efficient is given out 2.58cm and 1.52cm. Table 1 illustrated the DEM analysis parameters. The total circular elements of the jackstone are 507.
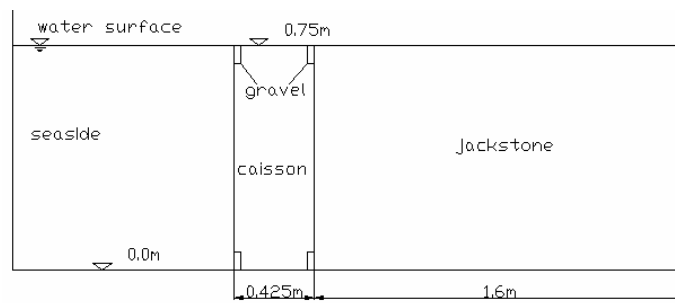
Fig.7 Analysis model of caisson

Table 1   DEM analysis parameters

Density of the circular element (kg/m^3)	2210
Density of the rectangular element (kg/m^3)	1637.64
Spring coefficient of element in the normal direction (N/m)	8.00E08
Spring coefficient of element in the tangent direction (N/m)	2.88E08
Damping coefficient of the element in the tangent direction (N·s/m)	4.030E03
Damping coefficient of the element in the normal direction (N·s/m)	2.418E02
Frictional angle on the bottom of the foundation (^{0})	31.0
Bonding strengthon the bottom of the foundation (N/m)	0
Time increment (s)	4.0E-07
Persisting time of earthquake (s)	2.0
Frictional angle between circular element and rectangular element (^{0})	31.0
Bonding strength between the circular element and rectangular element (N/m)	0
Frictional angle among the round elements(^{0})	24.0
Bonding strength among the circular elements (N/m)	0.0
Rolling resistance angle of the round element	24.0
Rolling resistance coefficient of the round element	0.6

4.2. Static Stress Analysis of the Model

The following method is used to simulate the building and filling process of the foundation during the distinct elements analysis. Firstly, the caisson is mounted. Secondly, the blocks are thrown at certain height. Lastly, the initial porous ratio of the jackstone is obtained from the distinct elements analysis. If the initial porous ratio can not satisfied the requirement, the frictional angle among the circular elements and Rolling resistance coefficient

among them are adjusted until the requirement on the initial ratio of the circular elements are attained. The computed parameters are confirmed from the experiment. In order to discuss the rationality on the analysis model of the caisson, the comparison of the linking model between the circular elements and rectangular elements is taken.

When the process of the block thrown ended, the stress is transferred among the circular elements is shown in Fig.8 and Fig.9. It is seen that there is obvious distinguish between the connecting strength of the circular elements back the caissons. The force calculated from the rectangular elements is less than that from the linking model. The safe coefficient obtained from the two different methods is obviously different. The linking model of circular elements can not effectively depict the shape of the caissons, so that the vertical force on the caisson transferred from the circular elements is great. The safety coefficient of caisson's horizontal slippage is big, that is to say, the engineering design according to this safety coefficient is dangerous.
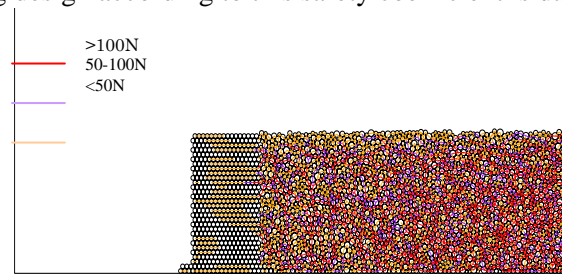

Fig.8 Stress transferring route between elements (linking model of circular elements)
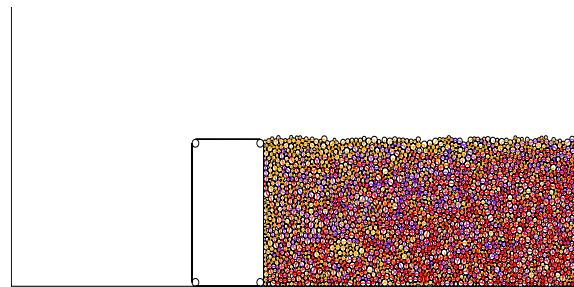

Fig.9 Stress transferring route between elements (linking model of rectangular elements)

4.3. Dynamic Stress Analysis

The dynamic stress analysis is developed based on the static stress. The dynamic stress is sine distribution. The maximum is 300gal. The frequent is 3Hz. The lasting time of earthquake is 2s.

Fig.10 illustrated the relation between the moving position of the caisson and the happening time of the earthquake. From Fig.10, the same phenomena as earthquake disaster happened is seen: the rectangular elements keep the rigidity (that is the whole characteristic of the caissons), the caissons simulated by the rectangular elements are gradually pushed to seaside so that the soil body back the caissons subsided. However, the position of the caissons rarely changes when earthquake is progressing so that it is difficult to affirm the real phenomenon on the earthquake disaster.

(a) linking model of rectangular elements   (b) linking model of circular elements
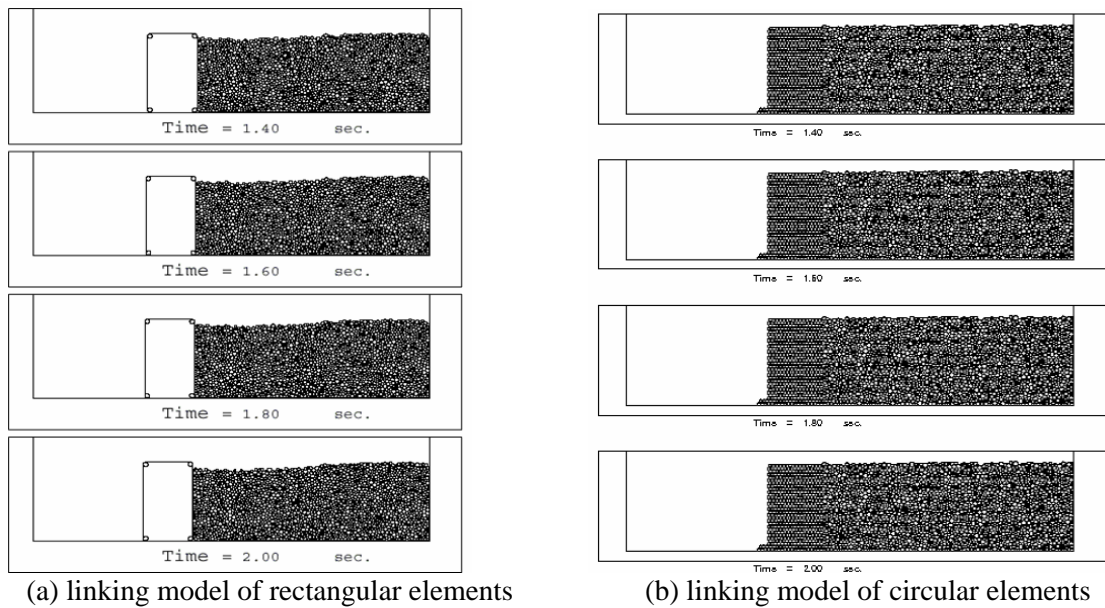
Fig.10 Moving position of box caisson under earthquake load

The horizontal displacements calculated respectively from the circular elements and rectangular elements are shown in Fig.11. The horizontal displacement obtained from model method of the rectangular elements is 13.3 centimeters, from the circular elements is 0.5 centimeter. It is known that the movement of the caissons is held back by the soil's pressure when the oscillated direction of the earthquake is to land. On the other hand, the caisson is pushed to the seaside when the vibration direction of the earthquake to the seaside and the acceleration attained certain value.

The vertical forces on the bottom of the caissons computed respectively from the rectangular elements and circular elements are illustrated in Fig.12. The initial vertical force on the caisson has large difference because the initial static stress on the caisson is different. The vertical force on the caissons hugely fluctuated because the position of the circular elements near the caissons excessively changed during the earthquake. As a whole, the vertical forces computed from linking model of the rectangular elements are less than those from the linking model of the circular elements. It is the reason that the horizontal resistance against linking model of the rectangular elements is quite small, the safe coefficient of resisting slippage is also small so that the horizontal displacement obtained from the rectangular elements is greater than that from the circular elements.
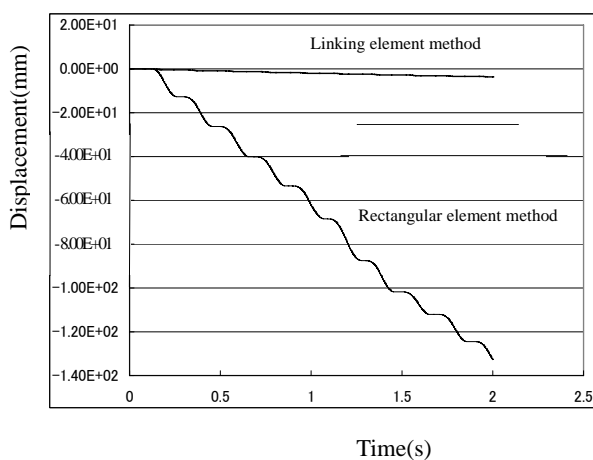
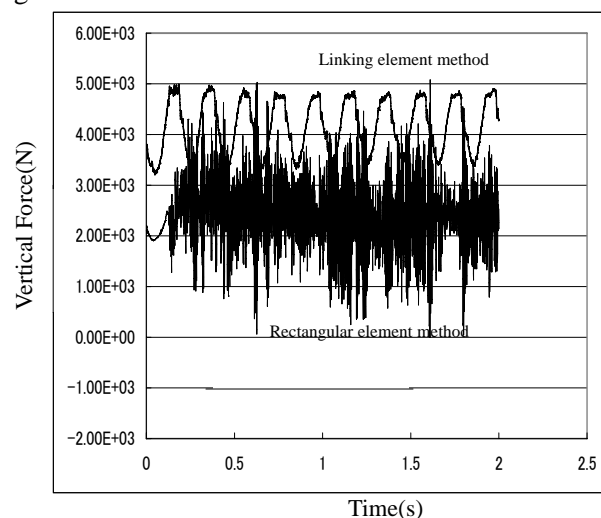

Fig.11 Plane displacement of box caisson under earthquake

Fig.12 variation of vertical loads of box caisson under earthquake

5. CONCLUSIONS

Based on the distinct element method, the rectangular elements applied to the interaction caissons structure with the grain body are developed. A simplified model is used to analyze the interaction of the caisson quay with jackstone under static load and dynamic load. A comparison about the results' difference between the rectangular element methods and the circular element methods to simulate the caisson structures is taken. The following results are obtained.

1) The distinct element method can be used to analyze the large deformation response of the caisson quay under earthquake loadings. The results show that the movement of the caisson to seaside and groundwork's sedimentation back the caissons are same as the real disaster after earthquake. The distinct elements method is not limited by the large deformation. The large deformation of the caisson quay can be quantificationally analyzed when the essential parameters are confirmed. Therefore, the distinct element methods are new approach to analyze the similar large deformation.

2) The rectangular element method is proposed to use in the real application. It is the reason that linking method of the circular element can't adequately depict the shape of the caissons, which leads to the vertical force transferred the caissons from the circular elements is big, then the frictional force against the caissons increases, so that the safety coefficient of the horizontal glide increase, therefore the engineering design from this safety coefficient is dangerous.

3) In order to quantificationally analyze the earthquake response of the caissons, the model experiment must be carried out while confirming the analysis parameters.

REFERENCES

Jibu T (1995). "The Harm of Fleet Establishment Leaded by Earthquake Happened on the South of Bingku ," J of Cicvil Acad., Vol 80, No 4, pp 6-10. (in Japanese)

Fleet Technique Institute, (1993). "The Harm of Fleet Establishment happened on GUNDOO in 1993," Fleet Technique Reference, No.766. (in Japanese).

SISUI, Y and Hakuno, M (1987). "The Numerical Simulation on Granular Liquid of the Quick Sand and Liquefaction," Volume of Earthquake Institute, Vol 62, pp 535-577. (in Japanese).

Meguro, K (1988). "using Granular Liquid numerical method to simulate the concrete structure," Volume of Earthquake Institute, Vol 63, pp 409-468. (in Japanese).

Cundall, PA (1971). "A Computer Model for Simulating Progressive, Large Scale Movement in Blocky Rocksystem," Symp. ISRM, Nancy, France, Proc., Vol 2, pp 129-136.

Cundall ,PA and Strack, ODL (1979). "A Discrete Numerical Model for Granular Assemblies," Geotechnique, Vol 29, No 1, pp 47-65.

R&D center of seacoast (2000). "Research on the outlay curtailment of the gravitational shore," Report. (in Japanese).