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Simulation of collapse of structures due to earthquakes using the extended distinct element method

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ABSTRACT: Taking into account the importance of different mechanisms of collapse of structures in mitigating casualties due to earthquakes, the Extended Distinct Element Method (EDEM) was applied to simulate collapse of structures in several well-known modes. The processes of seismic damage such as the collapse of the Cypress Interstate Bridge (Loma Prieta earthquake, 1989), the collapse by overturning of a slender structure, the collapse of soft-first-story type of building, the collapse of a building with a weak middle floor, the collapse of Hyatt Terrace Hotel Tower type (Philippine earthquake, 1990) and the pancake-type of collapse (Mexico earthquake, 1985) were successfully simulated. The collapse processes have so far been impossible to simulate by other numerical methods. The simulation results obtained in this study agree well with the seismic damage reported during the past earthquakes and we believe that the EDEM will prove to be a useful tool to simulate such phenomena.

1 INTRODUCTION

There have been widespread reports of many casualties due to structural collapses in the past earthquakes. In this study, the mechanism of collapse is investigated by simulating various modes of collapse process. Since fracture develops both in space and time domains, it is very important to study the process of collapse and also the structural behavior after collapse. Hakuno et al. (1988, 1989 and 1990) developed a new method from Cundall's (1971) Distinct Element Method (DEM) in order to simulate the behavior of discrete as well as composite and continuous media. The method was named the Extended DEM (EDEM) or Modified DEM (MDEM). The EDEM is applied to simulate dynamic behavior of structures due to earthquakes.

A new idea regarding application of the EDEM is also proposed in this study: the EDEM can be taken as an extended lumped mass system, the field of application of which is extended to the discontinuous media, unlike the standard lumped mass system which is applicable only to the continuous media. Although the improvement of computer system is remarkable in recent years, it is still impossible to use the EDEM model corresponding to the actual object when either the size of the objective structure to be modeled is very large or the objective medium is composed of many elements of microscopic size. Exact modeling with many small elements, however, is not necessary to obtain the fundamental vibration modes or fracture modes which are important in the engineering field. The elements that should be used in an analysis are based on individual's choice of size of the lumps of material that would be left after the collapse. This is the essence of the new idea of application of the EDEM proposed here.

With the conventional multi-degree-of-freedom system, which is often used for seismic response analysis, it is very difficult to simulate dynamic fracture process involving the occurrence of cracks. With the EDEM, however, total behavior; i.e., from the sound state to collapse is easily simulated. For example, dynamic properties of a structure which are gradually changing due to appearance or progression of fracture are simulated automatically.

2 EXTENDED DISTINCT ELEMENT METHOD

The Extended Distinct Element Method (EDEM) is a numerical method applicable not only to a homogeneous and perfectly discrete medium but also to a complex, heterogeneous and continuous one. Figs.1 and 2 show the EDEM modeling of a medium and the flow of the EDEM simulation respectively. The EDEM was developed by introducing pore-springs, which represent the effect of pore material between elements, and arrays of different material parameters, to extend the applications of the conventional DEM.

In the EDEM simulation, an aggregate of elements connected by pore-springs and behaving as one body gradually becomes nonlinear as the pore-springs are destroyed. At first, the EDEM model behaves as a continuous medium. As the pore-springs are destroyed according to the specified fracture criteria, it gradually loses continuity and finally behaves as a perfectly discrete medium (see Fig.3). This means thet material and geometrical nonlinearities can be readily incorporated and simulated. It also means that

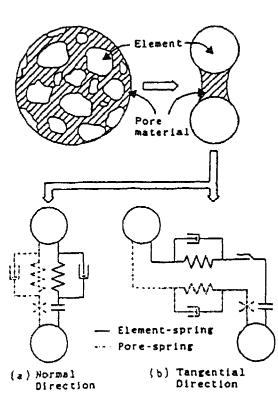


Fig.1 EDEM Modeling of a medium

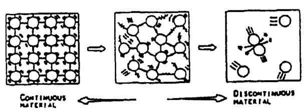


Fig.3 Behavior of the EDEM model

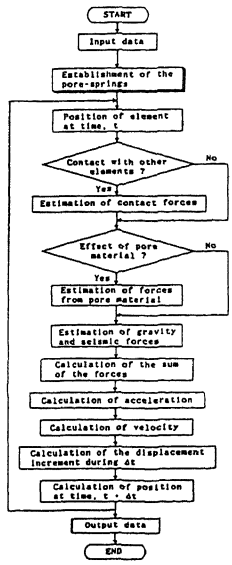


Fig.2 Flow of the EDEM simulation

phenomenon in which every element separates and moves widely after destruction of the pore-springs, such that a new stress field is formed by contacts between elements which were not previously in contact, can be simulated. With the pore-springs, rotation of the elements and the transmission of moment can be taken into account; moreover, an aggregate of elements connected by the pore-springs rotates as one body. Whereas the objective medium of the conventional DEM is limited to one that is homogeneous and perfectly discrete, the EDEM can deal with a series of behavior - from the sound state to a perfectly discrete state- of composite and continuous media.

The equations of motion of an element i having the mass m_i and the moment of inertia I_i are

$$m_i u + C_i u + F_i = 0 \qquad (1)$$

$$I_i \varphi + D_i \varphi + M_i = 0 \qquad (2)$$

where F_i is the sum of all the forces acting on the element, M_i the sum of all the moments acting on it, C_i and D_i the damping coefficients, u the displacement vector; and φ is the rotational displacement.

Because two kinds of forces act on an element (i.e., the force received from all the elements in contact and the force of all the pore material surrounding it), F_i and M_i are expressed as

$$F_i = F_{ie} + F_{ip} + m_i(g+\alpha) \qquad (3)$$

$$M_i = M_{ie} + M_{ip} \qquad (4)$$

where F_{ie} is the sum of forces from all the elements in contact; and F_{ip}, from all the pore material surrounding the element. M_{ie} and M_{ip} are the sums of all the moments from all the elements in contact and from all the pore material surrounding it respectively. These forces are obtained from the deformations of the element and pore-springs set in the normal and tangential directions. In equation (3), g is the acceleration due to gravity and α the external acceleration acting on it. As the fracture criterion of the pore-spring in the normal direction, a critical tensile strain β is specified; and in the tangential direction, Coulomb's equation is used. The time histories of u and φ are obtained step-by-step in time domain by the numerical integration of equations (1) and (2).

3 NUMERICAL RESULTS

To study the mechanisms of collapse modes and processes, we simulated the collapse processes of structures due to earthquakes using various models shown in Fig.4 through Fig.9. Fig.4 shows the collapse process of a double-deck bridge with hinges at the bottom ends of the upper deck columns. This is a simulation of the seismic damage of the Cypress Interstate Bridge as seen in the 1989 Loma Prieta earthquake (see Photo 1). The simulation of collapse by overturning of a slender building from resonance due to an earthquake is shown in Fig.5. The collapse of a building with a weak intermediate floor is simulated in Fig.6. In this case, concentrated fracture occurs on the weak floor like the ones produced by the Philippine earthquake of 1990 (see Photo 2). The result shown in

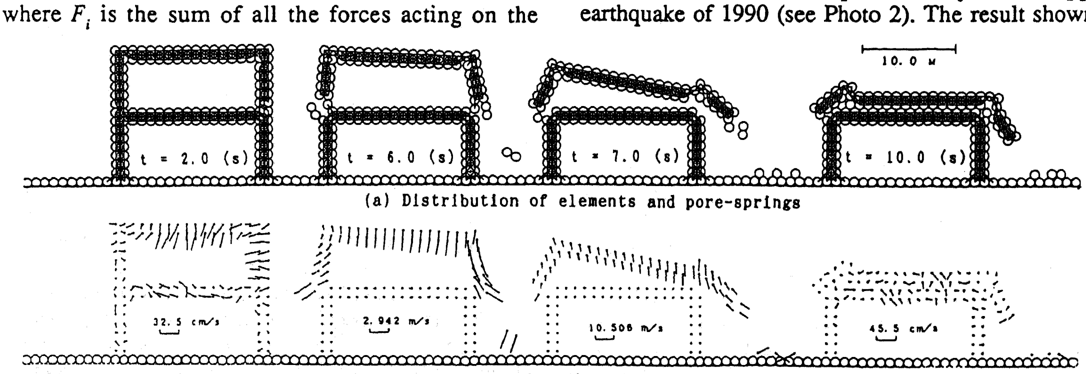


Fig.4 Collapse of a double-deck bridge with hinges at the bottom ends of the upper deck columns (Cypress Interstate Bridge as seen in the Loma Prieta earthquake, 1989)

Fig.7 indicates damage due to fracture on the first floor, which is the most common produced by Japanese earthquakes (see Photo 3). The tumbling type of collapse, which resembles the collapse of the Hyatt Terrace Hotel Tower in Baguio during the 1990 Philippine earthquake, is simulated in Fig.8. Simulation of the pancake-type of collapse is shown in Fig.9. This type of collapse, which was reported in the Mexico earthquake of 1985 (see Photo 4), is likely to occur when pillars and walls are weak; for instance, when they are composed of brick masonry.

Photo 3 Collapse of soft-first-story type building (Off-Miyagi prefecture earthquake, 1978)

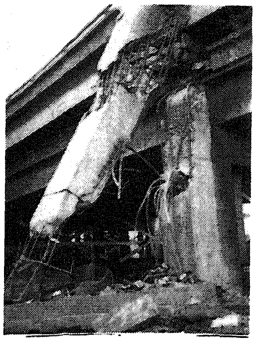


Photo 1 Collapsed Cypress Interstate double-deck bridge in California (Loma Prieta earthquake, 1989)

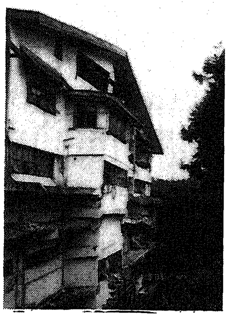


Photo 2 Partial collapse in the middle floor (Philippine earthquake, 1990)

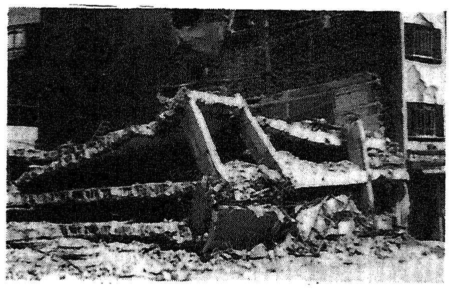


Photo 4 Complete collapse like a pancake (Mexico earthquake, 1985)

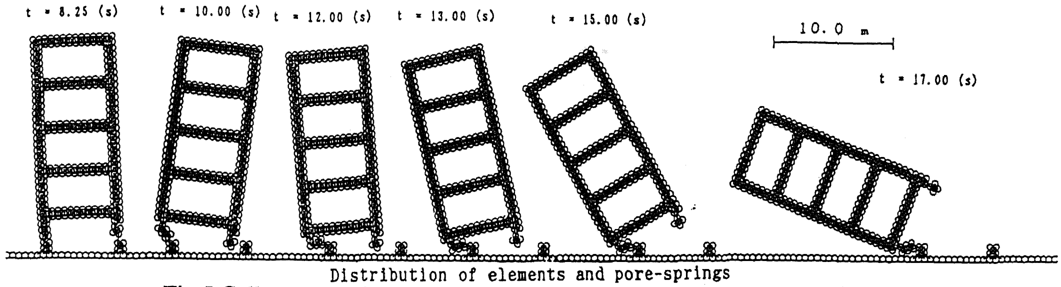


Fig.5 Collapse of a slender structure from resonance due to an earthquake

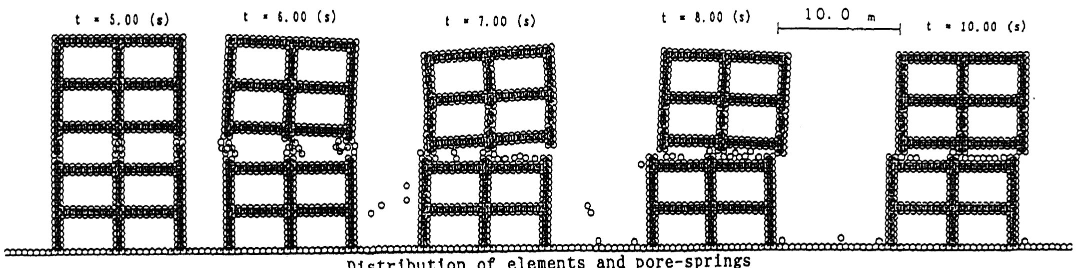


Fig.6 Collapse of a structure with a weak middle floor (as seen in the Philippine earthquake, 1990)

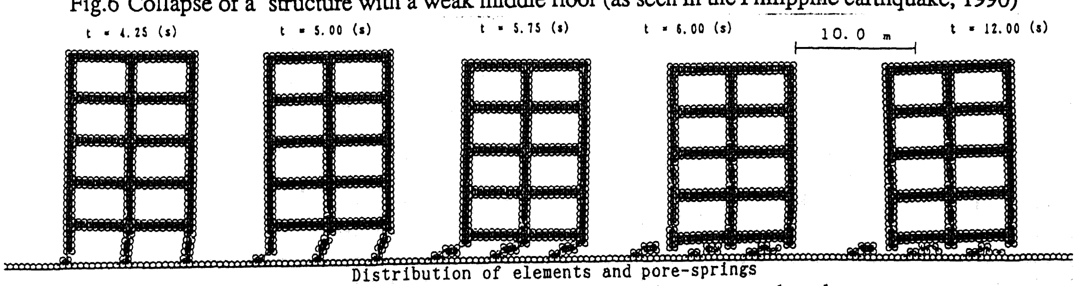
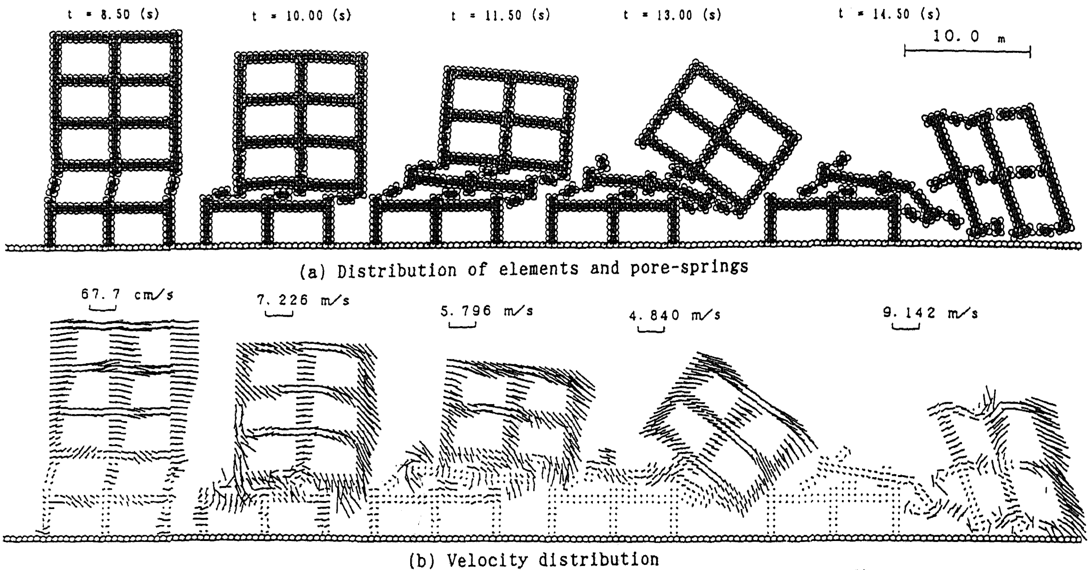


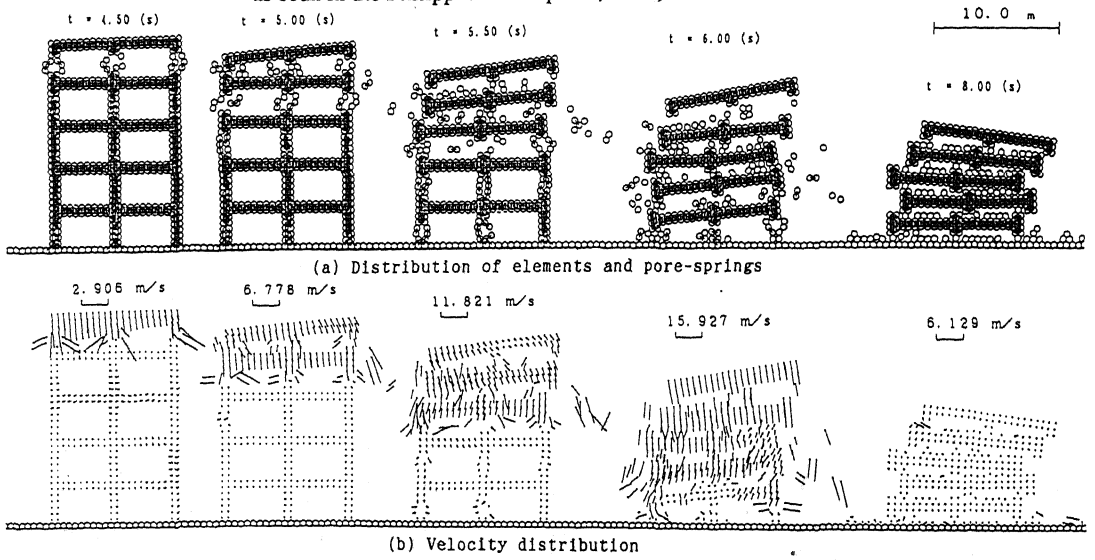
Fig.7 Collapse of a soft-first-story type structure due to an earthquake



(a) Distribution of elements and pore-springs

(b) Velocity distribution

Fig.8 Collapse of a structure (the Hyatt Terrace Hotel Tower type collapse, as seen in the Philippine earthquake, 1990)



(a) Distribution of elements and pore-springs

(b) Velocity distribution

Fig.9 Pancake-type of collapse of a structure (as seen in the Mexico earthquake, 1985)

4 CONCLUSIONS

To study the mechanisms of seismic damage, the collapse processes of structures due to earthquakes were simulated using the Extended Distinct Element Method (EDEM). A new idea of the EDEM application in which the EDEM model is taken as an extended lumped mass system is also proposed.

Whereas the phenomena treated in this study have so far been difficult to simulate by other numerical methods, our simulation results obtained in this study agree well with seismic damage reported during the past earthquakes. The EDEM, therefore, proves to be a useful tool to simulate such phenomena.

REFERENCES

Cundall, P. A. 1971. A computer model for simulating progressive, large scale movement in blocky rock Systems, Symp. ISRM, Nancy: France.Proc. vol.2: 129-136.

Iwashita, K. and Hakuno, M. 1990. Modified distinct element method simulation of dynamic cliff collapse, Structural Eng./ Earthquake Eng., Japan Society of Civil Engineers (JSCE), Vol.7. No. 1: 133-142.

Meguro, K., Iwashita, K. and Hakuno, M. 1988. Fracture tests of masonry concrete elements by granular assembly simulation, Proc. of 9WCEE, Vol.6: 181-186.

Meguro, K. and Hakuno, M. 1989. Fracture analyses of concrete structures by the modified distinct element method, Structural Eng./Earthquake Eng., JSCE, Vol.6, No.2. : 283-294.