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Estimation of ground-motion intensity from the upthrow of boulders

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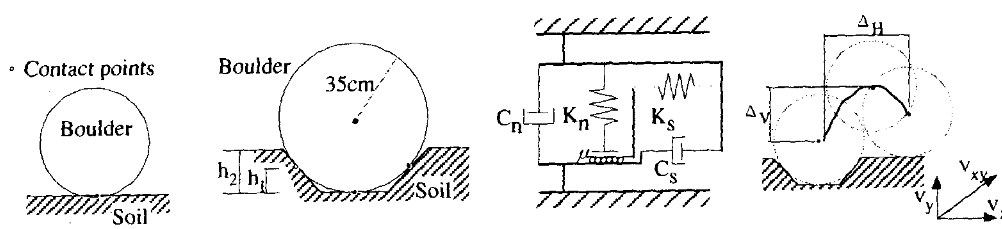
ABSTRACT : In this paper, the boulder upthrow phenomenon is interpreted through numerical simulations using a distinct element method and shaking-table experiments, and a method of estimating ground-motion intensity from the phenomenon is proposed.

1. INTRODUCTION

The estimation of near-field ground motion intensity is an important subject in earthquake engineering. However, the characteristics of near-field ground motion are not well known because of the limited amount of recorded data from the epicentral regions. Under such conditions, some post-earthquake investigation reports have pointed out that the upthrow of boulders in the epicentral region might be evidence of extremely strong ground motions. However, a method of estimating the ground-motion intensity from boulder upthrow phenomenon has not yet been established. In this paper, the upthrow phenomenon is interpreted through numerical simulations and shaking-table experiments, and a method of estimating ground-motion intensity is proposed.

2. NUMERICAL SIMULATIONS

We have conducted simulation analyses of the upthrow phenomenon based on the two-dimensional distinct element method [Cundall (1971)]. Figure 1 shows the analytical models used. The boulder is assumed to be circular and the soil surface is expressed using straight lines. Both the boulder and the soil surface are assumed to be rigid. Instead, interface elements expressing separation and sliding are provided at their contact points as shown in Fig. 1(c).



(a) Model for vertical input
(b) Model for vertical and horizontal input
(c) Element at contact point
(d) Maximum displacement and input velocity

Figure 1 Models for numerical analyses

2.1 Vertical Input

First, the boulder model shown in Fig. 1(a) is harmonically excited in the vertical direction. In the following, f_0, e, and V_y denote the natural frequency of the boulder-soil interaction system, the coefficient of restitution between the boulder and the soil, and the input velocity, respectively.

Figure 2 shows a typical example of the displacement time histories of boulder and soil in the vertical direction. The boulder and soil separate when the relative displacement of the boulder to the soil is positive. It is clear that the boulder increases the amount of separation after repeating a series of actions : jumping, falling, collision with the soil, and jumping again.

Figure 3 shows height Δ_V of maximum separation for velocity amplitude V_y=25-200 kine. The Δ_V decreases suddenly at a particular frequency (f_L) after increasing gradually and reaching the upper bound value within a frequency range of f_0>f, when the input frequency f is decreased and V_y is kept constant. The cut-off frequency f_L decreases as V_y increases, and the frequency range in which boulder upthrow may occur is extended accordingly. The height Δ_V of maximum separation also increases in proportion to the square of V_y. Moreover, the frequency range in which boulder upthrow can be caused for f_0=25 Hz is wider than that for f_0=2.5 Hz.

Based on these characteristics, an approximate estimation formula for Δ_V is introduced. The upper bound value of the maximum velocity of the boulder is given by $(1+2e+2e^2+...)\, V_y \fallingdotseq (1+3e)\, V_y$ if it is assumed that the collision and separation of the soil and boulder are always caused when the soil moves upward at the maximum velocity V_y. The coefficient (1+3e) indicates the upper bound value of the velocity amplification ratio of the boulder to the soil considering the nonlinear behavior of boulders. Therefore, the height Δ_V of maximum separation and the cut-off frequency f_L are expressed shown below.

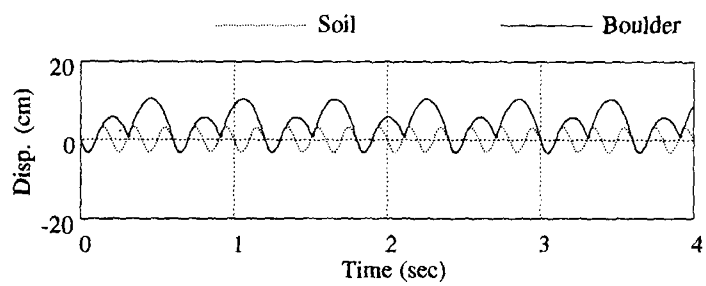


Figure 2 Jumping behavior under vertical input (V_y =100kine, e=0.3, f=5Hz, f_0=25Hz)

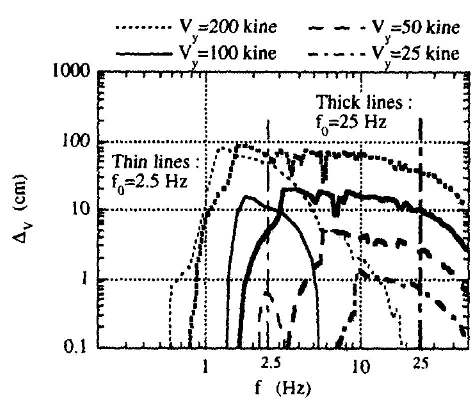


Figure 3 Maximum separation height (Vertical input, e=0.3)

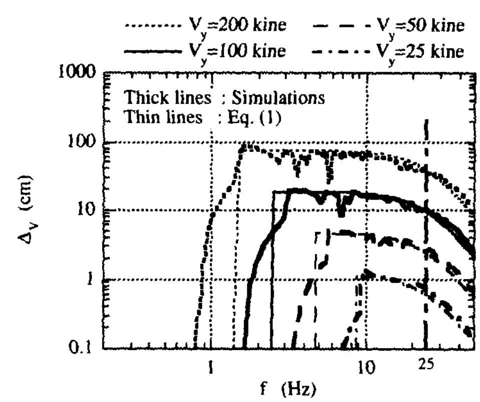


Figure 4 Evaluation of maximum separation height (Vertical input, e=0.3, f_0=25 Hz)

$$\Delta_V = \Delta_{0y} \cdot \{1/(1+(f/f_0)^3\} \qquad (f>f_L)$$
$$\text{where} \quad \Delta_{0y} = \{(1+3e)\,V_y\}^2/2g$$
$$1/f_L = 1/(2f_0) + 2/\{(1+3e)\,V_y\}g \qquad (1)$$

The Δ_{0y} is the maximum height when an object is thrown upward at an initial velocity of $(1+3e)\,V_y$. The relation $f=f_L$ indicates that the period of excitation is equal to the interval from the departure of a boulder from the soil to the next departure. The height of the maximum separation, estimated using Eq.(1), shows good correspondence with the response analysis results shown in Fig. 4.

2.2 Horizontal and vertical input

Next, harmonic excitation is applied to the analytical model shown in Fig. 1(b) in both the horizontal and vertical directions, simultaneously. Boulders with a radius of 35 cm are buried in the soil socket. The parameters of the analytical model shown in Table 1 are set according to Ohmachi (1992). The velocity amplitude of the horizontal or vertical component (V_x or V_y), the frequency of input f, and the shape of the socket varied in numerical simulations. The shape of the socket is determined based on the level h_1 of the contact point C and the burial depth h_2.

Figure 5 shows the height Δ_V of maximum separation and the maximum horizontal displacement Δ_H when h_1=10 cm and h_2=12 cm. The input direction is varied to keep the resultant velocity amplitude $V_{xy}=(V_x^2+V_y^2)^{0.5}$ defined in Fig. 1(d) equal to 103 kine. Variation in the maximum horizontal displacement Δ_H is relatively small compared with that in the height Δ_V of maximum separation when the input direction is changed. Therefore, we estimated the Δ_H according to the next equation similar to the Eq. (1).

$$\Delta_H = \beta \cdot \Delta_{0xy}, \qquad \Delta_{0xy} = \{(1+3e)\,V_{xy}\}^2/2g \qquad (2)$$

In the following, the value of the coefficient β is examined. Figure 6 shows the values of β when h_1=10 cm and h_2=12 cm. This figure shows the values when V_x is increased and V_y is kept at 100 kine, or when V_y is increased and V_x is kept at 100 kine. Figure 7 indicates the variation of β when V_{xy}=206 kine. The socket shape is changed by increasing h_1 from 5 cm to 20 cm, and keeping h_2/h_1=1.2. Coefficient β shows a decreasing tendency as burial depth decreases or the velocity amplitude increases, as shown in Figs. 6 and 7. This occurs because the boulder is apt to leave its socket, and the response velocity cannot be sufficiently amplified. However, it is clear that β is hardly affected by the input directions shown in Fig. 6. Therefore, the maximum horizontal displacement

Table 1 Parameters used in numerical analyses (Vertical and horizontal input)

Stiffness K_n	8.7×10^6N/m
Stiffness K_s	1.0×10^4N/m
Restitution coefficient e	0.3
Friction coefficient μ	0.8
Radius of circle element r	35 cm
Density of circle element	2.45 t/m^3

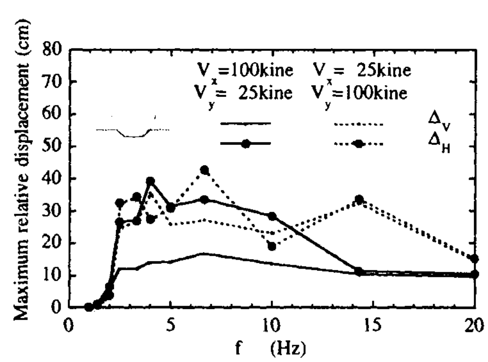


Figure 5 Maximum displacement of boulders (Vertical and Horizontal input: h_1=10 cm, h_2=12 cm)

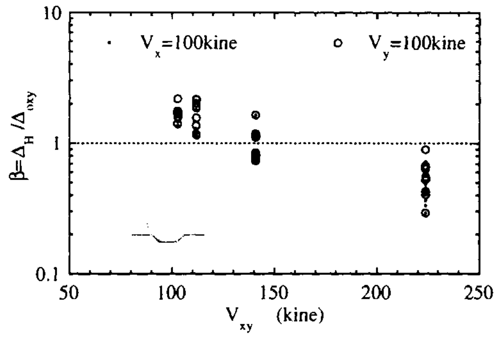


Figure 6 Normalized maximum horizontal displacement
(Vertical and Horizontal input: h_1=10 cm, h_2=12 cm)

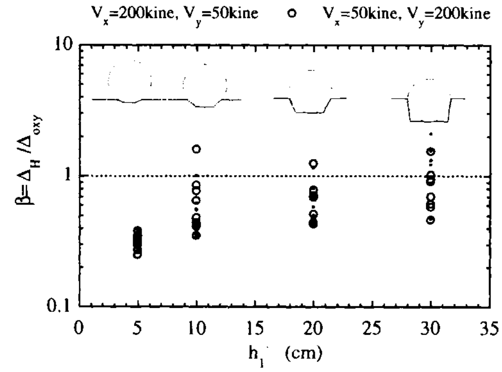


Figure 7 Normalized maximum horizontal displacement
(Vertical and Horizontal input: h_2/h_1=1.2)

Δ_H is associated with velocity amplitude V_{xy} by Eq. (2), though Δ_H is somewhat affected by the socket shape. In our study, β is approximately about 0.5 to 2. For instance, the velocity amplitude V_{xy} of 116 kine on the soil surface is estimated for Δ_H=50 cm by substituting β =2 and e=0.3 in Eq. (2). This velocity amplitude approximately equal to 100 kine is comparable to the near-field ground motions measured to date. Therefore, the estimation of ground motion intensity using Eq. (2) is considered appropriate.

3. SHAKING-TABLE EXPERIMENTS

We have conducted vibration experiments using a three-dimensional large-scale shaking table. The parameters of specimens are shown in Table 2. Boulder models are balls 5 cm to 13.5 cm in diameter made of marble or steel. Natural boulders are also used. Boulder models are placed in a hemisphere socket 10 cm in diameter, as shown in Fig. 8, or on the hexahedral soil model made of silicon rubber. Sine waves, Ricker wavelets, or near-field recordings (Imperial Valley Earthquake (1979) El Centro Array No.6) are adopted for input motions in the vertical or horizontal directions. The predominant frequencies of these input motions are less than 10 Hz, where amplification in the soil model is not observed in the vibration tests of the soil model. The control signals of the shaking table and paths of the boulder are measured. Boulder paths are measured using a laser-displacement meter positioned above the boulder model, or using a high-speed video camera. Photo 1 was taken using the video camera and shows the upthrown

Table 2 Properties of specimens

Soil	Young's modulus E	2.0 kg/cm ^{2}
	Weight per volume γ	1.0 t/m ^{3}
	Poisson's ratio ν	0.48
Boulder	Steel (S5 ~ S13.5)	Diameter : 5 cm ~ 13.5 cm
	Marble (B5 ~ B13.5)	Diameter : 5 cm ~ 13.5 cm
	Natural boulder	Weight: 3.82 kg
Restitution coefficient e		0.65 ~ 0.80

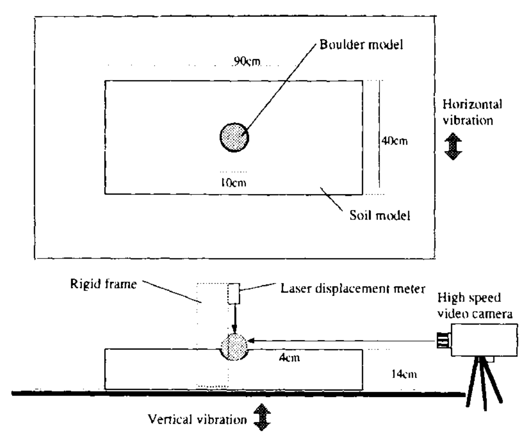


Figure 8 Schematic view of the shaking-table test

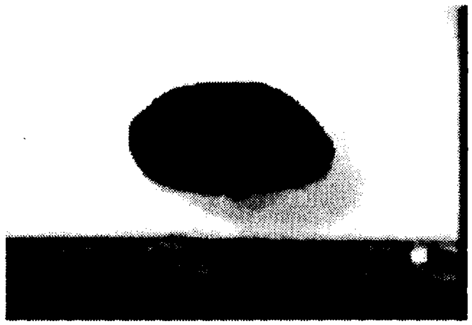


Photo 1 Upthrown natural boulder

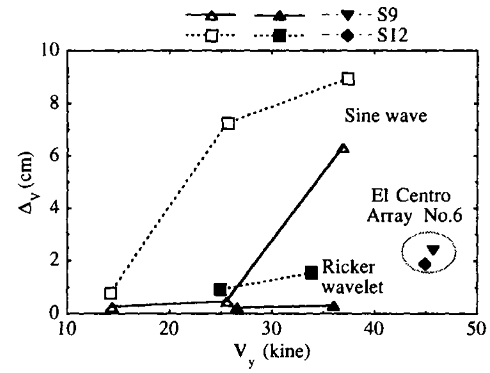


Figure 9 Maximum separation height (Vertical input)

natural boulder.

The relationship between the height Δ_V of maximum separation and the velocity amplitude V_y is plotted in Fig. 9. In these cases, sine waves with a frequency of 5 Hz, Ricker wavelets with a central frequency of 5 Hz, and the near-field recording (vertical component) are input in the vertical direction. Figure 10 shows the time histories of the upthrown boulders. Boulder models are steel balls of 9 cm (S9) or 12 cm (S12) in diameter. According to the results of vibration tests using white noise with a low velocity, the predominant frequency f_0 of S9 and S12 on the soil model is 13.8 Hz and 7.6 Hz, respectively. It is clear from Fig. 9 that Δ_V for Ricker wavelets is smaller than that for the sine wave input, and that boulders hardly leave the soil against impulsive excitations. Boulders are also hardly thrown into the air in the experiments using observed near-field motions. One reason for this may be that the duration time of the main shock is short for the upthrow. On the other hand, the upthown phenomenon of the S9 boulder under horizontal sine wave is shown in Fig. 11. The behavior of the boulder is globally random. However, the boulder collides with the soil several times before it leaves the socket. The motions of the boulder increase as the collision is repeated.

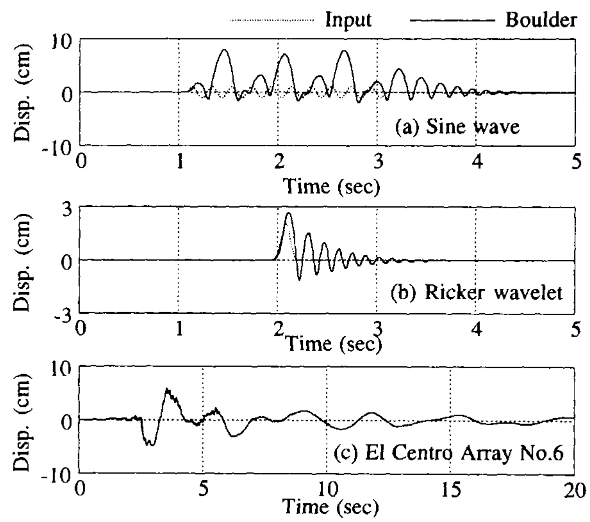


Figure 10 Time histories of displacement (S12 : Vertical input)

Next, Eqs. (1) and (2) are examined using the experimental results for sine waves. Figure 12 shows the comparison of Δ_V obtained through experiments with those obtained using Eq. (1). The frequency f is 5 Hz or 10 Hz and satisfies $f>f_L$. Here, the coefficient of restitution e between the boulder and soil models, which are evaluated based on free-fall experiments of boulders, are substituted into Eq. (1). The experimental results show good agreement with Eq. (1) except for several cases in which f is nearly equal to f_L. Figure 13 shows the relationship between Δ_H when the sine wave (f=5 Hz) is input horizontally and those estimated using Eq. (2), assuming $\beta=1$. It is clear that the values of Δ_H calculated using Eq. (2) are also good approximations of the experimental results.

4. CONCLUSIONS

The conclusions reached on the basis of the results of our studies are as follows:

(a) The upthrow phenomenon is mainly the result of the large-velocity amplitude of ground motions at the soil surface.

(b) Boulder upthrow is caused by periodic motion rather than impulsive motion.

(c) An equation by which the maximum velocity of ground motion is estimated from the horizontal displacement of a boulder has been proposed based on numerical simulations assuming the ground motion to be a sine wave. The proposed formula shows good correspondence with the results of our shaking-table experiments.

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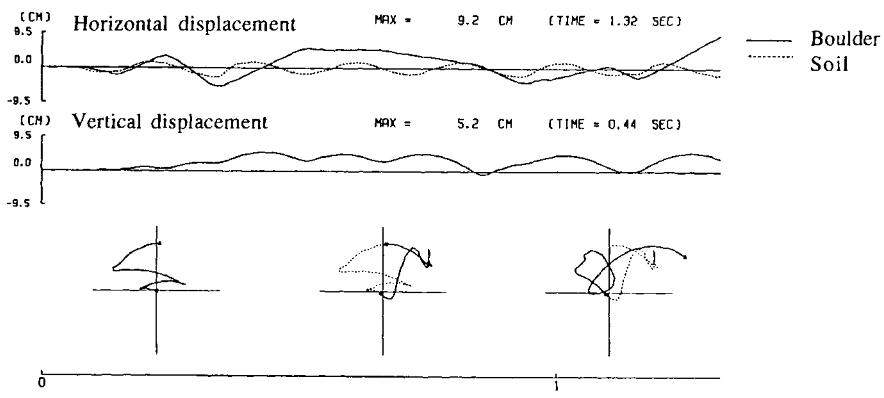

Figure 11 Paths and displacement time histories of S9 under sine wave input in the horizontal direction (f=5 Hz, V_x=47 kine)

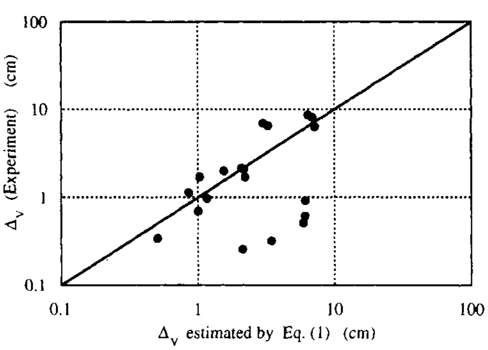

Figure 12 Comparison of Δ_V (Vertical input)

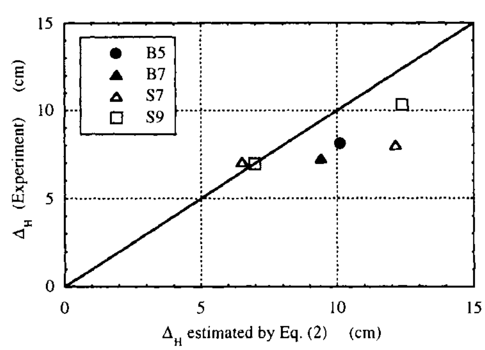

Figure 13 Comparison of Δ_H (Horizontal input)