Article

Computer modeling of dynamic ground motion due to explosive blasting and review of some modeling problems

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Numerical modeling is an approximate method. The validity of the algorithm used in the numerical method should carefully be investigated by providing whether the calculations performed by the method yield the results that are acceptable. A new technique was developed to predict the dynamic motion of ground induced by blasting, which utilized the finite element analysis, coupled with non-parametric source identification method. The results give the information on the frequency characteristics of ground motion as well as vibration levels. For the validity of the method, measured ground motions were compared with estimated ones. Good agreement was shown between measured ground motion and that calculated by the suggested method. Some problems involved in the numerical modeling were also identified.

1. Introduction

Explosive blasting has widely been used in the fields of mining, civil and construction engineering as a tool of rock excavation. While the past researches on the blasting quite depended on the empirical, and trial and error based methods, the development of numerical and experimental tools makes it possible to take scientific approach to higher level of blasting technique. The controlled blasting Lab., one of the National Research Laboratories in Korea, is a unique specialized group in explosive blasting and has performed quite extensive research projects. One of the interesting researches was to develop a technique for the prediction of dynamic ground response. Various kinds of numerical tools are available theses days, and each has its own modeling capability and some limitations in dynamic modeling.

2. Dynamic response of ground induced by blast loading

A necessary part of the planning of construction blasting operations is the estimation of potential damage to nearby structures. The noise and the vibrations transmitted through the ground may also affect the people around a blast site. These vibrations and the accompanying noise are often an annoyance to the people living and working near a blasting operation. Complaints associated with blasting have often become a target of public grievances in Korea. However, careful calculations and placement of the explosives can control these adverse effects of blasting.

2.1 Predictive equation

The ground motion can be measured as displacement, velocity or acceleration of a particle in the ground. Korea has no national standard yet for the acceptance level of blast-induced ground vibration, but peak particle velocity criteria, which was suggested in Seoul subway construction, has often been widely used. It is the criteria defined by peak particle velocity only regardless of the frequency content. Prediction of ground motion in particle velocity may be made without difficulty from the test blasting. In practical use, peak particle velocity can be plotted as a function of scaled distance of which concept is scaling the distance from a blast by explosive charge weight.

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The most general form used in Koreas for the prediction of ground vibrations is as follows:

$$PPV = K\left(\frac{D}{\sqrt{W}}\right)^n \ or\ K\left(\frac{D}{W^{1/3}}\right)^n \qquad (1)$$

where PPV is the peak particle velocity in cm sec^{-1} or mm sec^{-1}, W is the charge weight per delay in kg, D is the distance from a blast source in m. Propagation characteristics are influenced by rock properties, geological discontinuities and blast design parameters such as charge weight, distance from the source, blast pattern, and so on. Although those effects are reflected to the couple of constants, K and n, in the equation, it allows us to take very practical way for prediction.

While the peak particle velocity has been suggested as the best descriptor to assess the damage potential of structures, velocity itself is not sufficient to evaluate structural damage without considering tolerance of the structure[1)-4)]. Because structures respond differently to vibrations of differing frequency content, frequency content has become an increasingly important parameter in the measurement and analysis of ground vibrations from blasting. Based on the analysis of extensive technical data, the former U.S. Bureau of Mines and Office of Surface Mining recommended revised safe blasting vibration criteria for residential structures, depending on the peak particle velocity varying with respect to the frequency[5)]. The criteria incorporate an important element of response spectra technique in some respects. The German vibration standard, DIN 4150, is also of similar form for several types of structures[6)]. In order to assess the damage problems using the peak particle velocity associated with predominant frequencies, it is necessary to get the information on the history of ground motion as well as peak level of vibration.

One has a general tendency that at close in distances from a blast, high frequencies predominate the vibration record and that low frequencies do far from a blast. However, we failed to get the general formula like the scaled distance equation for predicting the frequency. Even if the basic information for preliminary design purpose is acquired from the test blasting, it may be quite different from what is measured during construction blasting due to the change in blast condition, media, etc. It is almost impossible to consider all the parameters experimentally in the design stage. In this regard, numerical modeling is a very useful tool to assess most possibilities that may occur.

2.2 Numerical modeling

One of the new techniques was developed by utilizing the finite element analysis, coupled with non-parametric source identification method. The basic concept is as follows. The relationship between input source and response in a linear system where principles of superposition are applied can be expressed as :

$$U(i\omega) = H(i\omega)\, P(i\omega) \qquad (2)$$

where $U(i\omega)$ and $P(i\omega)$ are complex Fourier spectra of response, $U(t)$, at a point and input motion $P(t)$, respectively; $H(i\omega)$ is transfer function defining the relationship between input and response; ω is frequency; and i is $\sqrt{-1}$. Because equation (2) is composed of frequency dependent three complex functions, one of the functions can be easily determined if the other two functions are given. When $U(i\omega)$ and $H(i\omega)$ are given, source function, $P(i\omega)$, is calculated as follows:

$$H(i\omega) = \frac{U(i\omega)}{P(i\omega)} \ \rightarrow\ P(i\omega) = \frac{U(i\omega)}{H(i\omega)} \qquad (3)$$

In order to reduce error more efficiently involved in estimating the frequency response function, a computer program called KIESSI was used to determine the function[7)]. In order to calculate a transfer function, $H(i\omega)$, the ground is modeled as

Table 1 Input data of physical properties used for analysis

	Shear wave velocity (m/sec)	Poisson's ratio	Density (g/cc)	Damping ratio (%)
G.L. 0 ~ -2 m	2,100	0.24	2.55	2.0
G.L. -2 m ~ -4 m	2,200	0.25	2.57	2.0
G.L. < -4 m	2,300	0.33	2.58	2.0

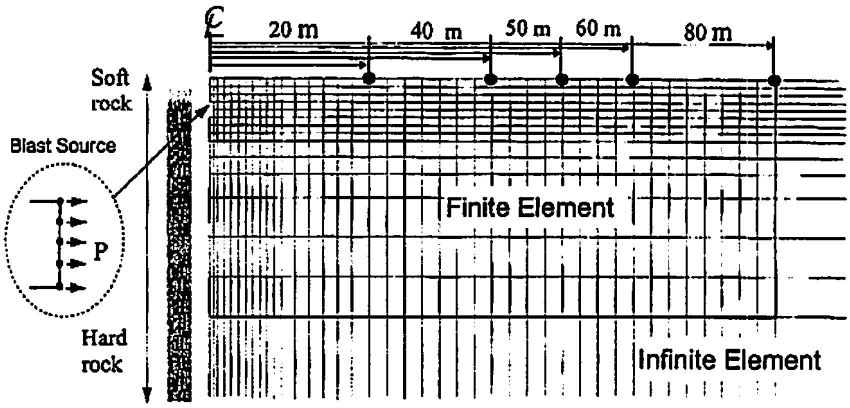
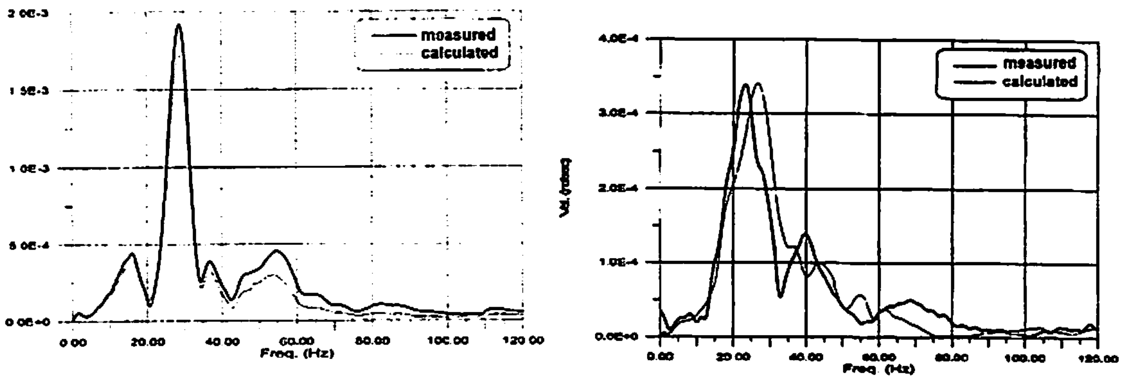


Fig. 1 Finite element mesh and blast modeling



(a) horizontal ground motion at 20 m (b) vertical ground motion at 60 m

Fig. 2 Fourier transform of velocity history

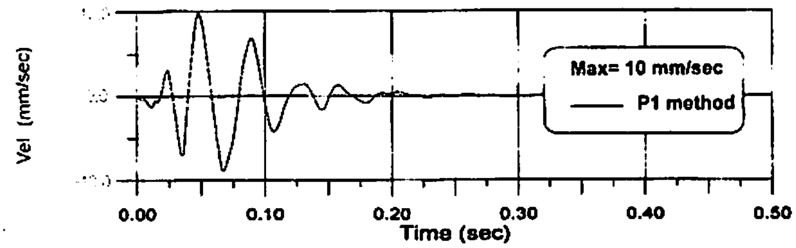


Fig. 3 Velocity history of vertical ground motion at 60 m, calculated

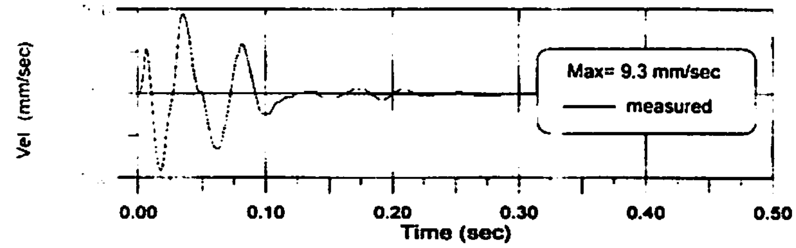


Fig. 4 Velocity history of horizontal ground motion at 60 m, measured

shown in Fig. 1 where axisymmetric finite elements coupled with infinite elements are used. The blast source is assumed to be of cylindrical type (1 m diameter x 2 m high) and located 3 m under the surface. Load is simplified to act in the horizontal direction only. Physical properties used in the analysis were determined from the laboratory tests on the core specimen recovered from the drilling holes in the field. Major ground properties are listed in Table 1[8].

2.3 Field measurement

Ground motions were measured through test blasts performed at the TangJin power plant construction site. Geophones were located at 20, 40, 50, 60, 80 m from the blast source, and time histories for velocity were measured in both vertical and horizontal directions. Estimation of the blast source was carried out using the measured vibration record at each location and the transfer function was calculated numerically. The results give the information on the frequency characteristics of ground motion as well as vibration levels. For the validity of the method, measured ground motions were compared with estimated ones. Figures 2-4 show the examples of selected results. The frequency spectrum of the vertical ground motion at 60 m from the blast source shows only about 5 Hz difference in peak frequency (see Figure 2b). Good agreement in general was shown between measured ground motion and that calculated by the suggested method.

2.4 Numerical problems

The problem, however, lies in the calculated source behavior as shown in Fig. 5. It looks quite different from the real blast source, i.e. it has no physical meaning. Some calculations using the FLAC showed ground responses different from the measured one or sometimes numerical instability when the pressure of explosive loading calculated

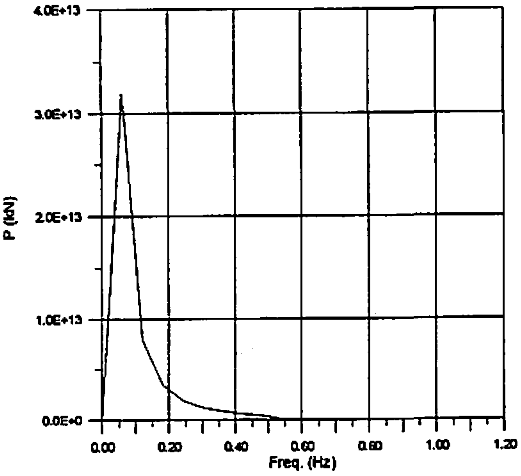
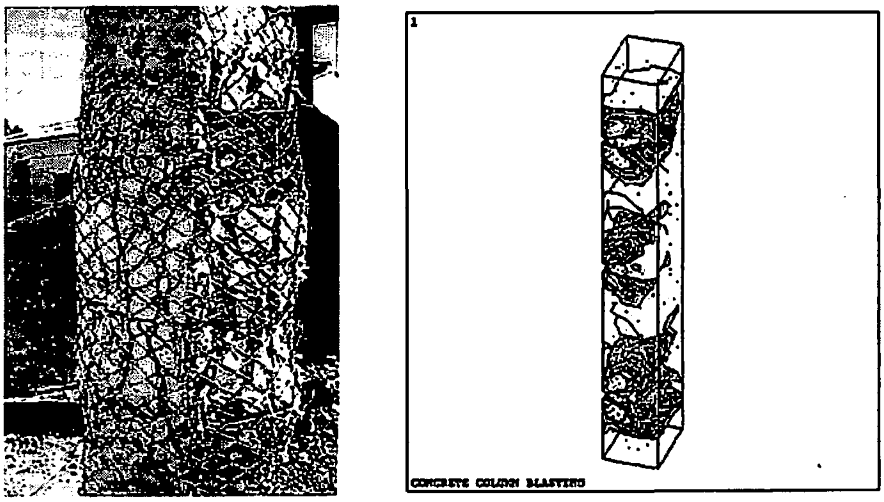
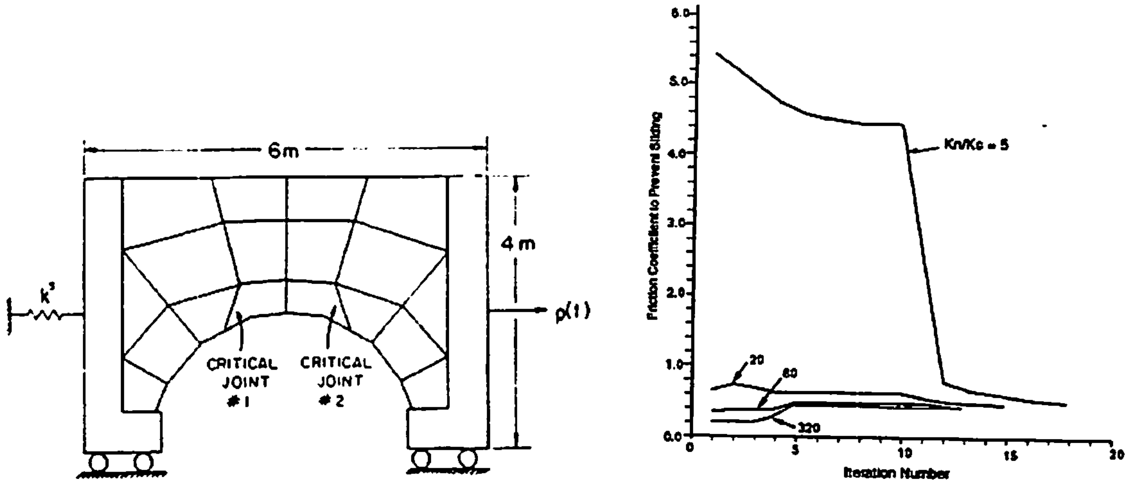


Fig. 5 Estimated blast source



(a) View after blasting (b) Numerical calculation, stress contour

Fig. 6 Explosive blasting of concrete column and numerical modeling



(a) Unstable arch example

(b) Limiting friction state (Kn = joint normal stiffness, Ks = joint shear stiffness)

Fig. 7 Analysis of limiting friction state for unstable arch mesh

by some equations suggested in a textbook was applied as a boundary condition[9]. One of the keys to the successful modeling by using the continuum-based analysis may be how to take care of the energy transfer to surrounding rock mass. The effects of fracturing and energy loss associated with it must be reflected to the boundary conditions. Comparison of the results between field scale experiment of explosive demolition of concrete columns and numerical modeling using the ANSYS based on Finite Element method was carried out. Reasonable result was obtained for calculation of crack growth with the size of the loading reduced to about one third. (see Fig.6) The sound understanding of variables and constitutive equation defining dynamic behavior would be another keys.

Distinct element technique is one of the powerful numerical tools for modeling the rock mass response in later stage of blasting. Major input variables related to material characteristics are joint properties and damping in the analysis. The significance of joint stiffness has not been paid much attention in most previous studies of the distinct element method. Some numerical results calculated by a Distinct Element code based on implicit algorithm showed that the stability of arch tunnel was independent of joint stiffness ratio (see Fig.7). But other results based on explicit algorithm showed that joint properties were very important parameters in the stability analysis and that the joint stiffness ratio associated with joint configuration could be used as an indicator[10].

In some quasi-static problems, joint stiffness has sometimes been selected just to prevent the numerical instability without special concern of real physical properties. The results showed that the response of distinct elements might be quite different depending on the frictional properties. Kinetic energy loss during impact and block response after impact were shown to be dependent on the joint stiffness ratio associated with the friction coefficient. If one is interested in the large displacement of the blocky system rather than deformation, the critical parameter would be not a joint stiffness but a stiffness ratio as input parameters. It, however, is worth noting that there might be a time mismatch between numerical model and real phenomena.

3. Conclusions

A new technique was developed to better predict the ground motion. It gives the information on frequency characteristics of ground motion as well as vibration levels. While the calculated ground motion showed good agreement with the measured one, the estimated blast source had some problems in physical meaning. There must exist another condition to satisfy physically both ground motion and source characteristics. It may depend on how to consider the effects of the fracturing into the continuum model and may need to refine the modeling parameters dominating the dynamic response of the system and that calculated by the suggested method. It was shown that joint stiffness ratio might be more critical factor in discontinuum modeling like distinct element method.

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