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Evaluation of blast-induced vibration effects on structures

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ABSTRACT

Safety-related structures of nuclear power plants have to be protected against the effects of possible hazards. Due to the difficulties of securing construction site for new plants in Korea, following ones are inevitably being built in the area adjacent to the existing plants. Growing concerns have been given to the effects of dynamic loading induced by blasting works near the plants. In this paper, a new method is proposed to predict the ground vibration for the evaluation of safety of blast design in its relation to the generation of ground motion.

INTRODUCTION

Nuclear power is given much weight in the total power in Korea. It accounts for 22.6 percent and will be extended up to 33.1% by the end of the year 2010. There are 11 units of nuclear power plants which are currently operating. 7 units are under construction and total 28 units will be operating in the year 2010. We, however, suffer from securing construction site for new plants due to the opposition by residents hostile to the plants. Thus following ones are inevitably being built in the area adjacent to the existing power plants.

Explosive blasting is generally chosen as a tool for rock excavation to prepare a plant site, and blasting operations are carried out near the existing plant. Blast-induced ground vibration may cause an environmental impact such as neighbour's complaints or damage on adjacent structures and facilities. Safety-related structures of power plants and facilities have to be protected against the effects of possible hazards due to blast vibration as well as natural phenomena like an earthquake. It was once experienced that operation of power generation was suspended. It is assumed to be caused by vibration exceeding to allowable limit, which was generated by construction work near the plant. In this regard, one of our concerns is focussed on the evaluation of the effects of blast design to prevent an impact from rock excavation on nearby structures and facilities.

Deep concerns have been recently given to the effects of dynamic loading generated by blasting works near the plants so as to maintain the safety of structures and facilities in power plants. Earthquakes have generally been considered a major dynamic design loading as a requirement of plant design, but the effects of blast-induced vibrations are not. In order to ensure the safety, rational safe criterion should be established and blast design should satisfy it, which requires the development of a model for prediction of parameters through more systematic measurement and analysis. Our own standard for safety level of blast vibration is not prepared yet, and foreign standards have been generally employed without theoretical and experimental verification. The main objective of the study is to develop a model for prediction of design parameters such as blast vibration level, frequency, etc.

SAFETY LIMIT OF BLAST-INDUCED GROUND VIBRATIONS TO STRUCTURES

When a blast is initiated, an explosive reaction takes place and produces energy causing various types of fracture of rock material. Some of the energy released from an explosive blasting is transmitted to the surrounding rock mass. About 5-20% of energy is known to be transmitted as elastic wave. It propagates and reaches the ground surface in a form of body and surface wave resulting in ground vibration.

The blast-induced ground vibration is not steady-state or continuous but transient. It can be described by three mutually perpendicular components: longitudinal, transverse and vertical directions. In general, experimental observations of threshold have been correlated with the maximum single component regardless of direction. The effects of blast impact are so dependent upon source characteristics and structural response. Differing cultures have often differing thresholds of the toleration of vibration. Summary of safety limit suggested by previous investigators is listed in Table 1[1-5]. As shown in Table 1, peak particle velocity has been suggested as the best descriptor to assess the damage potential of structures. The peak particle velocity is the maximum value associated with the motion of particles at a point of ground being considered.

Table 1. Summary of Suggested Safety Limit of Blast Vibration Level to Structure

Source	Parameters	Suggested Safety Limit
Edwards & Northwood, 1960	Particle velocity	5 cm/sec
Devine, 1966	Particle displ & scaled dist.	0.03", 50 ft/lb$^{1/2}$
Nicholls, et al, 1971	Particle velocity	5 cm/sec
Wiss & Nicholls, 1974	Particle velocity	7-20 in/sec
Siskind, et al, 1980	Particle velocity & Frequency	5 cm/sec for >40 Hz 1.2 cm/sec for <40 Hz

Although peak particle velocity has been widely used to quantify the damage potential of a vibration, velocity itself is not sufficient to evaluate structural damage without considering tolerance of the structure. In recent years frequency content has become an increasingly important parameter in the measurement and analysis of ground vibrations from blasting. Structures respond differently to vibrations of differing frequency content. Researches has been carried out on response spectra techniques intended to improve prediction of vibration damage to structures.

Based on the analysis of extensive technical data, the former U.S. Bureau of Mines and Office of Surface Mining recommended safe blasting vibration criteria for residential structures, depending on the peak particle velocity varying with respect to the frequency[4]. The criteria incorporate an important element of response spectra technique in some respects. The German vibration standard, DIN 4150, also similar criteria for several types of structures [6].

Some countries, like Australia, China, Russia, still adopt criteria defined by peak particle velocity only. There is, however, a growing tendency to adopt vibration criteria varying with respect to the frequency of the vibrations as in Germany, Swiss, and France. Korea has no formal codes for blast-induced ground vibration, but peak particle velocity criteria has often been widely used in urbane subway construction site. Figure 1 shows the examples of various safe criteria. The U.S.B.M recommended a safe particle velocity maximum of 5 cm/sec for residential structures for frequencies above 40 Hz, while DIN 4150, gave somewhat strict criteria of 1-4 cm/sec for industrial and concrete structures. A variety of national vibration limits are listed elsewhere[7].

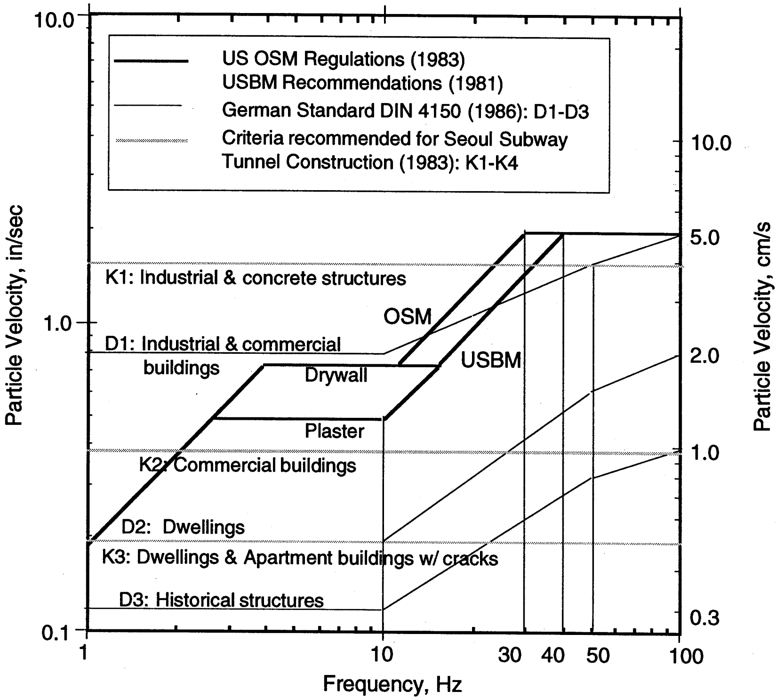


Figure 1. Comparison of safe criteria on blast vibration

Propagation equation

The blast-induced ground vibration decreases in amplitude with increasing distance. The ground motion can be measured as displacement, velocity or acceleration of a particle in the ground. The propagation characteristics are influenced by rock properties, geological discontinuities and design parameters such as charge weight, distance from the source, blast pattern, and so on. 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. The most general form used for the prediction of ground vibrations is given by:

$$PPV = K\left(\frac{D}{W^b}\right)^n \qquad (1)$$

where PPV is the peak particle velocity in cm/sec, W is the charge weight per delay in kg, D is the distance from a blast source in m. The constants K, n and b are empirical and site specific.

Analysis of measurement data shows that good correlation of results could be represented by square-root or cube-root scaling where the power b in D/W^b is 1/2 or 1/3, respectively[1, 8-11]. Figure 2 shows the regression lines representing the mean trend of peak particle velocity as a function of scaled distance. The lines were derived from test and construction blasts at various plant sites. In these cases, cube root scaling was found to give better correlation than root scaling. Effects of geology and other parameters related to blast source are included within the scatter of data about the mean trend of the attenuation in amplitude with distance.

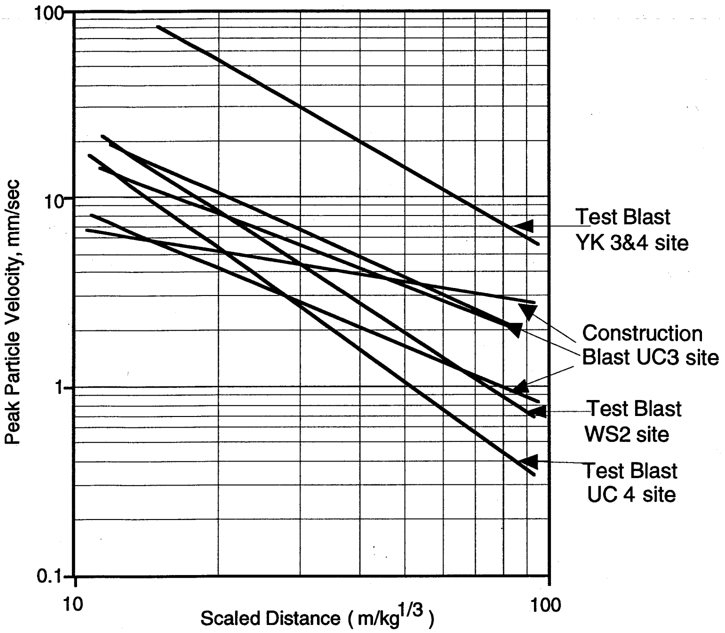


Figure 2. Peak particle velocity vs. scaled distance

PREDICTION OF FREQUENCY CHARACTERISTICS

Estimation of source loading

Relationship between input source and response in a linear system where principles of superposition is applied can be expressed as follows:

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

where U(iω) and P(iω) are complex Fourier spectra of response, U(t), at a point and input motion P(t), respectively; H(iω) 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(iω) and H(iω) are given, source function, P(iω), is calculated as follows:

$$H(i\omega) = U(i\omega)/P(i\omega) \dashrightarrow P(i\omega) = U(i\omega)/H(i\omega) \qquad (3)$$

Estimation of Blast Source in Frequency Domain

In the method of estimating the dynamic characteristics in frequency domain, calculation scheme as shown in Figure 3 is generally used to determine the frequency response function to reduce measurement error. 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 in which calculation scheme as shown in Figure 4 was employed[12]. The computer program is based on the 3-D axisymetric finite element method coupled with the infinite element method. Equation (4) yields more precise value approaching to the true one if error involved in the numerical modelling of transfer function is reduced although there contains certain amount of error in the measurement of response. Large amount of error can be introduced to the measurement depending on the field condition. The error involved in transfer function is, however, relatively small because the function is obtained numerically from the ideal condition. It is the basic idea of estimating source characteristics approaching to true value.

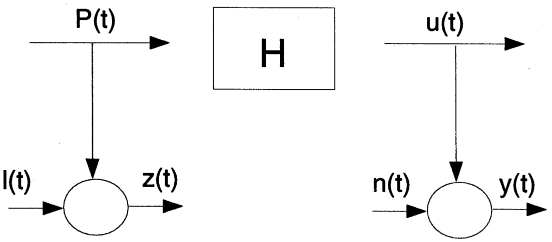


Figure 3. Conventional method to estimate frequency response function

$$\overline{P(f)} = \frac{S_{xy}(f)}{S_{xx}(f)} = \frac{\Im(E\,[x(t)y(t+\tau)])}{\Im(E\,[x(t)x(t+\tau)])} = \frac{\Im(E\,[(h+m)(u+n)])}{\Im(E\,[(h+m)(h+n)])} \qquad (4)$$

where $x = h+m$, $y = u+n$, $\Im$ = Fourier transform, τ = time delay
$P(f)$: true frequency input function which has no error, $P = U/H$
h, u: true system transfer function and response which has no error
x, y, z: estimated transfer function, measured response, and input function which has error
m, n, i: calculation error, measurement error, and input error
$S_{xx}(f)$: auto-power spectral density function of x
$S_{xy}(f)$: cross-power spectral density function of x and y

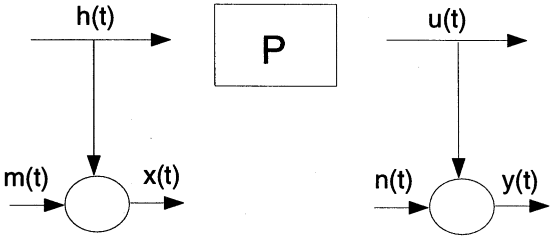


Figure 4. Introduced method to estimate frequency input function

ANALYSIS AND RESULTS

Prediction of Ground Motion

In order to calculate a transfer function, $H(i\omega)$, soil is modelled as shown in Figure 5 where axisymertric finite elements coupled with infinite elements are used. Blast source is assumed to be of cylindrical type (1 m dia. x 2 m high) and located 3 m under the surface. Load is simplified to act in horizontal direction only.

Physical properties used in the analysis are determined from the laboratory tests on the core specimen recovered from the drilling holes in the field. Major soil properties are listed in Table 2, where V_S is shear velocity, v is Poisson' s ratio, r is density, and x is damping ratio.

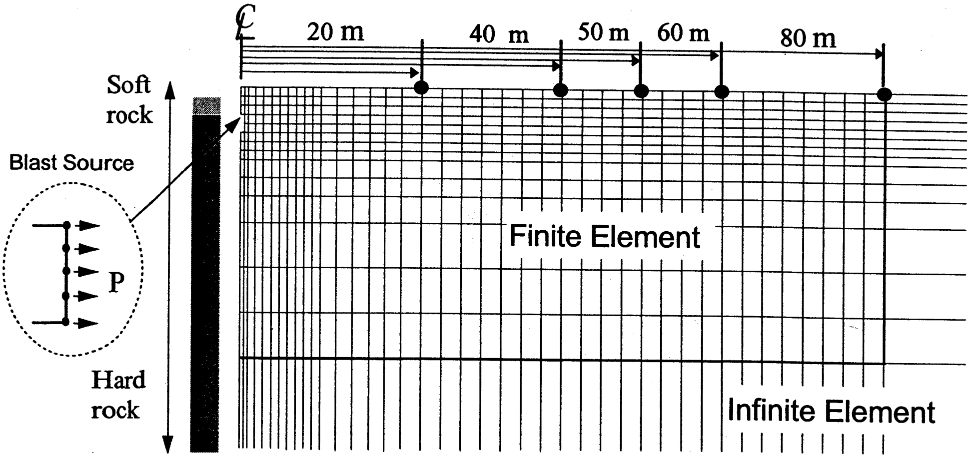


Figure 5. Finite element mesh and blast modelling

Table 2. Input data of physical properties used for analysis

	V_S (m/sec)	ν	ρ (t/m^3)	ξ
G.L. 0 ~ -2 m	2,100	0.24	2.55	0.02
G.L. -2 m ~ -4 m	2,200	0.25	2.57	0.02
G.L. -4 m ~ ∞	2,300	0.33	2.58	0:02

Ground motions were measured through test blasts performed at 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 direction. Estimation of blast source was carried out using the measured vibration record at each location and transfer function calculated numerically.

Responses of horizontal direction were computed at 20 m from the source, and in vertical direction at 40, 50 and 60 m, respectively, to verify estimated the blast source. The results are shown in Figure 6 to 9. Comparison of calculated responses with observed shows relatively good agreement but partly a little poor in dynamic characteristics and vibration level.

Using the suggested method, estimation of blast source is carried out. By using the measurement data at 20, 40, 50, and 80 m, and vertical ground motion at 60 m is predicted. The results are shown in Figures 10 and 11. Good agreements are shown between calculated responses and test data except for frequency content of computed responses are more overestimated than observed.

It is worth noting that error involved in modelling transfer function is so small although soil data of a blast site lacks precision and modelling of blast source is very simplified. Improvement of source modelling and strict investigation of a blast site will provide more precise prediction.

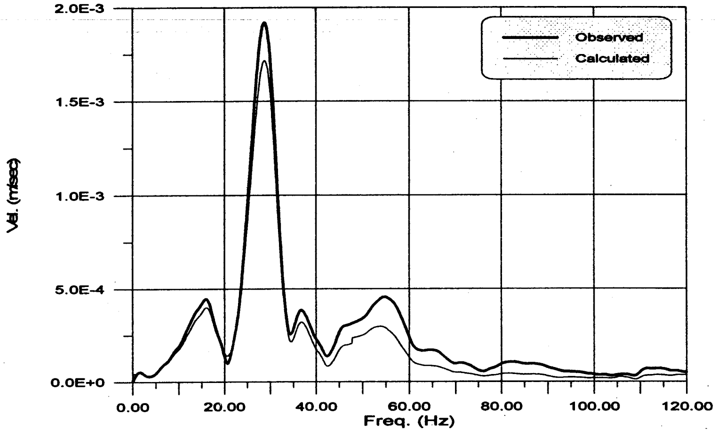


Figure 6. Fourier transform of velocity history of horizontal ground motion (at 20m)

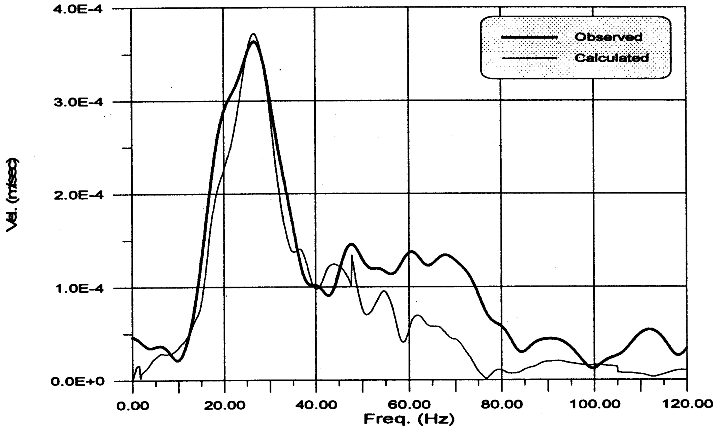


Figure 7. Fourier transform of velocity history of vertical ground motion (at 40m)

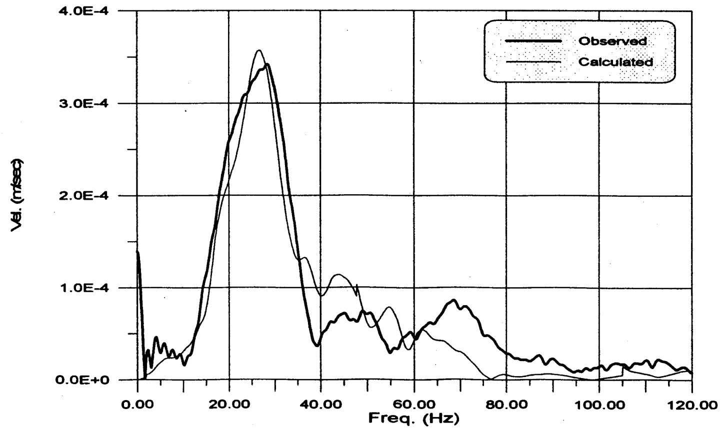


Figure 8 Fourier transform of velocity history of vertical ground motion (at 50m)

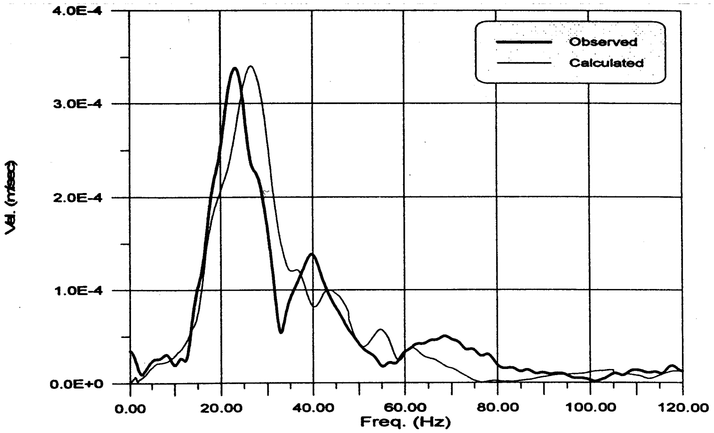


Figure 9. Fourier transform of velocity history of vertical ground motion (at 60m)

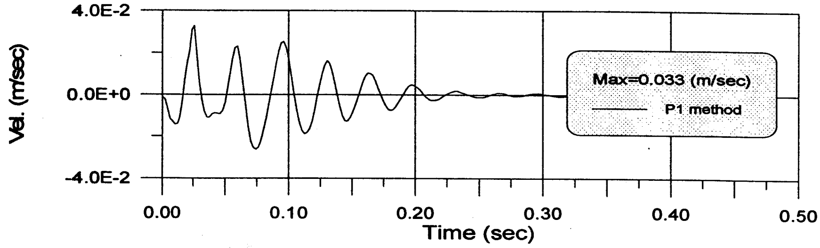


Figure 10. Velocity history of horizontal ground motion (at 20m, calculated)

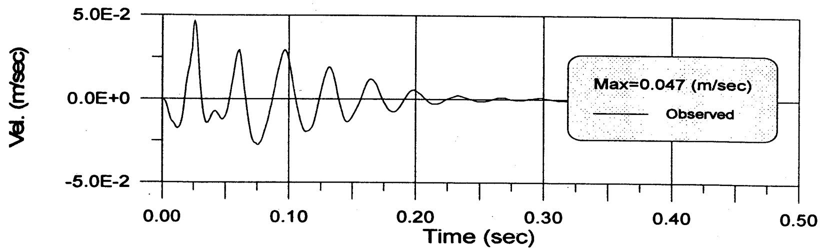


Figure 11. Velocity history of vertical ground motion (at 20m, measured)

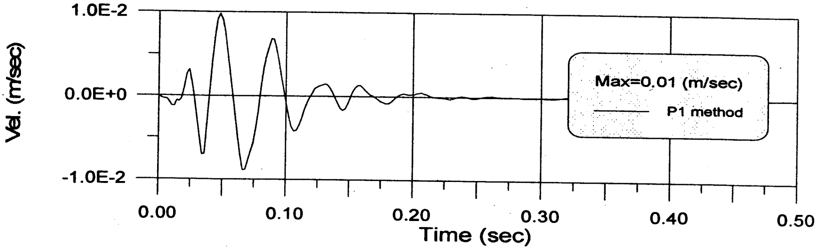


Figure 12. Velocity history of vertical ground motion (at 60m, calculated)

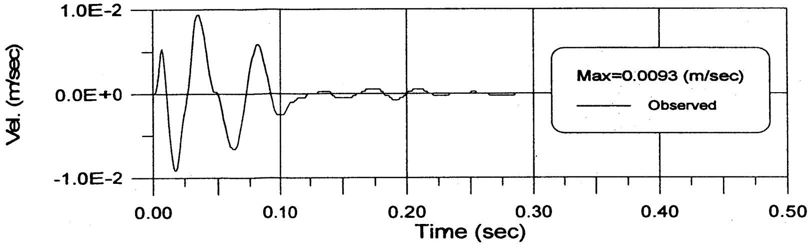


Figure 13. Velocity history of horizontal ground motion (at 60m, measured)

Analysis of Structural Response

In order to analysis the effects of frequency characteristics on structural response, some basic calculations were carried out. Typical blast vibrations were artificially generated of which waveforms have principal frequencies (P.F.) ranging from 5 to 40 Hz and peak particle velocity is 2.0 cm/sec. Blast load was estimated using the method described above before a structure introduced. A structure is then introduced and the response is calculated under the load. Figure 14 shows the axisymmetric finite element model of the ground and structure representing containment building.

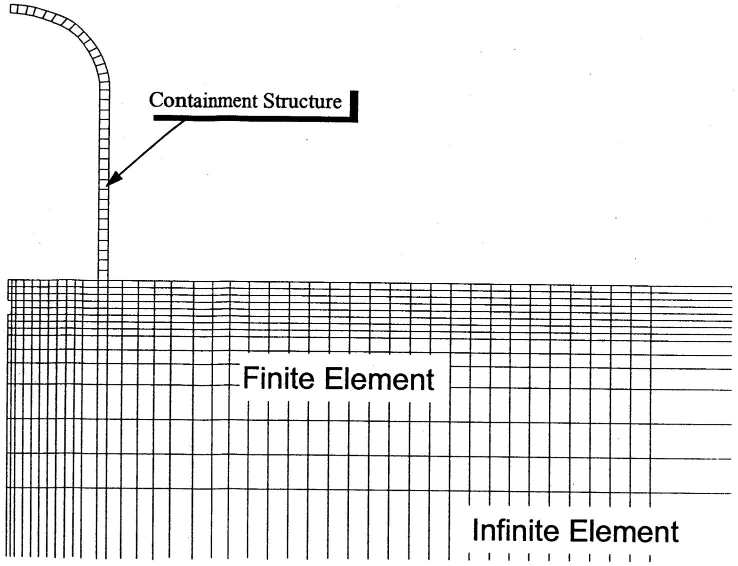
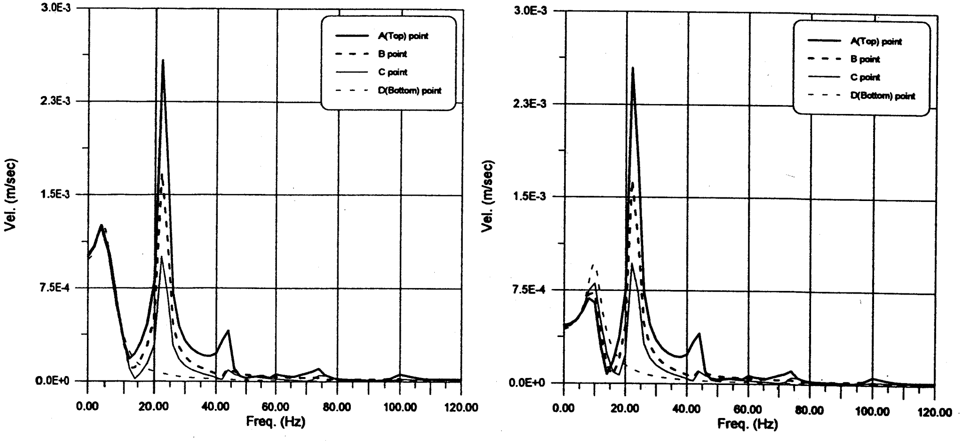
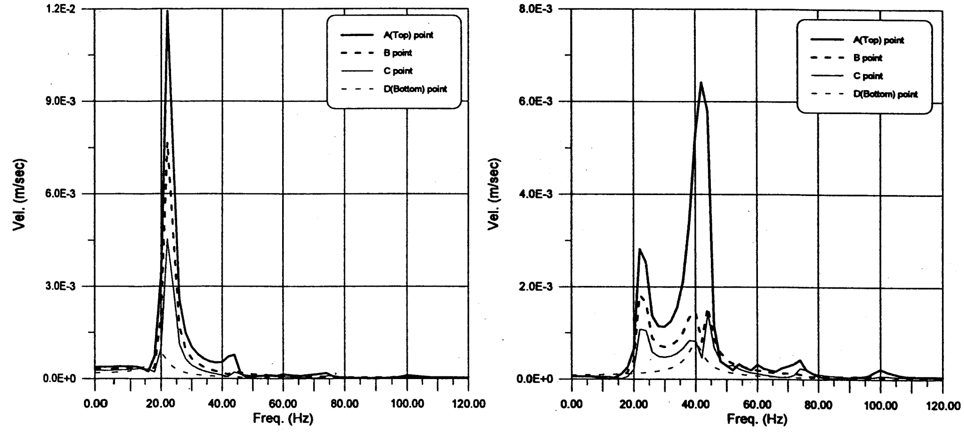


Figure 14. Finite element modelling of containment building and ground



(a) P.F. of input motion : 5 Hz (b) P.F. of input motion : 10 Hz



(c) P.F. of input motion : 20 Hz (d) P.F. of input motion : 40 Hz

Figure 15 Comparison of floor response spectrum

Some results of response calculation are shown in Figure 15. Summarizing the results, waveforms having principal frequencies of 5 to 10 Hz do not give significant effects on the structure. However, the response of upper part of structure is calculated to amplifier several times larger than that of input level. The results imply that the damage potential might appear in different way from that of generally suggested guidance level depending on the conditions of structure and ground.

CONCLUSION

A new technique was developed to make up for the weak points involved in plug-in type equations to predict a peak particle velocity of ground motion. It gives the information on frequency characteristics of ground motion as well as vibration levels. For the validity of the method, comparisons with measured ground motion were performed. Good agreement was shown between measured ground motion and that calculated one by the suggested method. It allows one to minimize the amounts of test blasts required for evaluation or predict precisely without test blasts if blast source is estimated for various charge condition and transfer function calculated according to distance for various site conditions.

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