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Earthquake simulation by explosives for studying the ultimate response of structures

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ABSTRACT : Earthquake simulation techniques using buried explosives have a great potential for investigating experimentally the overall seismic behavior of a nuclear reactor building in nearly full scale model in the field. For the feasibility study of such kind tests, 1/6 scale model of an ABWR type reactor building was employed for reference and prediction analyses were performed. The explosives array design and ground motion generated were evaluated by calculation based on 3-D wave propagation analysis. The structure response for the generated ground motions by explosive was also studied.

1. INTRODUCTION

Earthquake simulation techniques using buried explosives have a great potential for investigating experimentally the overall seismic behavior of a nuclear reactor building in nearly full scale model in the field.
The response of structures to earthquake motion has been the topic of many studies and investigations. Laboratory tests on scale and full-size models and tests of actual structures or components have been conducted. In performing the tests, the dynamic input has been generated by mechanical vibrators; buried explosive charges; building a test structure in a high seismic zone and waiting for an actual earthquake to occur; subjecting the structure through a series of static displacements (the so-called pseudo-dynamic tests);or an initial displacement ("snapback test").
The latter two techniques are primarily used for framed structures for components such as valve/piping assemblies. In addition to the traditional use of the "shake table", there have been many ingenious developments of mechanical testers, including eccentric vibrators that are attached to a floor. Except for buried explosives, all of these methods do not lend themselves to investigating the behavior of a structure that includes all the effects of "soil-structure interaction". Also, if a relatively high level of response is desired for an in-situ structure, these methods, except for buried explosives, are not appropriate or are applicable in only limited circumstances.
This paper focuses on the use of explosives to generate large earthquake-like ground motion which will cause severe damage to a nearly full size reactor building model. For the feasibility study of such kind tests, 1/6 scale model of an ABWR type reactor building was employed for reference and prediction analyses were performed. The explosives array design and ground motion generated were evaluated by calculation based on 3-D wave propagation analysis. The structure response for the generated ground motions by explosive was also studied. In this paper, array design of explosives, generated ground motions, scaling techniques of modeling and structure response are discussed.

2. TEST BUILDING AND SCALE LAW

For studying earthquake simulation techniques, an ABWR type reactor building was employed for a prototype building since it is considered as a standard plant type in the future in Japan (See Fig. 1). The larger test scale is preferable to study seismic response of building containing plant equipment in field tests, 1/6 scale is therefore selected to study a similarity law. As shown in Table 1, Cauchy scaling or Froud scaling can be considered as a scale law of the test.
The feature of the scale laws are that Cauchy scaling gives a constant density and reciprocal scale times acceleration, Froude scaling gives reciprocal scale times density and a constant acceleration.
For the seismic response tests considering soil structure interaction in a field, there is a limitation for the soil scale model of the gravity. Froude scaling is selected for the scale law of the test model in the feasibility study.
A ground geology having shear wave velocity of Vs=500m/s in 1/6 Froude scale corresponds to a hard rock geology with Vs=1225m/s in actual scale.

Table 1 Scale laws

Scaling of Dynamic Problems
Basic Wave Equation

$$\frac{\partial\sigma}{\partial x}=\rho\cdot\frac{\partial^2 u}{\partial t^2}+a_1\cdot\rho g$$

Scaled Wave Equation

$$\frac{\partial\sigma}{\partial x}=\left[\frac{k\rho\cdot k l^2}{k\sigma\cdot k t^2}\right]\cdot\rho\frac{\partial^2 u}{\partial t^2}+\left[\frac{k\rho\cdot kg\cdot kl}{k\sigma}\right]\cdot a_1\cdot\rho g$$

Scaling Requirements

$$\frac{k\rho\cdot k l^2}{k\sigma\cdot k t^2}=1 \quad ; \quad \frac{k\rho\cdot kg\cdot kl}{k\sigma}=1$$

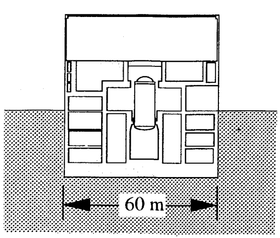


Fig. 1 Prototype building (ABWR)

	Parameters	Scale Factors	Cauchy Scaling	Froude Scaling
Five Key Parameters	Length	kl	[$1/\lambda$]	[$1/\lambda$]
	Stress	$k\sigma$	[1]	[1]
	Density	$k\rho$	[1]	λ
	Gravity	kg	λ	[1]
	Time	kt	$1/\lambda$	1/Sqrt (λ)
Parameters of Materials Properties	Area	kl^2	$1/\lambda^2$	$1/\lambda^2$
	Mass	$k\rho\cdot kl^3$	$1/\lambda^3$	$1/\lambda^2$
	Vs	kl/kt	1	Sqrt ($1/\lambda$)
	Modulus(E,G)	$k\sigma$	1	1
Parameters in Response	Frequency	1/kt	λ	Sqrt (λ)
	Displacement	kl	$1/\lambda$	$1/\lambda$
	Velocity	kl/kt	1	Sqrt ($1/\lambda$)
	Acceleration	kl/kt^2	λ	1
	Forces	$k\sigma\cdot kl^2$	$1/\lambda^2$	$1/\lambda^2$
	Stress	$k\sigma$	1	1

- length ratio : $\lambda >= 1$
- Only three key factors are independent to each other.
- [ ] indicates key factors which are assumed.
- Other two factors can be derived by the following equations.
  $k\rho\cdot kg\cdot kl/k\sigma=1$; $(k\rho\cdot kl^2)/(k\sigma\cdot kt^2)=1$

3. ESTIMATION OF EARTHQUAKE-LIKE GROUND MOTION BY EXPLOSIVES

To generate the required earthquake-like ground motion fitting with the target spectrum by buried explosives for seismic tests of structures in a field, the appropriate explosive array design and the prediction analysis of the ground motion to be generated are important techniques.
A finite differential method or two dimensional axisymmetric FEM method were used to the analysis in the past study but these methods are difficult to apply to the analysis of the large and complex array design. The assumptions in the two dimensional analysis are become not appropriate for the evaluation of far field ground motion from the explosive arrays. The method proposed here is composed of evaluating the ground motion of single cylindrical source using Green's function of three dimensional wave propagation theory in layered half space and integrating the all ground motions generated from each cylindrical source in the array.

Fig. 2 shows the concept view of the test by buried explosives arrayed several lines of bore hole for earthquake-like ground motion source. Each line of charge holes array will be detonated with time lag in order from farthest line to close to the structure. The earthquake-like ground motion at the location of the test structure can be analyzed by following procedure. Fig. 3 shows the numerical model of the body force from a cylindrical source applied to the surrounding soil.

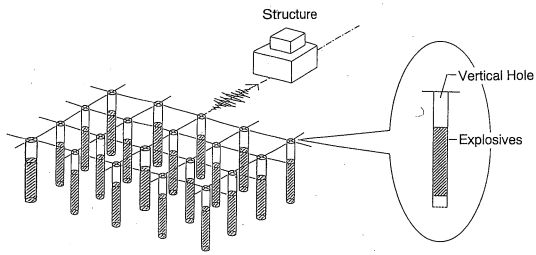


Fig. 2 Earthquake simulation test on model structure

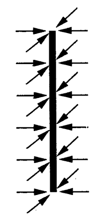


Fig. 3 Body force applied to the soil due to sxplosive

The distribution of the compression body force is assumed to be uniform along a cylindrical source. The numerical expression of the body force can be expressed as following equation (1).

$$\begin{aligned} F_x &= -M(t)\frac{\partial}{\partial x}\delta(x-x_S)\,\delta(y-y_S)\left[H(z-z_{S1})-H(z-z_{S2})\right] \\ F_y &= -M(t)\,\delta(x-x_S)\frac{\partial}{\partial y}\delta(y-y_S)\left[H(z-z_{S1})-H(z-z_{S2})\right] \\ F_z &= 0 \end{aligned} \tag{1}$$

where, M (t) denotes the equivalent source time function and xs, ys, zs1, zs2 represent the location of the source in the Cartesian coordinates.
Applying triple Fourier transform (double in the two horizontal directions and in time) to eq. (1) and decomposing P-SV waves and SH wave components, the Green's functions in the wave number domain comprising only P-SV waves are obtained. The Green's functions in the time space domain are described in the following form applying equivalent Fourier-Bessel transform to double Fourier transform in the inverse transformation.

$$\begin{aligned} u_r(r,t) &= \frac{1}{2\pi}\int_{-\infty}^{\infty}\int_{0}^{\infty} U_1(k,\omega)\, k\, J_1(kr)\,dk\,d\omega \\ u_z(r,t) &= \frac{1}{2\pi}\int_{-\infty}^{\infty}\int_{0}^{\infty} U_2(k,\omega)\, k\, J_0(kr)\,dk\,d\omega \end{aligned} \tag{2}$$

where, $U_1(k, \omega)$ and $U_2(k, \omega)$ represent the horizontal and vertical displacements in the frequency wavenumber domain respectively. In the near field of the explosive source, the ground motion would show strong nonlinear behavior by the strong detonation pressures, but the ground motion in some distance from the explosive source can be in linear behavior. The ground motion at observation point therefore is able to be evaluated using equivalent source time function which is given to generate as same velocity wave form as the empirical data of the past experiment.
In this analysis, source time function is assumed to be expressed in the following equation (3).

$$f(t) = a(1-\cos 2t_1)^2 \exp(-nt_1)$$
$$t_1 = 2\pi f_0 t \qquad (3)$$

where, value of the parameters a, n, and fo, are determined by try and error procedure untill the calculated waveform at the reference point fit to the empirical data.
Fig. 4 shows the soil properties of the analytical model and arrangement of the cylindrical source.
Fig. 5 shows plan view of the explosives array. The charge density is arranged as shown in Table 2 so that the unifoem velocity amplitude can be observed at taget point .
Fig. 6 shows the calculated waveform of the ground motion at the observation point in distance of 140m from the front array.

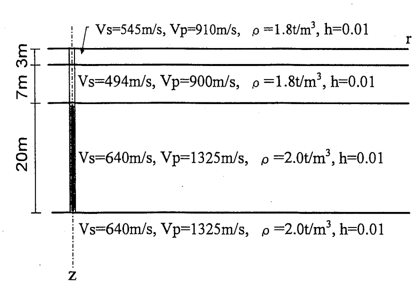


Fig. 4 Properties of soil model

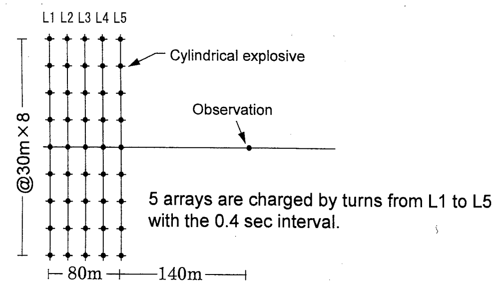


Fig. 5 Geometry of designed array

Table 2 Amount of Charges

	charge dencity (kg/m)	amount (ton)
L1	180	32.4
L2	150	27.0
L3	120	21.6
L4	90	16.2
L5	60	10.8
TOTAL		108.0

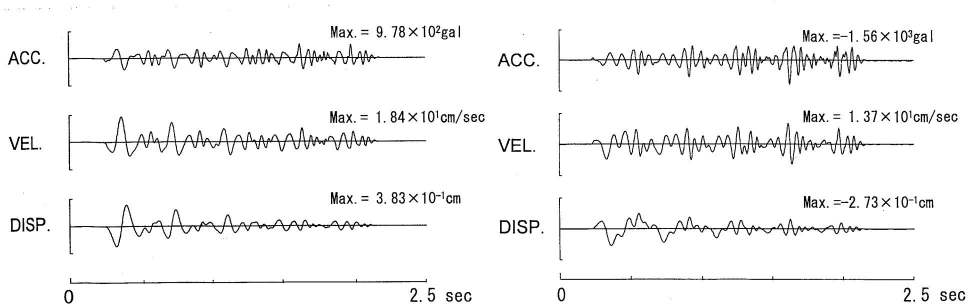
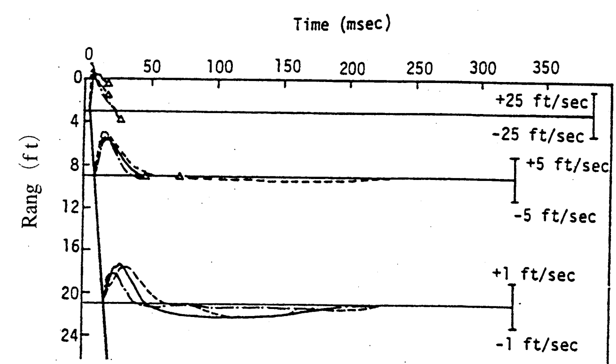


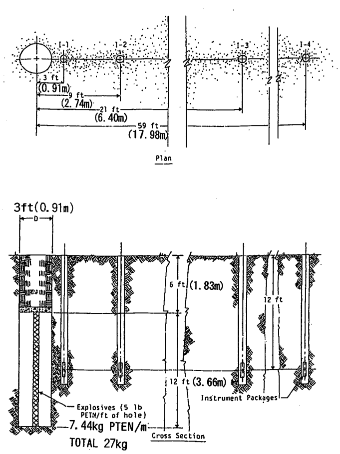
Fig. 6 Calculated ground motions

4. ESTIMATION OF EXPLOSIVE IMPACT SURROUNDING SOIL

To examin the possibility of analitical estimation of ground motion and the nonlinear region in the near field of charge hole, the prediction analysis of near field ground behavior using Nonlinear Dynamic Analysis of solid in Three Dimensions, DYNA3D was performed to simulate the functional tests conducted at McCormic Ranch in New Mexico as the DIHEST Improvement Program in 1978 by Higgins. C. J. . Outline of the reference test is shown in Fig. 7. The charge hole diameter is 0.91m. The charge density is 7.44kg/m. The charge length is 3.66m. The total amount of explosive is PETN 27kg. The sensors were installed at the distance of 0.91m, 2.74m, 6.40m, and 17.98m from the center of the charge hole.
In this analysis, 1/4 of the surrounding soil was treated as shown in Fig. 8 using solid element model. The boundary conditions are fixed in horizontal direction to represent symmetry condition and vertical direction is free for side boundary and fixed for bottom boundary. The yield function was used Mohr-Coulomb type. The tensile yield strength was taken 7.03kg/cm^2 as shown in Fig. 9. Fig. 10 shows the relationship between pressure and volumetric strain. The detonation pressure to input the charge hole surface was shown in Fig. 11 which was derived from the back fitting analysis to the pressure wave form of the past test result. The analysis was carried out in the time duration of 0.05 seconds from the detonation. The analysis steps were 2311 steps. The maximum ground velocity of analysis results were shown in Table 3 comparison with the observed value in the reference test.
The analysis results were shown good agreement with the test results. Fig. 12 shows the deformation of charge hole at the time 0.01second after detonation. The nonlinear regions were estimated 5m radius zone from the charge hole center line by the judgment that the nonlinear element was selected from the yield experience at least once yield in the yield history.

Accelerations from cylindrical shots





Soil properties

Depth	Vp(m/s)	Vs(m/s)
0 - 1 m	396	212
1 - 4.3 m	534	285
4.3 - 26 m	671	359

Testbed layout

Fig. 7 Outline of reference test

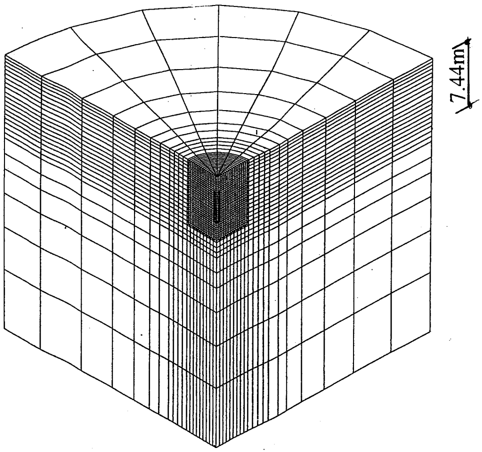


Fig. 8 Explosive impact analysis model

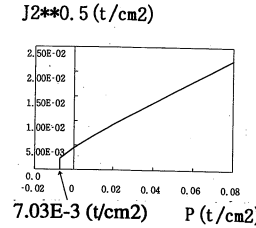


Fig. 9 Yield function (Mohr-Coulomb type)

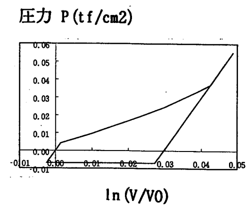


Fig. 10 Relationship between pressure and volimetric strain

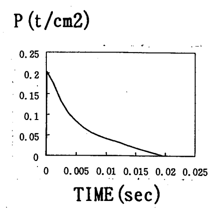


Fig. 11 Pressure time distribution of source

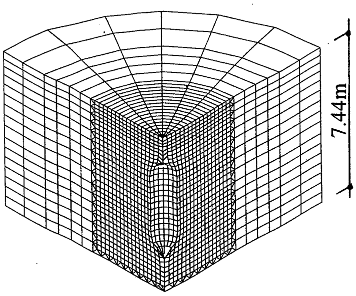


Fig. 12 Deformation of charge hole at the time 0.01 second

Table 3 Maximum ground velocity (unit : m/s)

Measuring point	I −1	I −2	I −3
Calcuration	2270	490	47
Observation	1740	335	55

5. STRUCTURAL RESPONSE

Seismic response analysis was performed on the 1/6 Froude-scale model of the prototype ABWR building. The earthquake-like ground motion calculated and the prototype earthquake which are shown in Fig.13 were applied to the model. The maximum acceleration was altemated up to six times to examine the effect of the magnitude on the responses of the building model. Fig.14 shows the maximum response in the shear skeleton curve at the GL level of the box wall. The hysteresis loops are also shown in the figure. The responses obtained from the earthquake-like ground motion input show a very good correspondence to the results of the prototype earthquake in terms of the maximum responses and the shapes of the hysteresis loops. The comparison of the results shows that the earthquake-like ground motions generated by the explosives can be used as a substitute of the prototype earthquake in the vibration test.

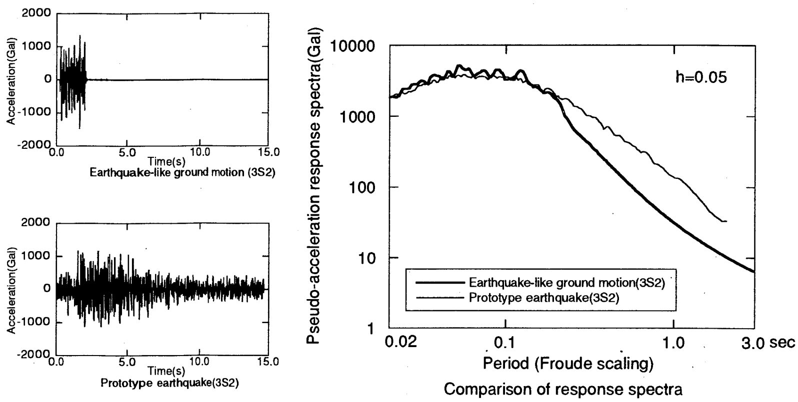


Fig. 13 Comparison of earthquake-like ground motion and prototype earthquake

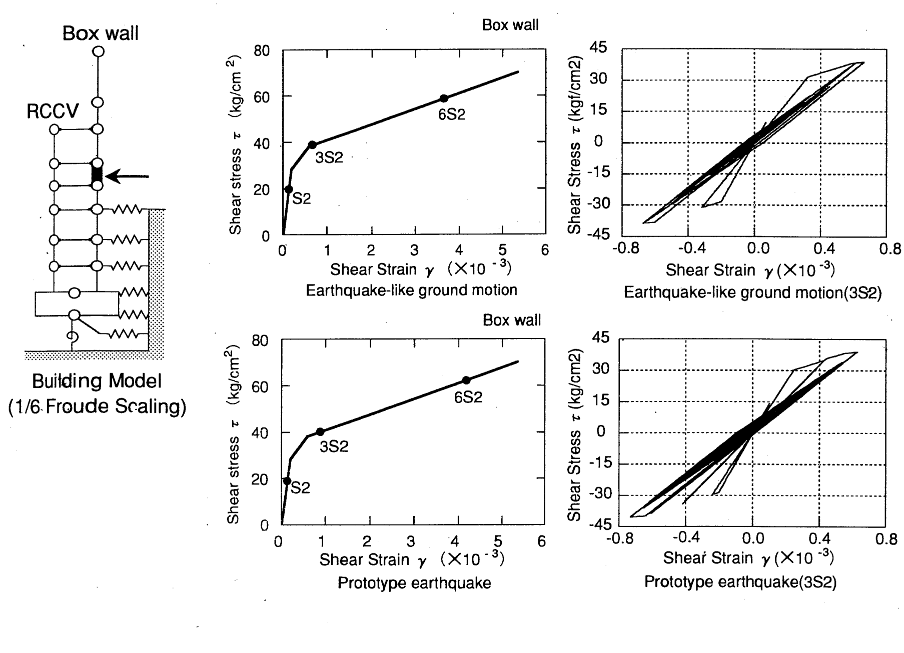


Fig. 14 Comparison of response analysis results on model structure and prototype building

6. CONCLUSION

In a feasibility study of the earthquake simulation tests by explosives, we performed prediction analyses of earthquake-like ground motions generated by explosives and structure damage by dynamic response. Followings are the summary of the study.

(1) Regarding test site geology, a shear wave velocity 500m/s is corresponds to a Froude scaled "hard rock" geology.

(2) Earthquake-like ground motions can be generated by suitable explosives array design as scaled $2 \times S_2$, $3 \times S_2$ and $6 \times S_2$ by approximate amount of explosives 100ton, 150ton and 300ton respectively.

(3) Dynamic response of a model structure by explosives corresponds to the response of a prototype building by earthquake.

(4) Earthquake simulation techniques using explosives have a great potential for investigating experimentally the overall seismic behavior of a nuclear structures in nearly full scale model in the field.

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