

## Discrimination of Underground Explosions from Microearthquakes through the Pure-Continental Path 순수 대륙 경로에서 미소지진과 지하 인공폭발의 구별

김소구(So Gu Kim)

한양대학교 지진연구소

### 요약/Abstract

한반도 남부의 순수 대륙을 통과한 지진파를 가지고 미소지진과 지하 인공 폭발의 구별에 관한 연구를 한다. 지하 인공 폭발과 미소지진의 파형 특성은 관측 및 이론 지진 기록지를 가지고 수행한다. 이러한 지진파 파형 특성은 주로 진원메커니즘이 전파 과정보다 강한 영향을 미친다. 미소지진에서는 double-couple진원, 그리고 폭발에서는 single-couple진원이 주어진다.

진원이 아주 천부층에 있을 때 Rayleigh파의 fundamental mode(1-6초 주기)인  $R_g$ 파와 guide파인  $L_g$ 파(8-12초 주기)가 잘 나타난다. 또한 폭발에서 SH파는 nodal line이 없기 때문에 초동 진폭이 약하게 나타남을 알 수 있다.

인공폭발의 이론 지진 기록지는 압축 초동의 P파와  $R_g$  및  $L_g$ 파가 나타남을 알 수 있다. 그 반면에 전자의 초동은 관측점에 따라 압축(compression)과 팽창(dilatation)이 나타났고  $L_g$ 파는 복잡하고  $R_g$ 파는 깊이가 커짐에 따라 사라지는 것을 알 수 있다.

Discrimination studies between microearthquakes and underground explosions are carried out in the pure-continental path of north-south within the Korean Peninsula. The characteristic waveforms for explosions and microearthquakes are investigated in the light of observation and synthetic seismograms. The characteristic waveform generation is mainly a function of source mechanism and ray-path and former influences more strongly than the latter. A double-couple source mechanism for microearthquakes and a single-couple(force) mechanism for explosions are presented in this study.

It is found for very shallow events to have outstanding of  $L_g$  waves in the transverse components that pass through the upper crust with period of 1-6 seconds and fundamental modes of Rayleigh waves,  $R_g$  in the vertical component with period 8-12 seconds. Furthermore it is pointed out that the first arrival amplitudes of SH waves for explosions are always small regardless of azimuth

of stations since there is non-existence of nodal lines for the explosion mechanism. Theoretical seismograms for explosions show the first motions of compression with short wavelengths as well as mostly fundamental modes of Rayleigh waves,  $R_s$  waves and  $L_s$  waves, whereas those of micro-earthquakes give either compression or dilatation according to the back azimuth epicenter to stations and poor or non  $R_s$  waves and complicated  $L_s$  waves, depending on the focal depth.

---

The present studies were supported by the Basic Science Research Institute Program, Ministry of Education, 1994(BSRI-94-5420)

## INTRODUCTION

The Discrimination studies between earthquake and underground nuclear explosions have been carried out by several seismologists (Nuttli and Kim, 1976 ; Dahlman and Israelson, 1979 ; Masse, 1981 ; Smith, 1993). The discrimination studies using teleseismic events have been highly studied and successful except for some anomalous events. Douglas et al. (1974) and Landers(1972) have found some anomalous earthquakes in Tibet and Kazakh. Kim and Nuttli(1976, 1977) also investigated some anomalous earthquakes and nuclear explosion in Eurasia using spectral analysis and magnitudes of body surface waves. It has been found that  $m_b / m_s$  values of anomalous earthquakes are close to those of underground nuclear explosions. Bruns(1971), Hanks and Wyss (1972) and Forth(1975) demonstrated the P-wave spectral to investigate corner periods and asymptotic slopes which can be explained in terms of source finiteness and fractional stress drop.

The local event discrimination between microearthquakes and underground explosions,

however, has not been studied eagerly so far. Furthermore the development of detectability of small-yield explosions whose epicentral distance is not greater than 400km have not been actively studied in Korea in the light of seismological aspects. For the sake of the local event detectivity study, we use local microearthquakes and explosions recored in the Korean Peninsula in collaboration with the reflectivity method of synthetic seismograms(Kind, 1989)

The left-lateral and right-lateral strike slip motions, and normal-fault and reverse-fault dip slip motions are applied for a double-couple source mechanism for earthquakes, whereas source mechanism for explosion is assumed to be a single-couple(force).

## BASIC THEORY OF SEISMIC DISPLACEMENTS

Following Ben-Menahem and Singh(1972), we obtain the following expression for the far-field displacements for elements area  $ds$  in the source coordinations and the initial magnitude of dislocation,  $u_0$ (see Fig.7).

$$u_r = i\omega g(w) u_{ds} / 2\pi (\beta^2 / \alpha^3) (n \cdot e_R) (e \cdot e_R) \exp[i(\omega t - K_\alpha R)] / R \quad (1)$$

$$u_{in} = i\omega g(w) u_{ds} / 4\pi \beta [(e \cdot e_n) (n \cdot e_R) + (n \cdot e_n) (e \cdot e_R)] \exp[i(\omega t - K_\beta R)] / R \quad (2)$$

$$u_\phi = i\omega g(w) u_{ds} / 4\pi \beta [e \cdot e_R + (n \cdot e_\phi) (e \cdot e_R)] \exp[i(\omega t - K_\beta R)] / R \quad (3)$$

Where  $w$  is an angular frequency and  $g(w)$  is the Fourier transform of the source time function  $g(w) = 1/iw$ ,  $\alpha$  and  $\beta$  are P- and S-wave velocities, and  $K_\alpha$  and  $K_\beta$  P- and S-wave wavenumbers. Equations (1), (2), (3) represent the seismic fields of P, SV and SH waves respectively. After rearrangement, the new form of the displacements for P, SV and SH waves.

$$\begin{aligned} u_p &= u_{ds} / 12\pi \beta (\gamma_n) (\beta / \alpha)^2 \gamma_n F [\exp i(\omega t - K_\alpha R)] + O(1/R^2) \\ u_{sv} &= u_{ds} / 24\beta (\gamma_n) \partial F / \partial i_n [\exp i(\omega t - K_\beta R) / R] \times O(1/R^2) \\ u_{sh} &= u_{ds} / 24\beta (\gamma_n) \text{csc} i_n \partial F / \partial \phi [\exp i(\omega t - K_\beta R) / R] + O(1/R^2) \end{aligned} \quad (4)$$

where  $F = F(\lambda, \delta; i_n, \phi)$  is given by Ben-Menahem and Singh (1972).

From the above-equation, the source is at  $O(r_h, 0, 0)$  and the observation point is at the distance  $R$  of the point  $(r, \theta, \phi)$ .  $i_n$  is a take-off angle of a seismic ray leaving from the source.

For the radial stress  $\sigma_r$  for a tamped shot for the explosion source (Rodean, 1971).

$$\sigma_r(\gamma, \tau) = \rho [\alpha^2 \partial \xi / \partial r + 2(\alpha^2 - 2\beta^2) \xi / r] \quad (5)$$

Where  $\xi$  = radial displacement

From relation between scalar potential  $\chi$  and

reduced displacement potential  $X$ .  $X$  is independent of  $r$  and is a function of  $\tau$  alone,

$$X(\tau) = \gamma \chi(\tau, t) \quad (6)$$

$\tau$  is retarded time and is defined as

$$\tau = t - (t - R_\alpha) / \alpha \quad (7)$$

$R_\alpha$  = elastic radians, wave equation for spherical P waves is

$$\partial^2 X / \partial \tau^2 = \alpha^2 \partial^2 X / \partial r^2 \quad (8)$$

Finally we derive the relation between the radial displacement  $\xi$  and the reduced-displacement  $X$  as

$$\xi(r, \tau) = -[(1/\alpha r) \partial X(\tau) / \partial \tau + X(\tau) / r^2] \quad (9)$$

and the relation between the reduced-displacement potential  $X$  and the stress  $\sigma_r$  at  $r = R_\alpha$  as

$$\begin{aligned} R_\alpha \sigma_r(R_\alpha, \tau) &= \rho [\partial^2 X(\tau) / \partial \tau^2 + (4\beta^2 / \alpha R_\alpha) \\ &\partial X(\tau) / \partial \tau + (4\beta^2 / R_\alpha^2) X(\tau)] \end{aligned} \quad (10)$$

$\xi(r, \tau)$ ,  $\sigma_r(R_\alpha, \tau)$  and  $X(\tau)$  may be solved by using Laplace transform (Rodean, 1971). Equations (1) to (10) represent the basic concepts for displacements of double-couple and single force source for an earthquake and an explosion, respectively.

Synthetic seismograms for P-SV waves and SH waves are generated in the vertical (P-SV waves) and in the tangential component (SH waves) respectively. The synthetic seismograms for earthquakes are dependent on the crust model as well as source parameters of mechanism, whereas explosions are dependent on the source crust model alone.

## DATA ANALYSIS AND INTERPRETATION

In order to compare the waveform characteristics of explosions with microearthquakes, we take into account four presumed underground explosions, two anomalous events and normal microearthquakes, which are recorded at Seoul. Figs. 1. and 2 represent explosion replosion recordings that occurred in the Huanghe region of North Korea. We can see strong  $L_g$  waves and  $R_g$  waves for these explosions. The explosion recordings of May 3, 6, 7, 27, 1988 belong to a series of the unknown explosions that oc-

curred from January to June, 1988 in North Korea. As shown in the seismogram the first motions of P-waves are all compressional and amplitudes of the first arrivals of SH-waves are relatively small in the E-W components. On the other hand, we can observe strong  $L_g$  waves in the transverse component and  $R_g$  waves of long period in the vertical component. We could not determine the exact parameters of the source due to lack of observations. We determined, however, the epicentral distance and direction as well as the origin time and magnitude for explosions.

In the light of the characteristics of the shal-

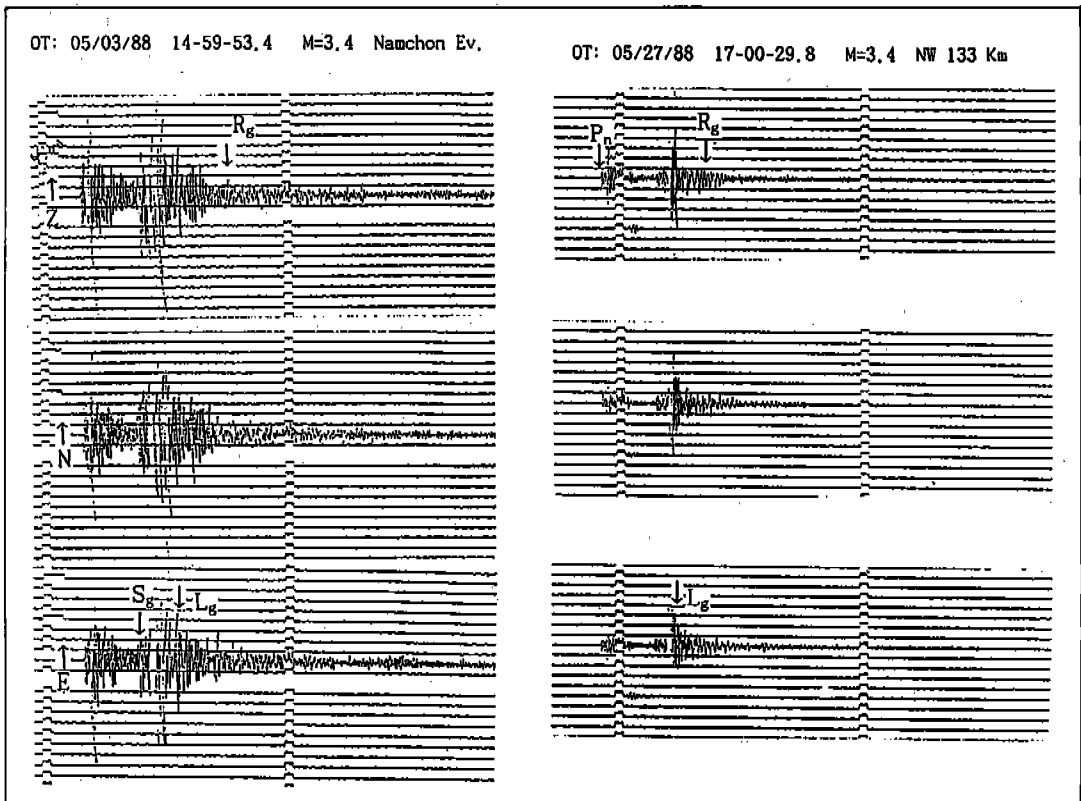


Fig. 1 The seismograms of the presumed explosions of May 3 and 27, 1988 on the three components.

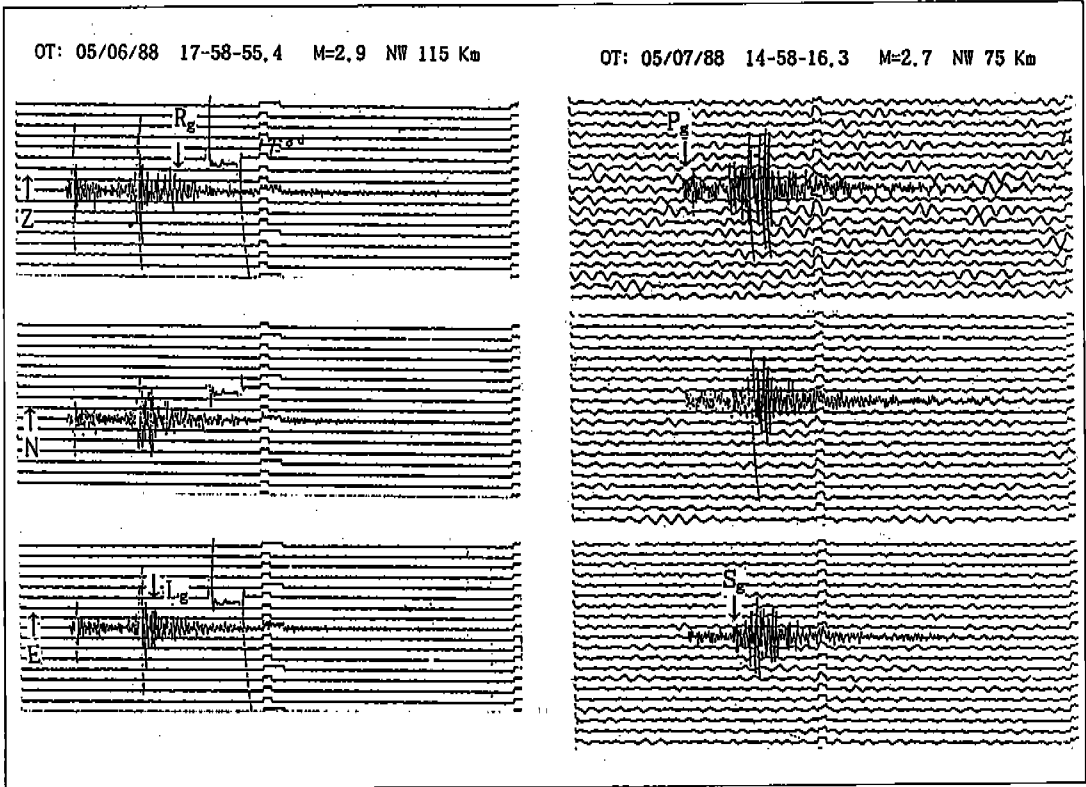


Fig. 2 The seismograms of the presumed explosions of May 6 and 7, 1988 on the three components.

low source,  $R_g$  waves of the fundamental modes of Rayleigh waves are extremely depth-dependent in both amplitudes and frequency content.  $L_g$  waves for explosions are mainly formed by P to SV conversion and closeness of source to the interface or the free surface, particularly enhancing strength of  $L_g$  waves in case of irregularities of the interfaces, the observation of  $L_g$  waves for explosions is a local wave-guide phenomenon that follows strong decrease of amplitudes with depth. The seismograms for Hongsung earthquake of October 7, 1978 and for Daekan earthquake of January 8, 1980 are not given(see Table.1) since they are found to be by very shallow-focus earthquakes of the

intermediate size( $M > 5.0$ ). It seems to be very artificial that the origin times of the events for the Figs. 1 and 2 almost exhibit the exact unit hour.

The events of December 1, 1980 and April 15, 1988 are considered as anomalous(skeptical) events in the light of strength of  $L_g$  wave and  $R_g$  wave generation. Particularly we can see strong  $L_g$  waves of the event, April 15, 1988 in the transverse component. This suggests that the closeness of this event source has the irregular interface or free surface. The seismograms of Figs. 4 and 5 indicate normal earthquakes that occurred in North and South Korea. The waveform characteristics of  $L_g$  wa-

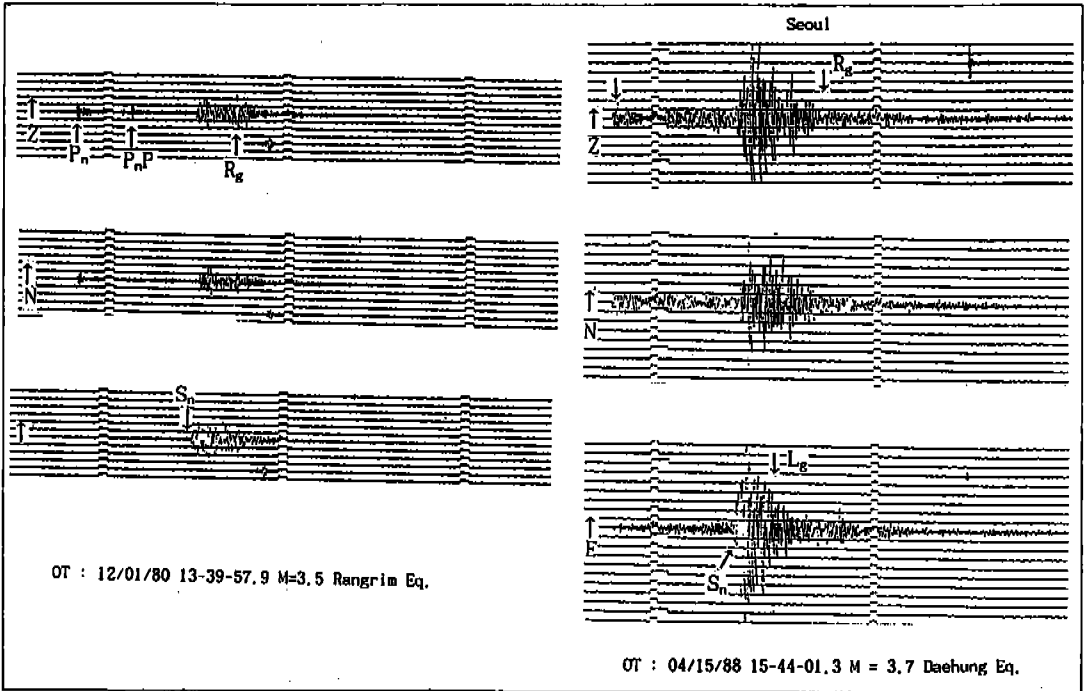


Fig. 3 The seismograms of the presumed anomalous events of December 1, 1980 and April 15, 1983 on the three components.

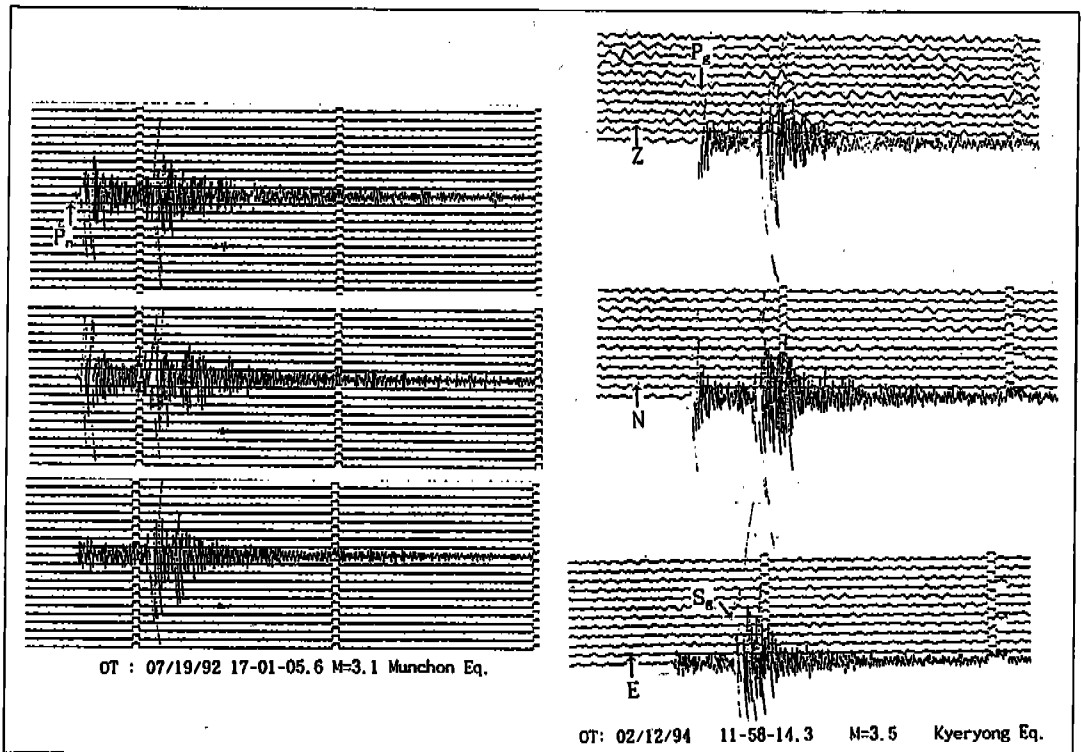


Fig. 4 Earthquakes of Munchon, July 19, 1992 and Mt. Kyerong, February 12, 1994 on the three components.

Table 1. Hypocenter parameters of seismic in this study.

Date M/D/Y	O.T(LST) H-M-S	Epicenter		M	Region
		Lat(N)	Long(E)		
10/07/78	18-19-52.2	36.6	126.7	5.0(MO)	Hongsung
12/01/80 AEE	13-39-57.9	40.7	127.2	3.5(MO) 3.8(NK)	Rangrim
01/08/80	08-44-13.3	40.2	125.0	4.9(ISC) 5.3(MO) 5.4(NK)	Daekwan Mt.Chonma h=3km
04/15/88 AEQ	15-44-1.3	40.3	126.9	3.7(MO)	Daehung h=5km
05/03/88 EX	14-59-53.4	38.3	126.2	3.4(MO)	Namchon
05/06/88 EX	17-58-55.4	NW	115kw	2.9(MO)	Hwanghe
05/07/88 EX	14-58-16.3	NW	75kw	2.7(MO)	Hwanghe
05/27/88 EX	17-00-29.8	NW	133kw	3.4(MO)	Hwanghe
06/23/89	00-26-0.1	36.7	127.8	3.5(MO)	Goisan
07/19/92	17-01-5.6	39.1	127.1	3.1(MO)	Munchon
03/01/93	12-00-42.9	35.6	126.9	3.9(MO)	Jungju
02/12/94	11-58-14.3	36.4	127.3	3.5(MO)	Mt.Kyerong

LST : Local Standard Time

AEQ : Anomalous earthquakes

EX : Wxplosions

MO : Korean Meteorological Administration

ISC : International Seismological Center

NK : North Korea

ves are a little complicated and weak for the Munchon earthquake, July 19, 1980 and the Mt. Kyerong earthquake, February 12, 1994. Besides we can hardly observe any  $R_s$  waves for these two earthquakes. This suggests that the sources of these two earthquakes are deep within the relative regularities of the interface. The seismograms of Fig.5 show strong SH waves as well as strength of  $L_s$  waves in the transverse components. Particulaly  $L_s$  waves of Jungju earthquake, March 1, 1993 exhibit a strong wave-guide phenomenon through the closeness

for the irregularities of the interface. No  $R_s$  waves are not observed for the earthquake of Goisan earthquake, June 23, 1989 and the Jungju earthquake, March 1, 1993, indicating that the depth of these earthquakes are deep( $h > 10$  km). We can see most of earthquakes near the fault zones in the seismotectonic map(Fig. 6). As a result, the earthquake occurrence is consistent with the major fault zones in the seismitectonic map(Masaitisa, 1964).

Synthetic seismograms for earthquakes and explosions are given in Figs. 8, 9, 10, 11 and 12 using Reflectivity method(Kind, 1989). The crustal model for Figs.8 and 9 is taken from Bouchon(1982) and S. J. Kim and S. G. Kim (1983) with changing of low-velocity sediment thickness of 2.0km( $\alpha=2.8$ km/s) and Moho P-wave velocity of 7.98km/s at 32km. The crustal models for Figs. 10, 11 and 12 selected from Krebes and Hron(1980) with changing of thick sediment of 6km( $\alpha=4.2$ km/s) and Moho P-wave velocity of 8.1km/s at 35km. The theoretical studies demonstrate that the shallow seismic source in the thin sediment generates large amplitudes fundamental and higher modes of Rayleigh waves. The generation of synthetic seismograms is a function of source mechanism and propagation path of seismic waves. Consequently the characteristic waveform of synthetic seismograms depend on parameters of the source mechanism is much greater than of crustal structure for body waves, but not for surface waves,  $R_s$  and  $L_s$  waves. It is evident that explosions generate little amplitudes of SH-wave motion and highly developed fundamen-

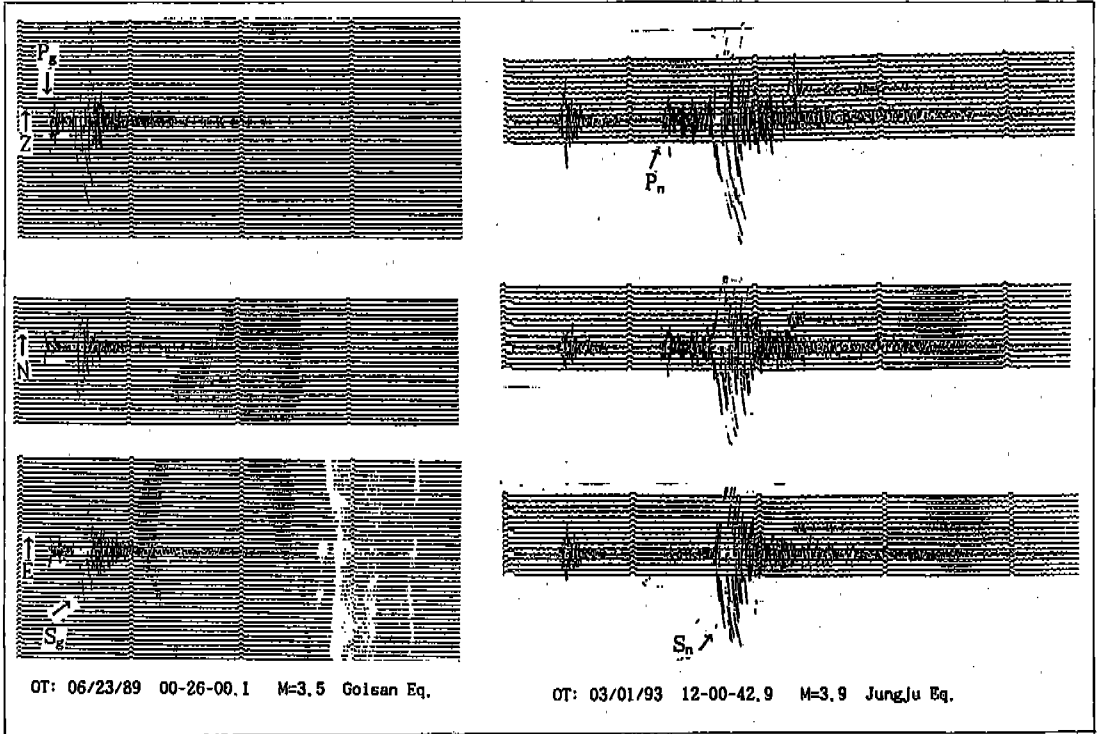


Fig. 5 Earthquake of Goisan June 23, 1989 and Jungju, March 1, 1993 on the three components.

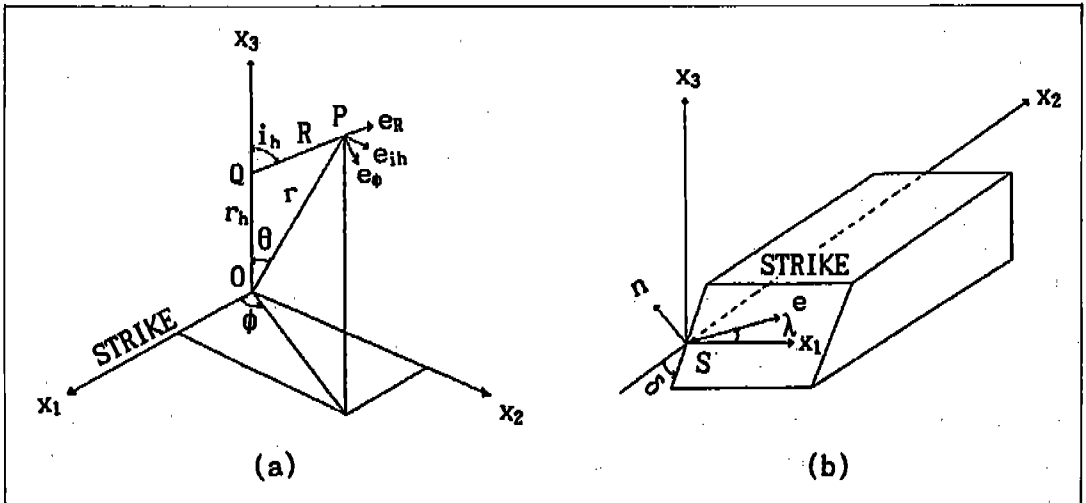
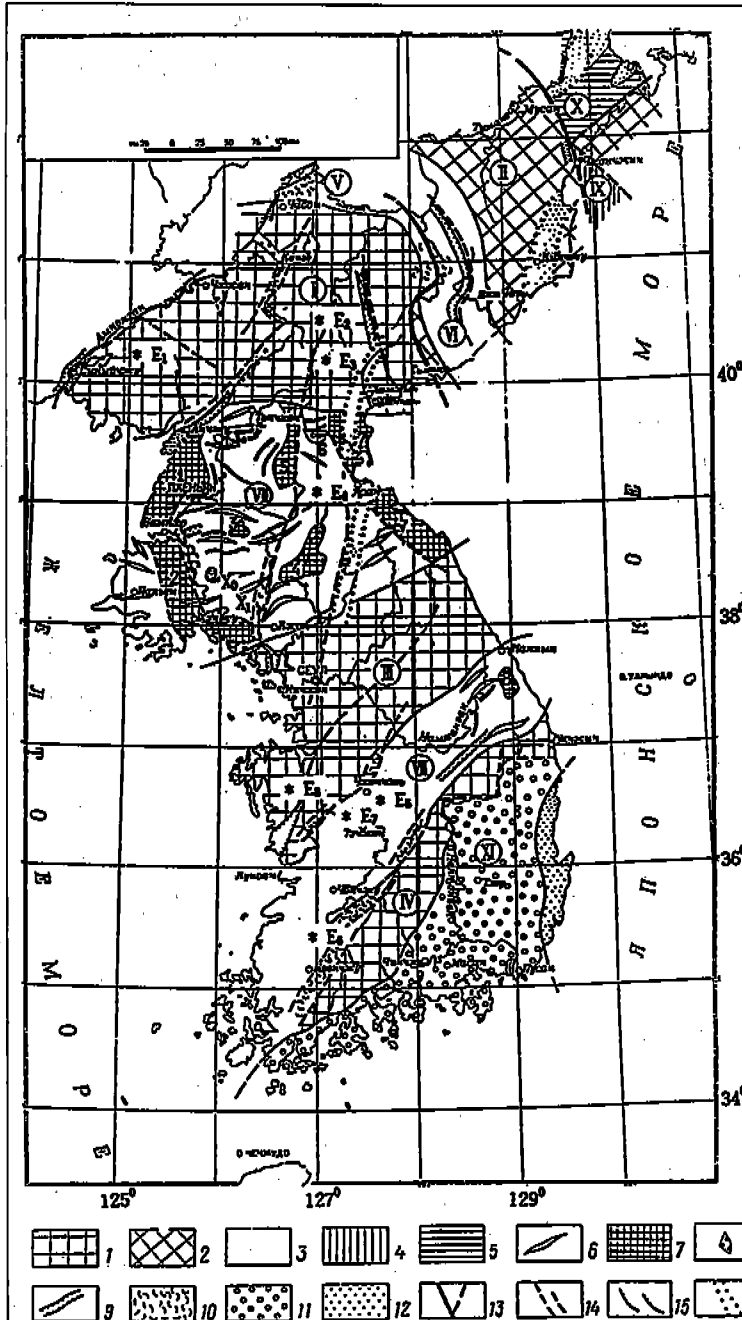


Fig. 7 Coordinate systems of a seismic source(a) and the fault plane geometry(b).





Seismotectonic Map of Korea

1 - Region of Archean folding.  
2 - Region of lower Proterozoic, folding: massifs/mountain-masses: I) Rangrim II) Kwanso III) Kyonggi IV) Sohaek (Yongnam) sedimentary Layer of the Platform, 3 - (Intraplate depression) bucklings filled with sediments for motion of the upper Paleozoic, silurian, lower and upper Paleozoic and lower Mesozoic origin: V) Anmangk group VI) Hyusan-Iwon group VII) Pyongnam group VIII) Okchon group Superimposed Geosyncline Zones. 4 - Region of late Precambrian (?) folding IX folding zone. 5 - Region of upper Paleozoic foldings: X) Tumangar graben of Sikhote-Alin geosyncline Mesozoic and Cenozoic superimposed structures. 6 - Brachy-synclinal structure of sedimentary layers in intraplate graben. 7 - projected Archean basement in graben: (1) Pyongwon (2) Sinchon (3) Chosok (4) Ichon (5) Yongduk (6) Yonghung (7) Sinsan-Anbyon (8) Jungbongsan. 8 - Graben-synclines of the sedimentary layer within massifs. 9 - Internal depression filled with sediments and volcanic formation of Khor-Lias and middle-upper Jurassic. 10 - internal depression filled with sediments and volcanic formation of upper Jurassic and Cretaceous. 11 - Marginal piedmont of the Tsushima Basin: XI) Region of Mesozoic folding of the Sakas geosyncline. 12 - Cenozoic depression and grabens. Major Faults and Fractures: 13 - Marginal structural belt (linear rise). 14 - Areas of fault accompanied with movement in the Mesozoic. 15 - Areas of faults (echelon folds) in the sedimentary layer on platform. 16 - faults accompanied with movements in the Cenozoic.

Fig. 6 Seismotectonic map of Korea, Masaitisa, 1964

tal modes and higher modes depending on the increasing focal depth.

Figs 8 and 9 indicate synthetic seismograms of P-SV(upper) and SH waves(lower) for an earthquake of a right-lateral strike motion and an explosion with a focal depth 300m using Reflectivity Method(Kind, 1989). We can see  $R_s$  and  $L_s$  waves for both explosion and earthquake recordings in case of a very shallow-focus( $h=1.0\text{km}$ ). Earthquakes, however, excited more  $R_s$  waves and higher modes than explosions. Explosion synthetic seismograms show

more high frequency content. Figs 10 and 11 exhibit synthetic seismograms of P-SV(upper) and SH waves(lower) for shallow-focus earthquakes of focal depth  $h=1.0\text{km}$  and  $h=15.0\text{km}$  respectively. We can observe  $R_s$  and  $L_s$  waves for the earthquakes with  $h=1.0\text{km}$ , while we can observe only  $L_s$  waves for the earthquake with  $h=15.0\text{km}$ . We can see strong  $L_s$  waves and weak  $R_s$  waves for the explosion seismograms of P-SV(upper) and SH waves(lower) in Fig 12. In case the source is located at the thick sediment of 6km, we also observe good

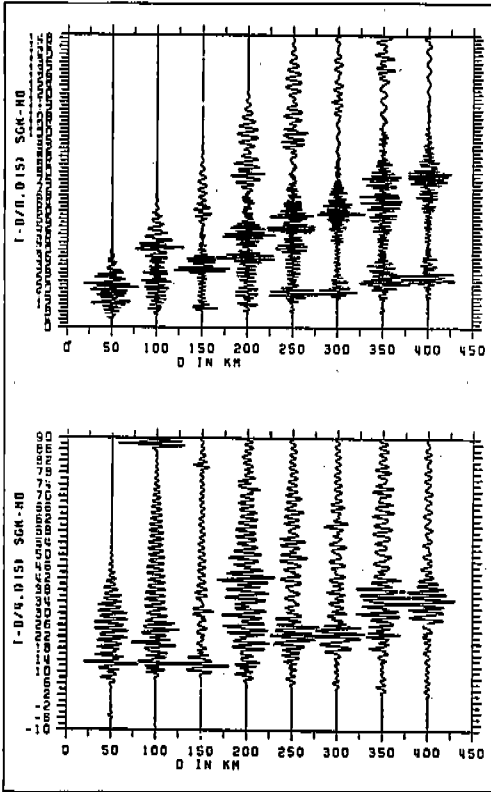


Fig. 8 Synthetic seismograms P-SV(upper) and SH waves (lower) for a shallow earthquake with a focal mechanism :  $\lambda_{\text{(source rise time)}}=1.0\text{s}$ ,  $h_{\text{(depth)}}=1.0\text{km}$ , sediment thickness :  $2\text{km}$ ,  $=2.8\text{km/s}$ .

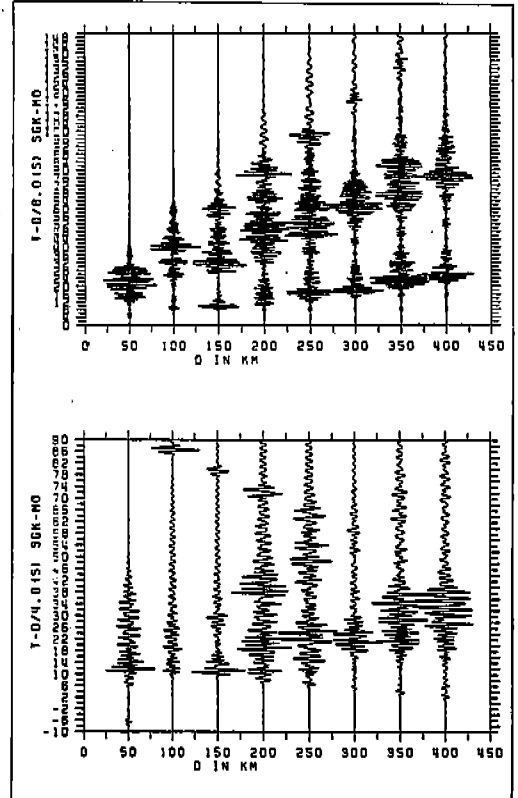


Fig. 9 Synthetic seismograms P-SV(upper) and SH waves (lower) for an explosion with the same model as Fig.8, except for  $t_{01}/0.25\text{s}$ ,  $h=0.3\text{km}$ .

and strong  $S_n$ (Moho refraction) and  $S_mS$ (Moho reflection) in Figs. 8, 9 and 10.

The correspondence between the synthetic and observation is quite good, indicating that the synthetic seismograms for explosion, indeed, are consistent with the observed presumed explosions. We have good observation of  $R_g$  and  $L_g$  waves of explosions in both observation(see Figs. 1 and 2) and synthetic seismograms(see Figs. 9. and 12). We try to exhibit the characteristic variation of waveforms of exp-

losions and earthquake by analyzing data from observed explosions and earthquakes as well as the synthetic seismograms. We have reached the conclusion that the source depth is of great significance for waveform generation of  $R_g$  waves and complexity of  $L_g$  waves for regional local events.

## DISCUSSION AND CONCLUSIONS

Most of phases for body waves on the seismograms account for either multiple events or

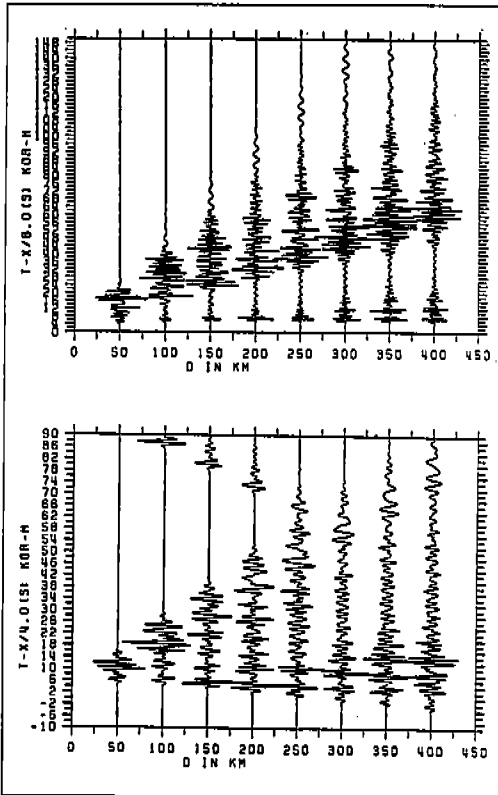


Fig. 10 Synthetic seismograms P-SV(upper) and SH waves (lower) for a shallow earthquake with a focal mechanism :  $\lambda_{(rake)} = 180.0$ ,  $\phi_{(strike)} = 49.0$ ,  $\phi_{(back azimuth)} = 170.0$ ,  $\delta_{(dip)} = 60.0$ ,  $t_0(\text{source rise time}) = 1.0s$ ,  $h_{(depth)} = 1.0km$ , sediment thickness ; 6 km,  $\alpha = 4.2km/s$ .

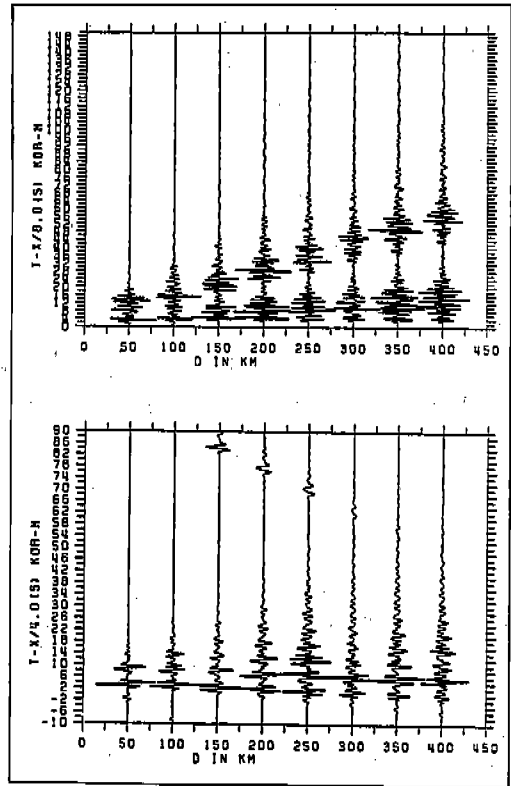


Fig. 11 Synthetic seismograms P-SV(upper) and SH waves (lower) for a shallow earthquake with the same model as Fig.10 except for  $h=15.0km$ .

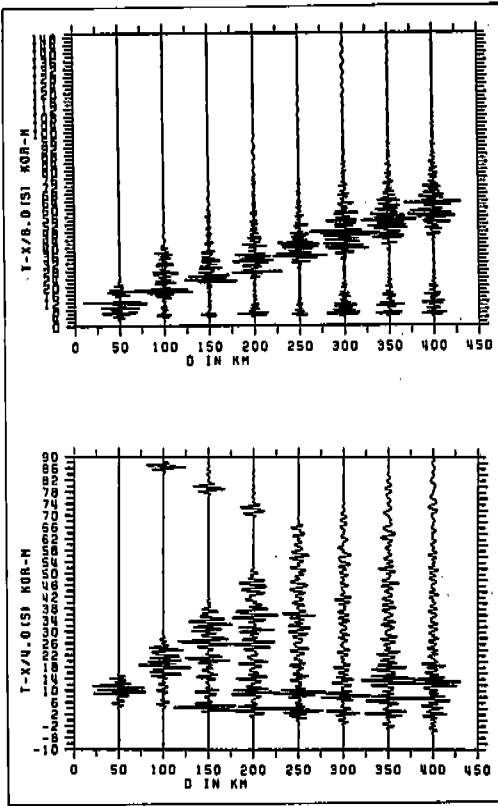


Fig. 12 Synthetic seismograms P-SV(upper) and SH waves (lower) for an explosion with the same model as Fig.10 except for  $h=0.3\text{km}$ ,  $t_0=0.5\text{s}$

many reflection and refraction(e.g.  ${}_pP$ ,  ${}_sP$ ,  $P_n$ ,  $P_nP$  ect) from the interface. The results of multiple reflection for SV and SH waves within the interface or the free surface demonstrate the generation of  $L_g$  waves and fundamental modes of Rayleigh waves( $R_g$ ). As the characteristics particle motion of surface waves  $L_g$  waves and  $R_g$  waves can be observed well in the transverse component and the vertical component, respectively. Should the source is in the basin of thin sediments( $\sim 2\text{km}$ ), we can observe large amplitudes long duration of  $R_g$  waves

due to P-SV conversion as well as the strength of  $L_g$  waves. Bouchon(1982) stated that the predominant phases through the pure-continental path are shown to be guided waves made up of SH and SV waves incident on the Moho at angles of incidence more grazing than critical angles and their multiple reflection.

From this research, we have found the following results :

- 1) The first motions of explosions are found to be compressional on the theoretical observational records regardless of the epicenter azimuth-to-station.
- 2) The first motions of microearthquakes are found to be compressional or dilational according to the epicenter azimuth-to-station due to variety of the source mechanism.
- 3) It is evident from this consequence that the source mechanism of microearthquakes represent a double-couple whereas that of the explosions is assumed to be a single-couple(force).

4) The explosions and shallow-focus earthquake( $h=1.0\text{km}$ ) generate outstanding  $L_g$  waves in the transverse component that through the upper crust with period of 1-6 seconds, and the fundamental Rayleigh waves,  $R_g$  waves with period 8-12 seconds in the vertical components. In case of very shallow-focus earthquakes, we obtain more higher and fundamental modes of Rayleigh waves. Most of shallow-focus earthquakes in the Korean Peninsula are found to have the focal depth of greater than 10km. Consequently we usually observe  $L_g$  and  $R_g$  waves for explosions in the Korean Penin-

sula.

5) The stations near nodal lines observe little or poor P-wave first motions and large SH-waves for earthquake, whereas they always observe large P-wave arrivals and little DH-wave arrivals regardless of epicenter azimuth for explosions.

6) It turned out to be clear that the events of 05/03/94, 05/06/94, 05/07/94, and 05/27/94 must be presumed explosions that occurred in series for the period January, 1988–June 1988 in North Korea.

## ACKNOWLEDGMENTS

The present studies were supported by the Basic Science Research Institute Program, Ministry of Education, 1994 project No. BSRI-94-5420, This work was also supported in part by Center of Mineral Resources Research (CMR), an affiliate of KOSEF, Korea University. I would like to thank both organizations for their financial support in the course of this work.

## REFERENCES

Ben-Menahem and Sarva Jit Singh(1972). "Computation of methods of elastic displacements in the earth" in *Methods in Computational Physics*, Vol. 12, Seismology : Body Wave and Source edited by Berni Alder, Academic Press, 299-375.

Bouchon, Michael(1982). The complete synthesis of seismic crustal phases at regional

distances, *J. Geophys. Res.* 87(B3), 1735-1741

Brune, J. N.(1970). Tectonic stress and spectra of seismic shear waves from earthquakes, *J. Geophys. Res.* 75, 4999-5009.

Camino, M., Bouchon, and B. Massinon(1984), Theoretical study of excitation, spectral characteristics, and geometrical attenuation of regional seismic phases, *Bull. Seism. Am.* 74(1), 79-90.

Dahman, O. and H. Israelson(1977). *Monitoring Underground Nuclear Explosions*, Elsevier, 440.

Douglas, A., J. A. Hudson, P. P Marshall and J. B. Young(1974). Research Note, Earthquake that look like explosions, *Geophys. J. R. Astr. Soc.* 36, 227-233.

Forsyth, D(1975). Couples of  $m_b : M_s$  variation within a central-Asian earthquakes sequence(Abstrcut), *Trans. Am. Geophys. Un.* 56, 1024.

Given, H. K, T. Nikolai, T. Tarasor, V. Zhuravlev, F. L. Vernon, J. Berger, I.L. Nersesov (1990). High-frequency seismic observations and location of closely spaced mining events, *Bull. Seism. Soc. Am.* 83, 1527-1546.

Rodean, Howard C.(1971). *Nuclear-Explosion Seismology*, U. S. Atomic Energy Commission, 157.

Smith, Albert T.,(1993). Discrimination of explosions from simultaneous mining blasts, *Bull. Seism. Soc. Am.* 83, 160-179.

tions in Eastern Kazakhstan, USSR with

- emphasis on chemical explosion experiments, *J. of Geophys. R.* 95, 295-307.
- Hanks, T. C. and M. Wyss(1972). The use of body-wave spectrum in the determination of seismic-source parameters, *Bull. Seism. Soc. Am.* 63, 561-589.
- Kim, Sang Jo and So Gu Kim(1983). A study of the structure of South Korea by using seismic waves. *J. Korean Inst. Mining Geology*, 16(1), 51-61.
- Kim, So Gu and O. W. Nuttli(1977). Spectra and magnitude characteristics of anomalous earthquakes, *Bull. Seism. Soc. Am.* 67, 463-467.
- Kind, R(1989). Personal Communication, Potsdam, Germany.
- Krebes, E. S. and F. Hron(1980). Synthetic seismogram for waves in a layered anelastic medium by asymptotic ray theory, *Bull. Seism. Soc. Am.* 70(6), 2005-2020.
- Landers, R(1972). Some interesting Central Asian events on the  $M_s : m_b$  diagram, *Geophys. J. R. Astr. Soc.* 26, 329-339.
- Masaitisa, V. N.(1964). *Geology of Korea*(in Russian) Nedra, Moscow, 264.
- Masse, Ronert P.(1981). Review of seismic model for underground nuclear explosions, *Bull. Seism. Soc. Am.* 71, 1249-1268.
- Nakanishi, K. K.(1980). The effect of focal depth and source type on synthetic seismograms in Identification of seismic Source-Earthquake or underground Explosion edited by E. Husebge and S. Mykkeltveit, *proc. Nato Advanced Study Insitute, Reidal*, 397-399.
- Nuttli, O. W. and So Gu Kim(1976). Surface waves magnitudes of Eurasian Earthquakes and Explosions, *Bull. Seism. Soc. Am.* 65, 693-709.
- Reamer, Sharon K. and Brian W. Stump(1992). Source parameter estimation for large, buried surface chemical explosions, *Bull. Seism. Soc. Am.* 82, 406-421.
- Riviere-Barbier, F. and L. T. Grant(1993). Identification and location of closely spaced mining events, *Bull. Seism. Soc. Am.* 83, 1527-1546.
- Rodean, Howard C.(1971). *Nuclear-Explosion Seismology*, U. S. Atomic Energy Commission, 157.
- Smith, Albert T.,(1993). Discrimination of explosions from simultaneous mining blasts, *Bull. Seism. Soc. Am.* 83, 160-179.

---

김소구  
 한양대학교 지진연구소  
 경기도 안산시 대학동 396  
 TEL : (0345) 400-5532  
 FAX : (0345) 82-2808