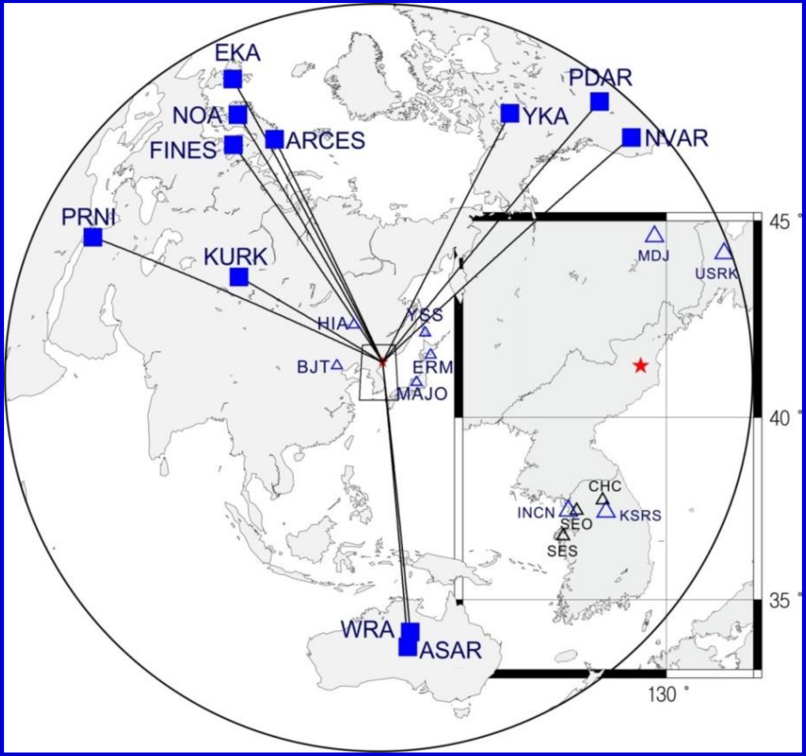
Source Depth and Characteristics of the DPRK’s Nuclear Tests [2006, 2009, 2013, 2016J (01/06/2016), 2016S (09/09/2016) and 2017] Using Regional and Teleseismic Data (T2.1)

S. G. Kim[1]*, Y. Gitterman[2], S. Lee[1,3], S. M. Koh[4], G. J. Lee[4] and H. S. Bae[5]

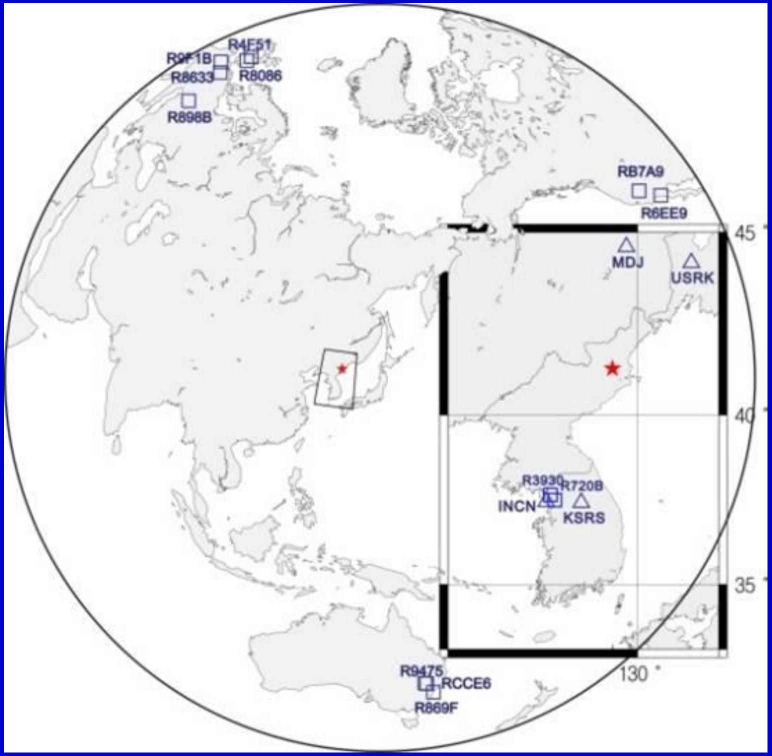
[1]Korea Seismological Institute, Goyang 10332, Republic of Korea
[2]Ben-Gurion University of the Negev, Beer-Sheva, Israel
[3]Department of Physics, Hanyang University, Seoul, Republic of Korea
[4] Korea Institute of Geoscience and Mineral Resources (KIGAM), Daejeon, Republic of Korea
[5] Geotech Consultant Co. Gunpo, Republic of Korea

Abstract: North Korea conducted underground nuclear explosions on October 9, 2006 (2006), May 25, 2009 (2009) , February 12, 2013 (2013) , January 6, 2016 (2016J), September 9, 2016 (2016S) and September 3, 2017 (2017). We estimated source depths for the North Korean nuclear tests using regional and teleseismic data. We found the burial depths for the 2006, 2009, 2013, 2016J, 2016S and 2017 tests to be 2.12 km, 2.06 km, 2.05 km, 2.06 km, 2.05 km and 1.97 km respectively selecting pronounced coherent spectral nulls using pP+P/sP+P and pPn + Pn/ sPn+Pn including spectral minima of the fundamental-mode Rayleigh wave amplitude spectra.. It should be noted that utilizing azimuth averaged spectra is appropriate to estimate depth for a nonlinear source in the nonlinear topographic region such as the North Korean nuclear test site. The synthetic spectral nulls of P-wave spectra at the near-filed and at the far-field including Rayleigh waves are in a good agreement with those of observations. The raypath through the subduction zone of the Pacific slab shows poor Love waves indicating that the low Q with high attenuation generates little Love waves in addition to the less trapped SH waves in the explosions. In particular we cannot clearly see the Love and Rayleigh waves in the particle motion for the 2006 test, however we cannot ensure if it may be due to scant S/N of a small event, or large dispersion of different raypath, or source configuration. We should also note that the possibility of the over-burial detonation would affect $M_S : m_b$ and seismic yields for the North Korean underground nuclear tests.

Teleseismic, Regional, local Seismic Networks & Raspberry Shake Seismographs

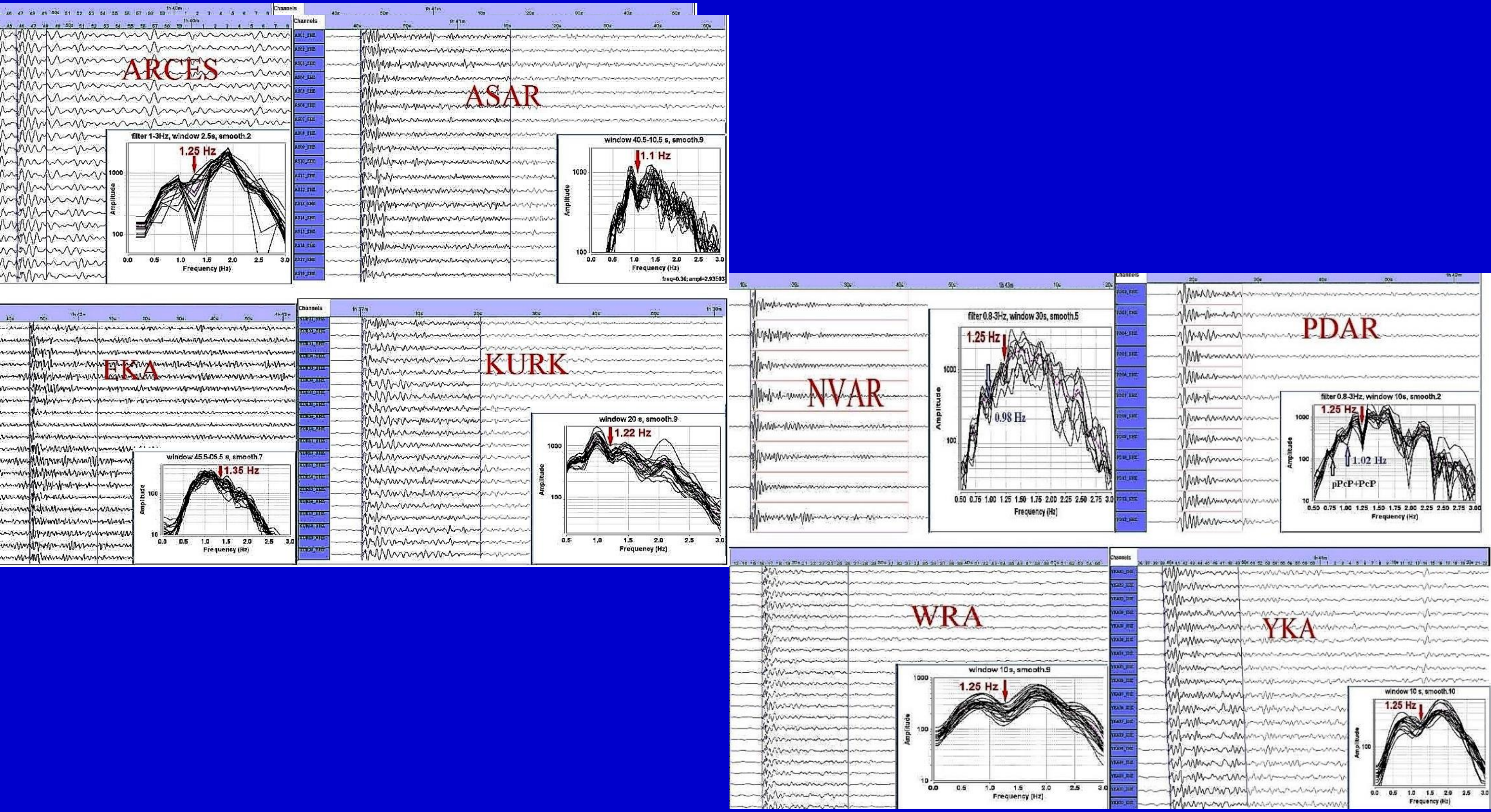


a) Teleseismic, Regional Seismic Arrays & Local Stations

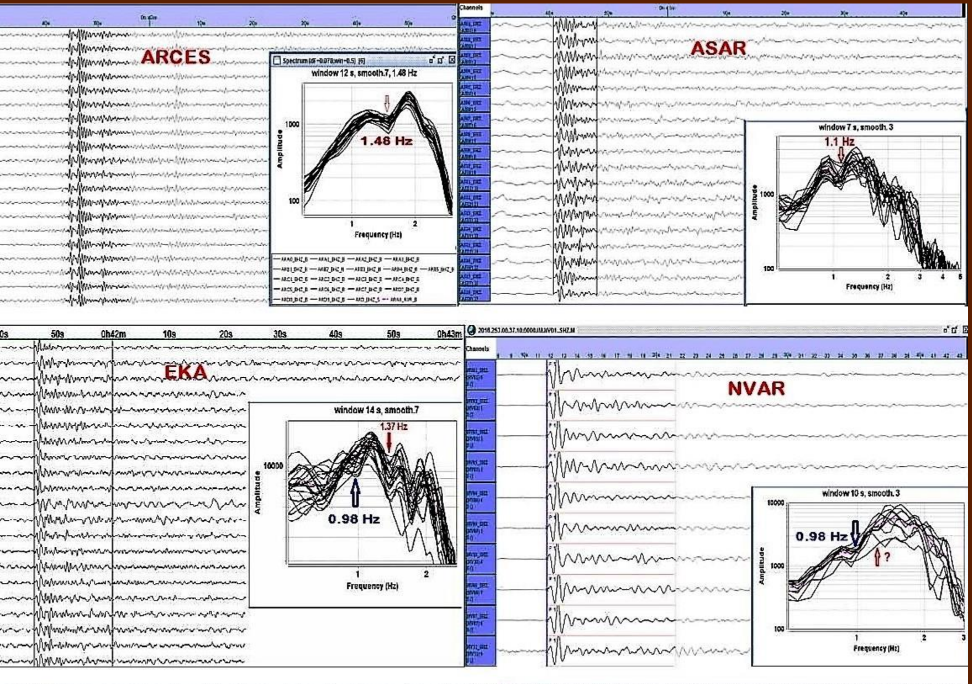


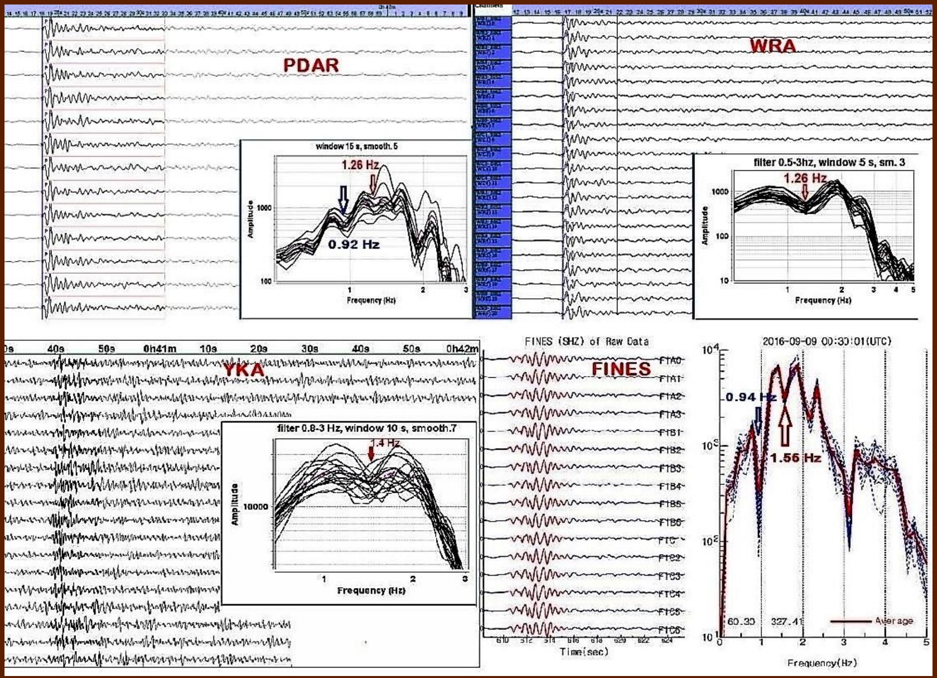
b) Raspberry Shake Seismographs

Seismograms & Spectral Nulls for the 2016J Nnuclear Test Using Teleseismic Arrays

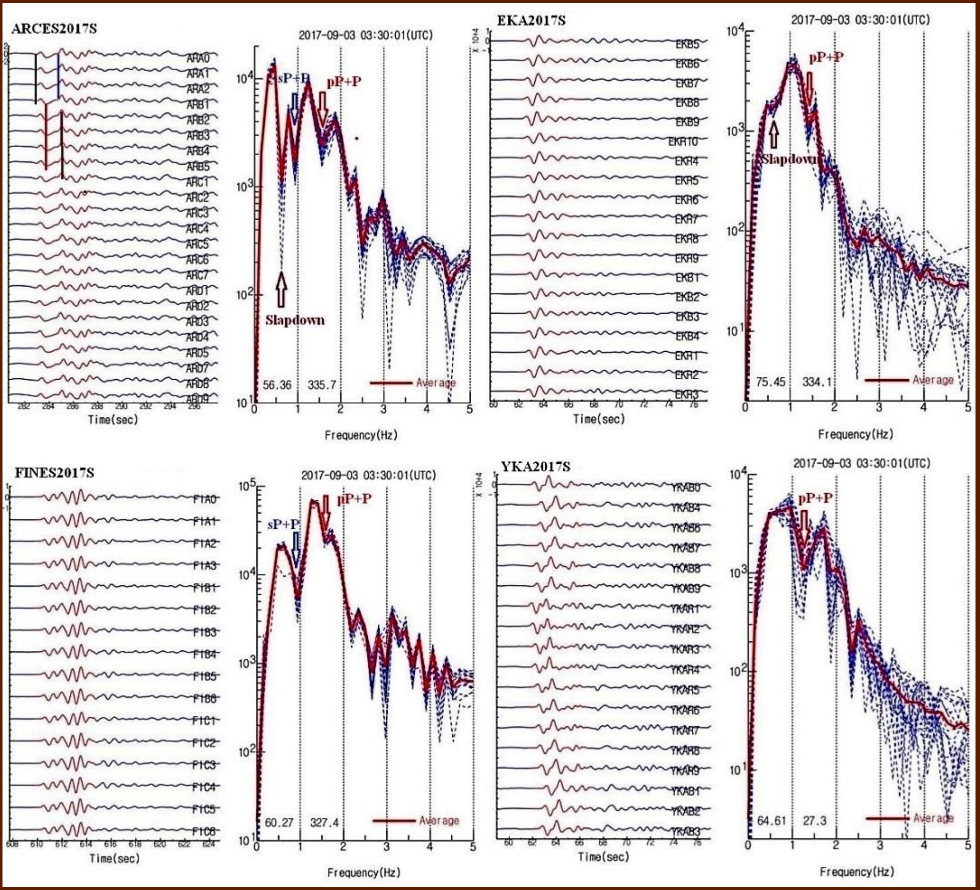


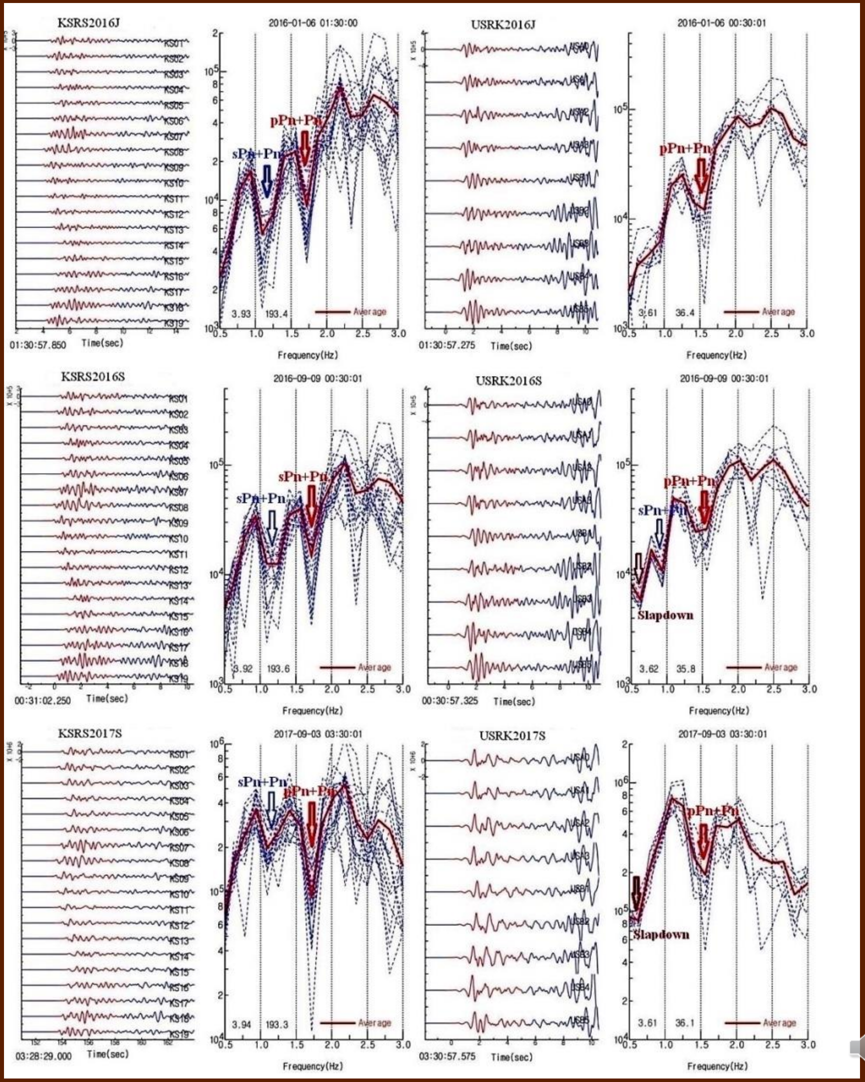
ARCES, ASAR, EKA, KURK, NVAR, PDAR, WRA and YKA teleseiamic arrays were used to determine depth for the North Korean nuclear tests on Sepiember 9, 2016 (2016S). The source depth is estimated by pP-P/sP-P delay times from the destructive interference (pP + P/sP+P) in the spectra.





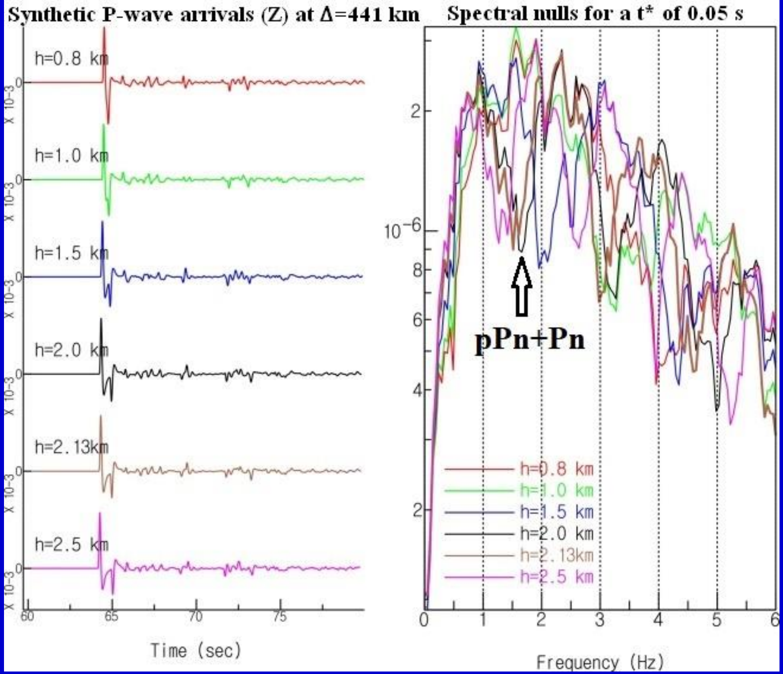
ARCES, EKA, FINES and YKA teleseiamic arrays were used to determine depth for the North Korean nuclear tests on September 3, 2017. The source depth is also estimated by pPn-Pn/sPn-Pn delay times from the destructive interference (pPn + Pn/sPn+Pn) in the spectra of KSRS and USRK Arrays for 2016J, 2016S and 2017 nuclear tests (right).





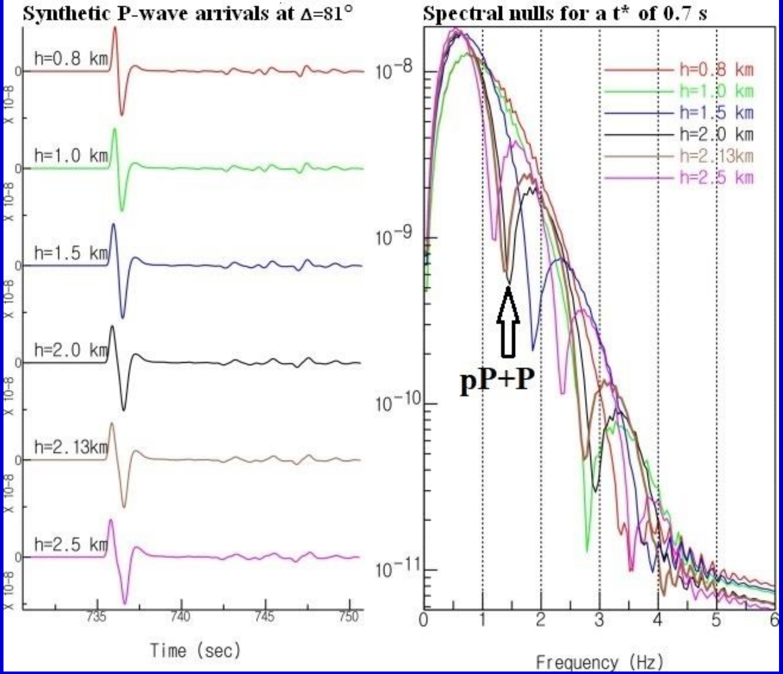
Synthetic Seismograms & Spectra for pPn+Pn and pP+P

Synthetic seismograms and spectra of the vertical component for regional and teleseismic data to account for a) a spectral null (minimum) due to the destructive interference at 1.75 Hz showing pPn + Pn for the near-field (441 km). b) at a spectral null at 1.25 Hz showing pP + P for the far-field (distance 81°) at a depth of about 2 km assuming the flat Earth model.



Synthetic P-wave arrivals (Z) at Δ=441 km

Spectral nulls for a t* of 0.05 s



Synthetic P-wave arrivals at Δ=81°

Spectral nulls for a t* of 0.7 s

Source depth using pP+P/sP+P for the 2016J nuclear test from teleseismic arrays

Array Names (Δ , AZ) (°)	**Spectral Null (Hz)**	**Take-off Angle (°)**	**Source Depth (km)**
ASAR (64.8, 175.1)	1.1	17.57	2.43
ARCES(56.4, 335.8)	1.25	18.91	2.16
EKA (75.5, 334.1)	1.35	15.56	1.96
ISN (73.5, 295.6)*	1.28	16.13	2.07
KURK (35.6, 302.8)	1.22	22.86	2.27
NORES(66.2,331.9)	1.25	17.15	2.14
NVAR (79.7, 47.5)	1.25 (0.98)	14.62 (8.25)	2.11 (1.92)
PDAR (81.0, 39.5)	1.25 (1.02)	14.33 (8.09)	2.11 (1.85)
WRA (61.1, 174.3)	1.25	18.40	2.15
YKA (64.7, 27.4)	1.25	17.57	2.14
Average depth, km			**2.11±0.15**

Table 2
Source depth using pP+P/sP+P for the 2016S nuclear test. Distance (Δ) and AZ (direction to the station) are measured in degrees.

Array Names (Δ, AZ) (°)	Spectral Null (Hz)	Take-off Angle (°)	Source Depth (km)
ASAR (64.8, 175.1)	1.1	17.57	2.43
ARCES(56.4, 335.8)	1.48	18.91	1.82
EKA (75.5, 334.1)	1.37 (0.98)	15.56 (8.77)	1.93 (1.93)
FINES(60.3, 327.4)	1.56 (0.94)	16.13 (9.09)	1.70 (2.01)
NVAR (79.8, 47.4)	(0.98)	14.62 (8.25)	(1.92)
PDAR (81.0, 39.5)	1.26 (0.92)	14.33 (8.09)	2.09 (2.03)
WRA (61.1, 174.3)	1.26	18.40	2.13
YKA (64.7, 27.4)	1.40	17.57	1.91
Average depth, km			**1.99±0.18**

Table 3
Source depth for the 2017 nuclear test

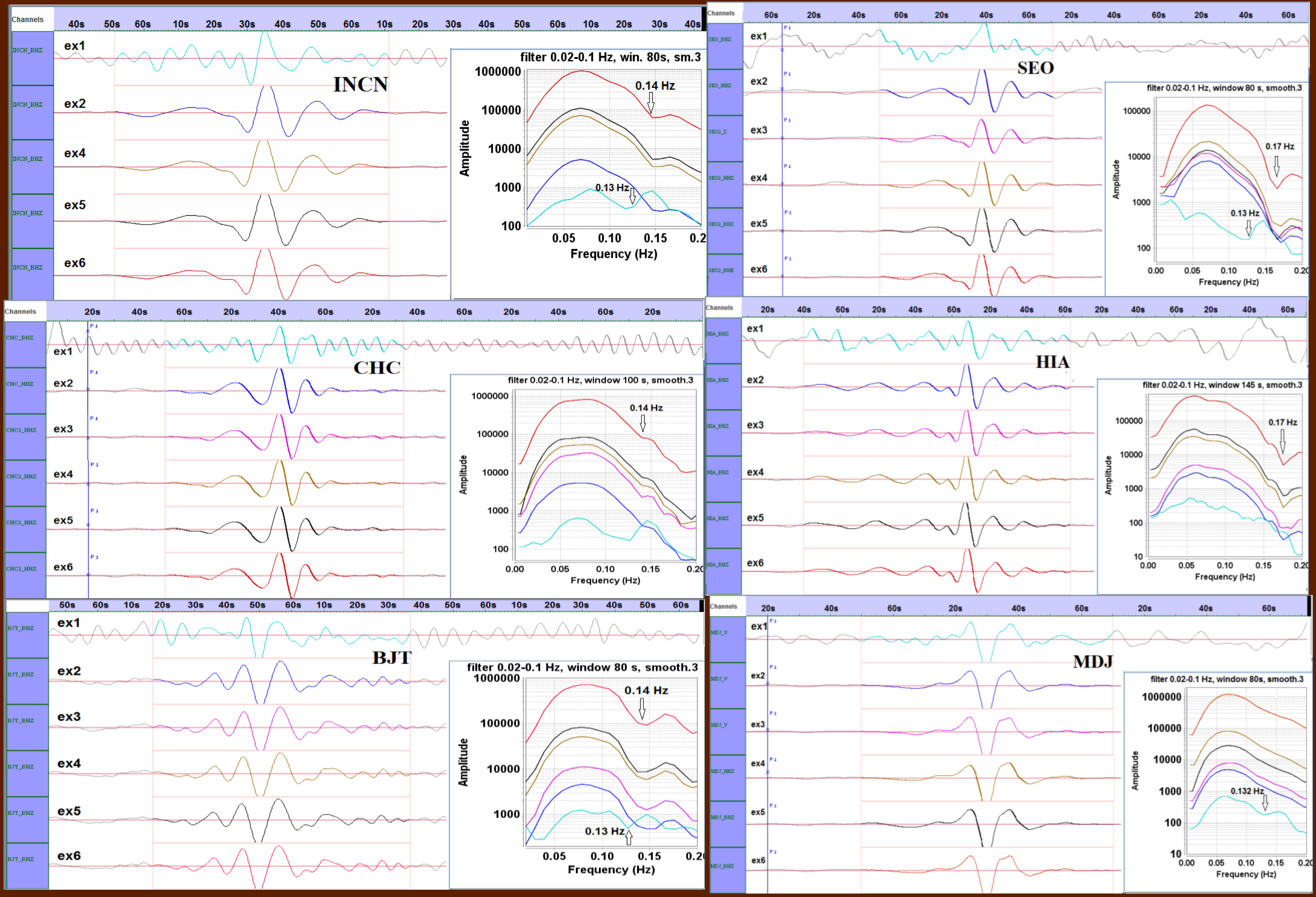
Array names (Δ, AZ) (°)	spectral null (Hz)	take-off angle (°)	source depth (km)
ASAR (64.8, 175.2)	none	17.57	none
ARCES (56.4, 335.8)	1.47 (0.95)	18.91 (10.62)	1.83 (2.01)
EKA (75.5, 334.1)	1.40	15.56	1.89
FINES (60.3, 327.4)	1.57 (0.97)	18.62 (10.46)	1.71 (1.95)
NORESS (66.2, 332.0)	1.35	17.14	1.98
PDAR (81.0, 39.6)	1.33	14.33	1.98
WRA (61.2, 174.4)	1.43	18.40	1.88
YKA (64.7, 27.4)	1.24	17.57	2.05
Average depth , km			**1.92± 0.10**

Depth Estimation Using pPn+Pn/sPn+Pn Spectral Nulls Using KSRS and USRK for the 2016J, 2016S and 2017 Nuclear Tests

Event names of NuclearTest Year	KSRS spectral null (Hz)/ depth (km)	USRK spectral null (Hz)/ depth (km)	MDJ spectral null (Hz)/ depth (km)	Averge depth (km)
2016J	1.72 (1.14) 1.96 (2.13)	1.56 2.12	1.71 (1.10) 1.94 (1.92)	2.01±0.09
2016S	1.72 (1.17) 1.96 (2.08)	1.54 (0.92) 2.15 (2.30)	1.71 (0.95) 1.94 (2.23)	2.11±0.13
2017	1.72 (1.19) 1.96 (2.04)	1.58 2.09	1.67 (1.07) 1.97 (1.98)	2.01±0.05

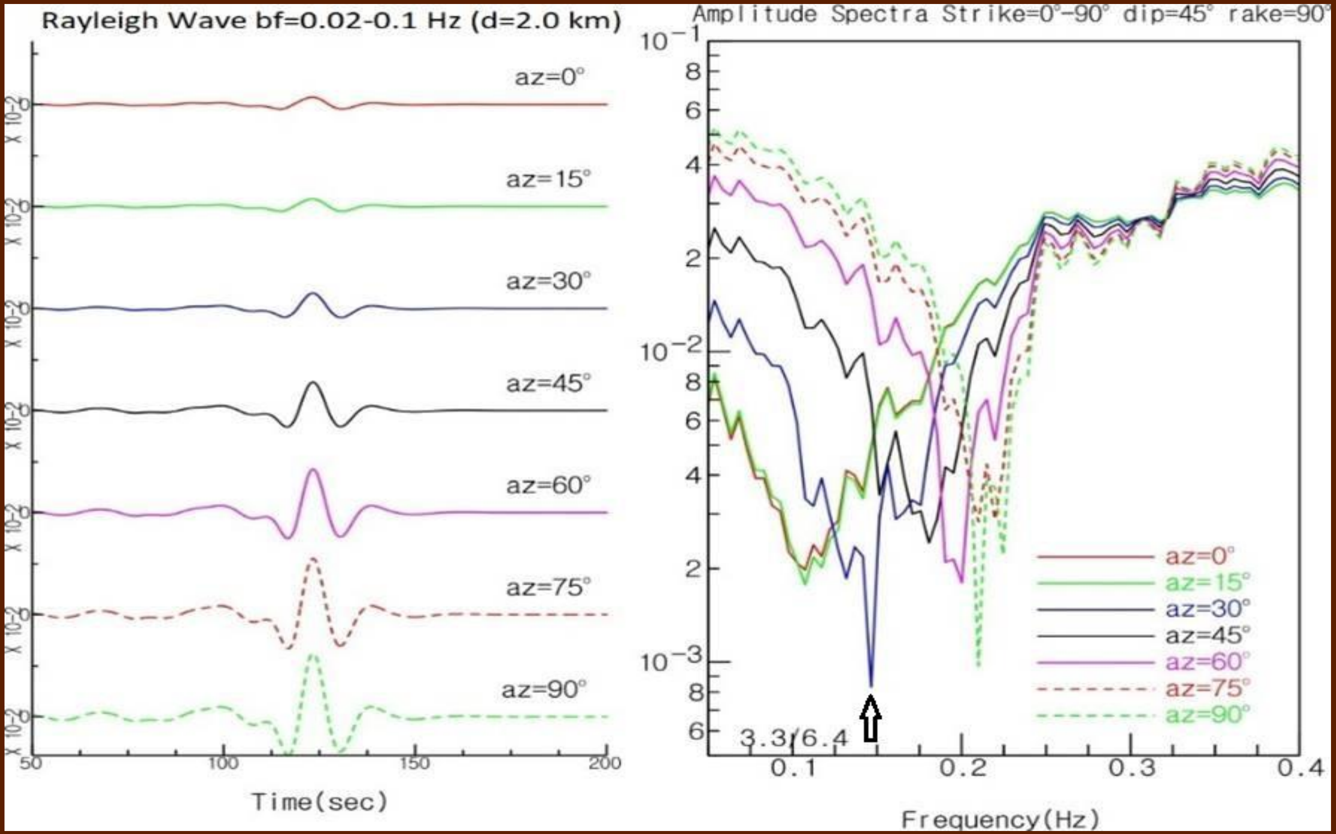
The numbers in the brackets refer to spectral nulls and depths via sPn-Pn delay times including a take-off angle of sPn phase

The fundamental-mode Rayleigh wave amplitude spectra band-passfiltered between 0.02 - 0.1 Hz. The spectral nulls for the North Korean nuclear tests are estimated at 0.14 Hz at BJT, CHC and INCM whereas 0.17 Hz at SEO and HIA escept for the 2006 test showing 0.13 Hz.

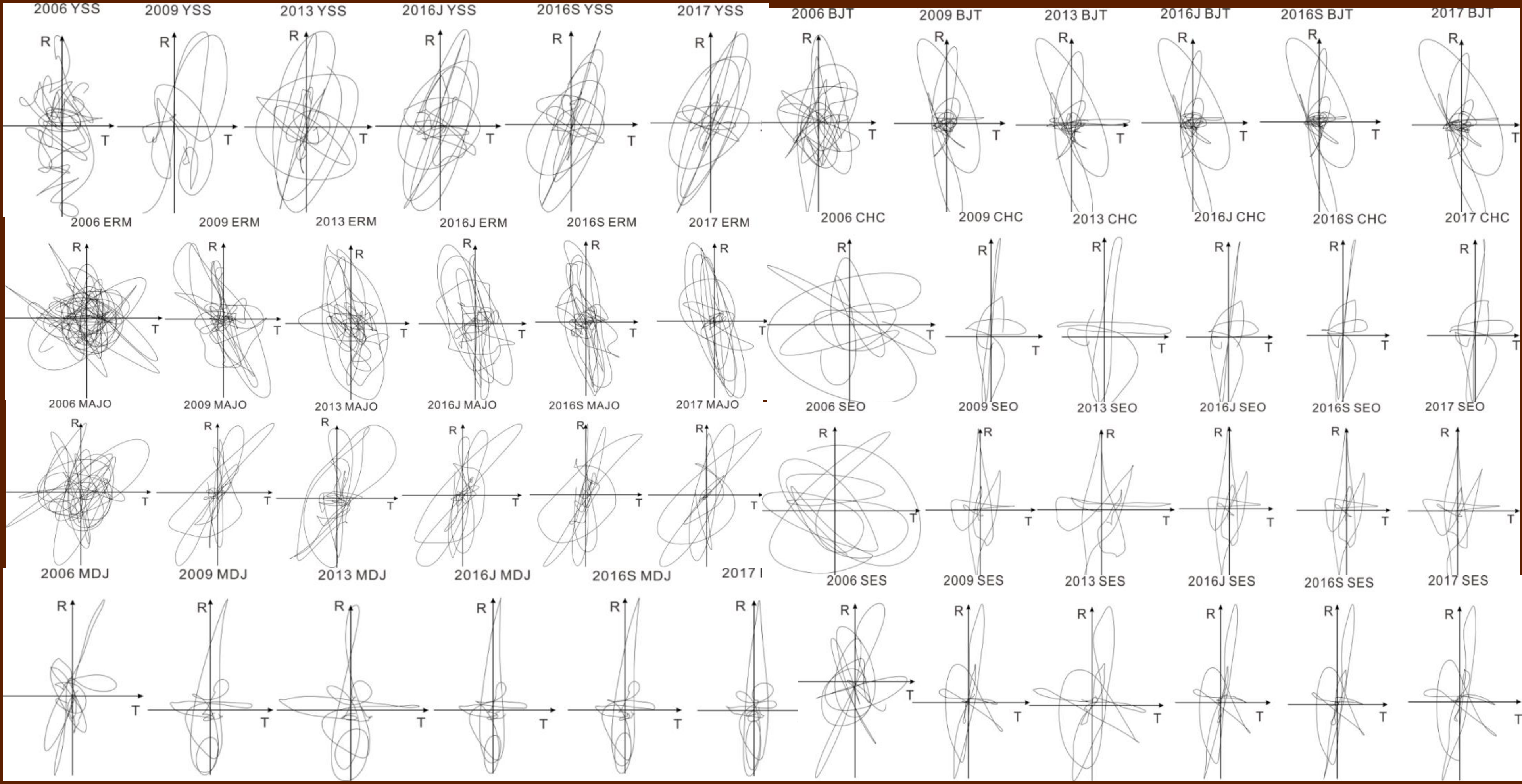


Synthetic Seismograms and Spectra for Fundamental-mode Rg-waves

The synthetic seismograms and spectra of Rg-waves are band-pass filtered between 0.02-0.1 Hz to obtain the fundamental-mode based on the Korea model considering a general mechanism for an explosion with dip 45° and rake 90° varying with every 15° of strike to 90°. The higher amplitude at an azimuth of 90° attributes the large radiation pattern of Rayleigh wave and it decreases again up to 180°. We found the most fitting depth (2 km) at 0.14-0.15 Hz at an azimuth of 30° which corresponds to the observations in this study which is also consistent with the moment tensor inversion for the 2006 test.



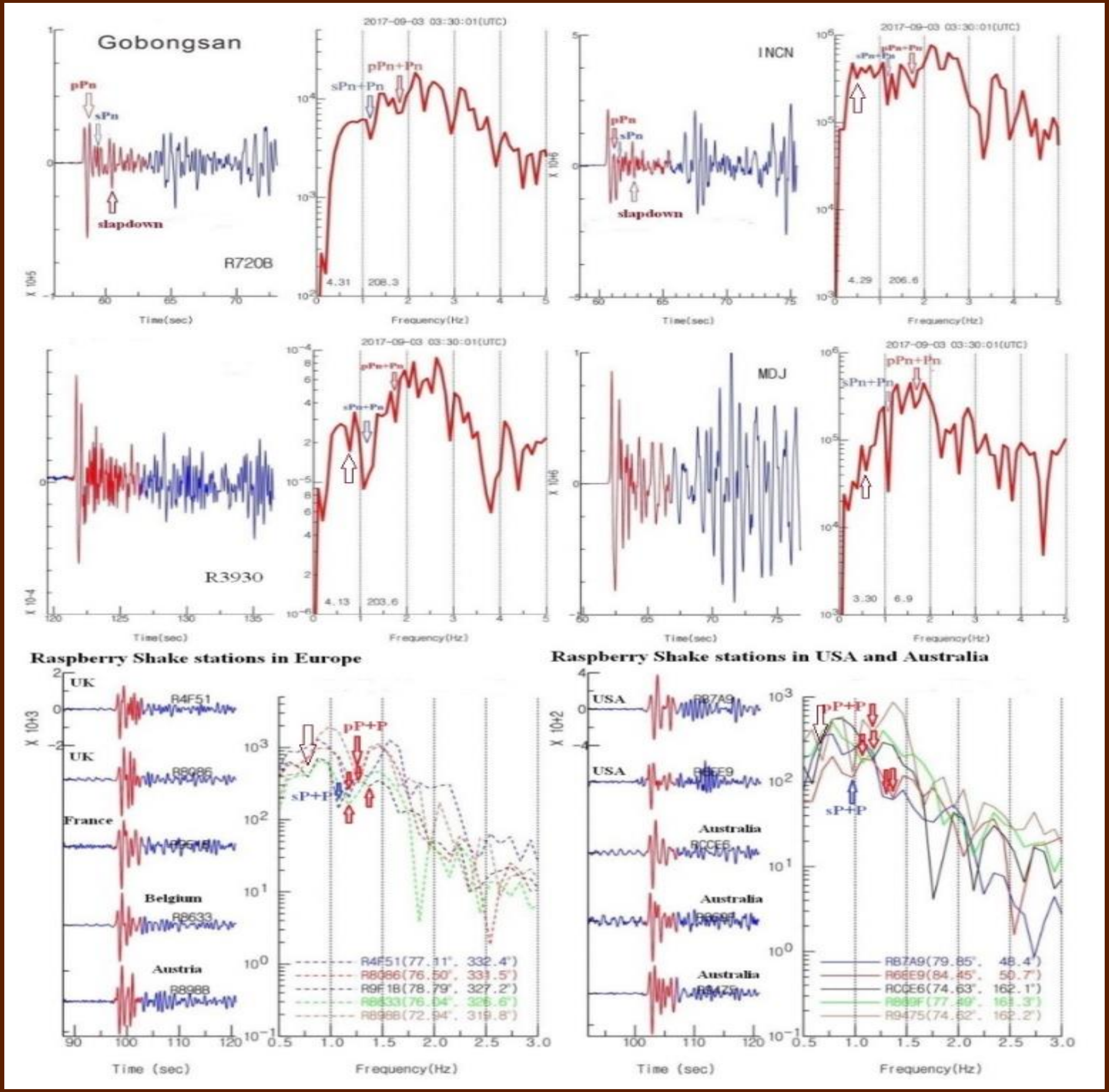
Particle Motions of Surface Waves on Radial (Rayleigh waves) and on Tangential (Love waves) Components for DPRK's Nuclear tests



Raspberry Shake Seismographs (Local & Teleseismic)

The surface spall closures (slapdown phases) appear at 0.57 Hz (after 1.75 seconds from the onset in the local stations (Gobongsan and INCN) as well as teleseismic Raspberry Shake Seismographs showing second downswing or upswings.

Spectral analysis for the 2017 test using regional stations R720B, R3030, INCN and MDJ (upper) and Raspberry Shake Seismographs in UK, Europe, USA and Australia (lower).



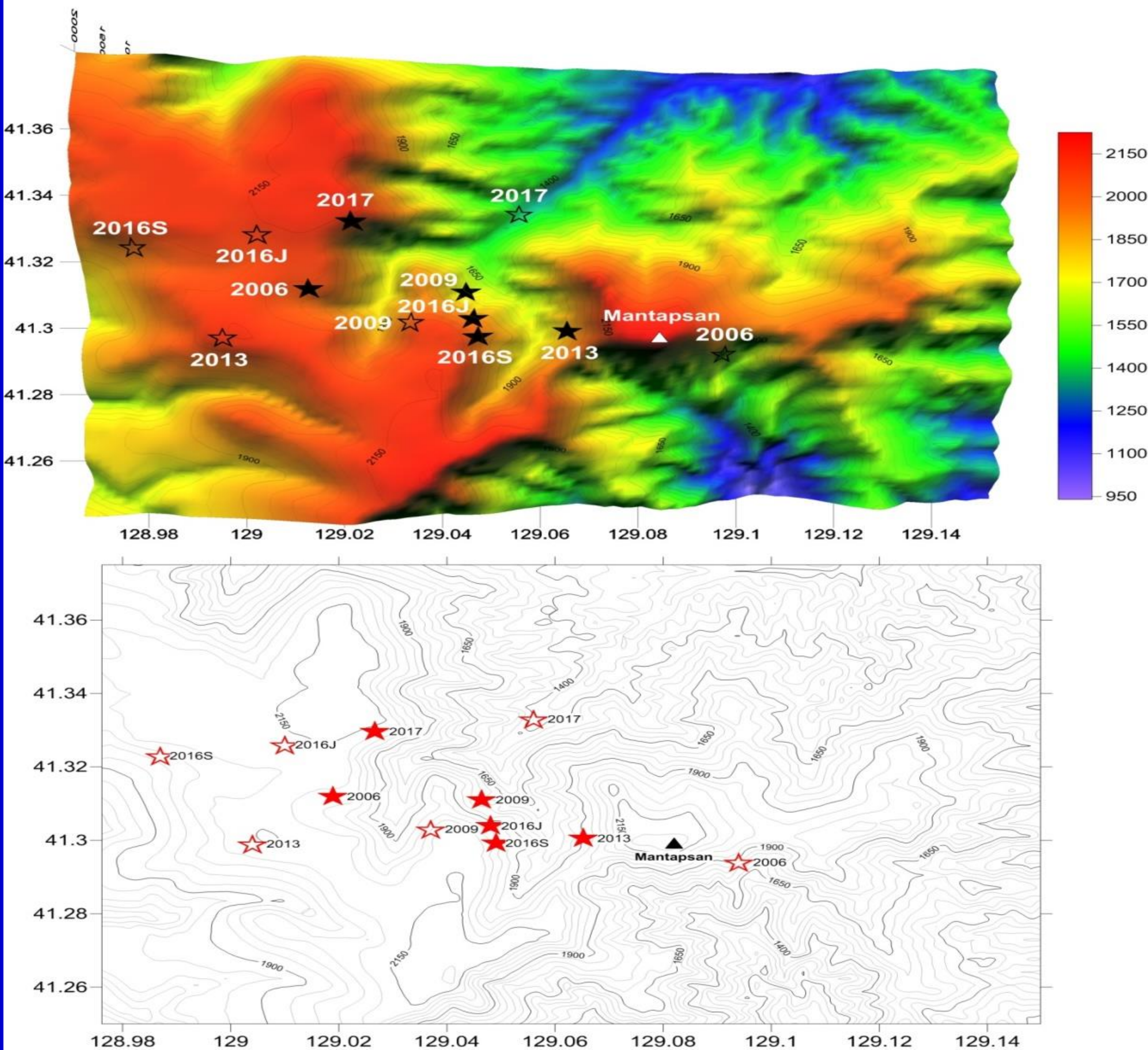
Spectral nulls and depths using the global Raspberry Shake seismographs for the sixth nuclear explosion of DPRK (09/03/2017). There are some shoulders at the second downswing or upswing phases implying that a source has a slapdown (spall-closure) phase at 0.57 Hz (after 1.75 s from the onset of the explosion)

Raspberry Shake codes	Δ/AZ (°)	pP + P/ depth (Hz)/(km)	sP + P/ depth (Hz)/(km)	Take-off angle (i, j) (°)	Comments Slapdown and/or Collapse event
R4F51	77.11/ 32.4	1.19/2.22		15.19	2nd upswing slapdown
R8086	76.50/331.5	1.25/2.11		15.29	2nd downswing slapdown
R9F1B	76.74/331.2	1.38/1.92	1.08/1.75	15.25, 8.60	2nd downswing slapdown
R8633	76.04, 326.6	1.19/2.22		15.37	2nd downswing slapdown
R898B	72.94/319.8	1.25/2.12		16.13	3rd upswing slapdown
RB7A9	79.85/48.4	1.31/2.01		14.65	
R6EE9	84.45/50.7	1.36/1.94	0.99/1.90	13.35, 7.54	
RCCE6	74.63/162.2	1.17/2.30		15.87	
RB69F	77.49/161.3	1.09/2.42		15.13	2nd double peak slapdown
R9475	74.62/162.2	1.17/2.27	0.99/1.91	15.87. 8.95	2nd double peak slapdown
Average depth,	km	**2.15± 0.15**	**1.85± 0.07**		**mean DOB = 2.00**

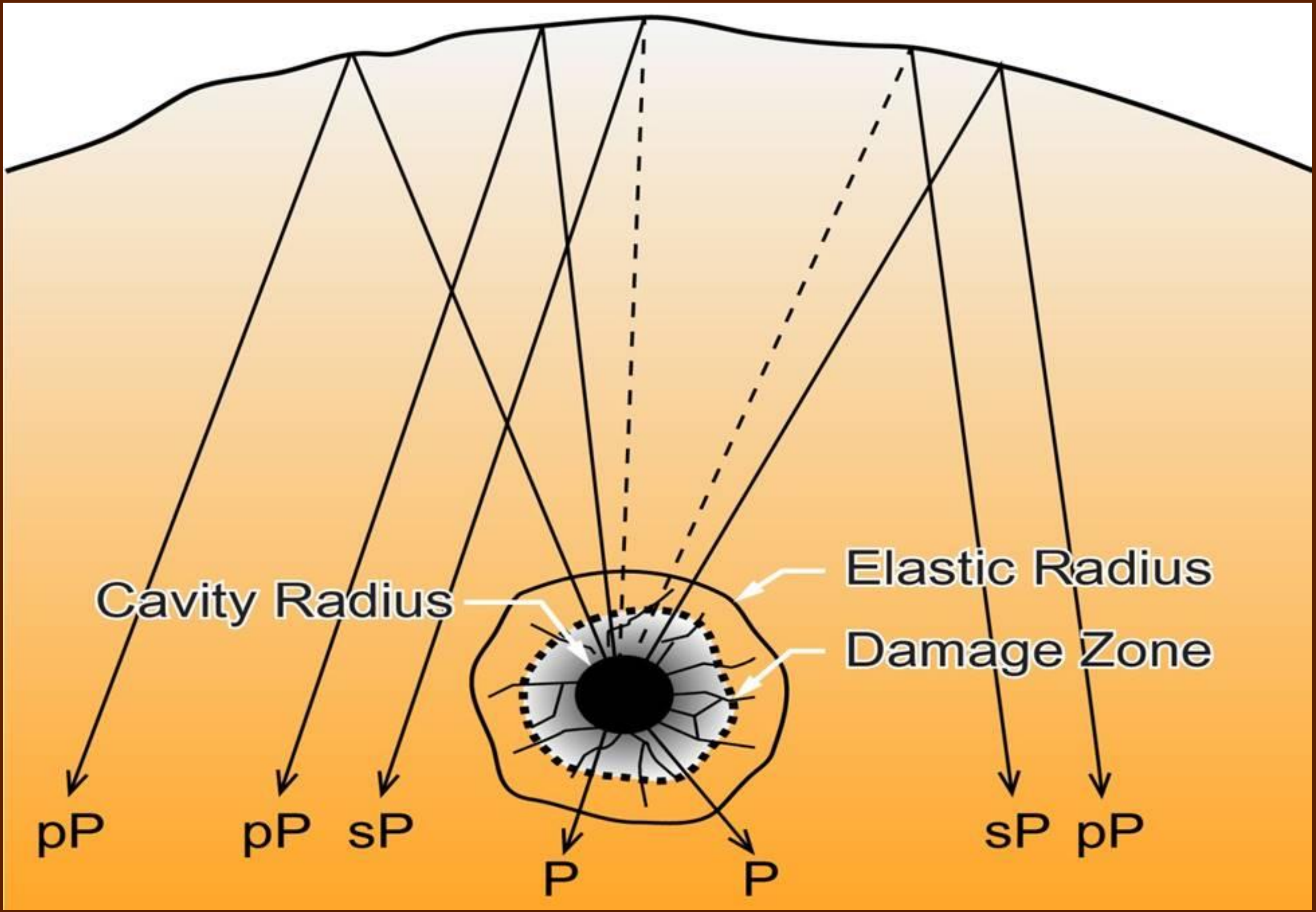
Spectral nulls and depth using pPn-Pn and sPn-Pn delay times. There are slapdown phases (spall closure) showing brown arrows 1.75 seconds later from the onset of P-wave arrivals which may be related to the slapdown phase of a thermonuclear explosion on September 3, 2017.

Stations code	Δ/AZ (°)	pPn + Pn / depth (Hz/km)	sPn + Pn/ depth (Hz/ km)	Comments
R720B	4.31/208.3	1.71/1.97	1.18/2.06	Slapdown and/ or collapse event
R3930	4.13/203.6	1.74/1.94	1.07/2.27	
MDJ	3.30/6.9	1.67/1.97	1.07/1.98	
INCN	4.29/206.6	1.76/1.91	1.17/2.08	Slapdown and/ or Collapse event
KSRS	3.94/193.3	1.72/1.96	1.19/2.04	
USRK	3.61/36.1	1.58/2.09		
Average depth, km		**1.97±0.06**	**2.08±0.01**	**Mean DOB = 2.03**

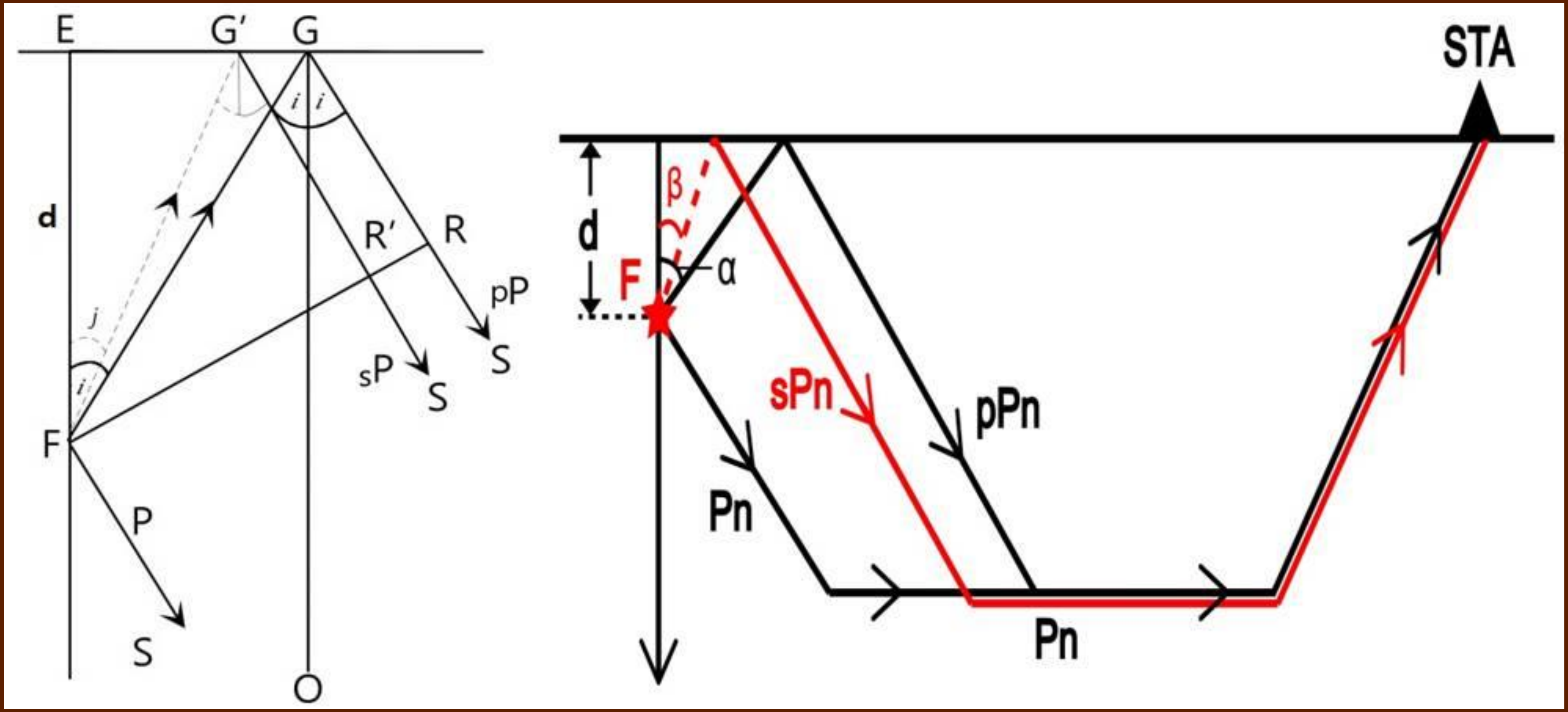
Topography map using 2D and 3D around the test site area is constructed using the numerical geology configuration data (1:25000) from National Geographic Information Institute . Closed stars, open stars and a triangle represent epicenters with event year determined by IDC (CTBTO), NEIC (USGS) and Mantapsan. The 3D and 2D topography maps around the North Korean nuclear tests show shallow slope (almost flat) near the test sites, especially epicenters determined by IDC/CTBTO.



DPRK's underground nuclear explosion source sketch at a depth of around 2 km with gas cavity radius of around 15-57 m and inelastic volume radius of about 200-300 m (Closman, 1969)



Depth Phases (pP, sP, pPn and sPn) for Detonation Depth



a) Ray trajectories of P, pP and sP at a source of the nuclear test. *i* and *j* are take-off angles for pP and sP ray-path . G, G', R and R' indicate the contact points on the surface and on the ray-path by pP and sP. S and O represent seismic stations and the center of the Earth, respectively using the flat Earth model. b) Ray trajectories of P, pPn and sPn at a source of α is a crtical angle Pn (take-off angle of pPn) and β is a take-off angle of sPn. Depth, d can be calculated using travel time delays of pPn-Pn and sPn-Pn .

Depth Calculation Using Depth Phases and Fundamental-mode Rg-wave Spectra

$d = (pP-P)Vp/2\cos(i)$ ……………… …………………………………………………………………………(1)

where i is a take-off angle

$d = (sP-P)VpVs/[Vp\cos(j) + Vs\cos(i)]$…………………………………………………………………(2)

where j is the take-off angle of sP calculated from arcsin [Vs/Vp sin (i)]

$d = (pPn-Pn)Vp/2\cos(\alpha)$ ……………………………………………………………………..(3)

$d=(sPn-Pn)/F(Vp, Vs, Vn, \alpha, \beta)$…………………...(4)

where $F=[VpVn\cos(\alpha) + VsVn\cos(\beta) - VpVs\cos(\alpha)\sin(\beta)-VpVs\cos(\beta)\sin(\alpha)]/ VpVsVn\cos(\alpha)\cos(\beta) = \{\cos(\alpha)[VpVn-VpVs\sin(\beta)]+\cos(\beta)[VsVn-VpVs\sin(\alpha)]\}/\cos(\alpha)\cos(\beta) VpVsVn$, α and β are take-off angles for pPn and sPn phases. $\alpha = \arcsin(Vp/Vn)$ and $\beta = \arcsin[Vs/Vp\sin(\alpha)]$ by Snell's law.

the horizontal displacement eigenfunction u1 and vertical displacement eigenfunction u3 are as follows:

$$u1 = \partial\varphi/\partial x - \partial\psi/\partial z$$

$$u3 = \partial\varphi/\partial z + \partial\psi/\partial x \qquad (13)$$

from equation (12)

$$u1 = Aik[\exp(-0.8475kz - 0.5773\exp(-0.3933kz)]\exp[ik(x-ct)]$$

$$u3 = Aik[0.8475\exp(-0.8475kz - 1.4679\exp(-0.3933kz)]\exp[ik(x-ct)] \qquad (14)$$

Considering taking real parts, the horizontal and vertical displacement eigenfunctions for the fundamental-mode Rayleigh waves are as follows:

$$u1 = -Ak\sin(kx-\omega t)[\exp(-0.8475kz) - 0.5773\exp(-0.3933kz)]$$

$$u3 = -Ak\cos(kx-\omega t)[0.8475\exp(-0.8475kz) - 1.4679\exp(-0.3933kz)] \qquad (15)$$

where A= amplitude, $\omega=2\pi f$ and $k=2\pi fh/c$ when $z=d$

From equation 14, at the depth where u1is null, its amplitude changes sign.

$$1-0.5733\exp(0.4542kz) = 0 \qquad (16)$$

Therefore $d = 0.1923c/fnull$ (17)

where c=Rg-wave velocity, 1.46 km/sec from Rayleigh Equation (Udias, 1999) and fnull spectral minimum of the Fundamental-mode Rayleigh wave amplitude spectra.

Conclusions

- Source depths were found to be 2.12, 2.06, 2.05, 2.06, 2.05 and 1.97 km for the 2006, 2009, 2013, 2016J, 2016S and 2017 tests respectively by spectral nulls of body wave spectra from teleseismic arrays and regional arrays including spectral minima for the fundamental-mode of Rayleigh wave (Rg-wave) amplitude spectra.
- We found strong Rayleigh waves and weak Love waves from particle motions of surface waves indicating that there are strong enough P-SV interferences reflected from the free surface even if some explosions (2013 test) represent distinct Love waves because of cracks or block movements in the pre-existing tectonic stress. In particular, poor Love waves in the subduction zone are due to low Q with high attenuation from a low velocity zone overlying a high velocity.
- The over-burial detonation would affect magnitude and seismic yield.