일본 난카이 지역에서 발생 가능한 대지진에 대한 합성 파형 시뮬레이션 및 한반도 지역 지진동에 미치는 영향에 관한 고찰

서울대학교 물리천문학부

이재석

Nankai Trough Earthquake

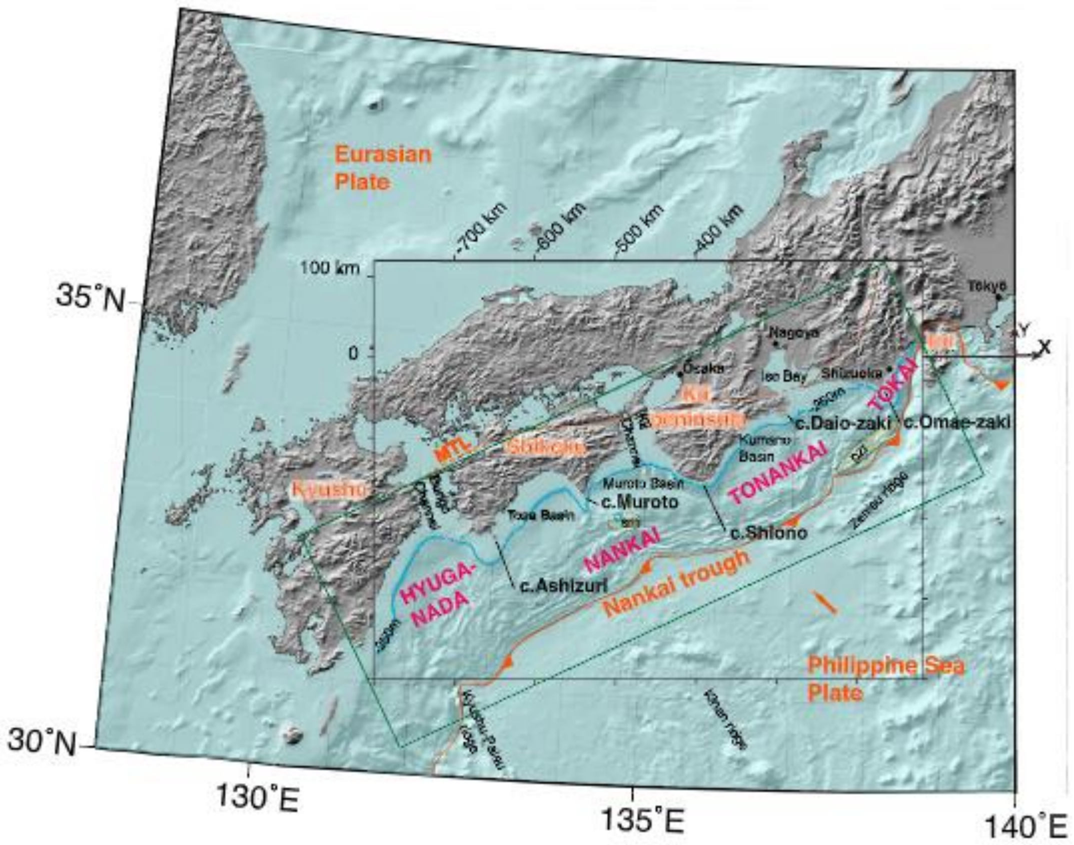
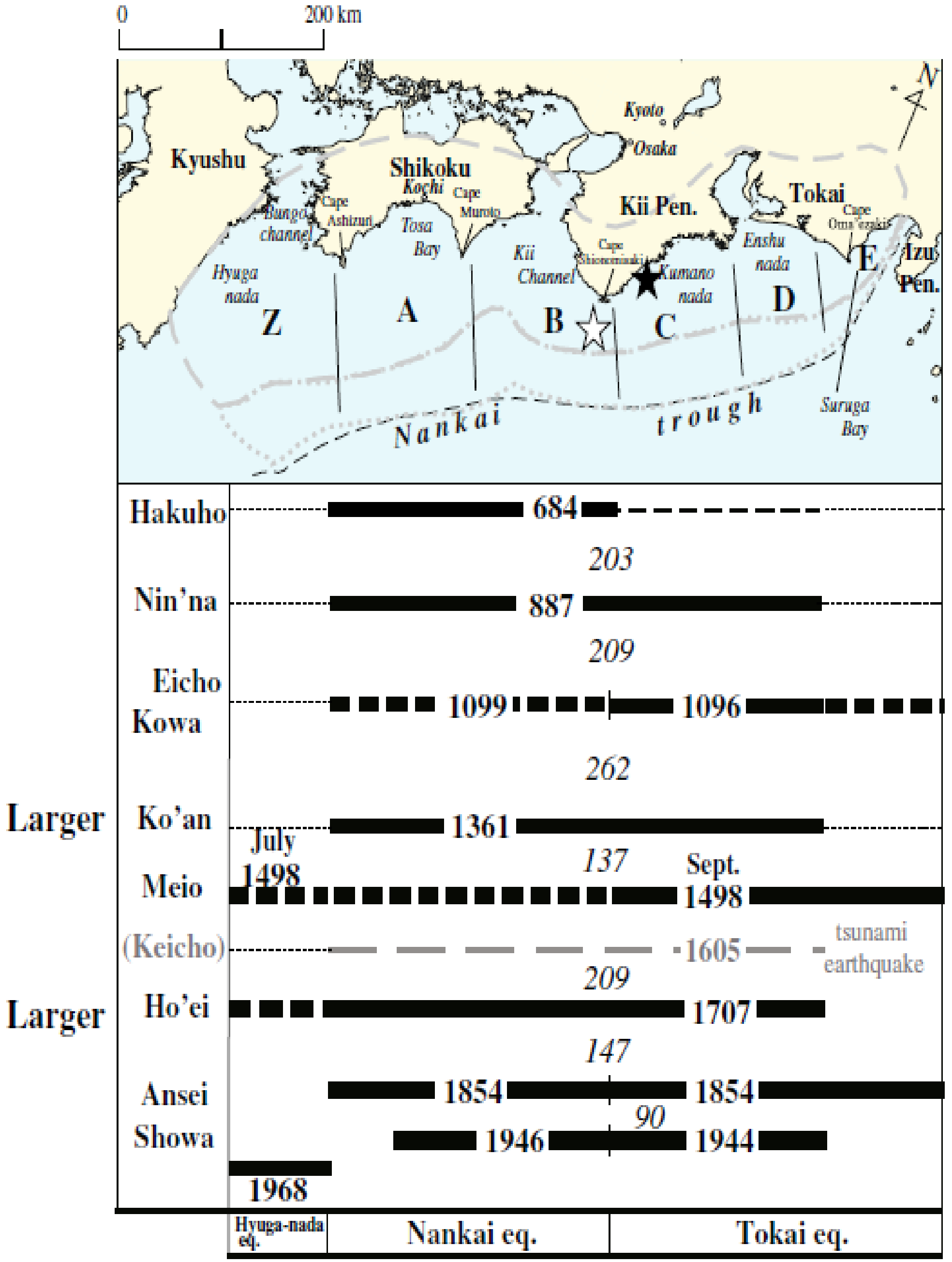


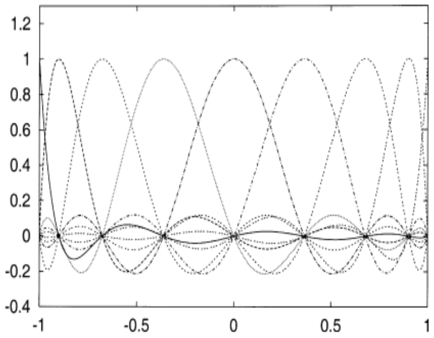
Figure 1. Topographic map of southwest Japan. The −250 m isodepth in the shelf bank is underlined with thick blue-gray contour. Abbreviations 'sm,' 'pzr' and 'c.' stand for subducted seamount, subducted paleo-Zenisu ridge and cape, respectively. Black rectangle shows the computation area shown in the following, and the XY coordinate system used, whose origin is located at (35°N, 140°E). Rotated green rectangle shows the area covered by free surface elements.



(Hok et al., 2011) / (Hyodo et al., 2014)

Spectral Element Method (SEM)

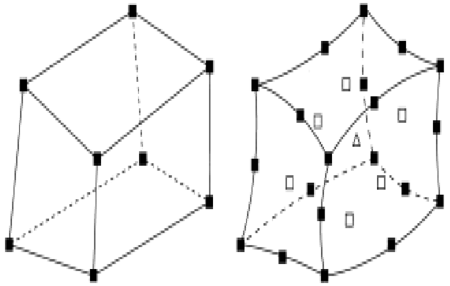
Lagrange Polynomial Approximation



$$l_\alpha^{nl}(\xi) = \frac{(\xi-\xi_0)\cdots(\xi-\xi_{\alpha-1})(\xi-\xi_{\alpha+1})\cdots(\xi-\xi_{nl})}{(\xi_\alpha-\xi_0)\cdots(\xi_\alpha-\xi_{\alpha-1})(\xi_\alpha-\xi_{\alpha+1})\cdots(\xi_\alpha-\xi_{nl})}$$

$$l_\alpha^{nl}(\xi_\beta) = \delta_{\alpha\beta}$$

$$\boldsymbol{x}(\xi,\eta) = \sum_{a=1}^{n_a} N_a(\xi,\eta)\boldsymbol{x}_a$$



Weak formulation

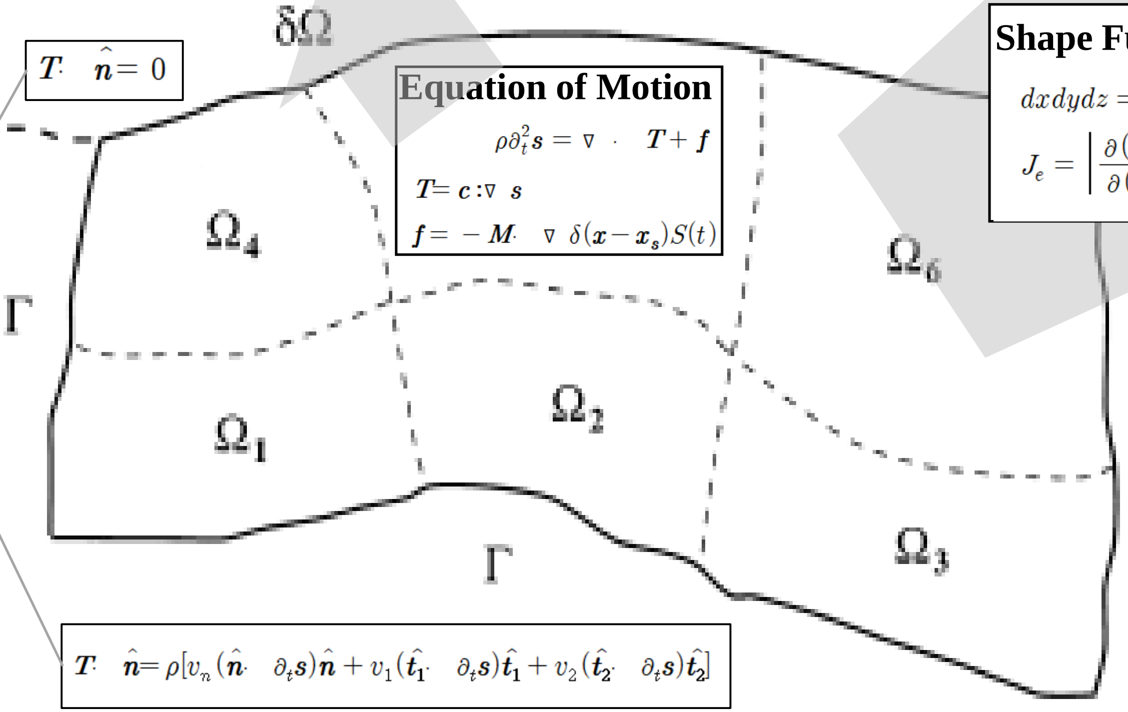
$$\int_\Omega \rho \boldsymbol{w} \cdot \partial_t^2 \boldsymbol{s}\, d^3\boldsymbol{x} = -\int_\Omega \nabla \boldsymbol{w} : \boldsymbol{T} d^3x + \boldsymbol{M} : \nabla \boldsymbol{w}(\boldsymbol{x}_s) S(t)$$
$$+ \int_\Gamma \rho[v_n(\hat{\boldsymbol{n}} \cdot \partial_t \boldsymbol{s})\hat{\boldsymbol{n}} + v_1(\hat{\boldsymbol{t}}_1 \cdot \partial_t \boldsymbol{s})\hat{\boldsymbol{t}}_1 + v_2(\hat{\boldsymbol{t}}_2 \cdot \partial_t \boldsymbol{s})\hat{\boldsymbol{t}}_2] \cdot \boldsymbol{w}\, d^2\boldsymbol{x}$$

Gauss-Lobatto-Legendre Point

$$(1-\xi^2)P'_{nl}(\xi) = 0$$

$$f(\boldsymbol{x}(\xi,\eta,\zeta)) \approx \sum_{\alpha,\beta,\gamma=0}^{n_l} f^{\alpha\beta\gamma} l_\alpha(\xi) l_\beta(\eta) l_\gamma(\zeta)$$

$$f^{\alpha\beta\gamma} = f(\boldsymbol{x}(\xi_\alpha,\eta_\beta,\zeta_\gamma))$$



$\boldsymbol{T} \cdot \hat{\boldsymbol{n}} = 0$

Equation of Motion

$$\rho \partial_t^2 \boldsymbol{s} = \nabla \cdot \boldsymbol{T} + \boldsymbol{f}$$
$$\boldsymbol{T} = \boldsymbol{c} : \nabla \boldsymbol{s}$$
$$\boldsymbol{f} = -\boldsymbol{M} \cdot \nabla \delta(\boldsymbol{x}-\boldsymbol{x}_s) S(t)$$

Shape Function

$$dx\,dy\,dz = J_e\, d\xi\, d\eta\, d\zeta$$
$$J_e = \left| \frac{\partial(x,y,z)}{\partial(\xi,\eta,\zeta)} \right|$$

GLL Integration Rule

$$\int_{\Omega_e} f(\boldsymbol{x}) d^3x = \int_{-1}^{1}\int_{-1}^{1}\int_{-1}^{1} f(\boldsymbol{x}(\xi,\eta,\zeta)) J_e(\xi,\eta,\zeta)\, d\xi\, d\eta\, d\zeta$$
$$\approx \sum_{\alpha,\beta,\gamma=0}^{n_l} \omega_\alpha \omega_\beta \omega_\gamma f^{\alpha\beta\gamma} J_e(\xi_\alpha,\eta_\beta,\zeta_\gamma)$$

Boundary Condition

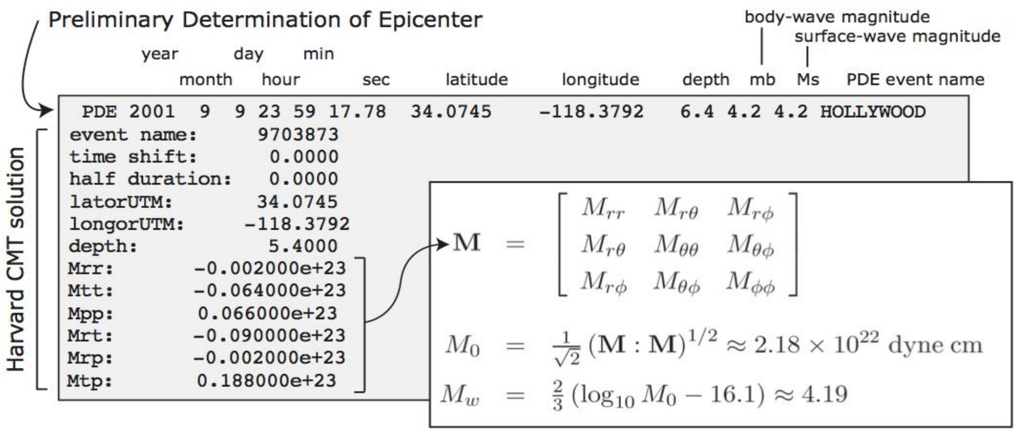
$$\boldsymbol{T} \cdot \hat{\boldsymbol{n}} = \rho[v_n(\hat{\boldsymbol{n}} \cdot \partial_t \boldsymbol{s})\hat{\boldsymbol{n}} + v_1(\hat{\boldsymbol{t}}_1 \cdot \partial_t \boldsymbol{s})\hat{\boldsymbol{t}}_1 + v_2(\hat{\boldsymbol{t}}_2 \cdot \partial_t \boldsymbol{s})\hat{\boldsymbol{t}}_2]$$

(Komatitsch & Tromp, 1999)

Earthquake Event

- 2016_04_01 Nankai Earthquake
  - -Mw 5.9
  - -Lat: 33.38° Lon: 136.39 ° Depth: 18.8km
  - -necis.kma.go.kr 기상청 지진관측소 자료
  - -32개 광대역 속도관측소 & 시추공 광대역 속도관측소
  - -Point Source Model (Global CMT Catalog)
  - -East Asia Model (Kim et al., 2016) / 1D-PREM (Dziewonski & Anderson, 1981)

- 1946_12_20 Nankai Earthquake
  - -Mw 8.4
  - -Lat: 33.03 ° Lon: 135.62 ° Depth: 30.0km
  - -Finite Fault Model (Tanioka & Satake, 2001. | Baba et al., 2002)
  - -Rupture Velocity: Vs (3.496km/s) | 0.75*Vs (2.622km/s)
  - -Half-Duration: 0.7s

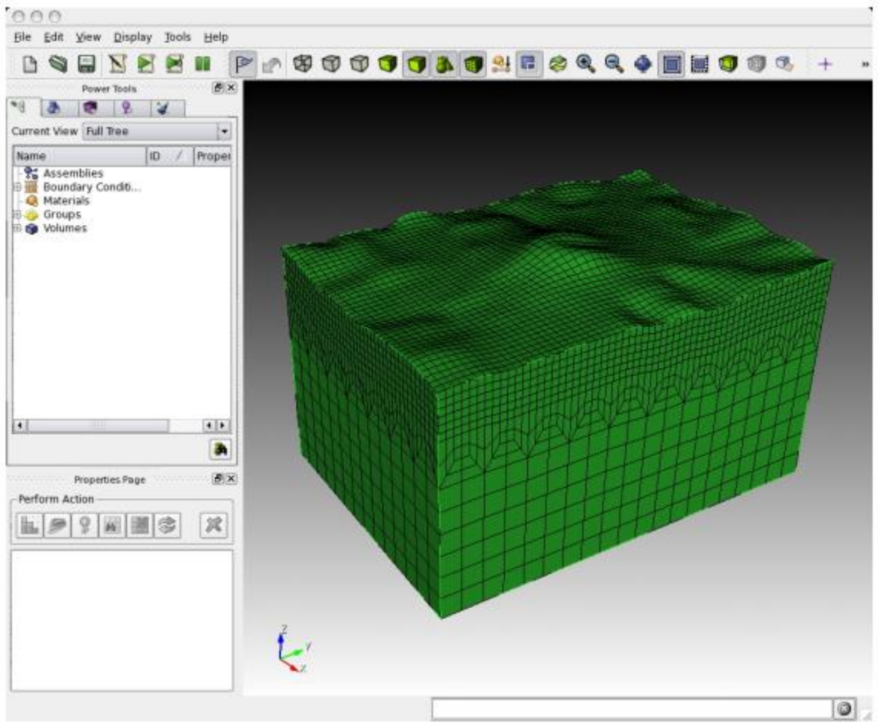


(SPECFEM3D-Cartesian Manual)

Simulation

- Mesh Generation – Trelis
  - -한반도와 일본을 포함한 1300km*900km*170km mesh
  - -Topography Data from SRTM(http://srtm.csi.cgiar.org)
  - -element size 4km → computed maximum frequency = (element size)/(wave velocity)

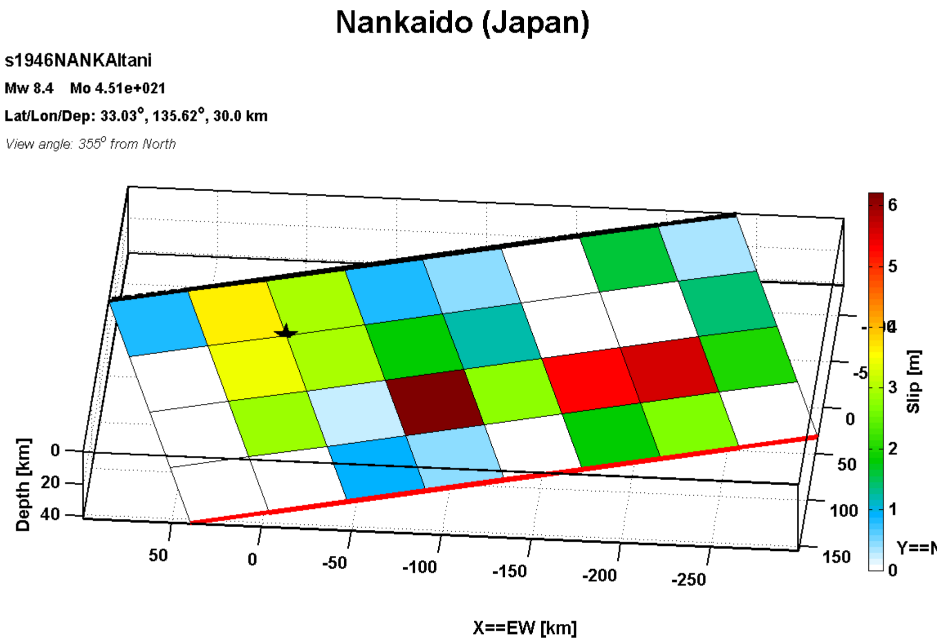
- Computation – SPECFEM3D Cartesian
  - -dT = 0.04s
  - -Nstep = 20000
  - -cpu 200: ~10hrs

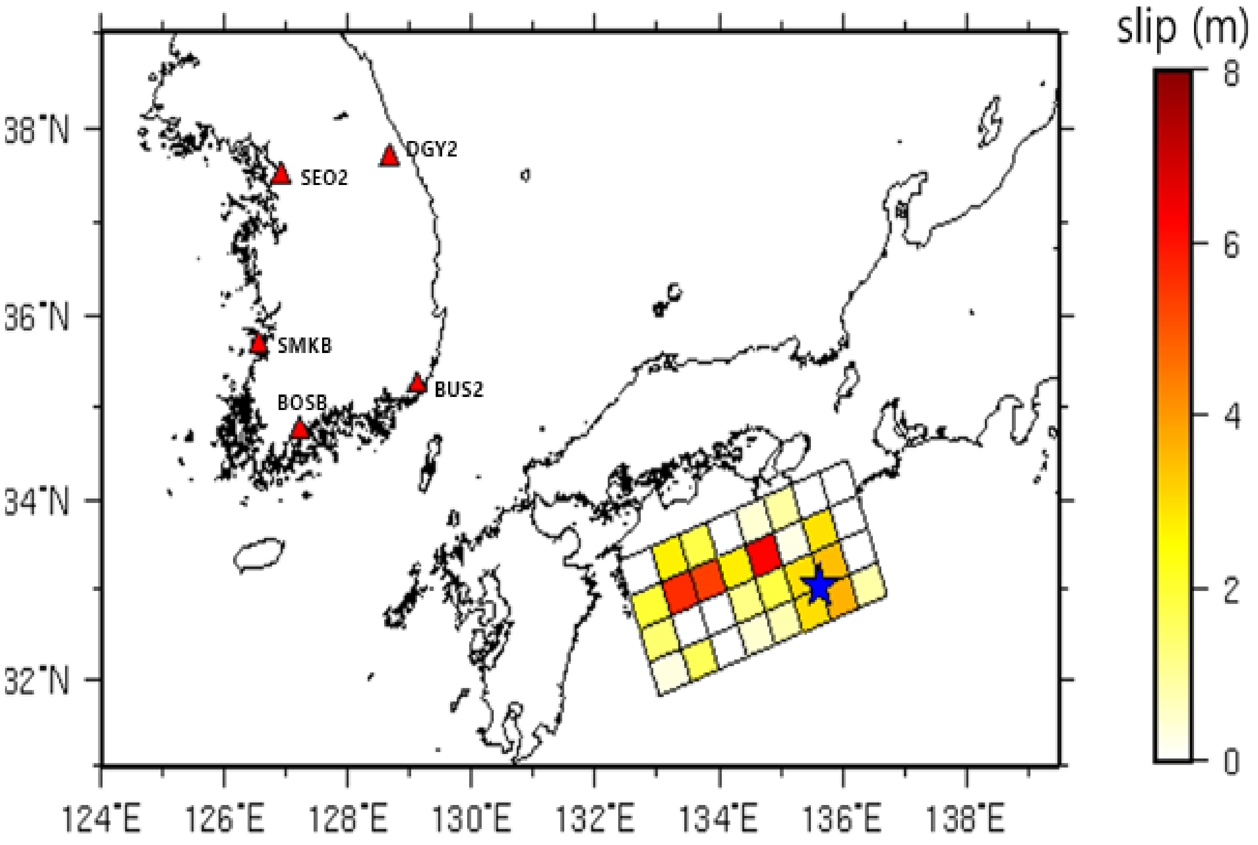


(SPECFEM3D-Cartesian Manual)

1946 Nankai Earthquake Finite Fault Model
-(Tanioka & Satake, 2001)

- Tsunami waveform inversion
- Strike: 250.00° / Dip: 33.38° / Rake: 120.00 °
- 29 subfaults - 45km*45km
- Slip distribution: 0 ~ 6.22m





(Tanioka & Satake, 2001)

1946 Nankai Earthquake Finite Fault Model -(Baba et al., 2002)

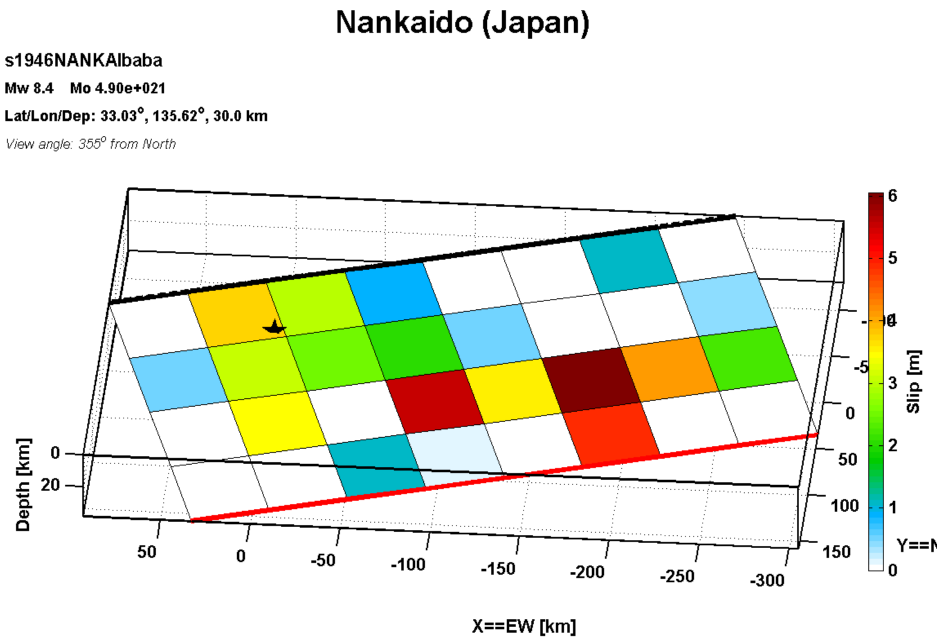
- Modified Philippine Sea Plate Model

    -combined marine seismic survey results and seismicity data

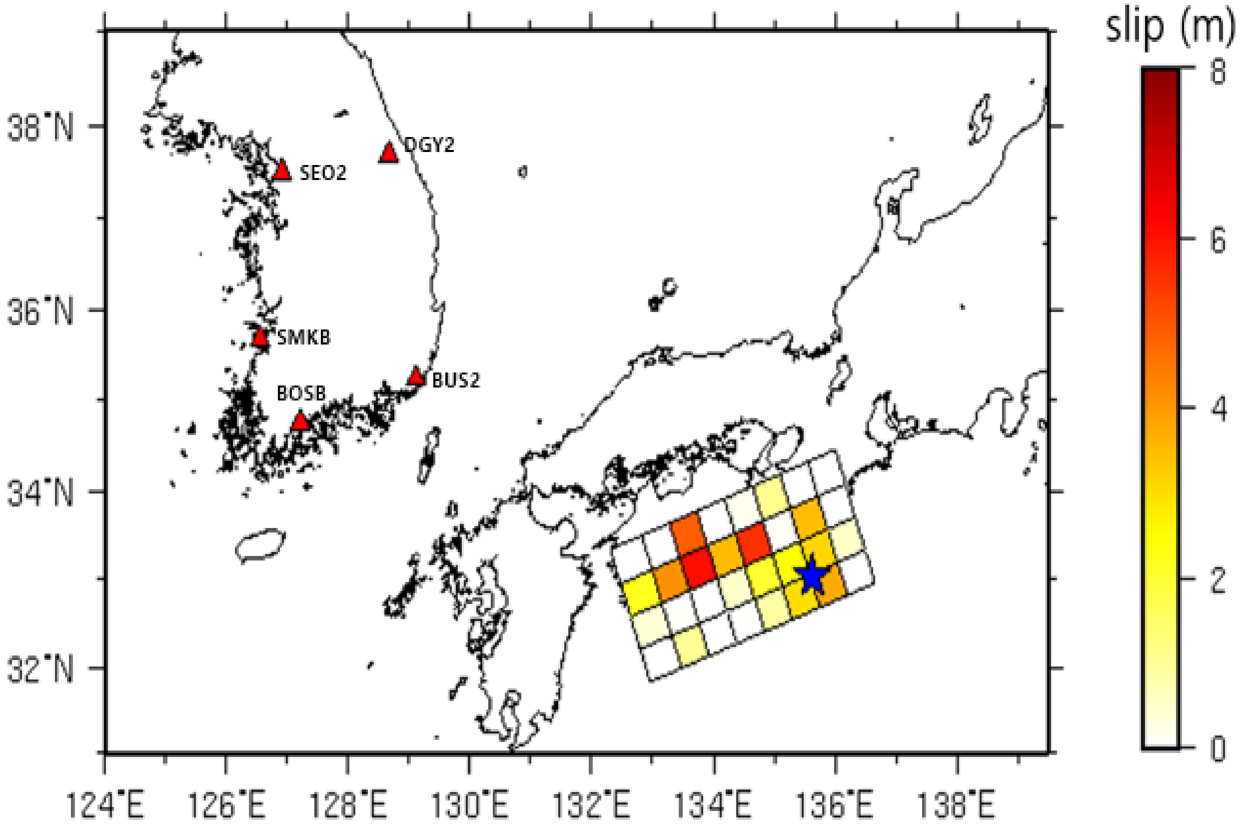
    -Dip: 13.00 ° → 12.00 °

    -Seismic Moment: 4.51E+21→4.9E+21

    -Slip distribution variance: $132.22m^2$ → $112.95m^2$

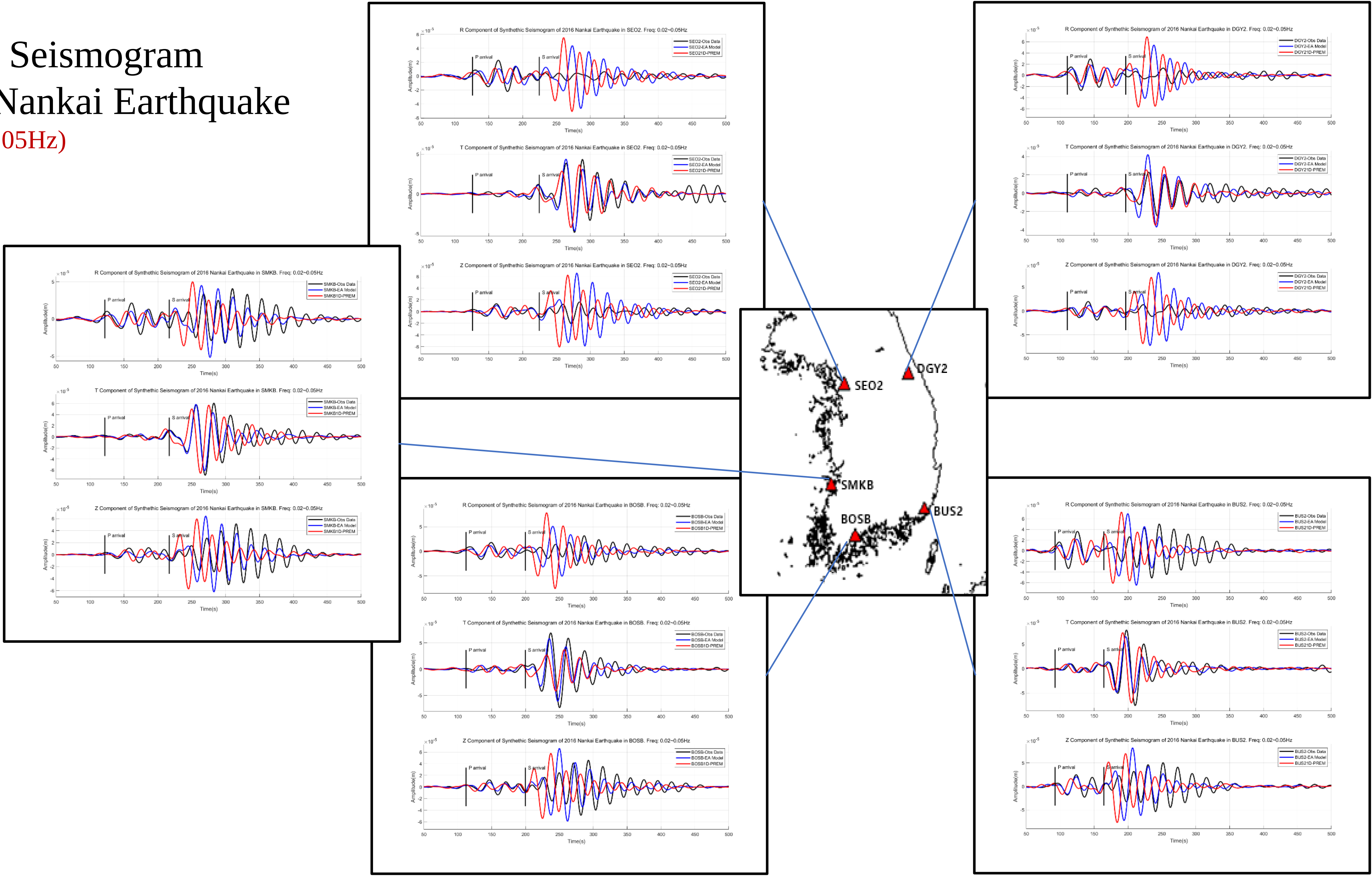


(Baba et al., 2002)

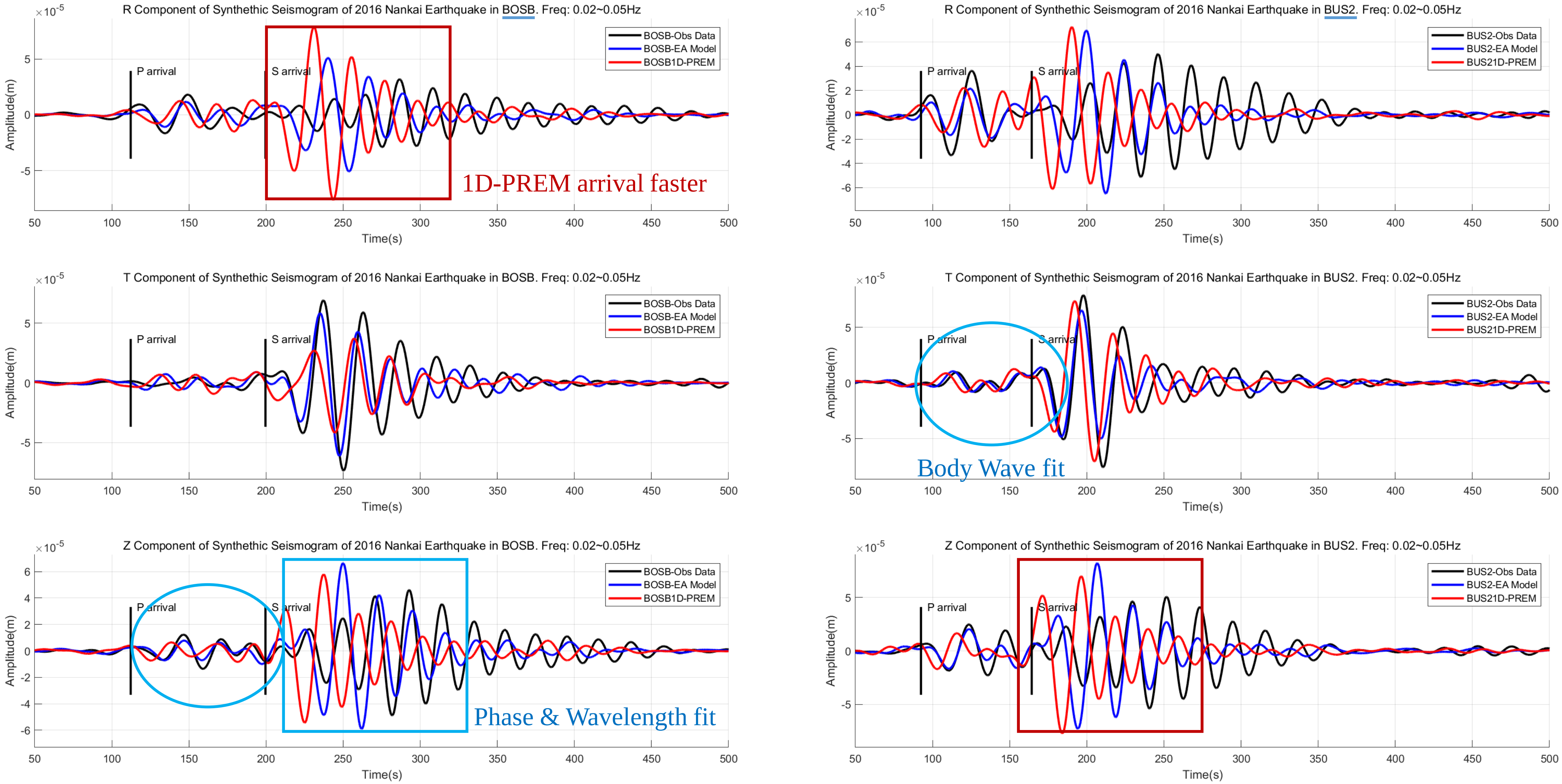


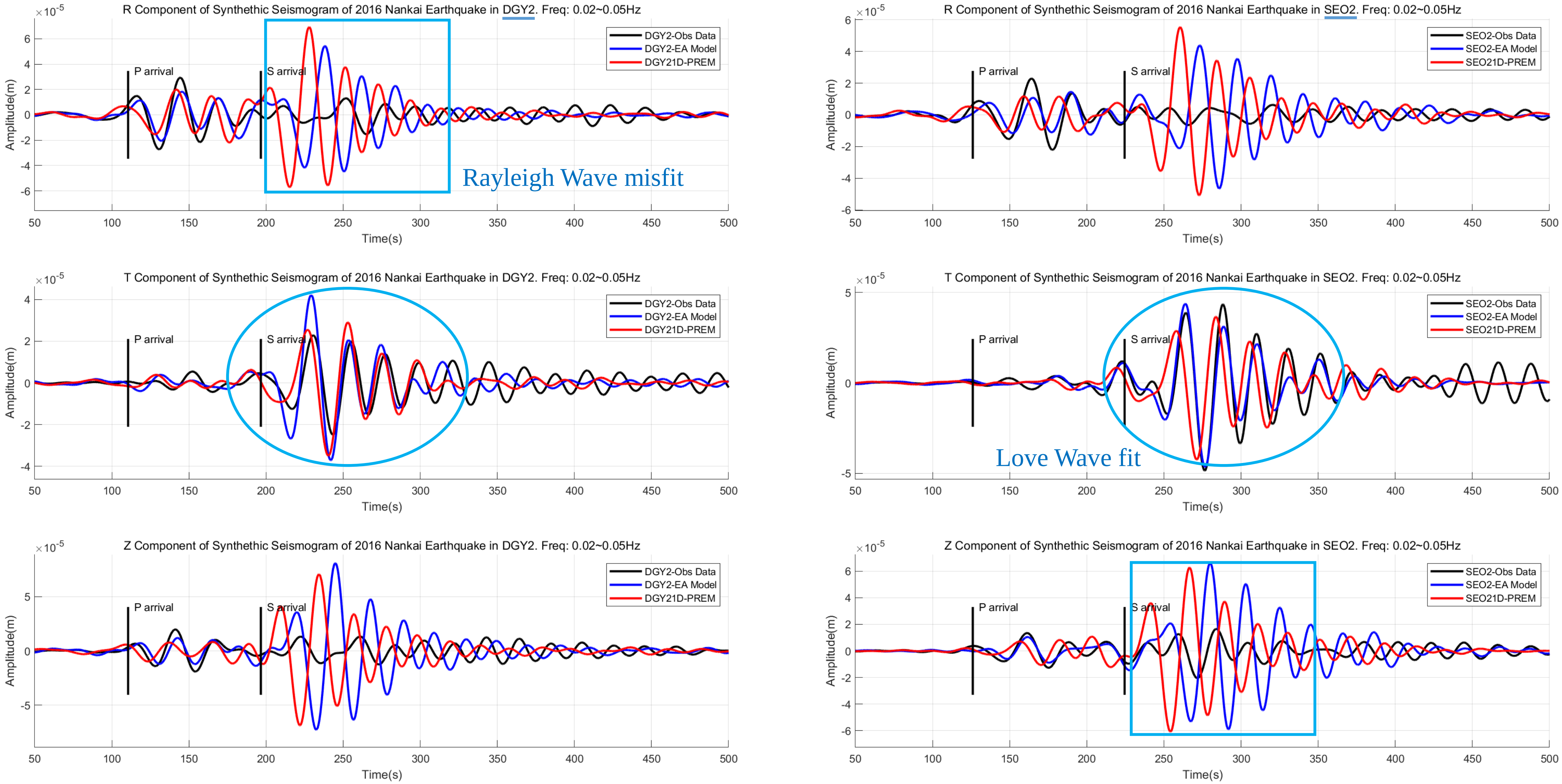
Synthetic Seismogram
Of 2016 Nankai Earthquake

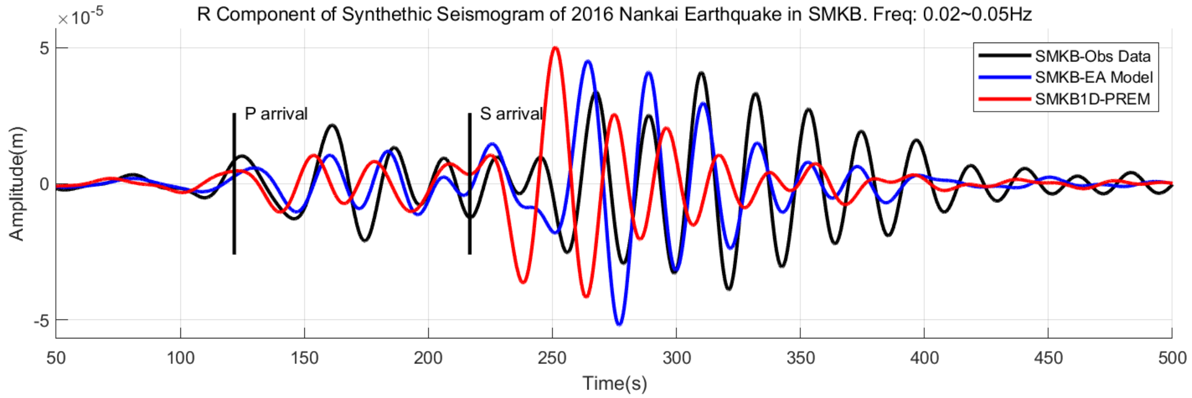
(Freq: 0.02~0.05Hz)

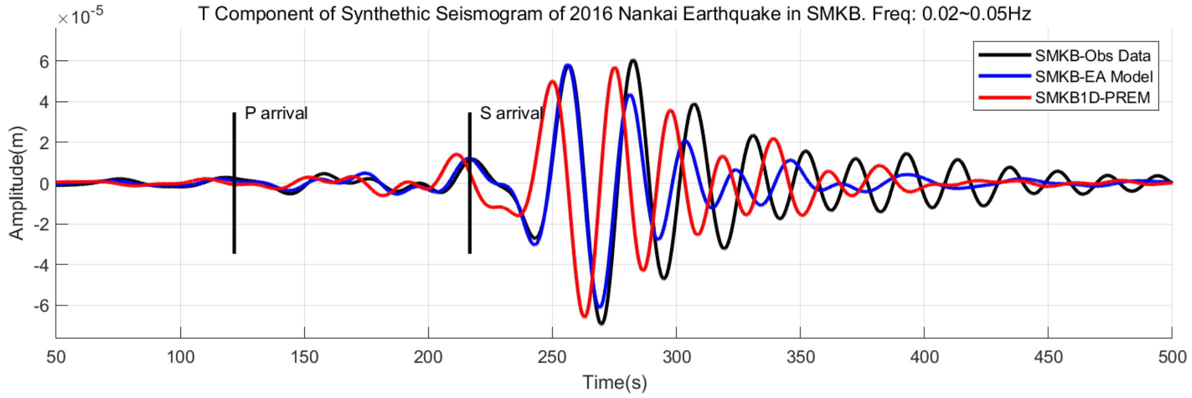


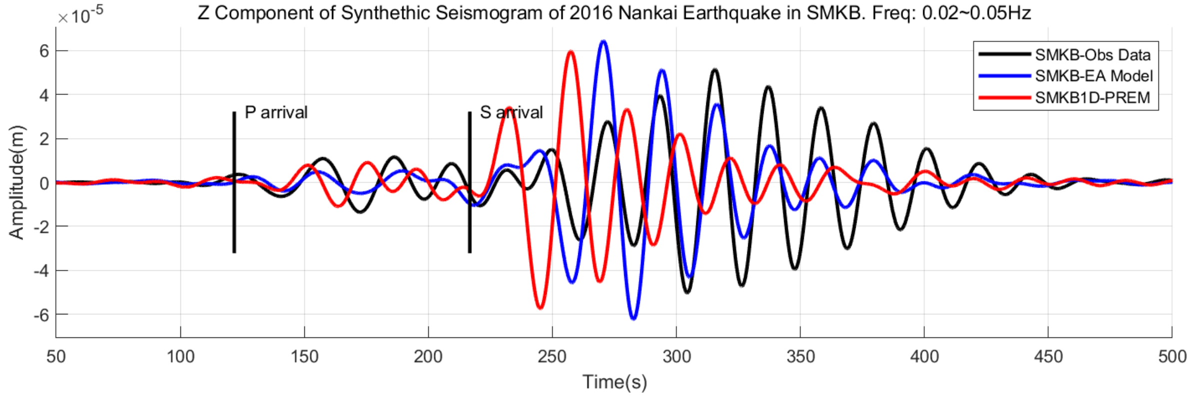
Stations closer to event fit better




R Component of Synthethic Seismogram of 2016 Nankai Earthquake in DGY2. Freq: 0.02~0.05Hz
DGY2-Obs Data
DGY2-EA Model
DGY21D-PREM
P arrival
S arrival
Rayleigh Wave misfit
Amplitude(m)
Time(s)
R Component of Synthethic Seismogram of 2016 Nankai Earthquake in SEO2. Freq: 0.02~0.05Hz
SEO2-Obs Data
SEO2-EA Model
SEO21D-PREM
T Component of Synthethic Seismogram of 2016 Nankai Earthquake in DGY2. Freq: 0.02~0.05Hz
T Component of Synthethic Seismogram of 2016 Nankai Earthquake in SEO2. Freq: 0.02~0.05Hz
Love Wave fit
Z Component of Synthethic Seismogram of 2016 Nankai Earthquake in DGY2. Freq: 0.02~0.05Hz
Z Component of Synthethic Seismogram of 2016 Nankai Earthquake in SEO2. Freq: 0.02~0.05Hz

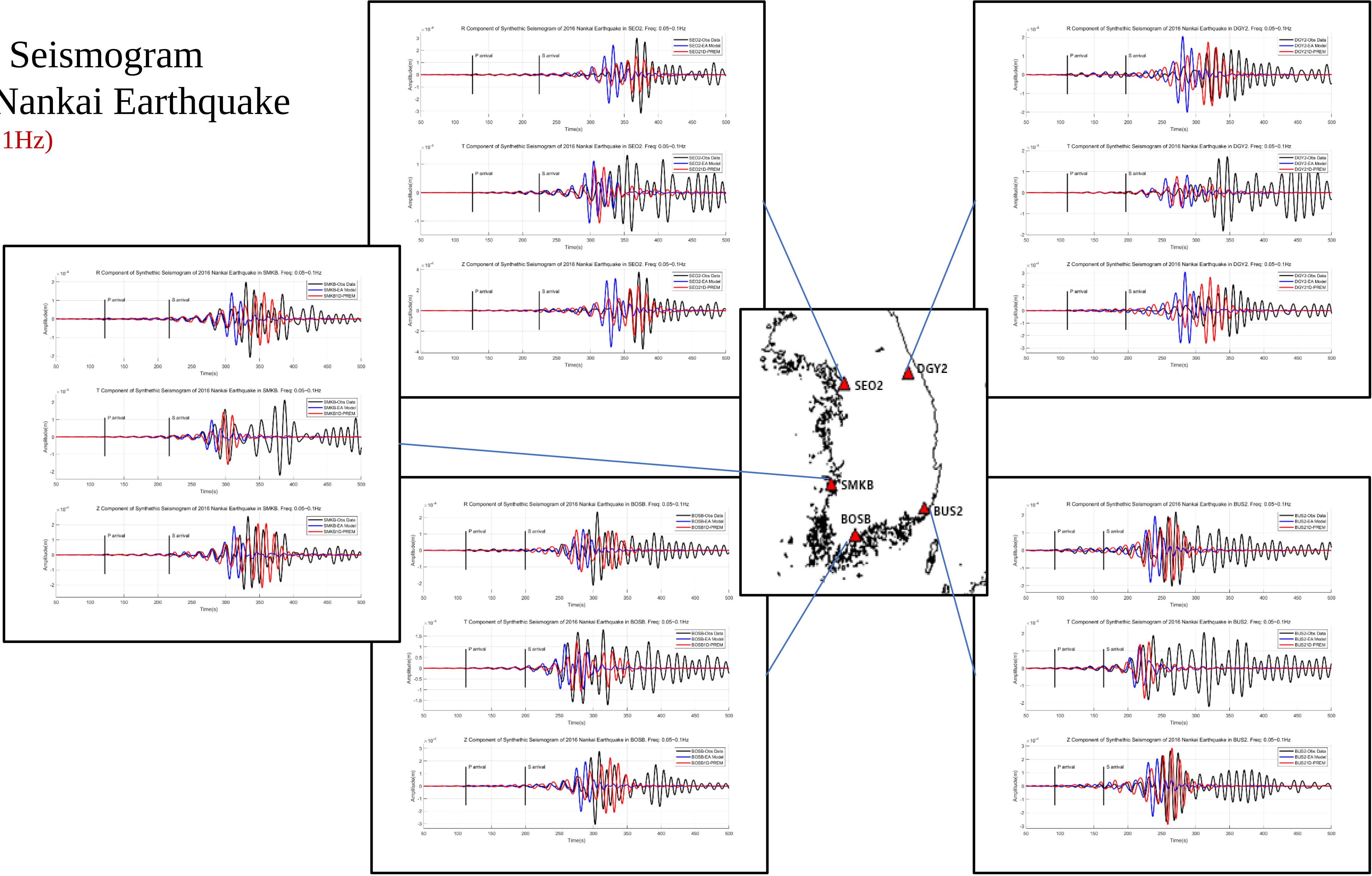

R Component of Synthethic Seismogram of 2016 Nankai Earthquake in SMKB. Freq: 0.02~0.05Hz
×10^-5
Amplitude(m)
Time(s)
P arrival
S arrival
SMKB-Obs Data
SMKB-EA Model
SMKB1D-PREM

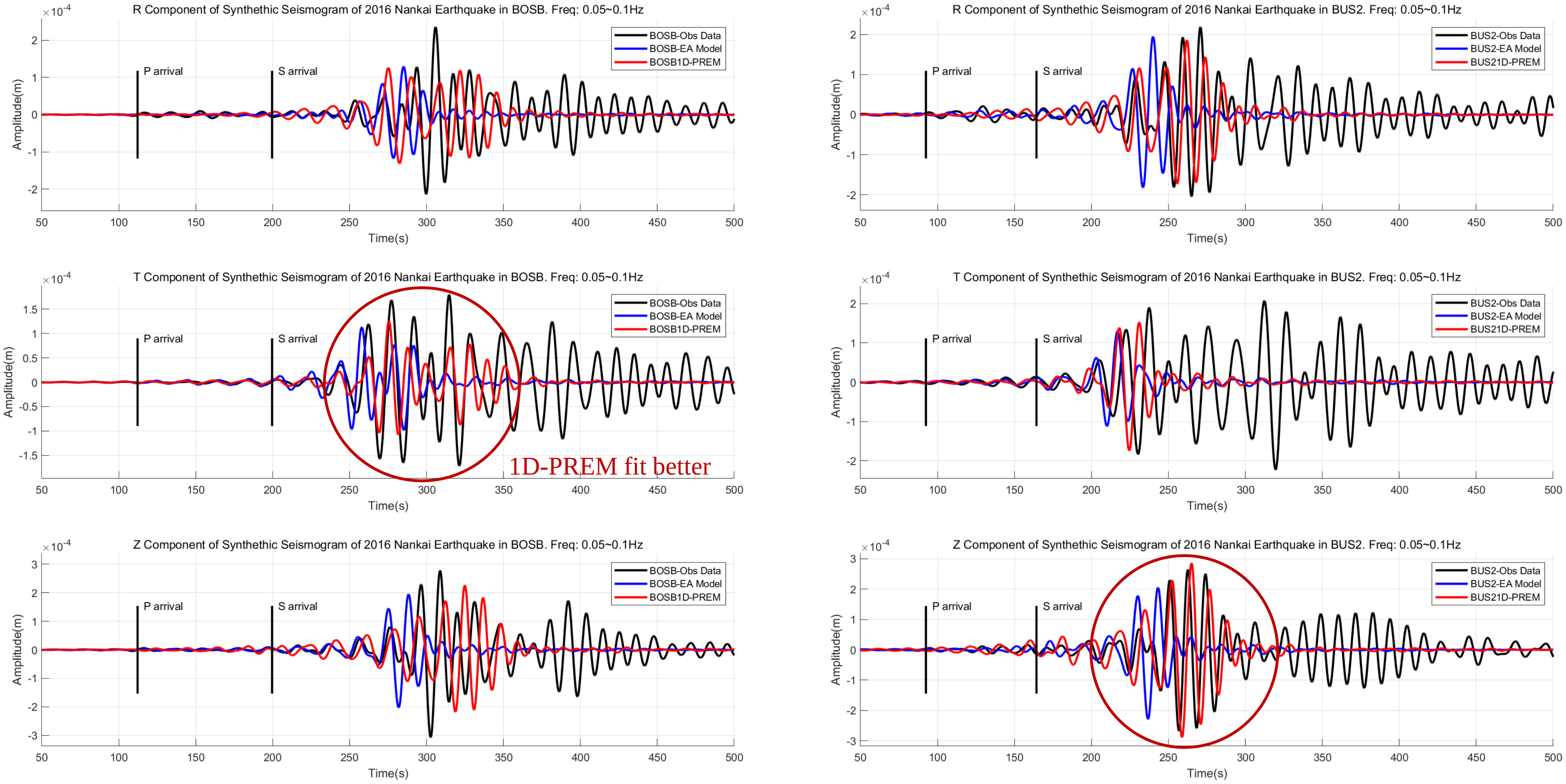

T Component of Synthethic Seismogram of 2016 Nankai Earthquake in SMKB. Freq: 0.02~0.05Hz
×10^-5
Amplitude(m)
Time(s)
P arrival
S arrival
SMKB-Obs Data
SMKB-EA Model
SMKB1D-PREM

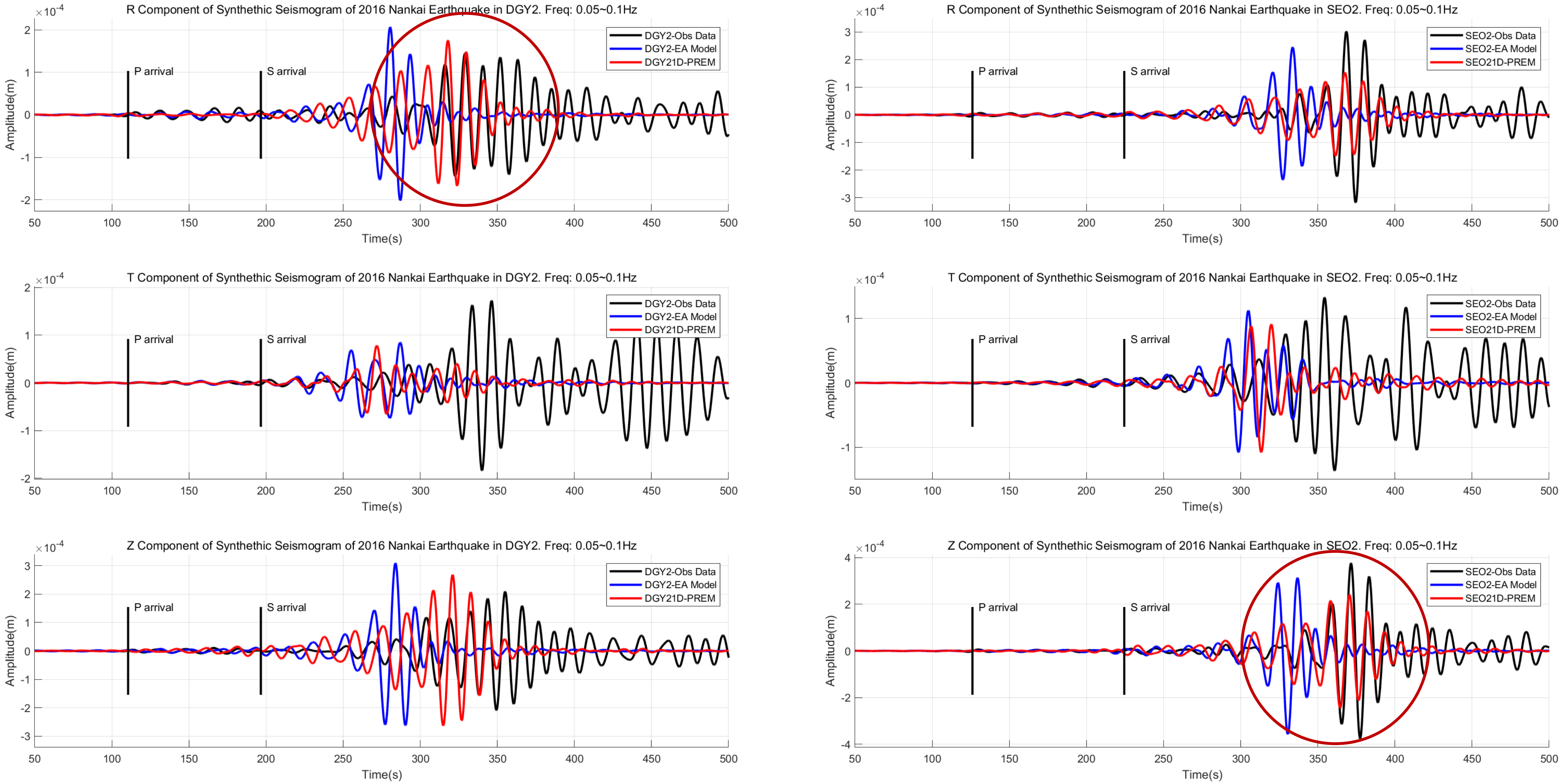

Z Component of Synthethic Seismogram of 2016 Nankai Earthquake in SMKB. Freq: 0.02~0.05Hz
×10^-5
Amplitude(m)
Time(s)
P arrival
S arrival
SMKB-Obs Data
SMKB-EA Model
SMKB1D-PREM

Synthetic Seismogram Of 2016 Nankai Earthquake

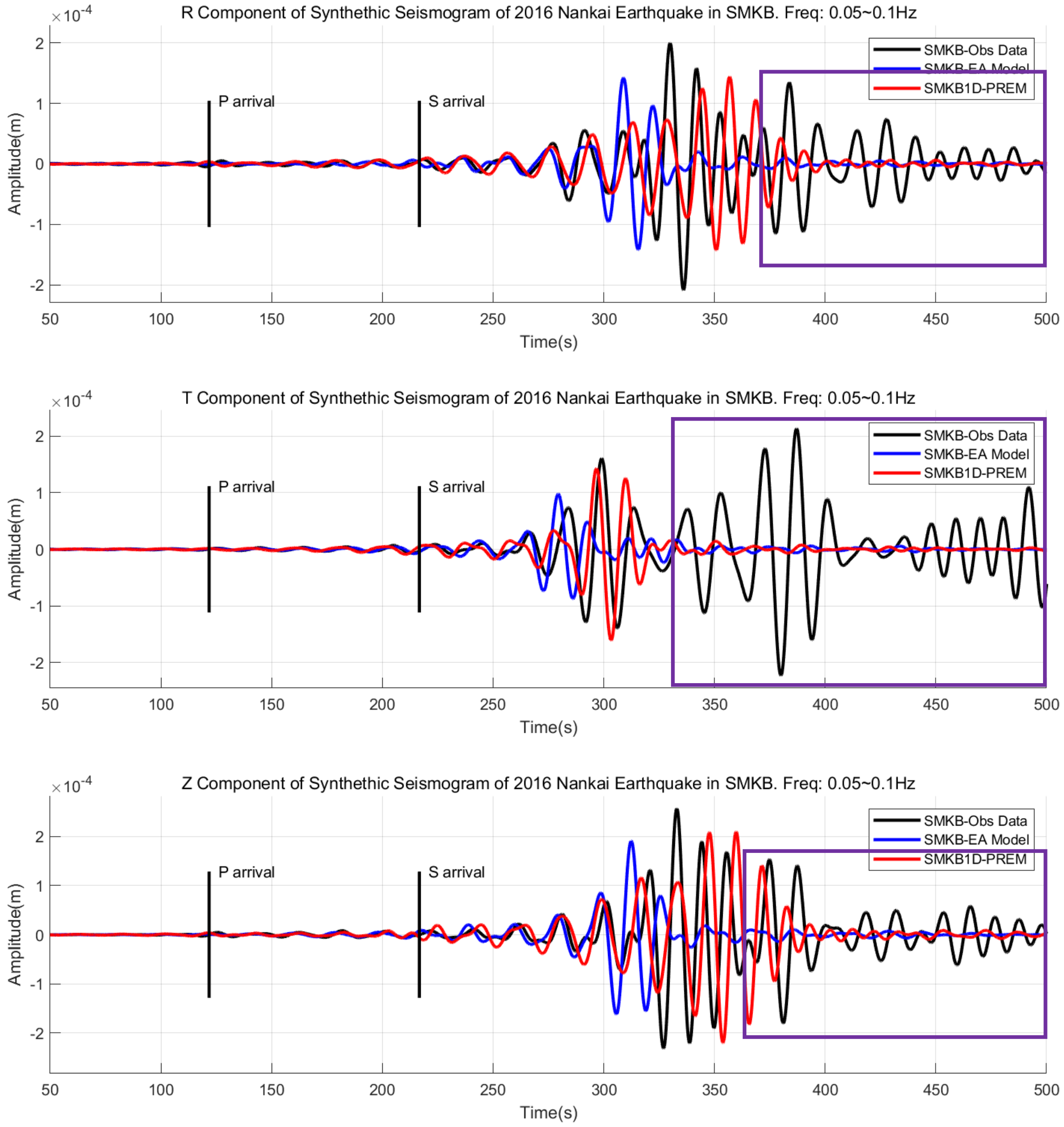
(Freq: 0.05~0.1Hz)




R Component of Synthethic Seismogram of 2016 Nankai Earthquake in BOSB. Freq: 0.05~0.1Hz
BOSB-Obs Data
BOSB-EA Model
BOSB1D-PREM
P arrival
S arrival
Amplitude(m)
Time(s)
R Component of Synthethic Seismogram of 2016 Nankai Earthquake in BUS2. Freq: 0.05~0.1Hz
BUS2-Obs Data
BUS2-EA Model
BUS21D-PREM
P arrival
S arrival
Amplitude(m)
Time(s)
T Component of Synthethic Seismogram of 2016 Nankai Earthquake in BOSB. Freq: 0.05~0.1Hz
BOSB-Obs Data
BOSB-EA Model
BOSB1D-PREM
P arrival
S arrival
1D-PREM fit better
Amplitude(m)
Time(s)
T Component of Synthethic Seismogram of 2016 Nankai Earthquake in BUS2. Freq: 0.05~0.1Hz
BUS2-Obs Data
BUS2-EA Model
BUS21D-PREM
P arrival
S arrival
Amplitude(m)
Time(s)
Z Component of Synthethic Seismogram of 2016 Nankai Earthquake in BOSB. Freq: 0.05~0.1Hz
BOSB-Obs Data
BOSB-EA Model
BOSB1D-PREM
P arrival
S arrival
Amplitude(m)
Time(s)
Z Component of Synthethic Seismogram of 2016 Nankai Earthquake in BUS2. Freq: 0.05~0.1Hz
BUS2-Obs Data
BUS2-EA Model
BUS21D-PREM
P arrival
S arrival
Amplitude(m)
Time(s)



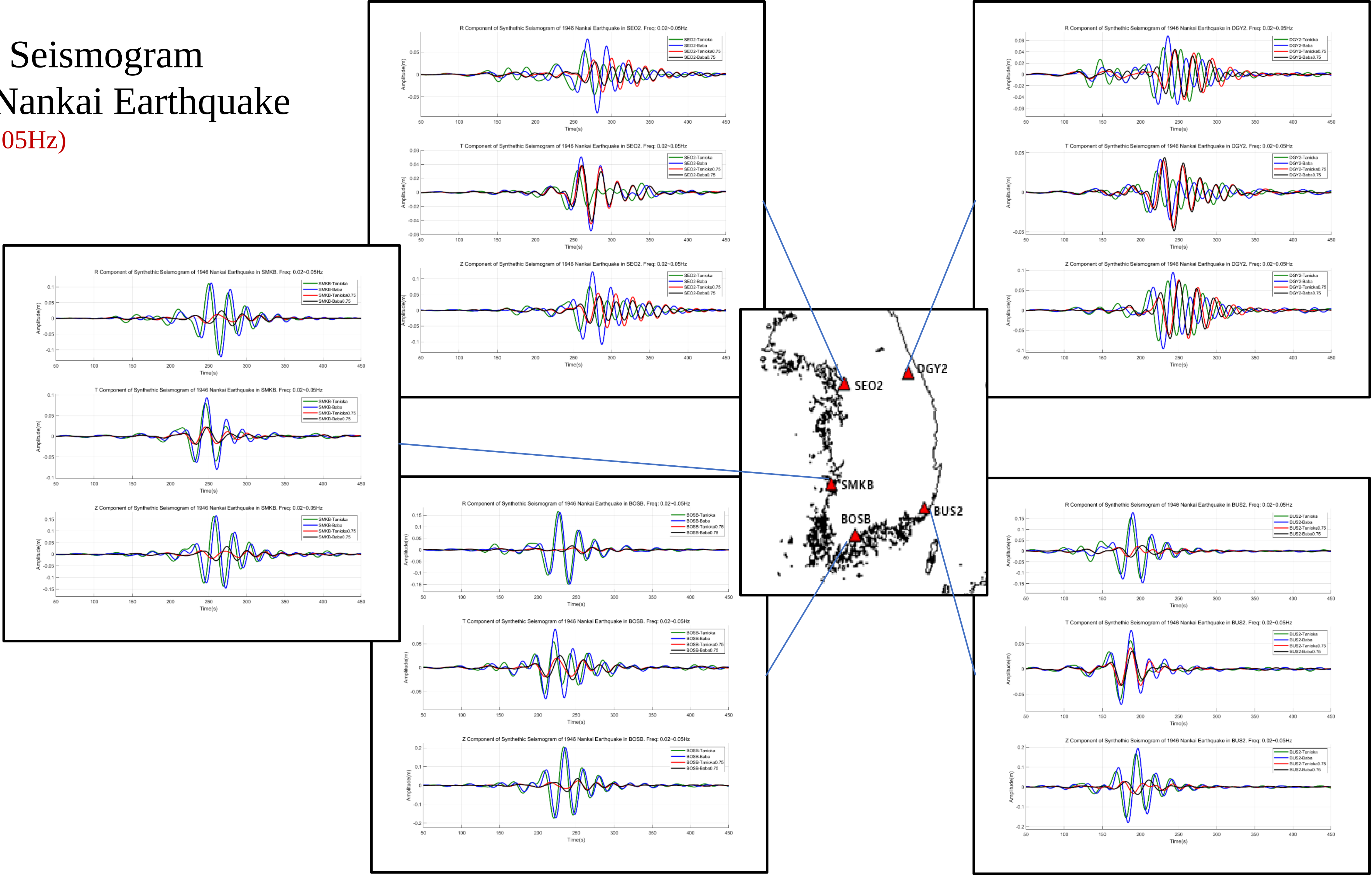
R Component of Synthethic Seismogram of 2016 Nankai Earthquake in DGY2. Freq: 0.05~0.1Hz
DGY2-Obs Data
DGY2-EA Model
DGY21D-PREM
P arrival
S arrival
Amplitude(m)
Time(s)
R Component of Synthethic Seismogram of 2016 Nankai Earthquake in SEO2. Freq: 0.05~0.1Hz
SEO2-Obs Data
SEO2-EA Model
SEO21D-PREM
T Component of Synthethic Seismogram of 2016 Nankai Earthquake in DGY2. Freq: 0.05~0.1Hz
T Component of Synthethic Seismogram of 2016 Nankai Earthquake in SEO2. Freq: 0.05~0.1Hz
Z Component of Synthethic Seismogram of 2016 Nankai Earthquake in DGY2. Freq: 0.05~0.1Hz
Z Component of Synthethic Seismogram of 2016 Nankai Earthquake in SEO2. Freq: 0.05~0.1Hz

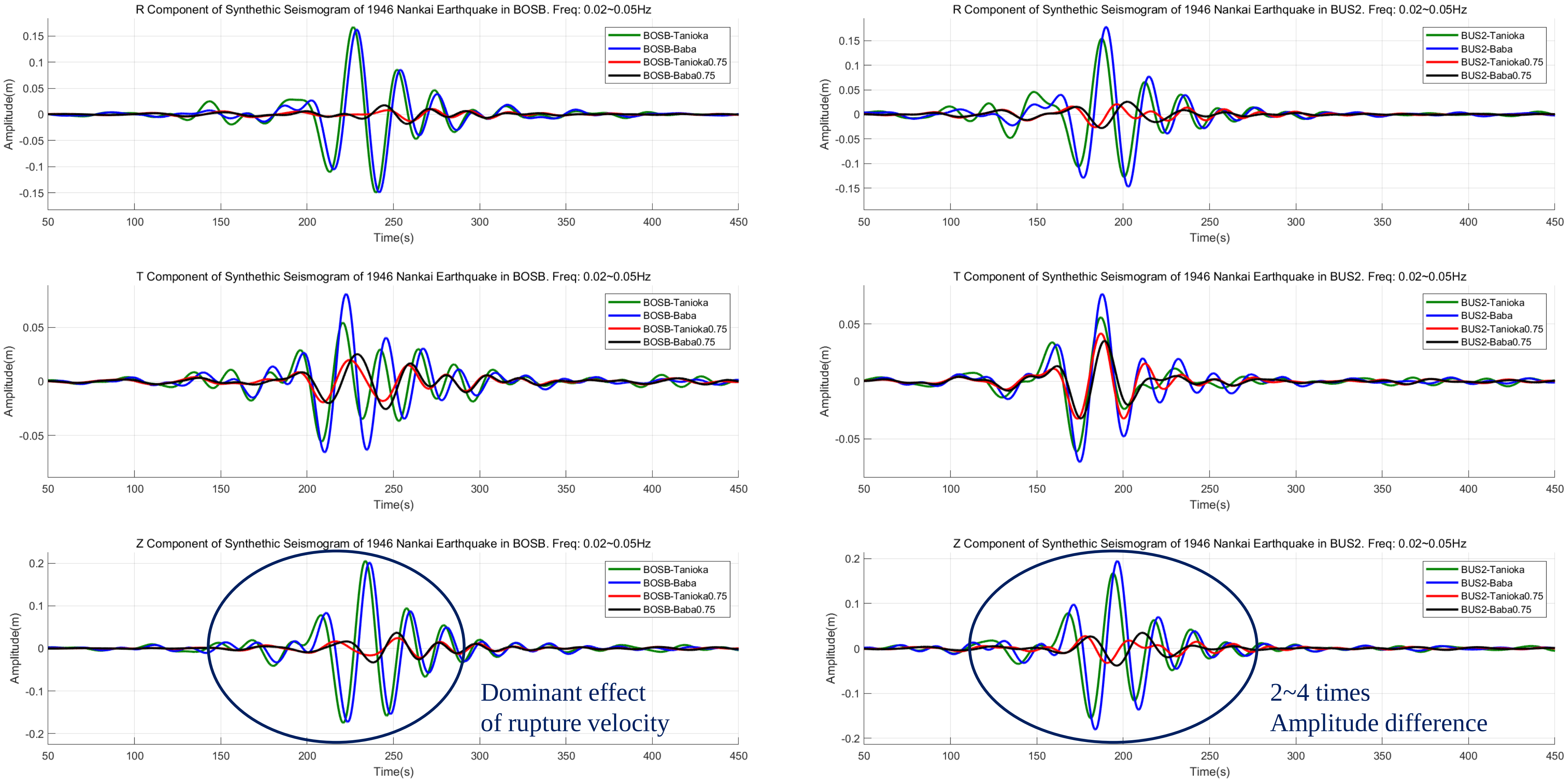


Surface wave dispersion
→ crust effect?

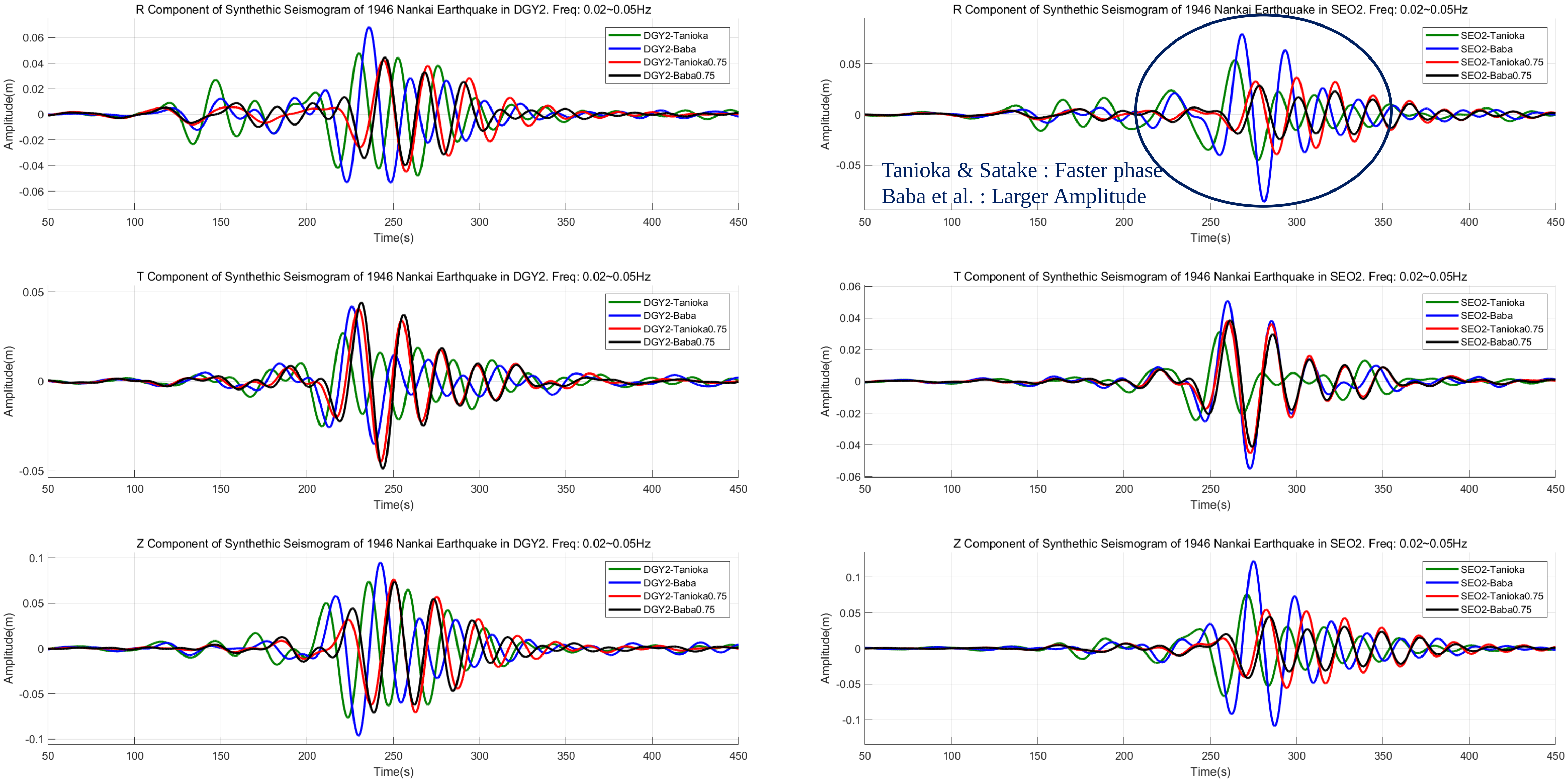
Synthetic Seismogram Of 1946 Nankai Earthquake

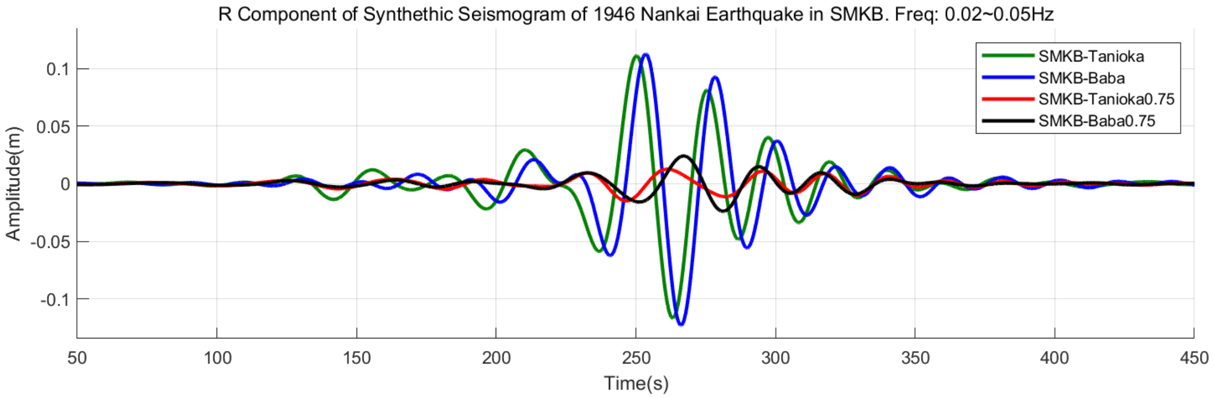
(Freq: 0.02~0.05Hz)

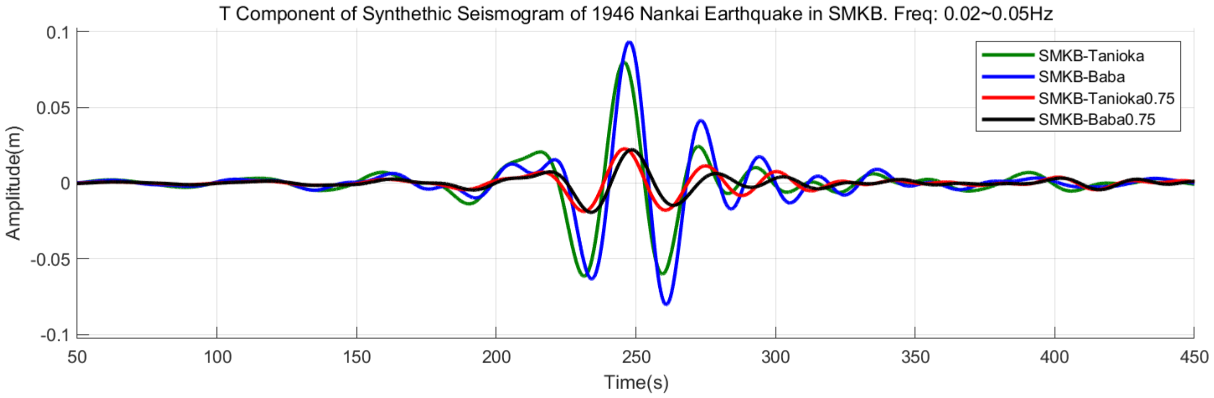


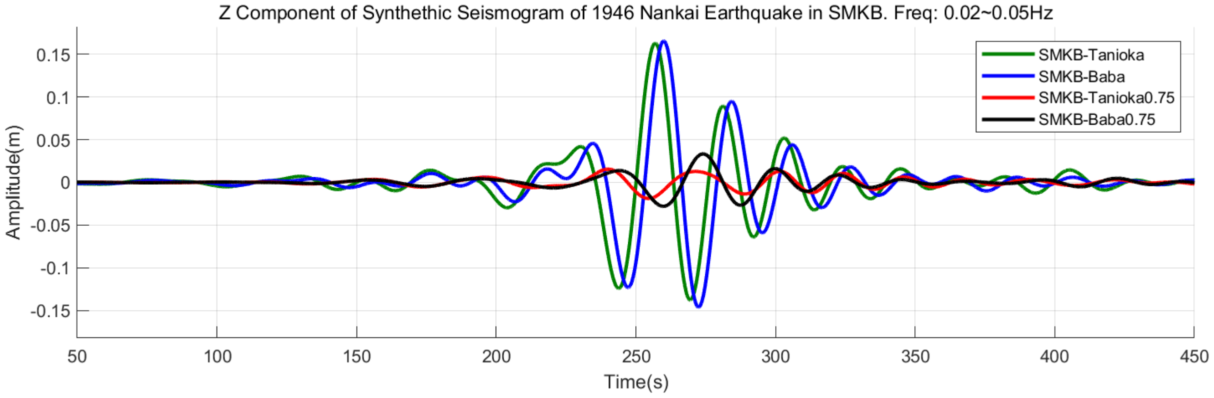


R Component of Synthethic Seismogram of 1946 Nankai Earthquake in BOSB. Freq: 0.02~0.05Hz
BOSB-Tanioka
BOSB-Baba
BOSB-Tanioka0.75
BOSB-Baba0.75
Amplitude(m)
Time(s)
R Component of Synthethic Seismogram of 1946 Nankai Earthquake in BUS2. Freq: 0.02~0.05Hz
BUS2-Tanioka
BUS2-Baba
BUS2-Tanioka0.75
BUS2-Baba0.75
Amplitude(m)
Time(s)
T Component of Synthethic Seismogram of 1946 Nankai Earthquake in BOSB. Freq: 0.02~0.05Hz
BOSB-Tanioka
BOSB-Baba
BOSB-Tanioka0.75
BOSB-Baba0.75
Amplitude(m)
Time(s)
T Component of Synthethic Seismogram of 1946 Nankai Earthquake in BUS2. Freq: 0.02~0.05Hz
BUS2-Tanioka
BUS2-Baba
BUS2-Tanioka0.75
BUS2-Baba0.75
Amplitude(m)
Time(s)
Z Component of Synthethic Seismogram of 1946 Nankai Earthquake in BOSB. Freq: 0.02~0.05Hz
BOSB-Tanioka
BOSB-Baba
BOSB-Tanioka0.75
BOSB-Baba0.75
Amplitude(m)
Time(s)
Dominant effect
of rupture velocity
Z Component of Synthethic Seismogram of 1946 Nankai Earthquake in BUS2. Freq: 0.02~0.05Hz
BUS2-Tanioka
BUS2-Baba
BUS2-Tanioka0.75
BUS2-Baba0.75
Amplitude(m)
Time(s)
2~4 times
Amplitude difference


R Component of Synthethic Seismogram of 1946 Nankai Earthquake in DGY2. Freq: 0.02~0.05Hz
DGY2-Tanioka
DGY2-Baba
DGY2-Tanioka0.75
DGY2-Baba0.75
Amplitude(m)
Time(s)
R Component of Synthethic Seismogram of 1946 Nankai Earthquake in SEO2. Freq: 0.02~0.05Hz
SEO2-Tanioka
SEO2-Baba
SEO2-Tanioka0.75
SEO2-Baba0.75
Tanioka & Satake : Faster phase
Baba et al. : Larger Amplitude
Amplitude(m)
Time(s)
T Component of Synthethic Seismogram of 1946 Nankai Earthquake in DGY2. Freq: 0.02~0.05Hz
DGY2-Tanioka
DGY2-Baba
DGY2-Tanioka0.75
DGY2-Baba0.75
Amplitude(m)
Time(s)
T Component of Synthethic Seismogram of 1946 Nankai Earthquake in SEO2. Freq: 0.02~0.05Hz
SEO2-Tanioka
SEO2-Baba
SEO2-Tanioka0.75
SEO2-Baba0.75
Amplitude(m)
Time(s)
Z Component of Synthethic Seismogram of 1946 Nankai Earthquake in DGY2. Freq: 0.02~0.05Hz
DGY2-Tanioka
DGY2-Baba
DGY2-Tanioka0.75
DGY2-Baba0.75
Amplitude(m)
Time(s)
Z Component of Synthethic Seismogram of 1946 Nankai Earthquake in SEO2. Freq: 0.02~0.05Hz
SEO2-Tanioka
SEO2-Baba
SEO2-Tanioka0.75
SEO2-Baba0.75
Amplitude(m)
Time(s)

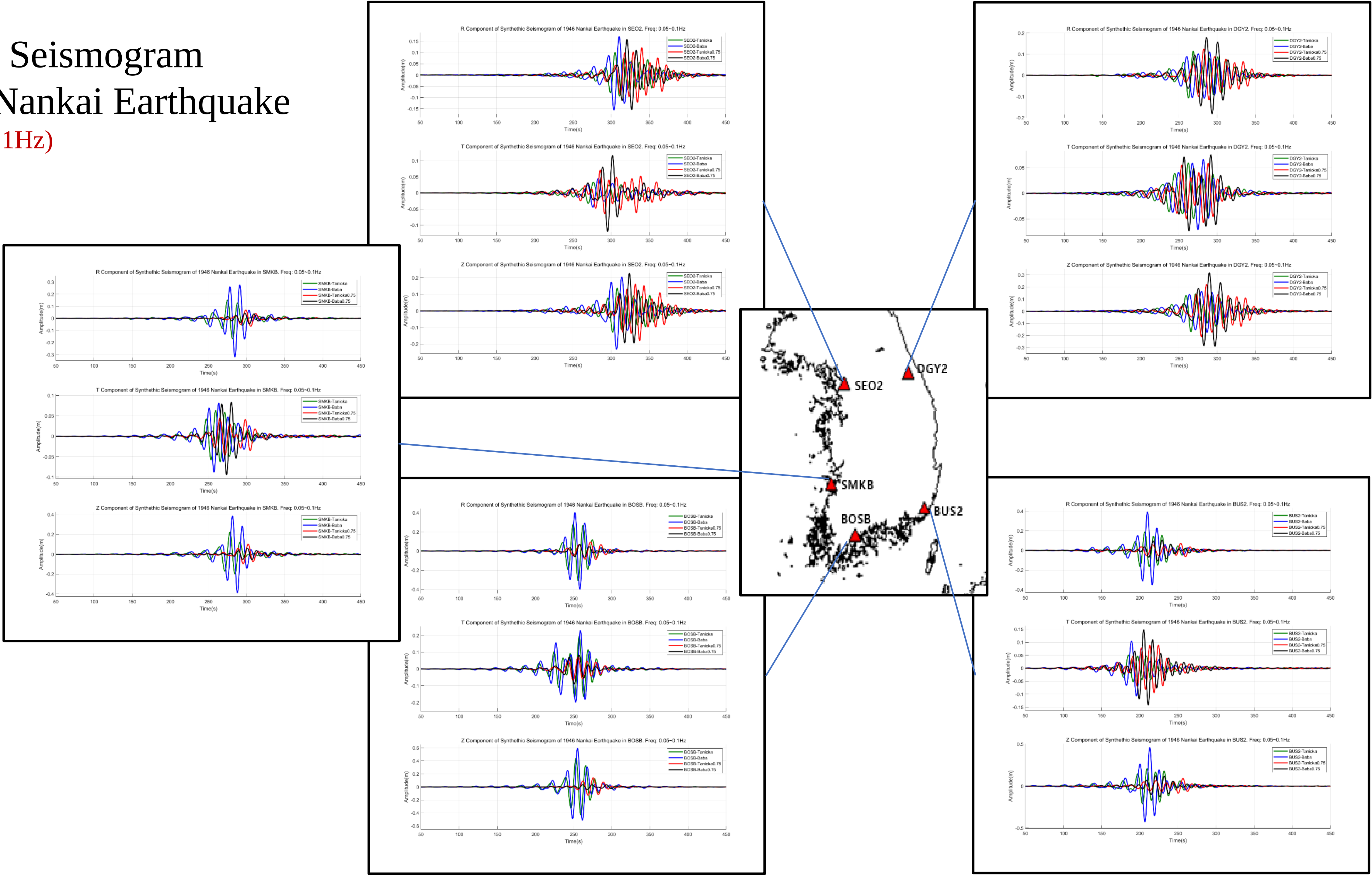

R Component of Synthethic Seismogram of 1946 Nankai Earthquake in SMKB. Freq: 0.02~0.05Hz
SMKB-Tanioka
SMKB-Baba
SMKB-Tanioka0.75
SMKB-Baba0.75
Amplitude(m)
Time(s)


T Component of Synthethic Seismogram of 1946 Nankai Earthquake in SMKB. Freq: 0.02~0.05Hz
SMKB-Tanioka
SMKB-Baba
SMKB-Tanioka0.75
SMKB-Baba0.75
Amplitude(m)
Time(s)

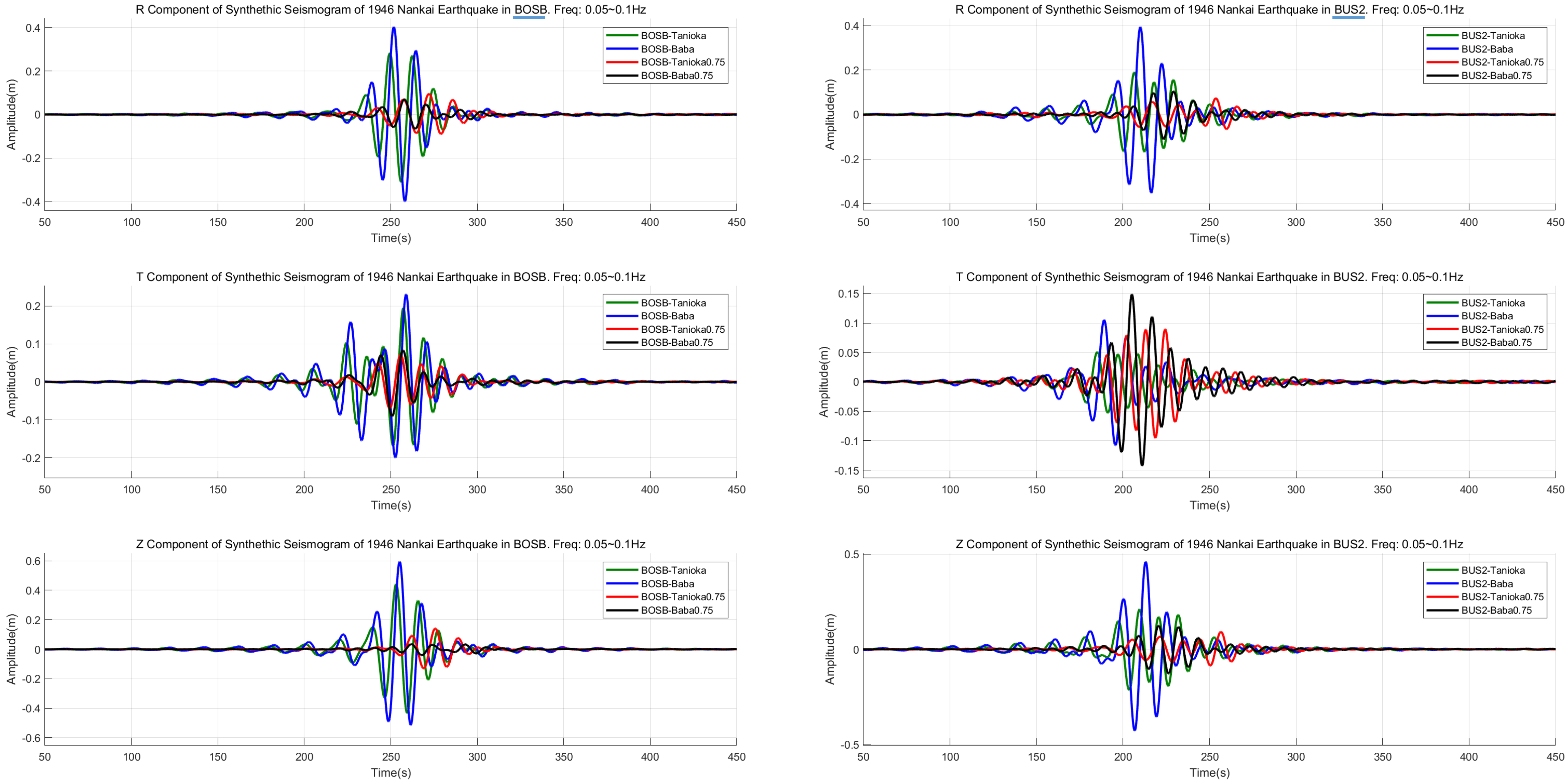

Z Component of Synthethic Seismogram of 1946 Nankai Earthquake in SMKB. Freq: 0.02~0.05Hz
SMKB-Tanioka
SMKB-Baba
SMKB-Tanioka0.75
SMKB-Baba0.75
Amplitude(m)
Time(s)

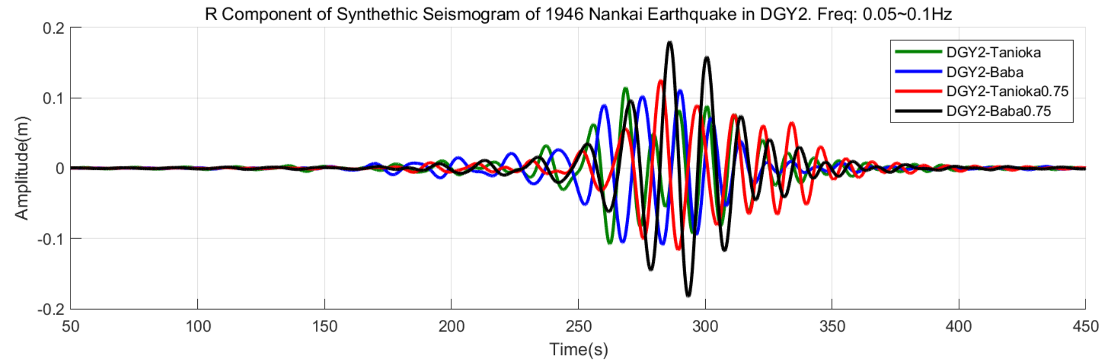
Synthetic Seismogram Of 1946 Nankai Earthquake

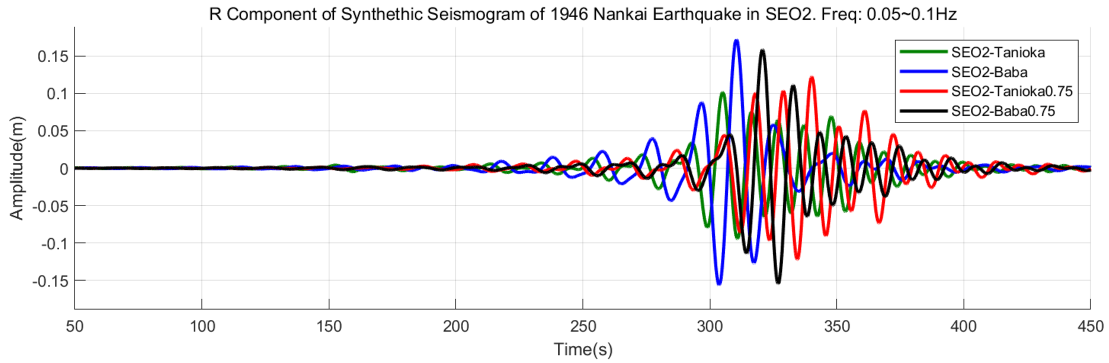
(Freq: 0.05~0.1Hz)

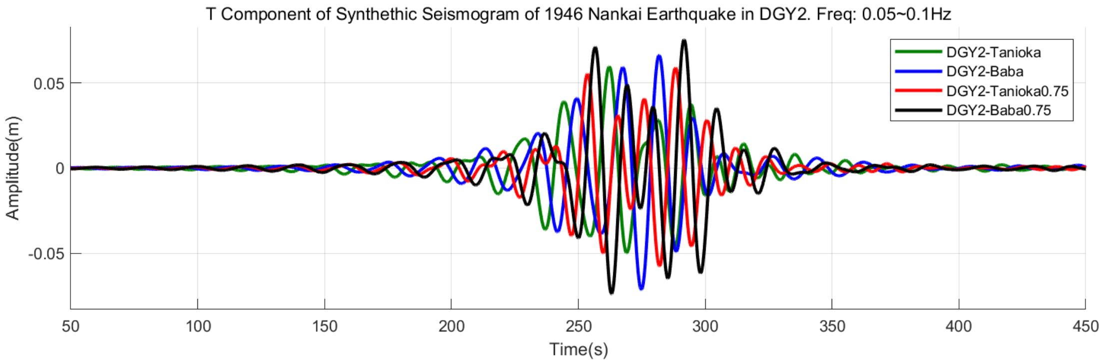


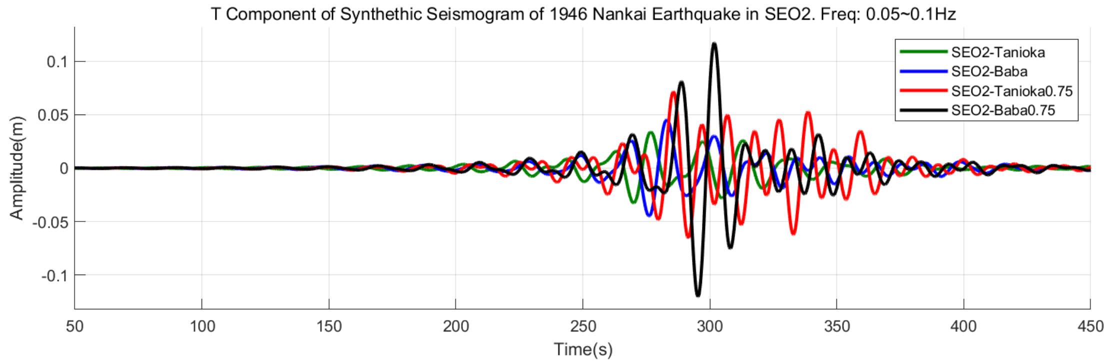
Stations closer to event fit better

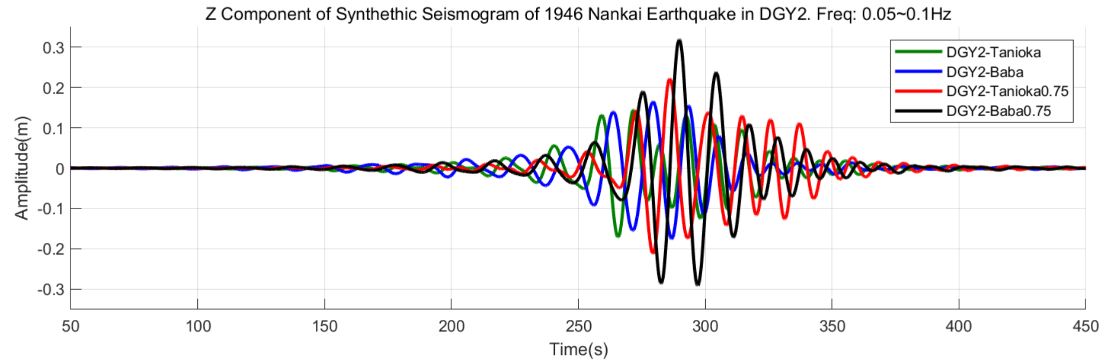


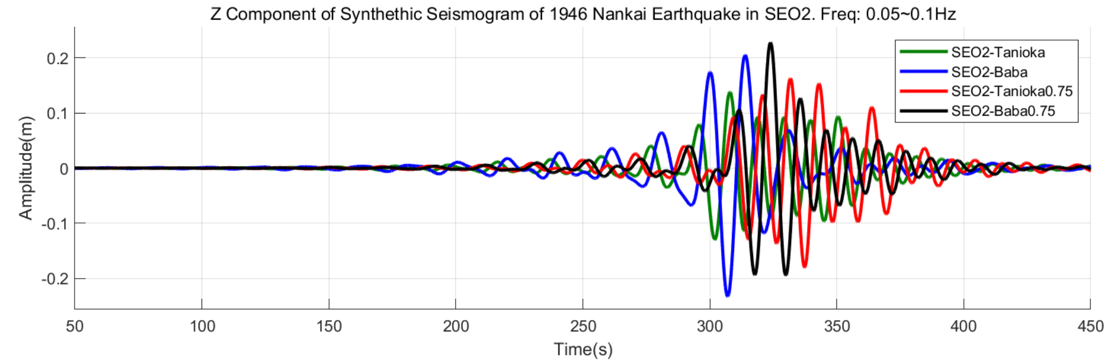

R Component of Synthethic Seismogram of 1946 Nankai Earthquake in DGY2. Freq: 0.05~0.1Hz
DGY2-Tanioka
DGY2-Baba
DGY2-Tanioka0.75
DGY2-Baba0.75
Amplitude(m)
Time(s)

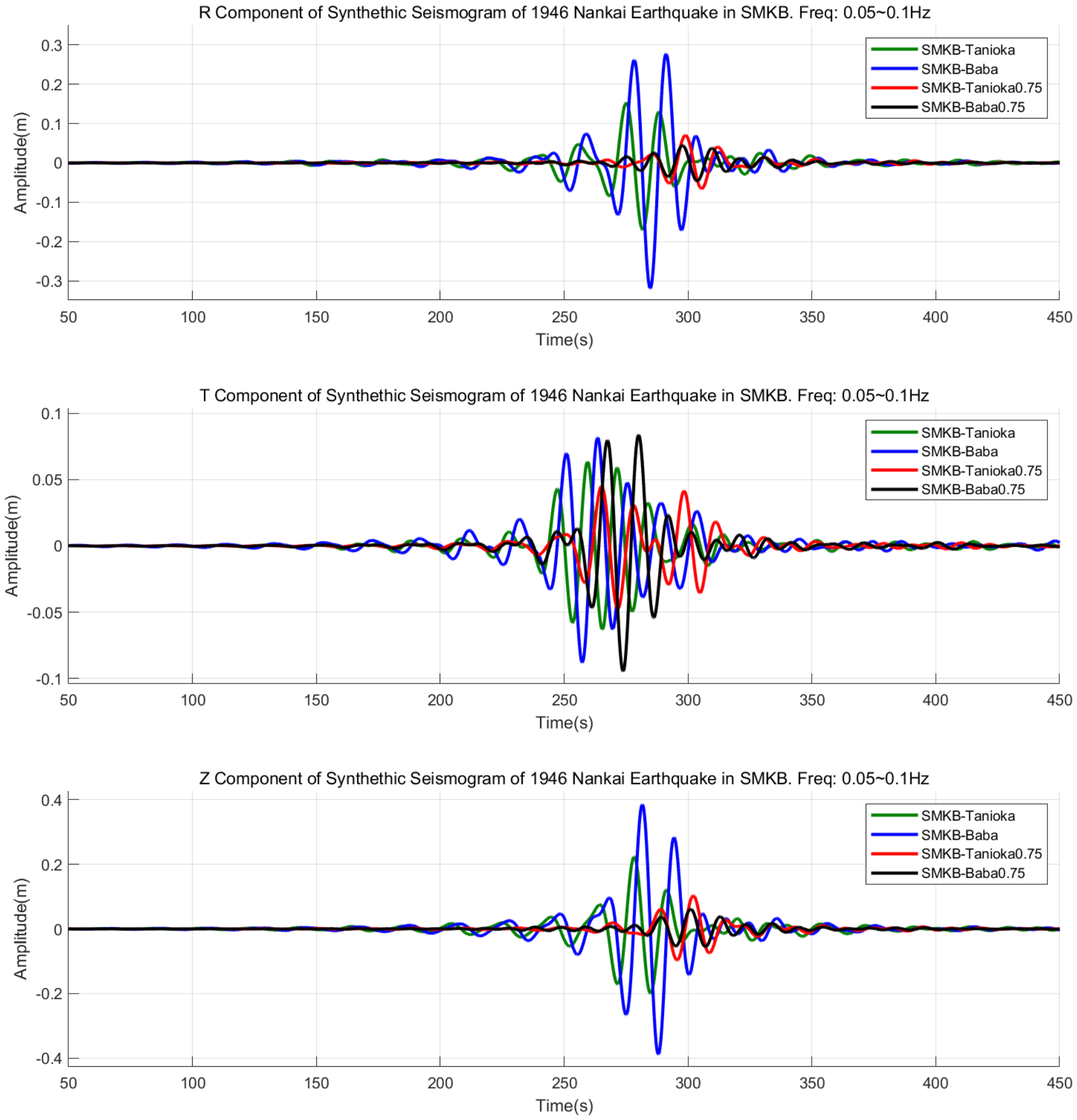

R Component of Synthethic Seismogram of 1946 Nankai Earthquake in SEO2. Freq: 0.05~0.1Hz
SEO2-Tanioka
SEO2-Baba
SEO2-Tanioka0.75
SEO2-Baba0.75
Amplitude(m)
Time(s)


T Component of Synthethic Seismogram of 1946 Nankai Earthquake in DGY2. Freq: 0.05~0.1Hz
DGY2-Tanioka
DGY2-Baba
DGY2-Tanioka0.75
DGY2-Baba0.75
Amplitude(m)
Time(s)


T Component of Synthethic Seismogram of 1946 Nankai Earthquake in SEO2. Freq: 0.05~0.1Hz
SEO2-Tanioka
SEO2-Baba
SEO2-Tanioka0.75
SEO2-Baba0.75
Amplitude(m)
Time(s)


Z Component of Synthethic Seismogram of 1946 Nankai Earthquake in DGY2. Freq: 0.05~0.1Hz
DGY2-Tanioka
DGY2-Baba
DGY2-Tanioka0.75
DGY2-Baba0.75
Amplitude(m)
Time(s)


Z Component of Synthethic Seismogram of 1946 Nankai Earthquake in SEO2. Freq: 0.05~0.1Hz
SEO2-Tanioka
SEO2-Baba
SEO2-Tanioka0.75
SEO2-Baba0.75
Amplitude(m)
Time(s)


R Component of Synthethic Seismogram of 1946 Nankai Earthquake in SMKB. Freq: 0.05~0.1Hz
SMKB-Tanioka
SMKB-Baba
SMKB-Tanioka0.75
SMKB-Baba0.75
Amplitude(m)
Time(s)
T Component of Synthethic Seismogram of 1946 Nankai Earthquake in SMKB. Freq: 0.05~0.1Hz
SMKB-Tanioka
SMKB-Baba
SMKB-Tanioka0.75
SMKB-Baba0.75
Amplitude(m)
Time(s)
Z Component of Synthethic Seismogram of 1946 Nankai Earthquake in SMKB. Freq: 0.05~0.1Hz
SMKB-Tanioka
SMKB-Baba
SMKB-Tanioka0.75
SMKB-Baba0.75
Amplitude(m)
Time(s)

Conclusion

- 2016 Nanaki Earthquake: East Asia Model | 1D-PREM | Observation Data Comparison
  - East Asia model:
    - 0.02Hz~0.05Hz Body Wave & Love Wave: fit well
    - High Frequency & Rayleigh Wave: not fit so well
  - 1D-PREM:
    - High Frequency Surface Wave: fit well
    - Arrive faster than EA

- 1946 Nankai Earthquake: Different Finite Fault Model & Different Rupture Velocity Comparison
  - Kinematic parameters are important

- Future Research:
  - Limitation of kinematic parameters

  -pseudo-dynamic source model based on statistical analysis on kinematic source parameters of dynamic rupture models
  - Quantitative analysis of synthetic seismograms

(Seok Goo Song, 2016)

Table 1. A set of model parameters for pseudo-dynamic source modelling.

	Model parameter	Description
1-Point Statistics	μ_{slip}	Mean slip
	μ_{V_r}	Mean rupture velocity
	$\mu_{V_{max}}$	Mean peak slip velocity
	σ_{slip}	Standard deviation of slip
	σ_{V_r}	Standard deviation of rupture velocity
	$\sigma_{V_{max}}$	Standard deviation of peak slip velocity
2-Point Statistics	a_x	Correlation length in the along-strike direction (six parameters: slip versus slip, slip versus V_r, slip versus V_{max}, V_r versus V_r, V_r versus V_{max} and V_{max} versus V_{max})
	a_z	Correlation length in the along-dip direction (six parameters: slip versus slip, slip versus V_r, slip versus V_{max}, V_r versus V_r, V_r versus V_{max} and V_{max} versus V_{max})
	ρ_{max}	Maximum correlation coefficient (three parameters: slip versus V_r, slip versus V_{max} and V_r versus V_{max})
	RD_x	Response distance in the along-strike direction (three parameters: *slip* versus V_r, *slip* versus V_{max} and V_r versus V_{max})
	rD_z	Response distance in the along-dip direction (three parameters: slip versus V_r, slip versus V_{max} and V_r versus V_{max})

For autocorrelation, ρ_{max} is one and rD_x and rD_z are zero by definition. rD_x and rD_z are excluded in this study. Thus, 21 model parameters are considered in total (6 for 1-point statistics and 15 for 2-point statistics).

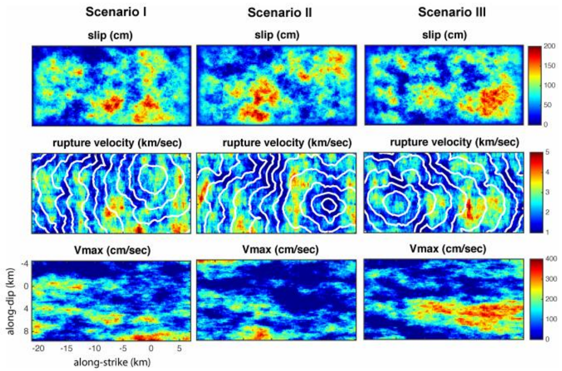


Figure 6. Source modelling examples. The first set of sampled values in Table 4 is used as input source statistics.

감사합니다.