

MIDAS SQUARE 공학 기술강연

# 지역고유 지진지반운동 합리적 평가 활용

Reliable Estimation and Applications of Region-Specific Earthquake Ground Motions

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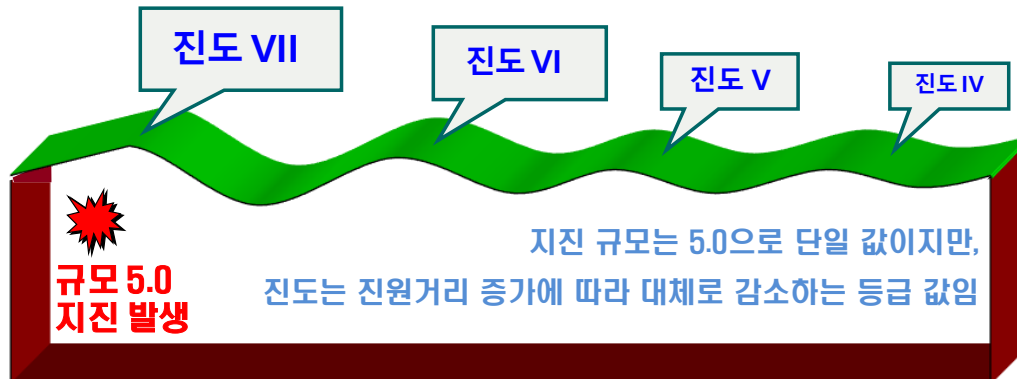
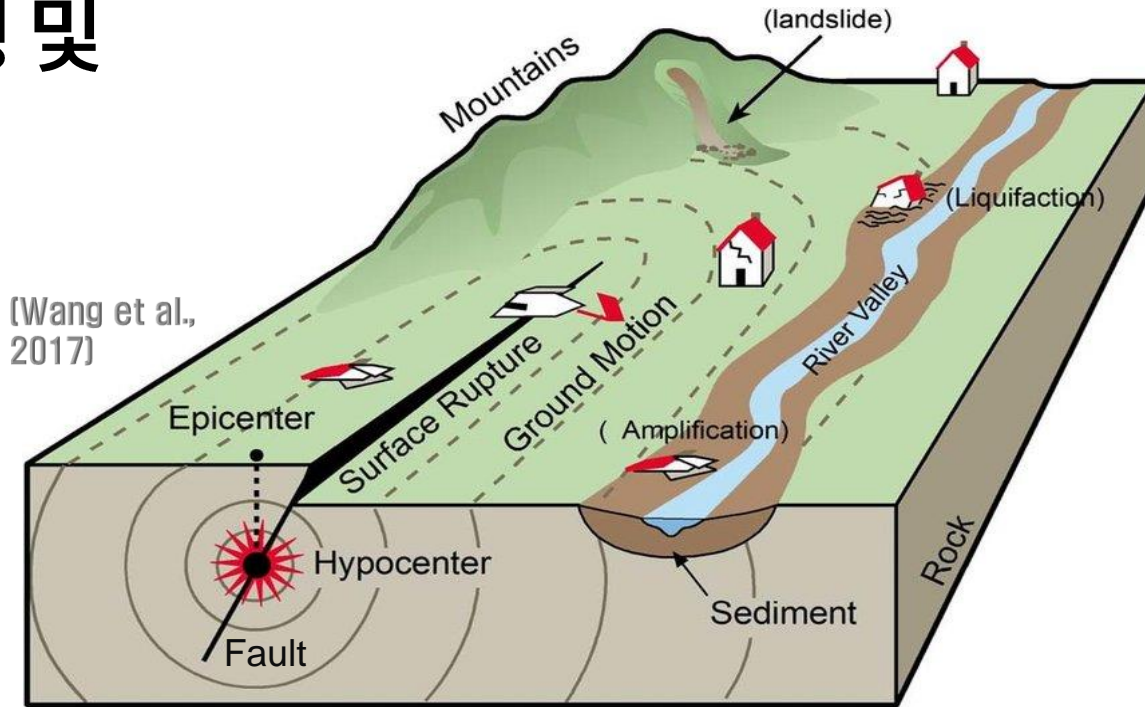
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04 지역 지진지반운동 평가 및 활용

# 한반도 지역 지진발생 환경

# 지진 발생 및 지반운동 체감



## 다양한 진도 등급

MMI

I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
---	----	-----	----	---	----	-----	------	----	---	----	-----

RF

I	II	III	IV	V	VI	VII	VIII	IX	X
---	----	-----	----	---	----	-----	------	----	---

JMA

I	II	III	IV	V	VI	VII
---	----	-----	----	---	----	-----

MSK

I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
---	----	-----	----	---	----	-----	------	----	---	----	-----

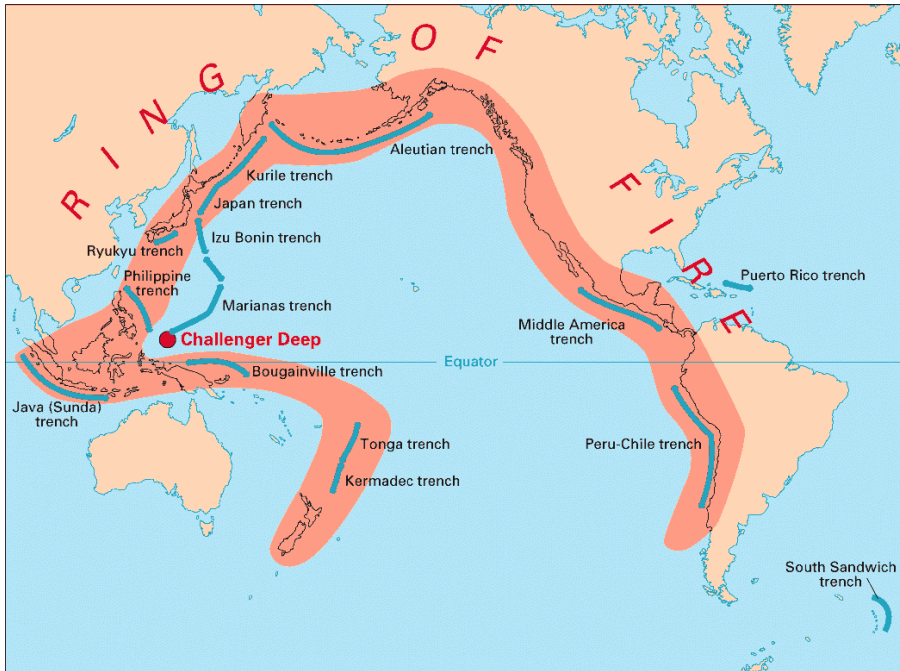
MMI : Modified Mercalli Intensity Scale

RF : Rossi-Forel Intensity Scale

JMA : Japanese Meteorological Agency Scale

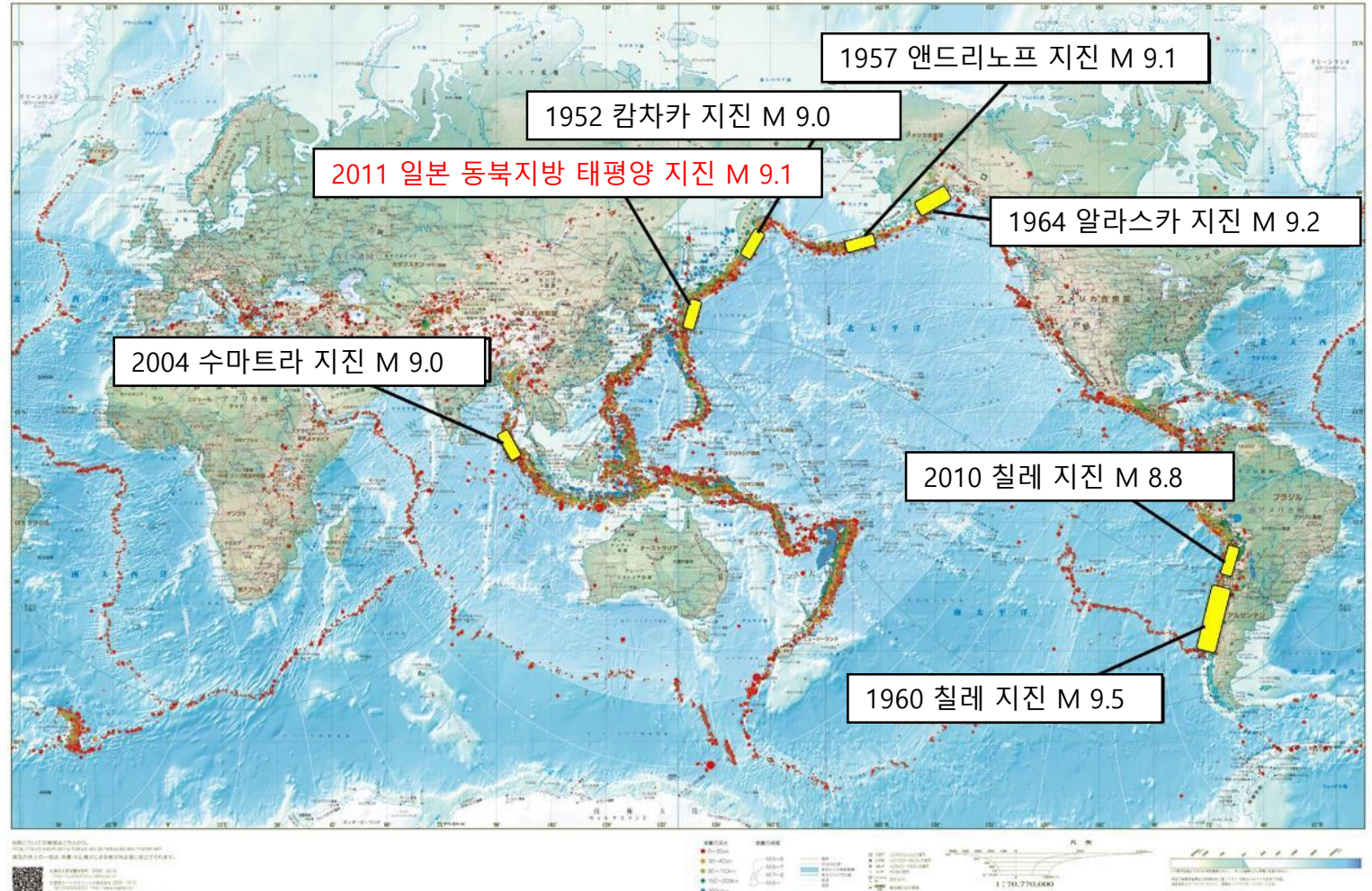
MSK : Medvedev-Spoonheuer-Karnik Scale

# 전세계 주요 계기지진 분포



## 대륙 판 간의 충돌에 따른 응력 축적 및 대규모 지진 발생

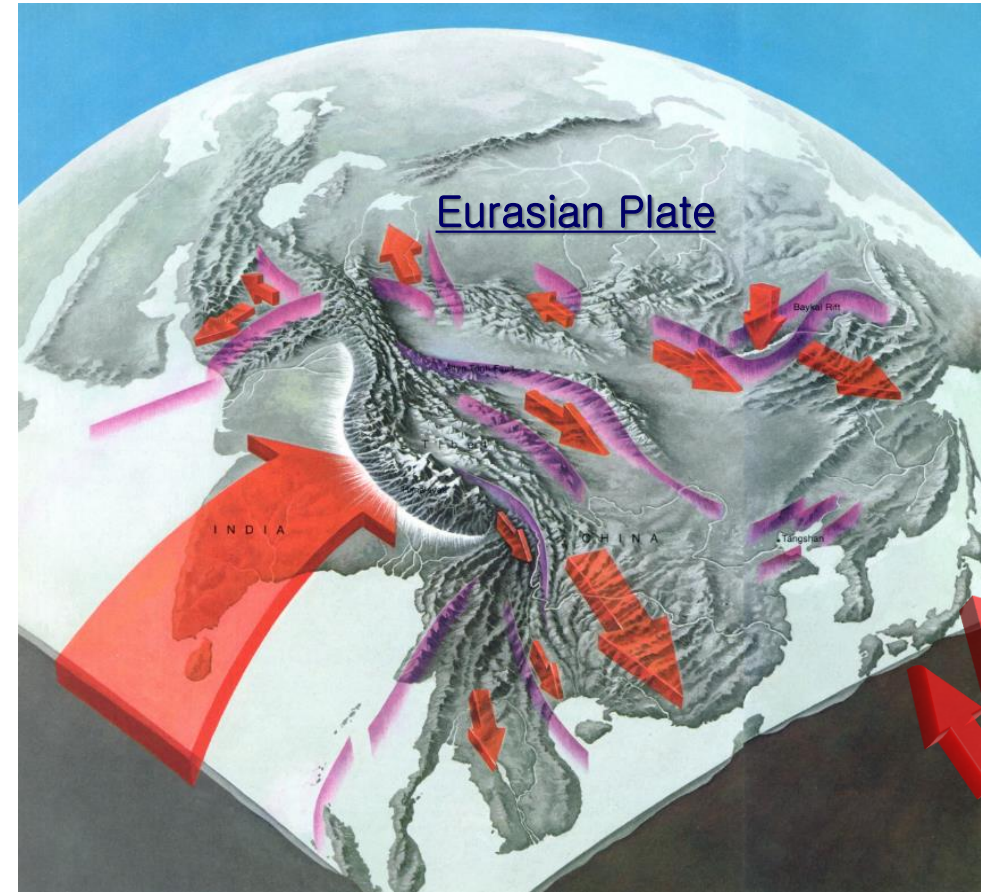
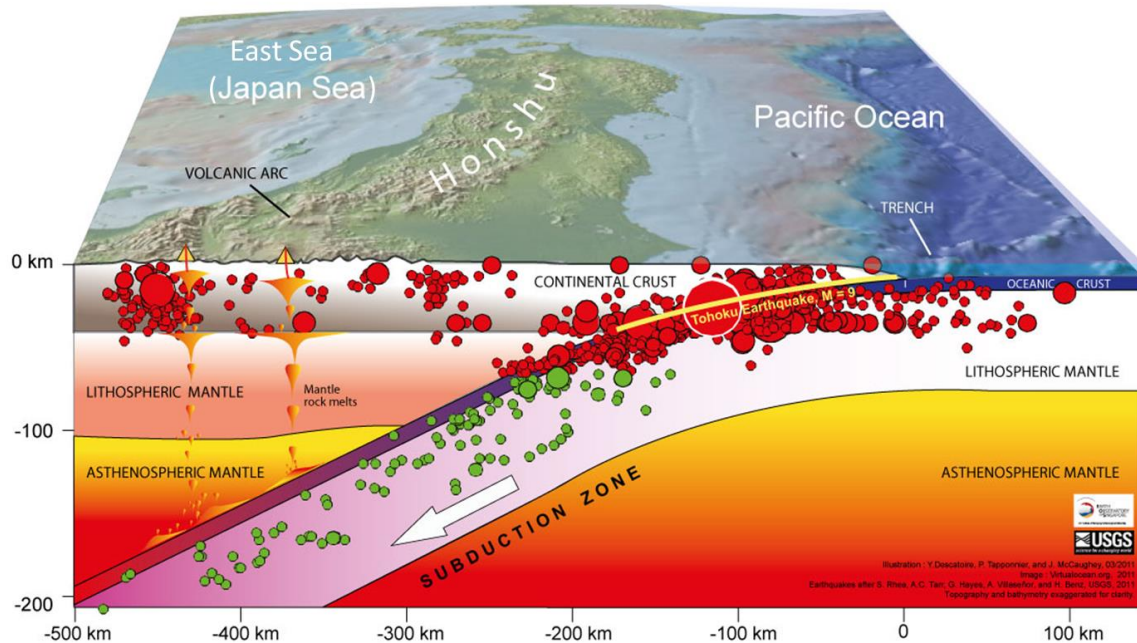
(Distributed by Earthquake Research Institute, the University of Tokyo, 2015)



# 유라시아판 응력 전달 및 동일본 대지진 발생

2011년 일본 도호쿠(동일본) 대지진(M 9.0) 발생

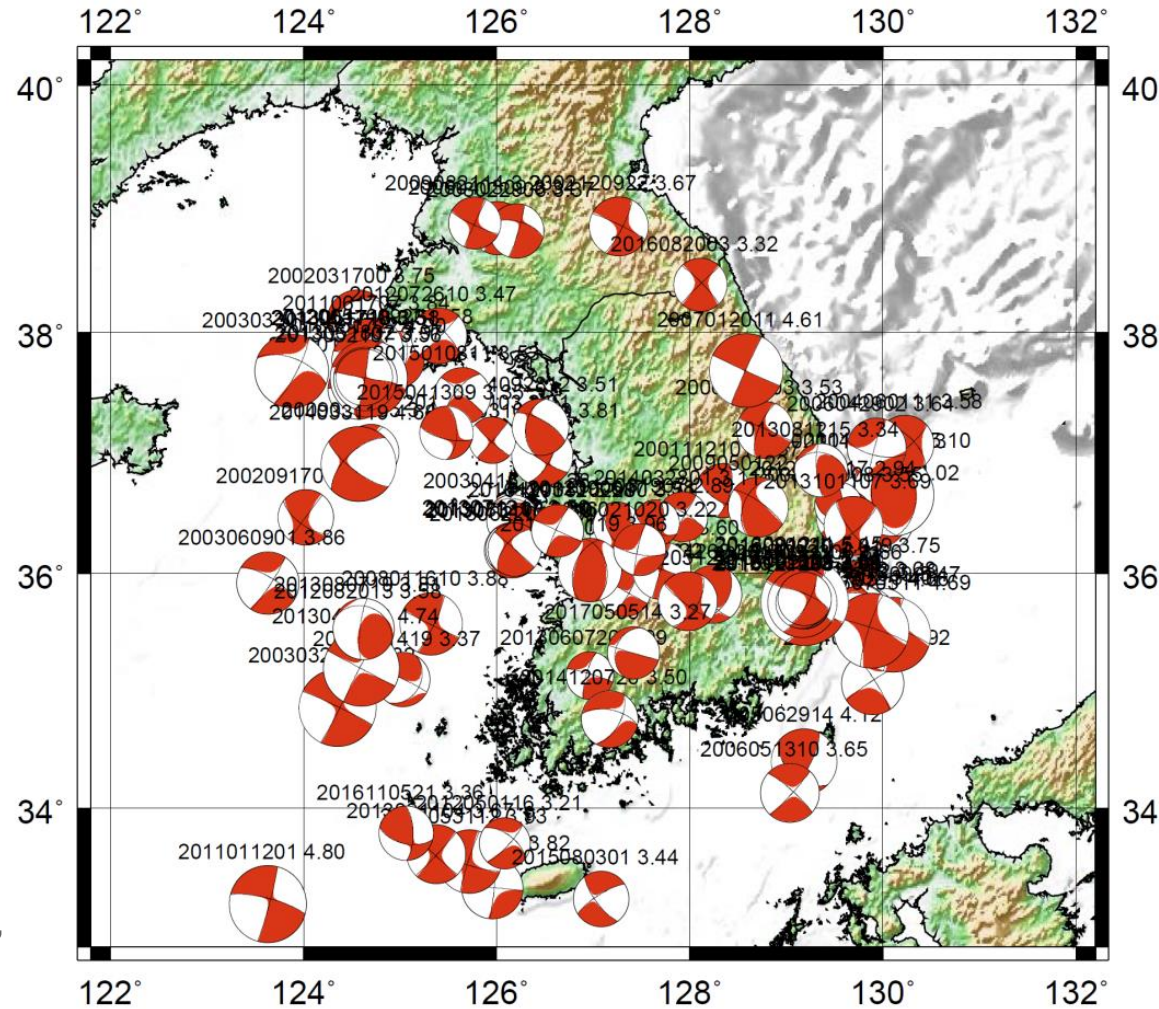
JAPAN



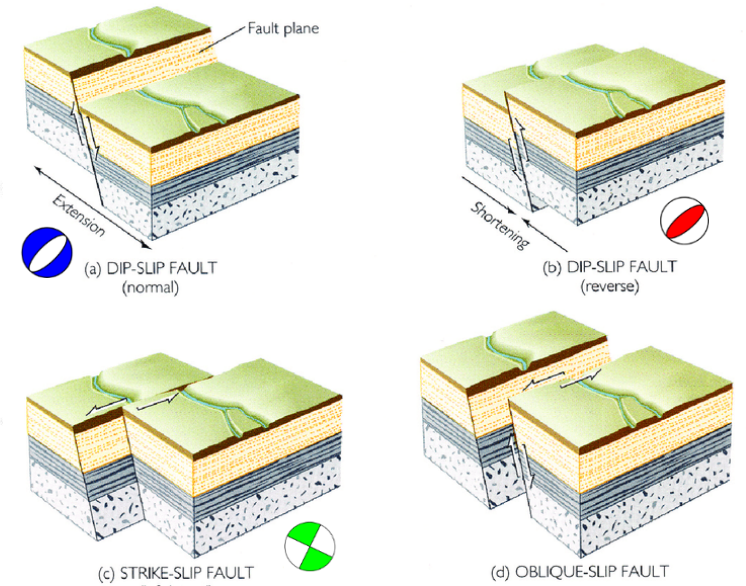
(Ballard, 1983)

In a collision that began at least 40 million years ago, India has rammed 2,000 km into Eurasia and piled up the Himalayas and the lofty Tibetan Plateau. Pinned against Siberia, parts of China and central Asia are squeezed aside. Arrows on edge show motion along (lavender strips) like the Altyn Tagh; those lying flat show motion of crustal blocks. As the blocks carom and jostle, one pair far from the impact zone are knocked apart, opening up a rift (plunging arrow) that cradles Siberia's mile-deep Lake Baykal, the world's deepest lake.

# 한반도 주요 관측지진 진앙 및 단층면해

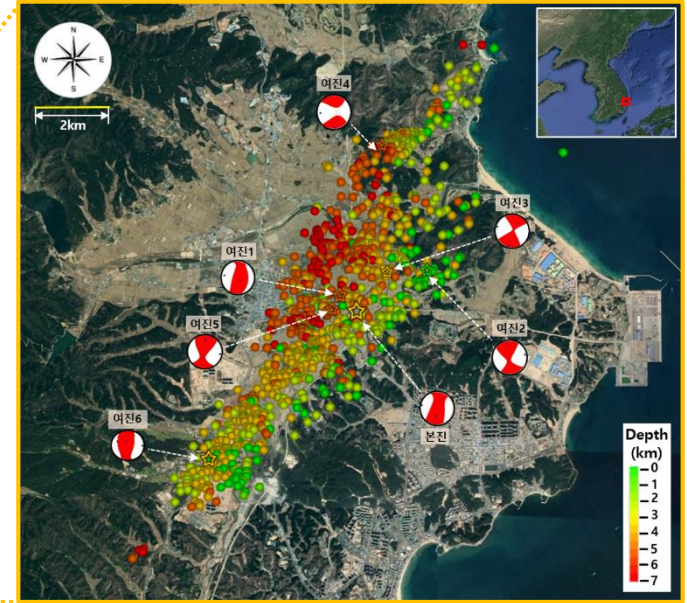
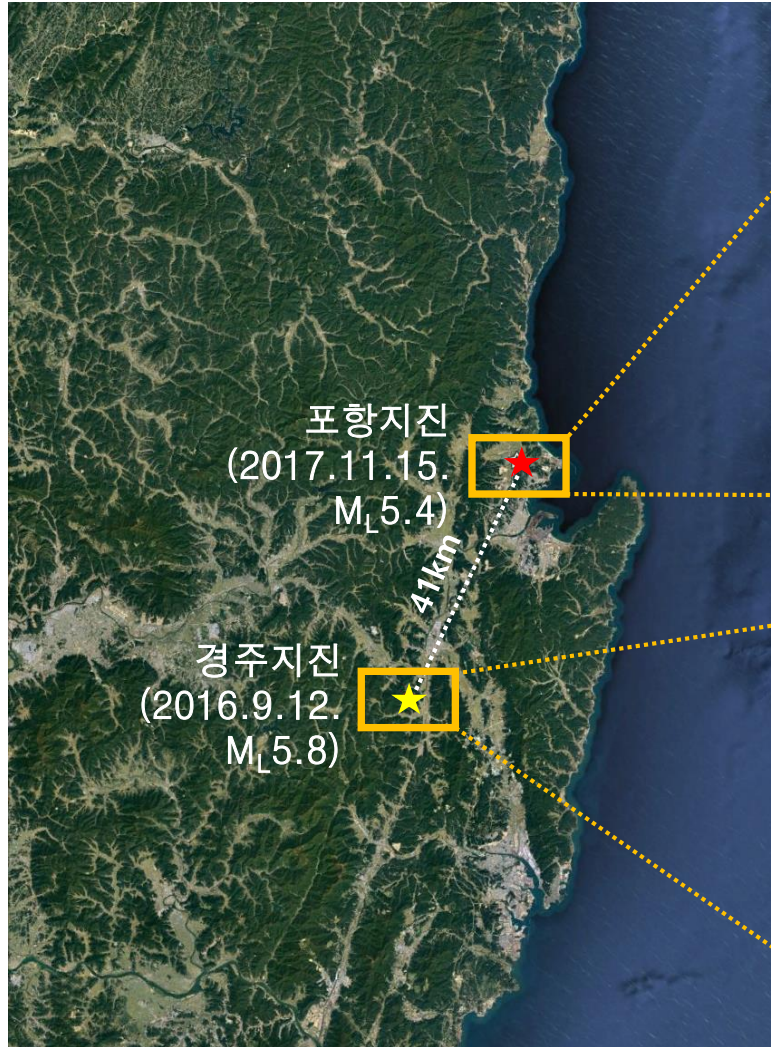


[한국지질자원연구원,  
2018]

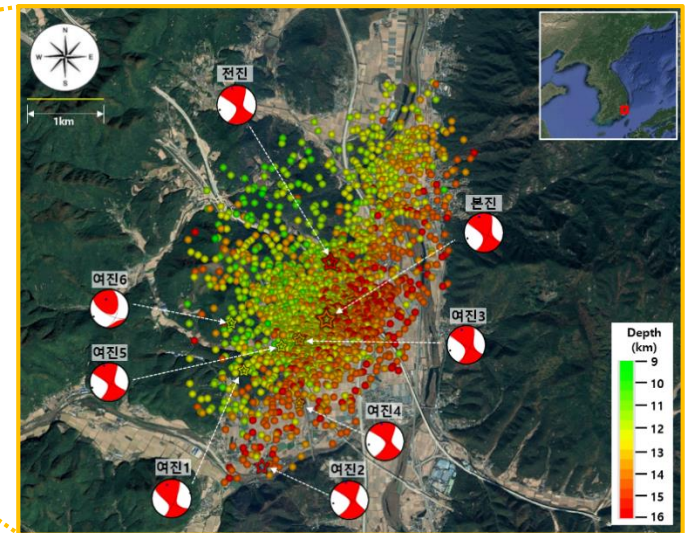


[Press & Siever, 2000]

# 한반도 동남권 주요 지진 발생 (2016년 경주, 2017년 포항)

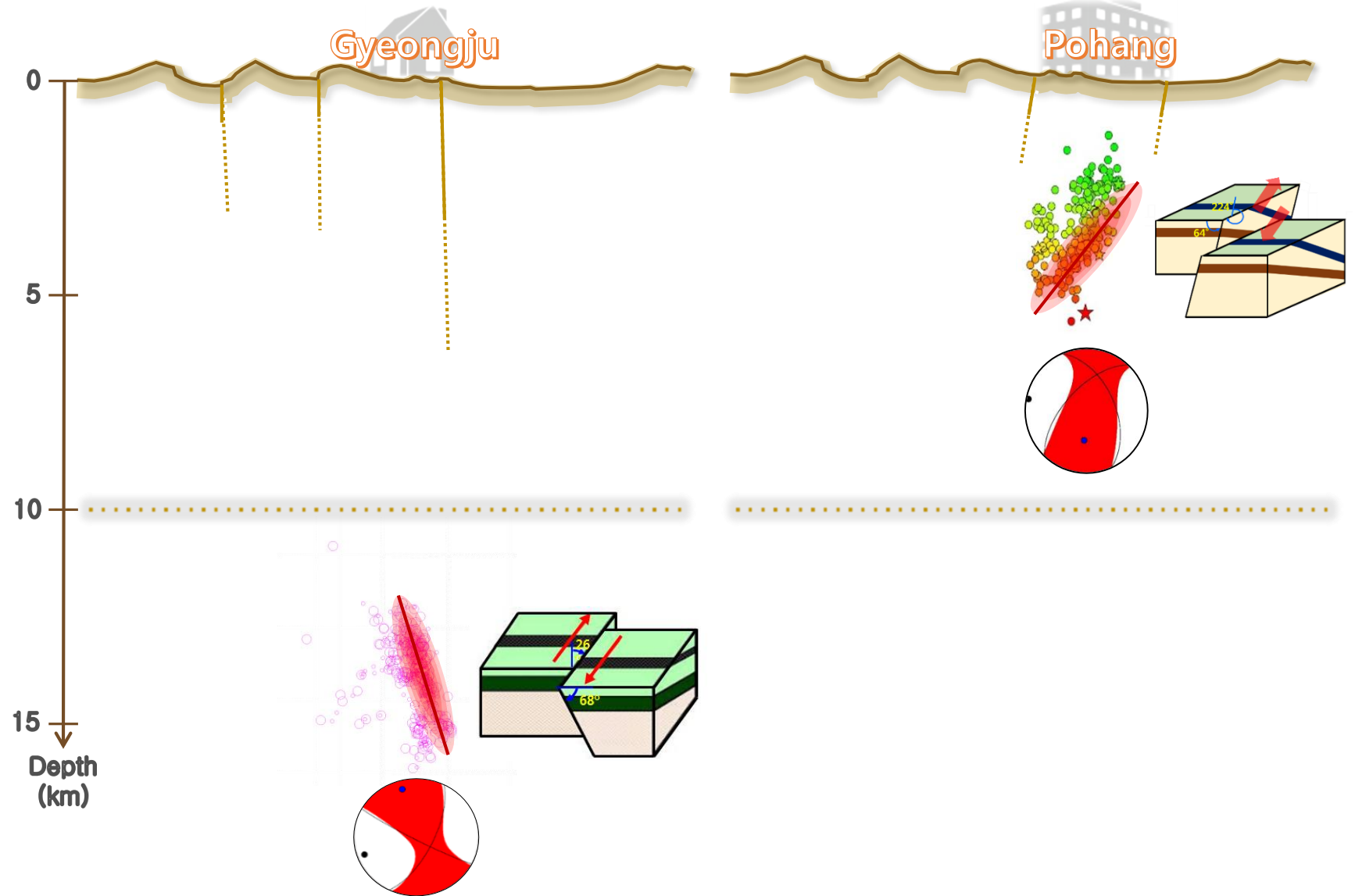


[한국지질자원연구원, 2018]



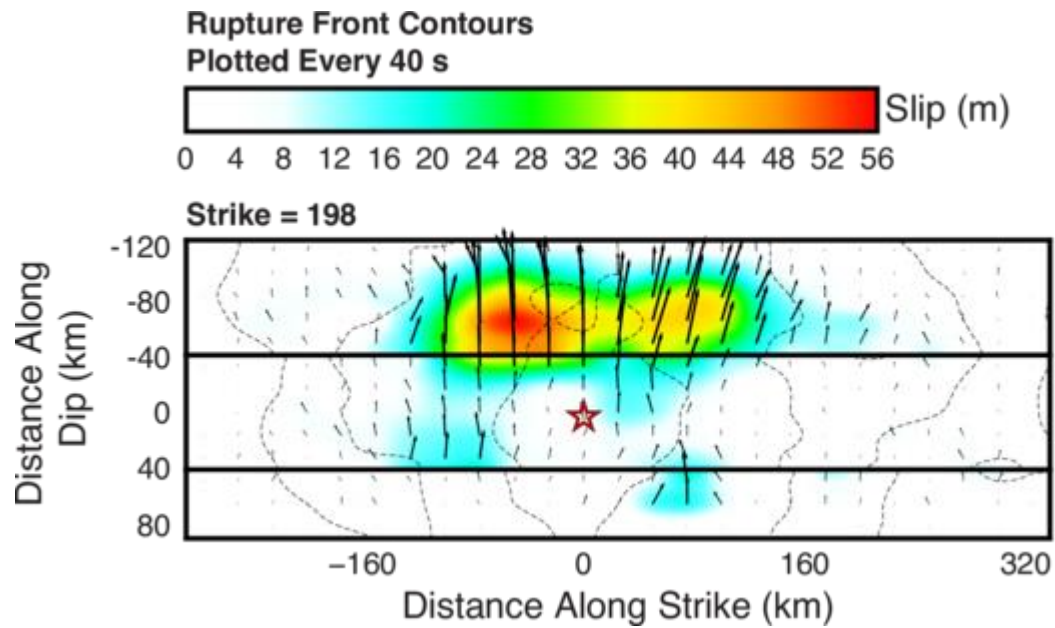


# 경주지진 ( $M_L$ 5.8)과 포항지진 ( $M_L$ 5.4) 본진 지진원 특성 비교



# 2011년 일본 도호쿠 대지진 (M 9.1) 단층 파열 분포

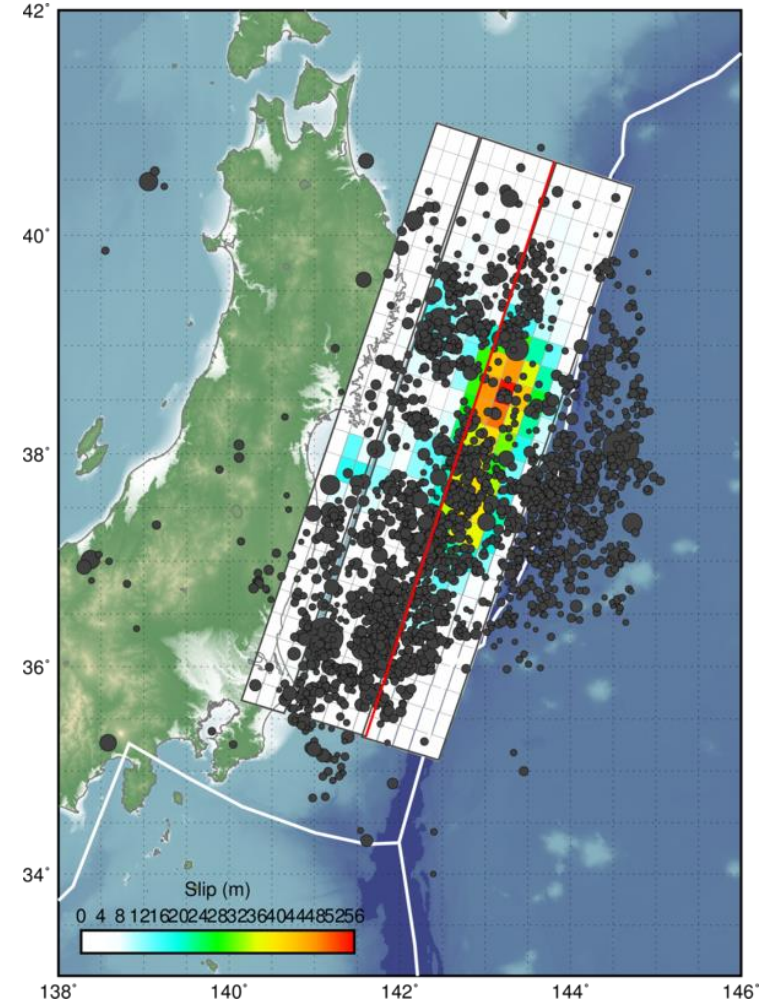
## Cross-section of Slip Distribution



Depth Relative to  
Hypocenter (24.4 km)

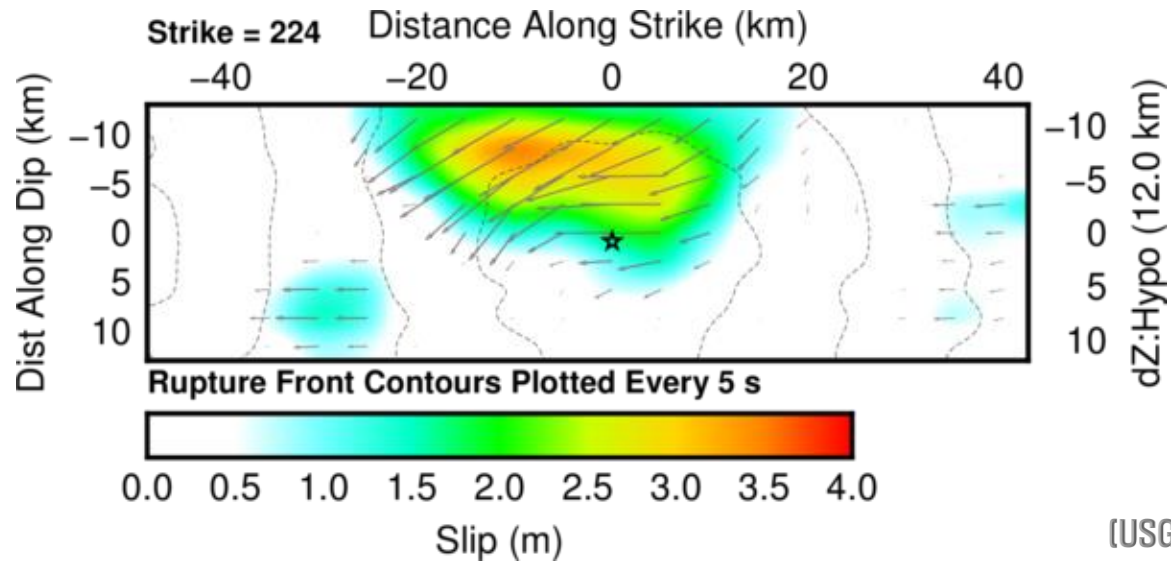
[USGS, 2018a]

## Surface Projection

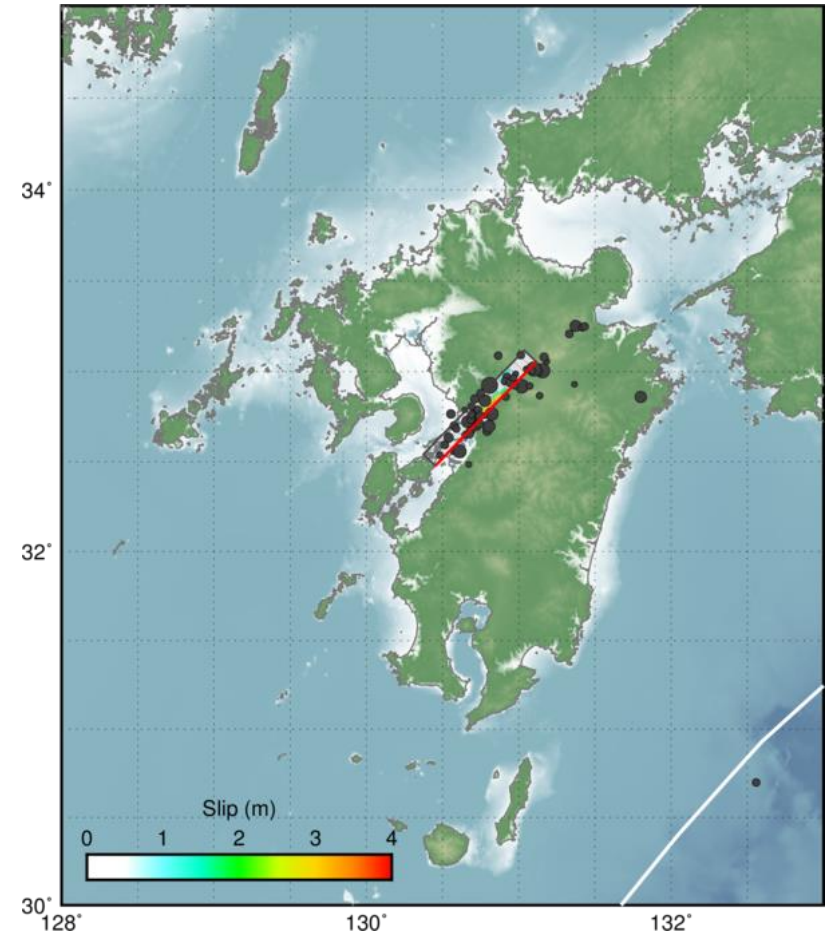


# 2016년 일본 구마모토 지진 (M 7.0) 단층 파열 분포

## Cross-section of Slip Distribution

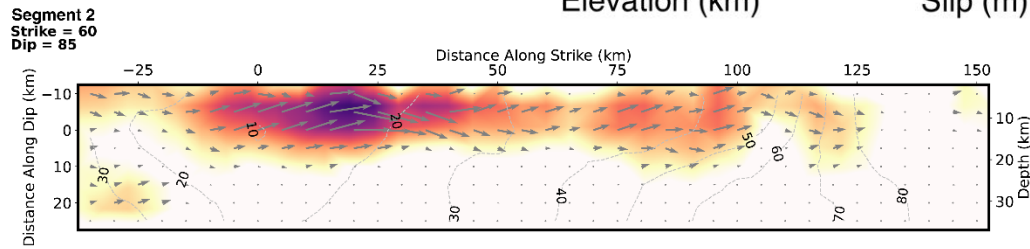
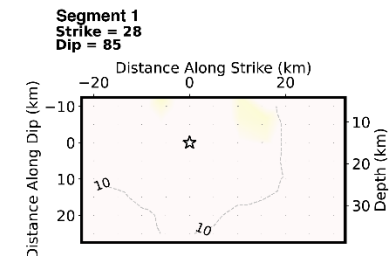
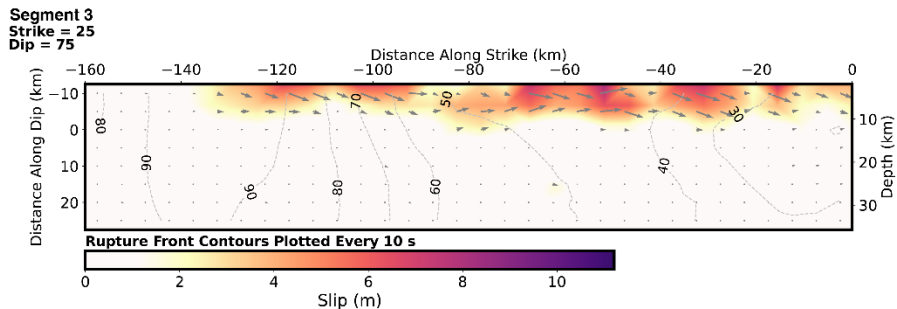


## Surface Projection

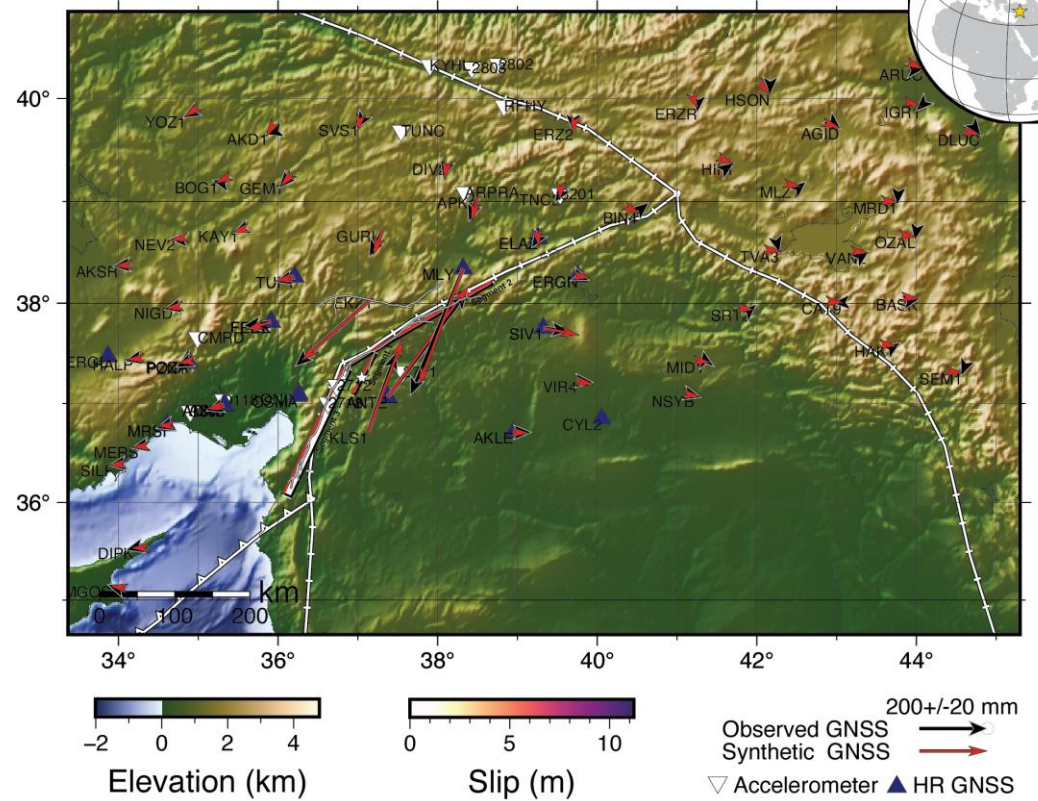


# 2023년 2월 튀르키예-시리아 지진(M 7.8) 단층 파열 분포

## Cross-section of Slip Distribution



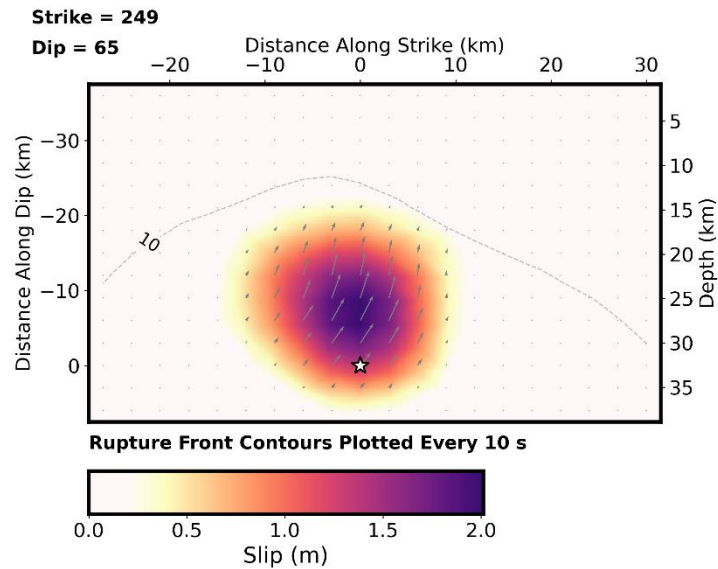
## Surface Projection



(USGS, 2023)

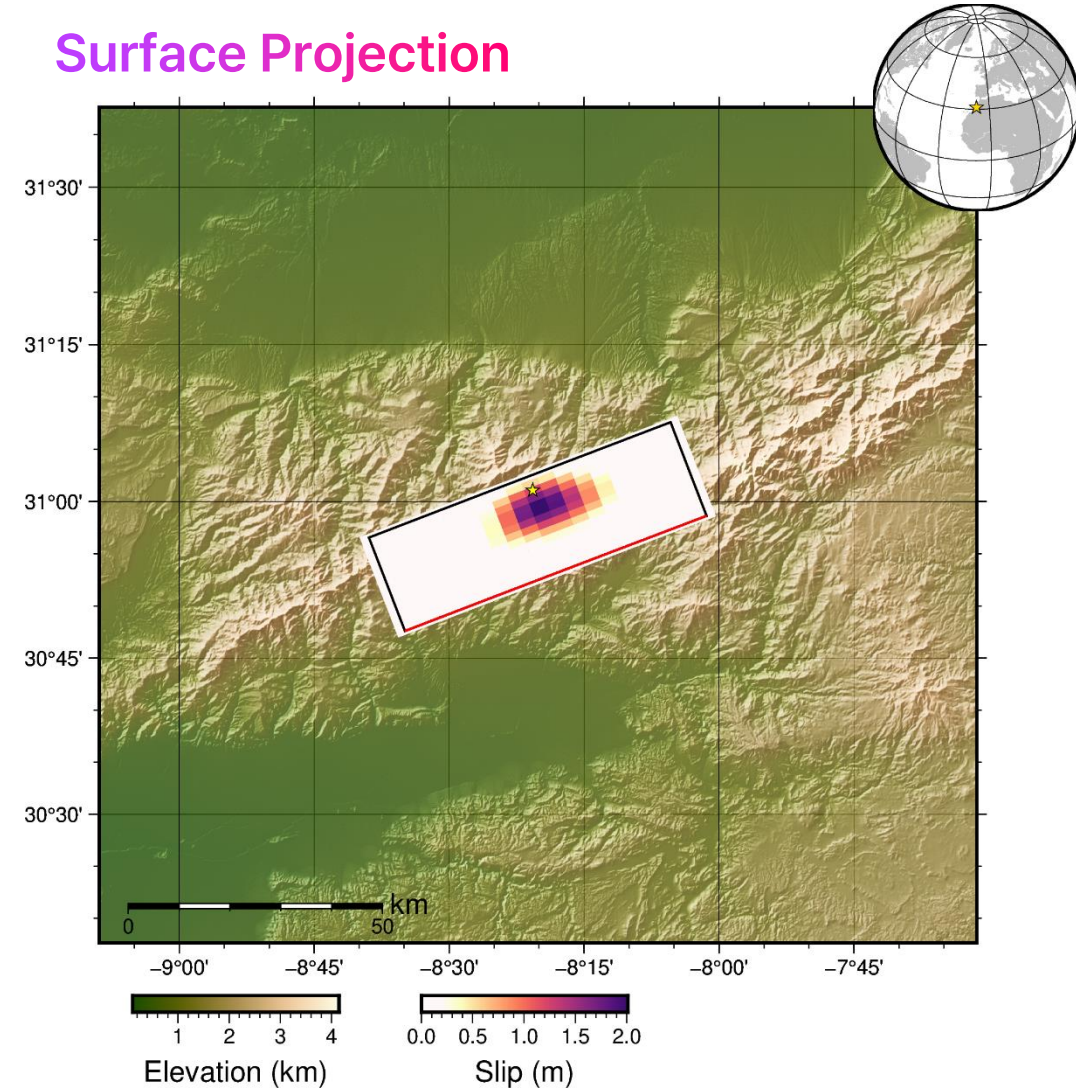
# 2023년 9월 모로코 지진 (M 6.8) 단층 파열 분포

## Cross-section of Slip Distribution



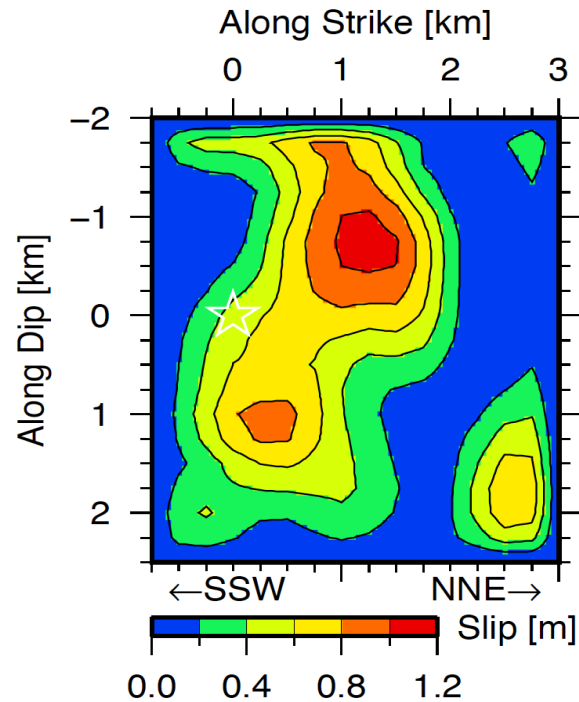
(USGS, 2023)

## Surface Projection

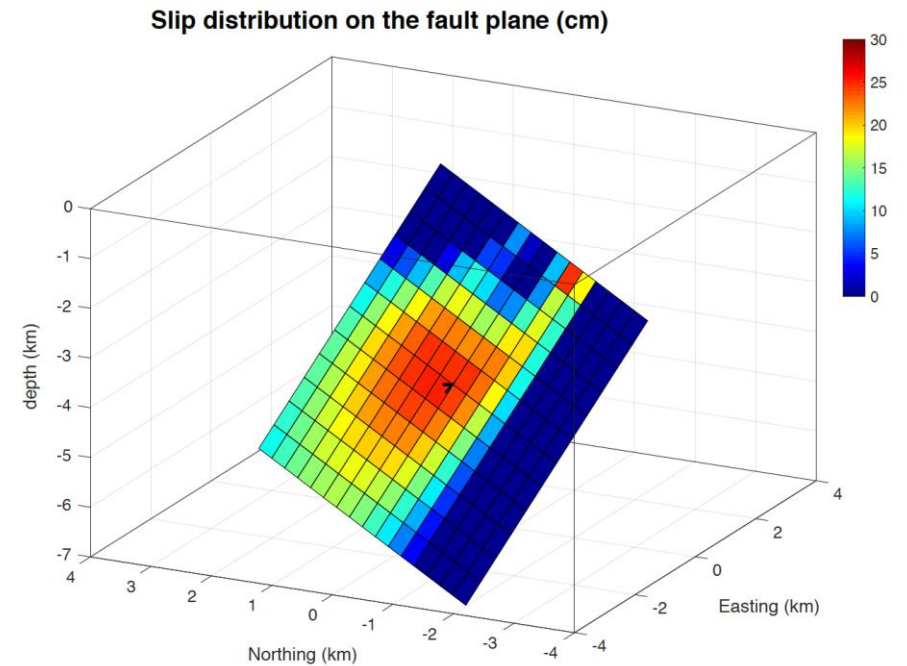


# 2016년 경주지진 ( $M_L$ 5.8) 및 2017년 포항지진 ( $M_L$ 5.4) 단층 파열 분포

2016년 경주지진 ( $M_L$  5.8)  
단층 파열 분포



2016년 포항지진 ( $M_L$  5.4)  
단층 파열 분포



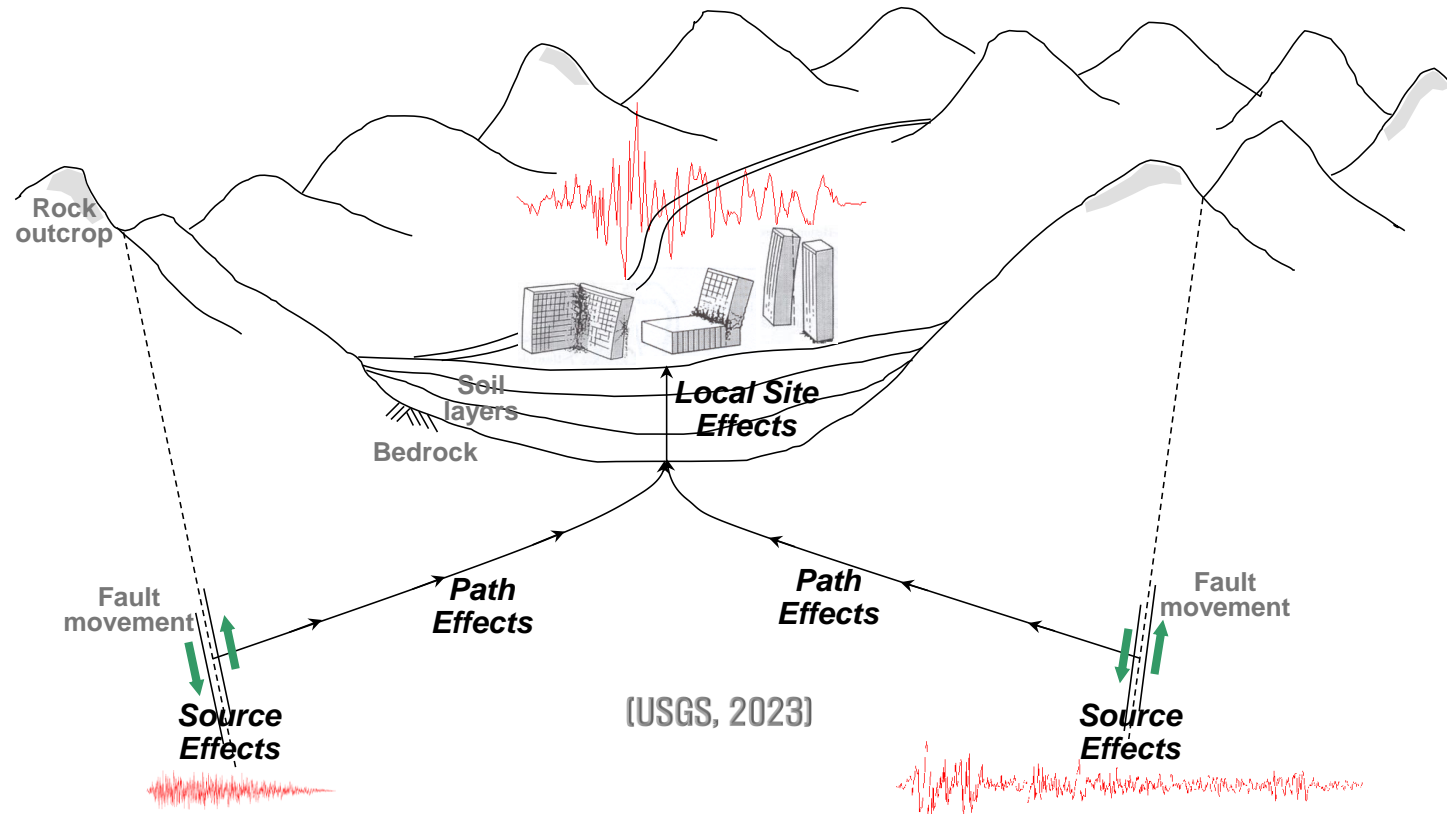
[한국지질자원연구원, 2018]  
(USGS, 2023)

# 한반도 지역고유 지반조건

# 지진지반운동

## 지진지반운동(Earthquake Ground Motion)

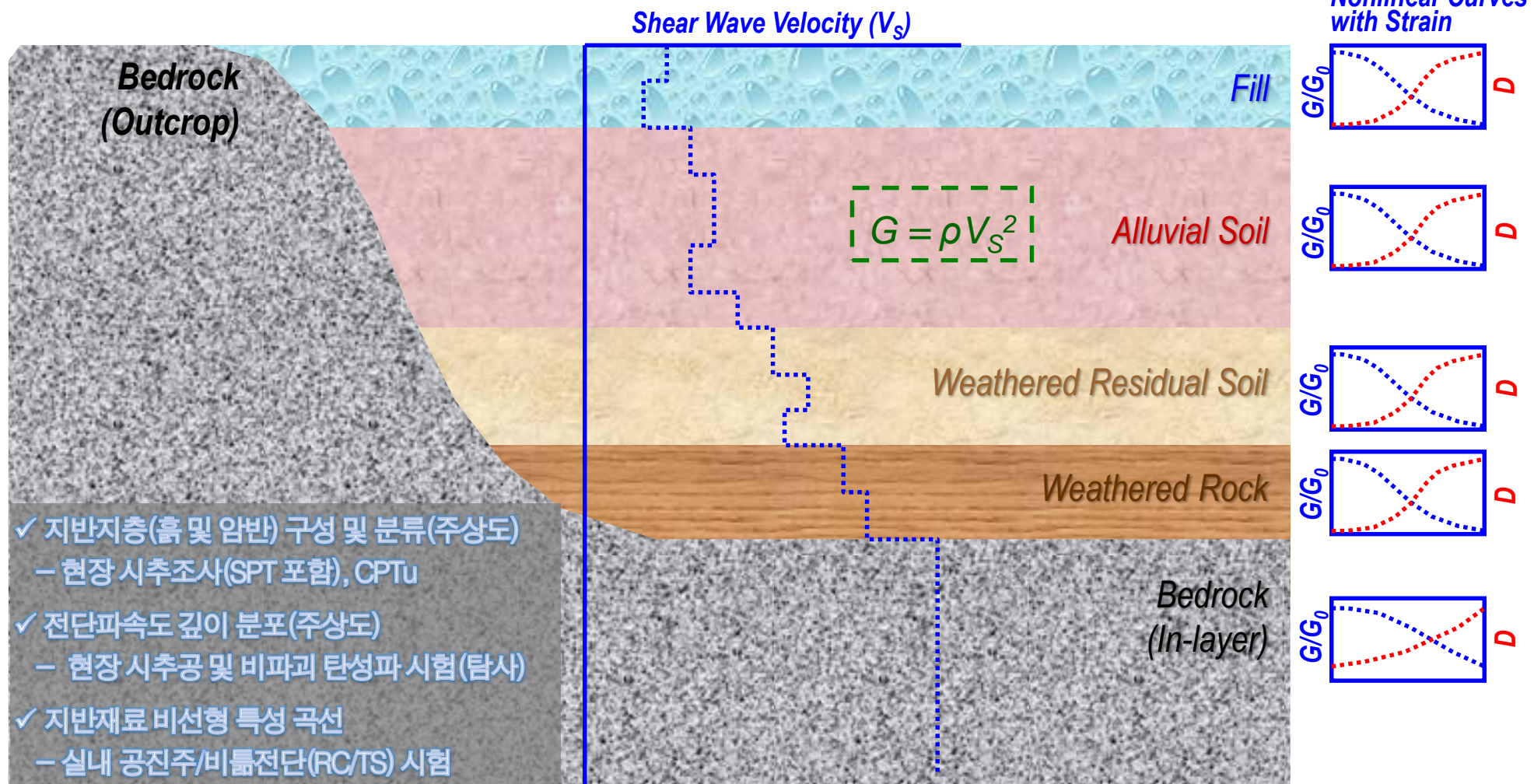
- 지진 발생에 따라 지반(암반/토사)을 통해 전달되어 지표면 부근에서 경험하는 진동
- 영향 인자인 진원효과(source effect), 경로효과(path effect), **부지효과(site effects)** 존재
- 지표면 부근에서의 크기(진폭), 진동수(주파수) 성분, 지속시간 등이 다른 지반운동으로 인해 지진 피해 정도/분포는 물론 피해 양상의 차이 발생





# 부지효과 (지진운동 증폭/감폭) 관련 주요 지반동적 특성

## 지반지진공학 관점 주요 지반동적 특성 획득/결정

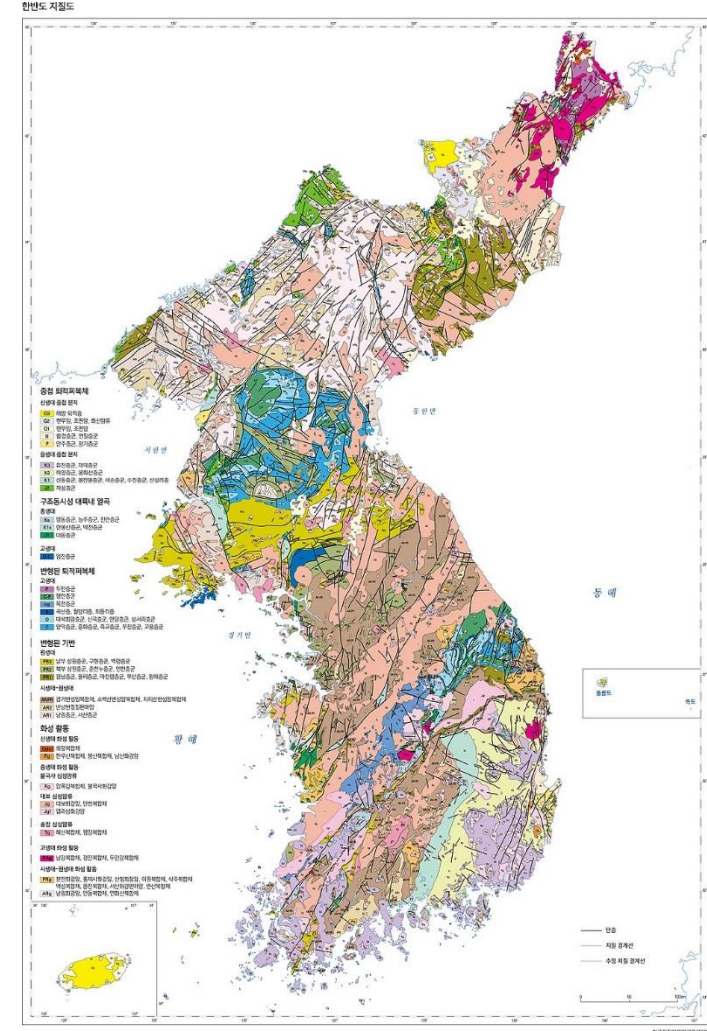


# 한반도 지형 및 지질

## 한반도 지형



## 한반도 지질 (1/1,000,000)



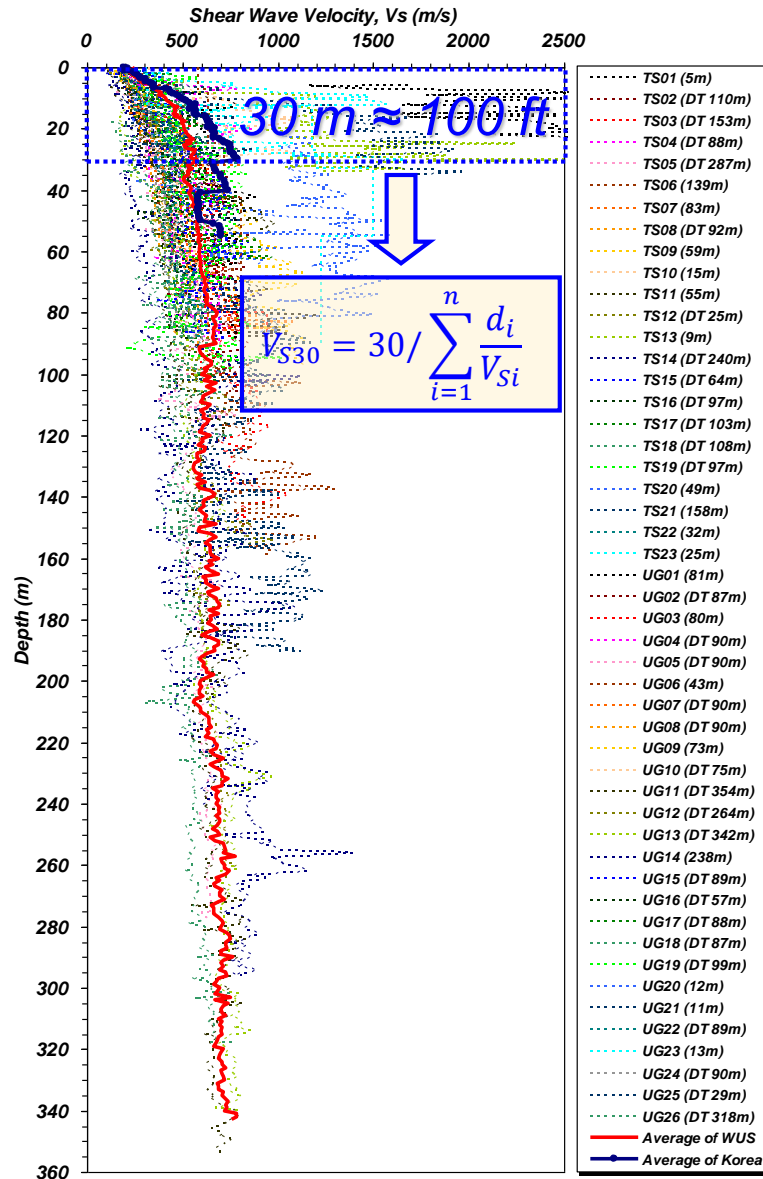
# 한반도와 미국서부 지역 전단파속도( $V_s$ ) 및 기반암심도( $H$ ) 비교

기반암 심도( $H$ )까지의 전단파속도( $V_s$ ) 분포 이용 부지주기( $T_G$ ) 산정

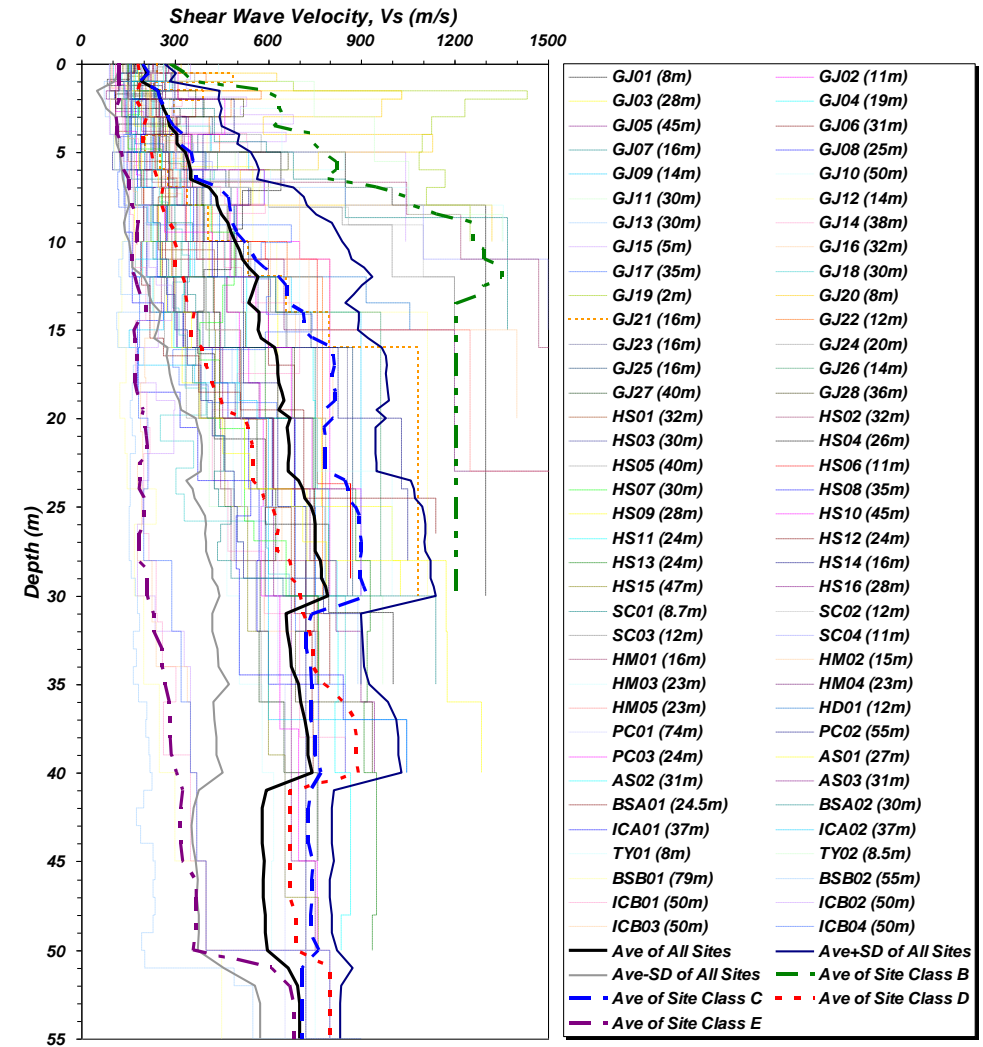
$$T_G = 4 \sum_{i=1}^n \frac{D_i}{V_{Si}}$$

(Sun et al., 2005)

## 미국서부 $V_s$ 분포(기반암심도) 비교



## 한반도 $V_s$ 분포(기반암심도)



(Sun, 2015)

# 단일 변수 $V_{S30}$ 토대 부지분류

## 내진설계 지반(부지)분류 (from NEHRP 1997)

Site class	Description	$V_{S30}$ (m/s)
A	Hard rock	$V_{S30} > 1500$
B	Rock	$760 < V_{S30} \leq 1500$
C	Very dense soil and soft rock	$360 < V_{S30} \leq 760$
D	Stiff soil	$180 < V_{S30} \leq 360$
E	Soft soil	$V_{S30} < 180$
F	Soils requiring site response analysis	

(BSSC, 1997)

## 내진설계 부지(지반)분류

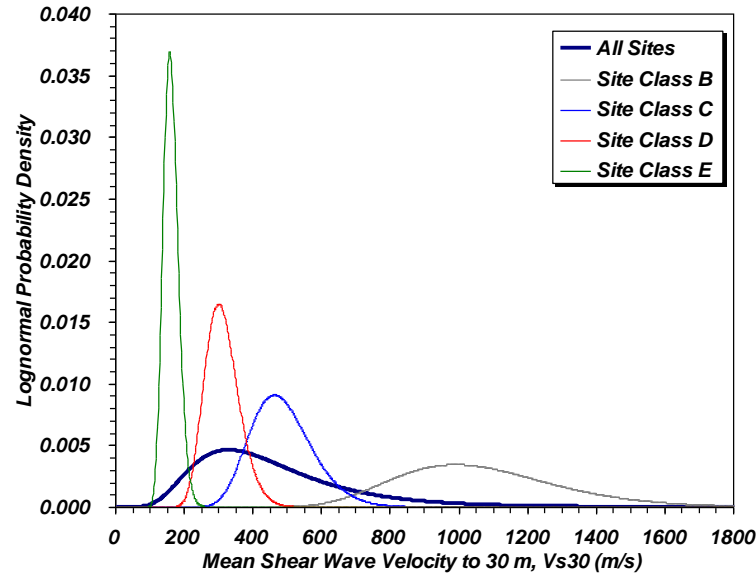
(NEHRP 2020)

Site class	Description	$V_{S30}$ (ft/s)
A	Hard rock	$> 5,000$
B	Medium hard rock	$> 3,000$ to 5,000
BC	Soft rock	$> 2,100$ to 3,000
C	Very dense sand or hard clay	$> 1,450$ to 2,100
CD	Dense sand or very stiff clay	$> 1,000$ to 1,450
D	Medium dense sand or stiff clay	$> 700$ to 1,000
DE	Loose sand or medium stiff clay	$> 500$ to 700
E	Very loose sand or soft clay	$< 500$
F	Soils requiring site response analysis	

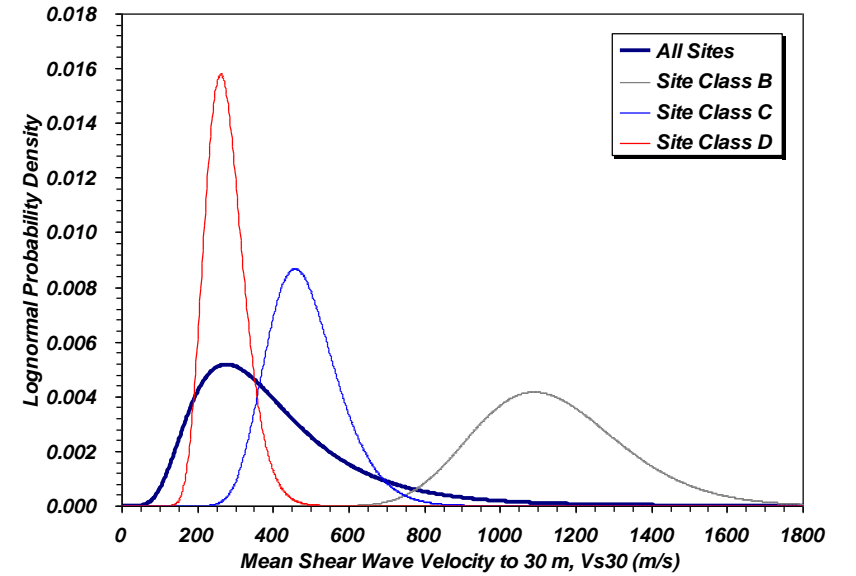
(BSSC, 2020)

# 한반도와 미국서부 지역 $V_{S30}$ 분포

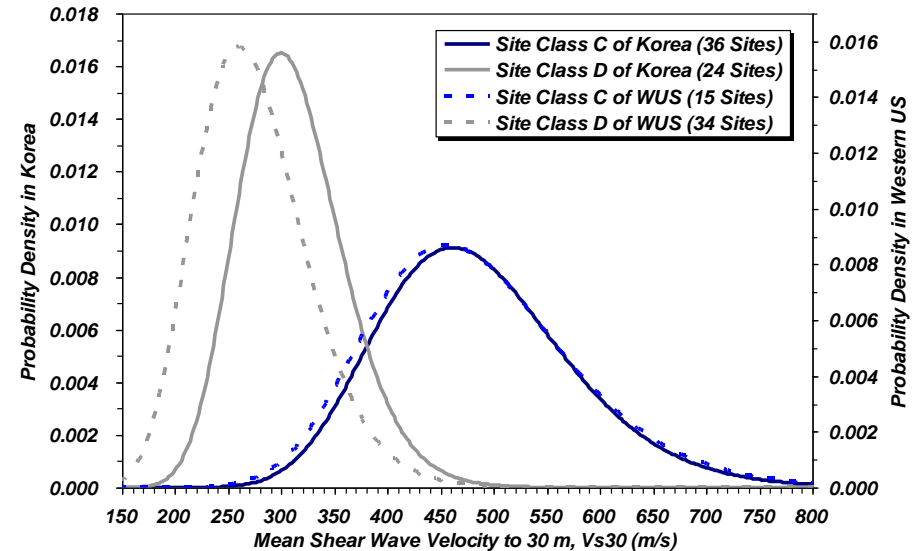
한반도  $V_{S30}$  확률 분포



미국서부  $V_{S30}$  확률 분포



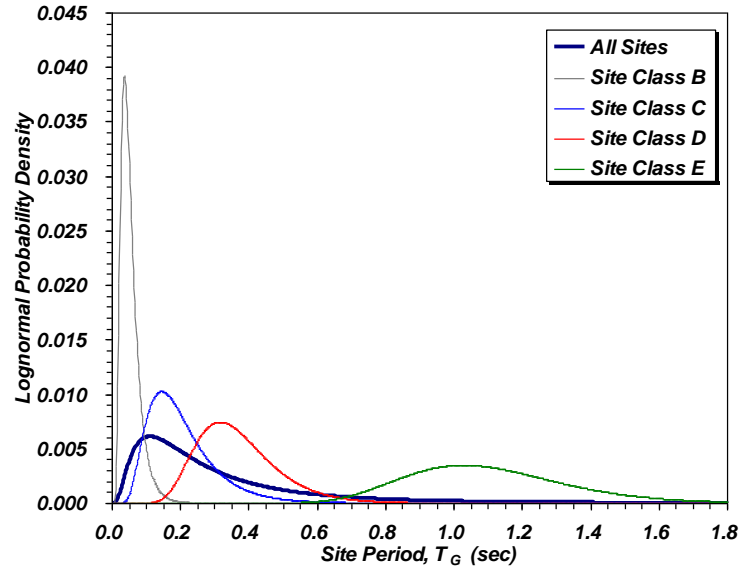
부지분류 C 및 D 조건의  
한반도와 미국서부  
 $V_{S30}$  확률 분포 비교



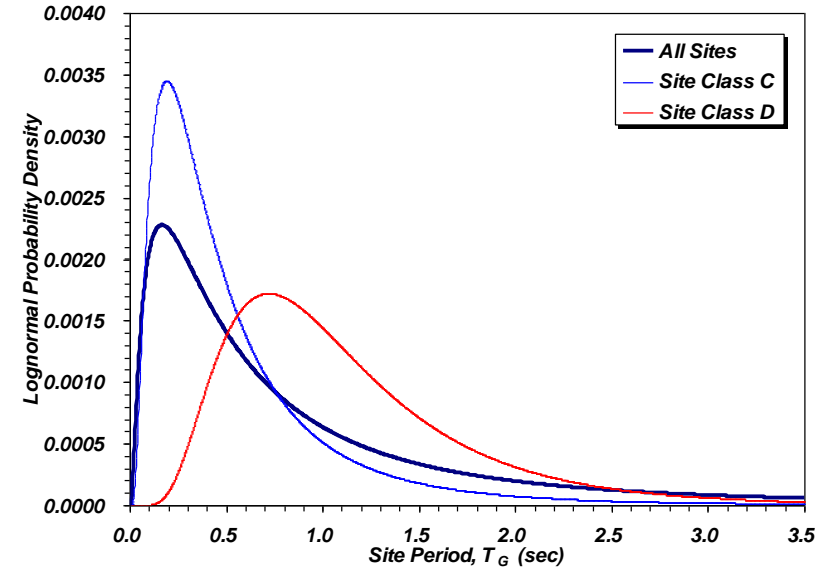
(Sun, 2015)

# 한반도와 미국서부 지역 부지주기( $T_G$ ) 분포

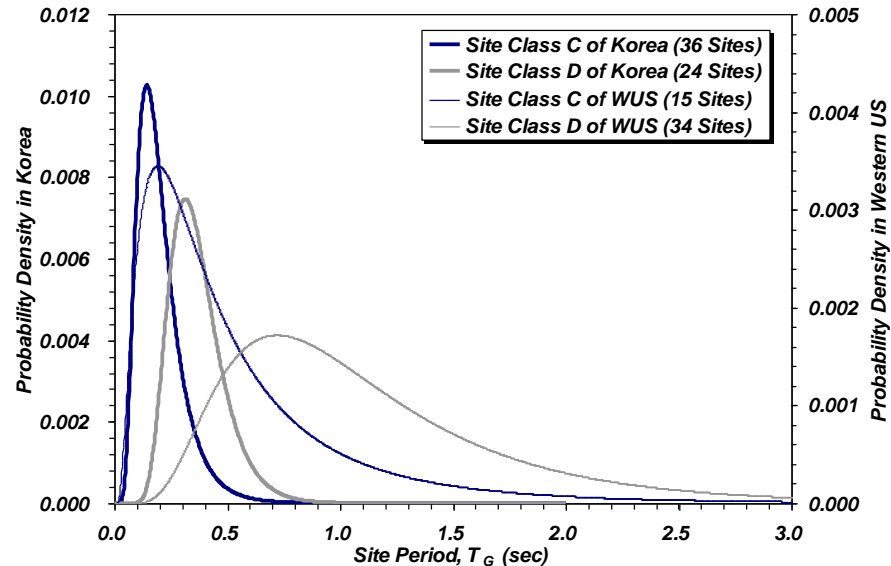
한반도  $T_G$  확률 분포



미국서부  $T_G$  확률 분포



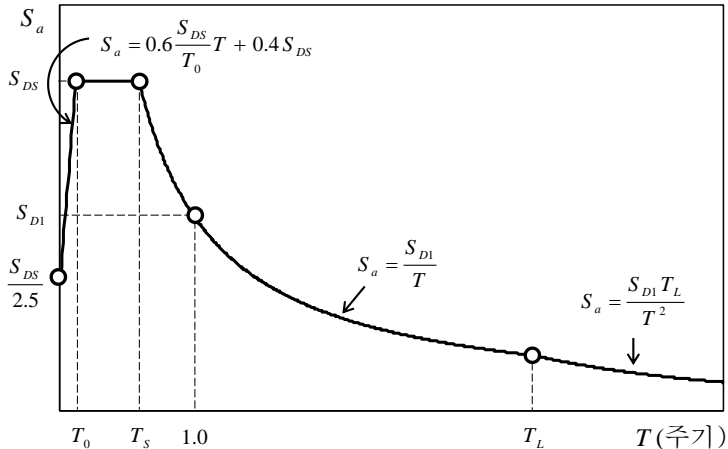
부지분류 C 및 D 조건의  
한반도와 미국서부  $T_G$   
확률 분포 비교



# 현행 국내 내진 설계기준 지반(부지) 분류

## 설계응답가속도스펙트럼

(KDS 41 17 00 : 2019 [국토교통부, 2018]  
건축물 내진설계 기준) [국토교통부, 2019]



## 지반(부지)의 분류 (KDS 17 00 00 : 2018 내진설계 일반; KDS 41 17 00 : 2019 건축물 내진설계 기준)

지반종류	지반종류의 호칭	분류기준	
		기반암 깊이, \$H\$ (m)	\$V_{S,Soil}\$ (m/s)
\$S_1\$	암반 지반	1 미만 (3 미만)	(기반암: \$V_S \ge 760\$ m/s 지층)
\$S_2\$	얕고 단단한 지반	1~20 이하	260 이상
\$S_3\$	얕고 연약한 지반		260 미만
\$S_4\$	깊고 단단한 지반	20 초과	180 이상
\$S_5\$	깊고 연약한 지반		180 미만
\$S_6\$	부지고유의 특성평가 및 지반응답해석이 필요한 지반		

## 단주기 지반증폭계수(\$F\_a\$)

지반종류	유효지반가속도(\$S\$)		
	\$S \le 0.1\$	\$S = 0.2\$	\$S = 0.3\$
\$S_2\$	1.4	1.4	1.3
\$S_3\$	1.7	1.5	1.3
\$S_4\$	1.6	1.4	1.2
\$S_5\$	1.8	1.3	1.3

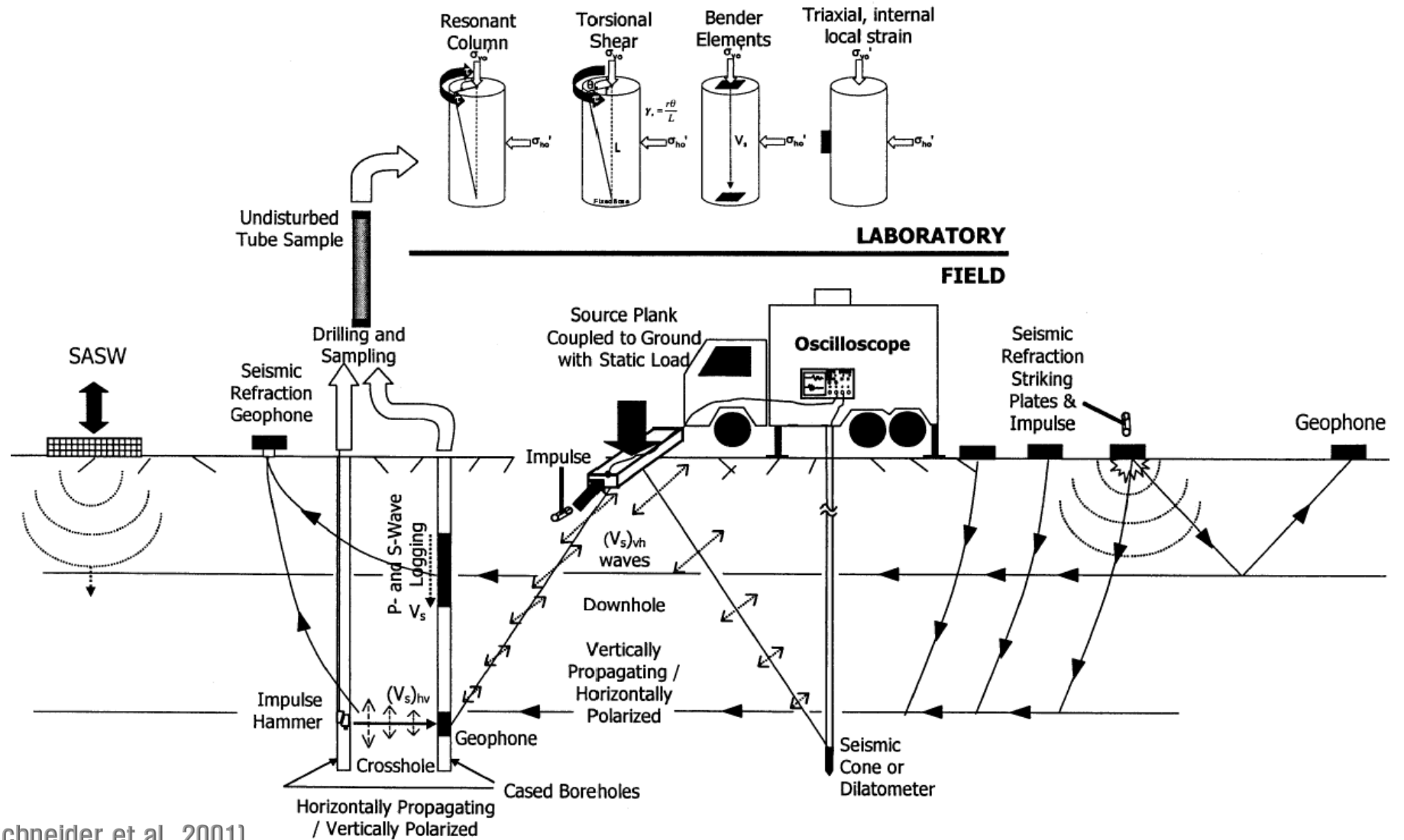
## 장주기 지반증폭계수(\$F\_v\$)

지반종류	유효지반가속도(\$S\$)		
	\$S \le 0.1\$	\$S = 0.2\$	\$S = 0.3\$
\$S_2\$	1.5	1.4	1.3
\$S_3\$	1.7	1.6	1.5
\$S_4\$	2.2	2.0	1.8
\$S_5\$	3.0	2.7	2.4

# 지진공학 관점 지반특성 합리적 결정



# 전단파속도( $V_s$ ) 획득 목적 주요 지반조사 기법



[Schneider et al., 2001]

# $V_s$ 획득 원위치(현장) 시험 기법 구분

## 시추공(관입) 시험 기법

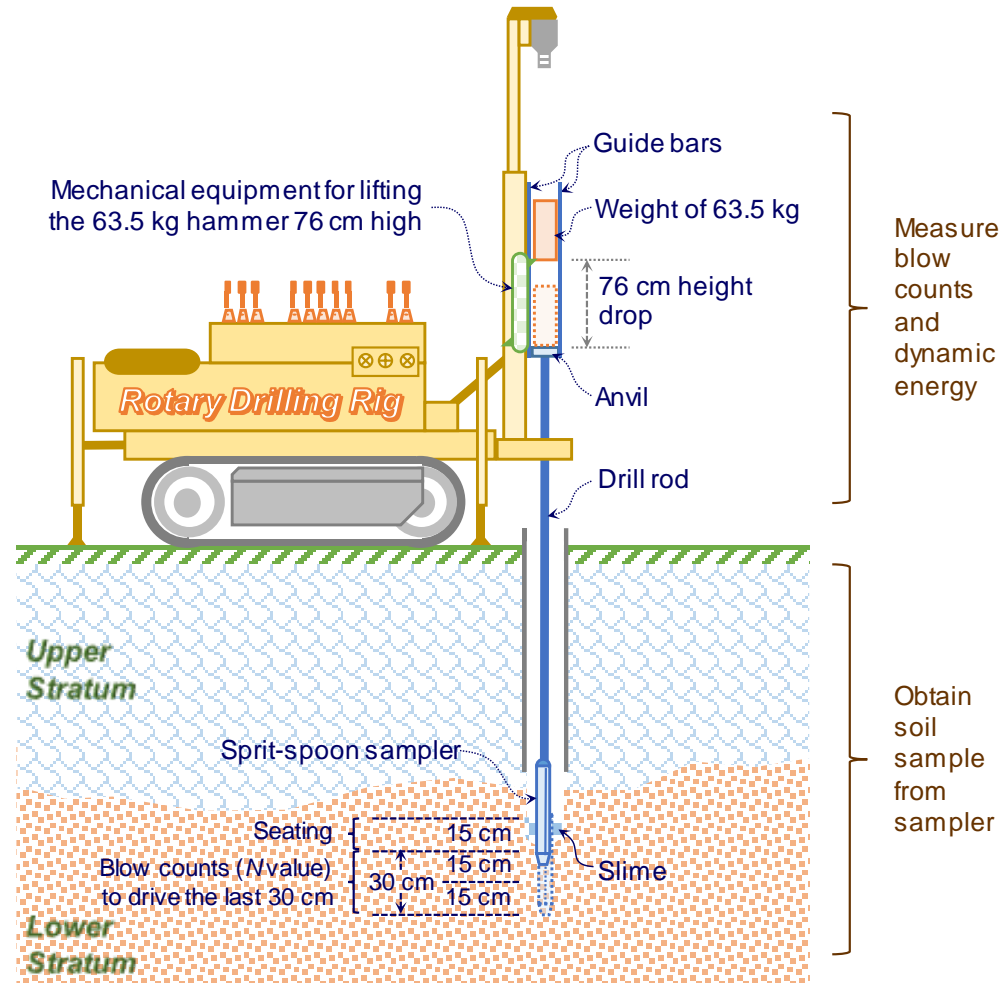
- 시추공간(크로스홀) 탄성파 시험 기법 (Crosshole seismic method)
- 하향식(다운홀) 탄성파 시험 기법 (Downhole seismic method)
  - ✓ 탄성파 하이브리드 관입 시험 기법: 탄성파콘, 탄성파딜라토미터 등
- 상향식(업홀) 탄성파 시험 기법 (Uphole seismic method)
- 시추공내(인홀) 탄성파 시험 기법 (Inhole seismic method)
  - ✓ 유체 매개 검층: 완전파형 음파 검층, 부유식 탄성파 검층 등

## 비파괴(비관입) 기법

- 지표면 반사법 탐사 기법 (Surface reflection method)
- 지표면 굴절법 탐사 기법 (Surface refraction method)
- 표면파 탐사 기법 (Surface wave methods) ◀ **지반공학 분야 주요 적용**
  - ✓ SASW (Spectral Analysis of Surface Waves), MASW (Multichannel Analysis of Surface Waves) 등

# 시추조사 및 표준관입시험 (SPT)

지반지층 구성 확인을 위한 시추조사 실시 및 SPT 수행을 통한  $N$  값 획득

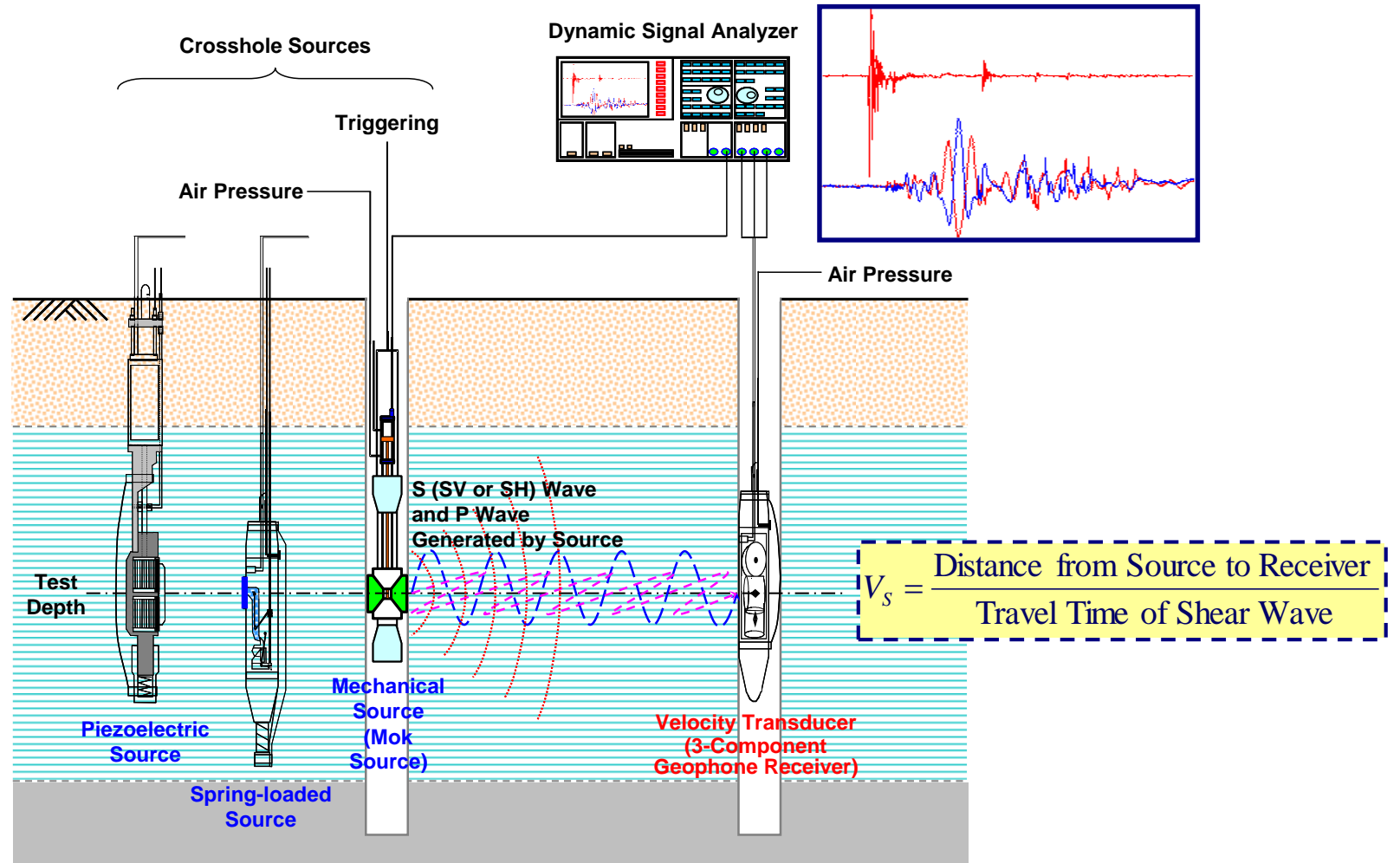


[Sun et al., 2022]



# 크로스홀 (Crosshole) 탄성파 시험

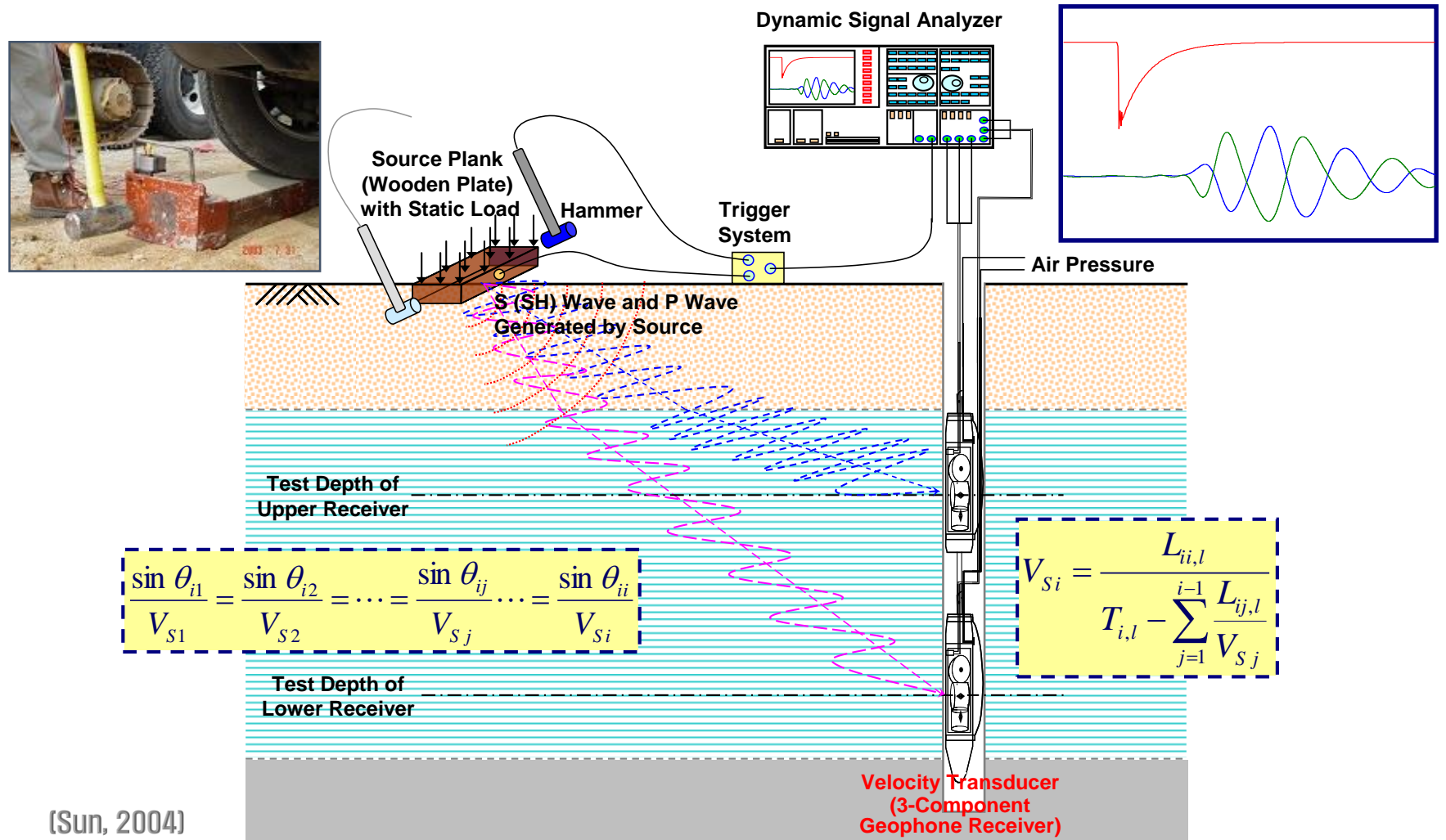
발진(가진) 시험공 및 수신(감진) 시험공 적용 수행



(Sun, 2004)

# 다운홀 (Downhole) 탄성파 시험

## 지표면 발진 및 시험공 내 수신 적용 수행



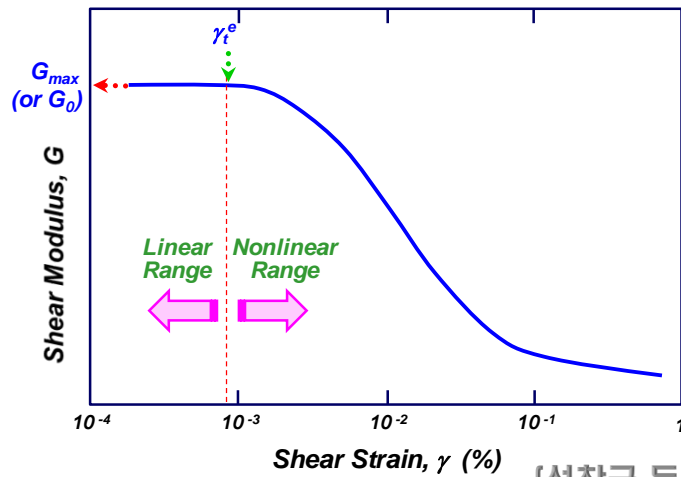
(Sun, 2004)

# 이원적 변형률 대상 탄성파 하이브리드 시험

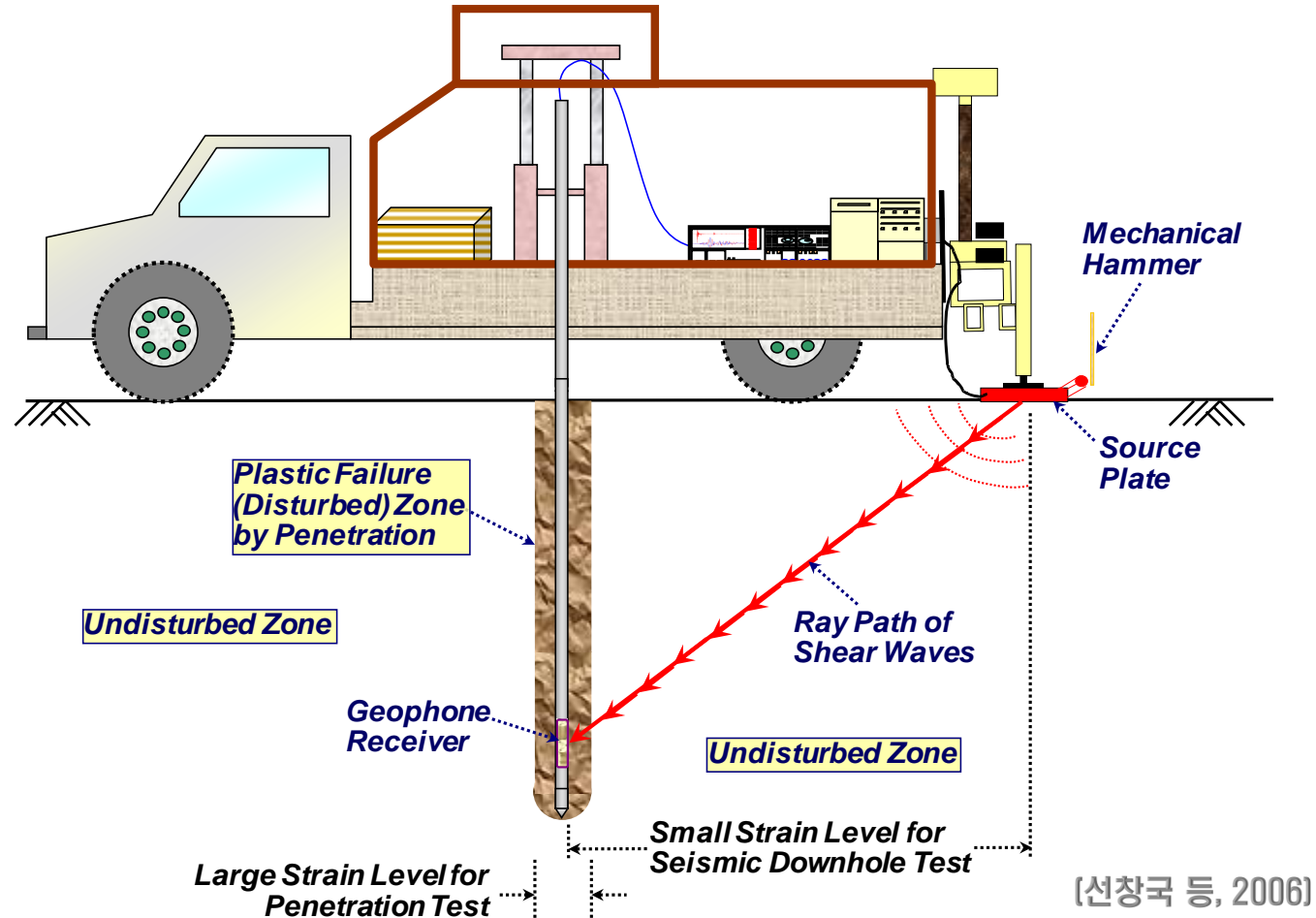
## 탄성파 피에조콘/딜라토미터 관입 시험(SCPTu/SDMT)

일반적 관입 시험 기반 다운홀 탄성파 시험 기법 도입/적용

### 지반 강성 비선형 변화(감소) 곡선

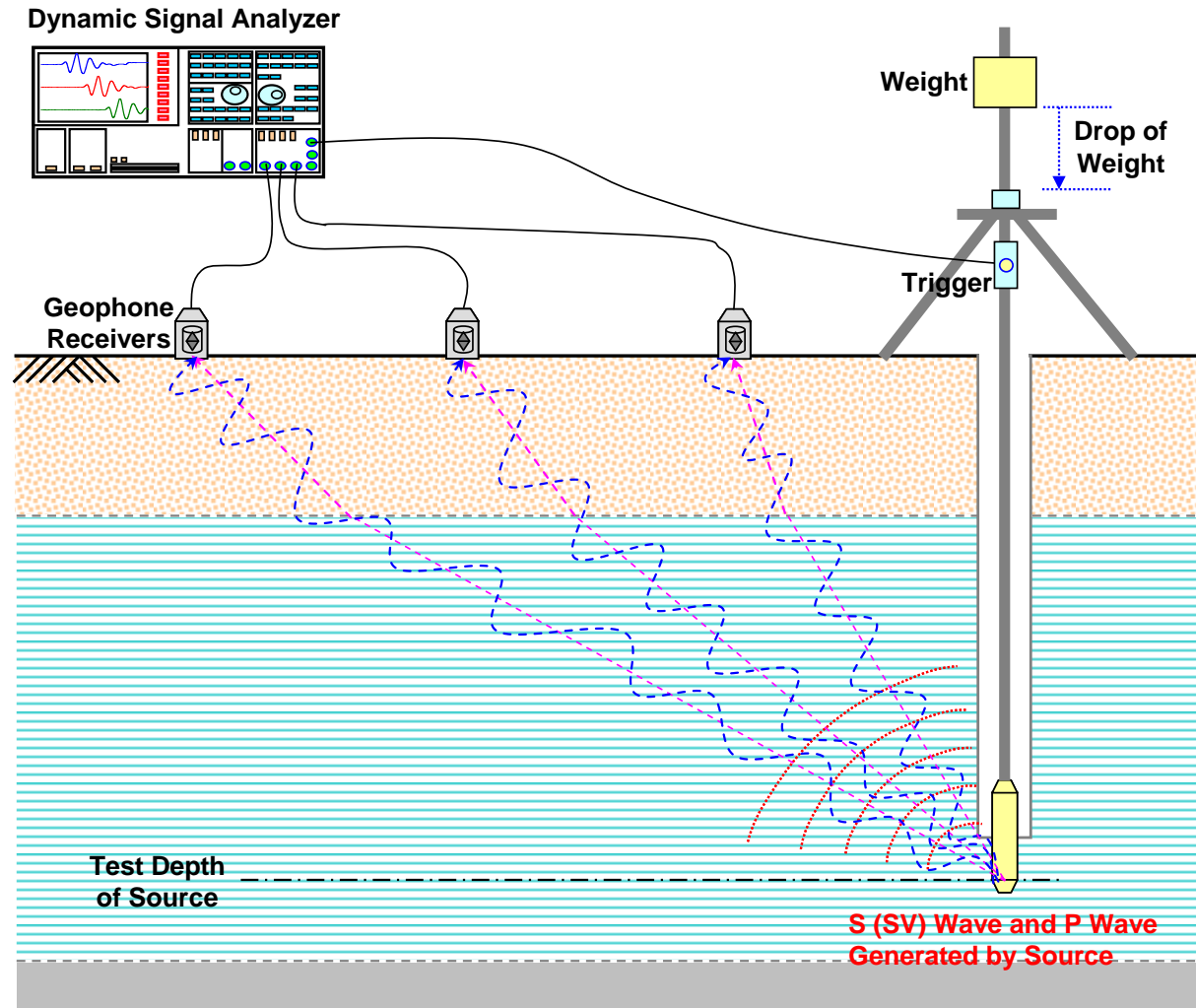


[선창국 등, 2012]



# 업홀(Uphole) 탄성파 시험

## 시험공 내 발진 및 지표면 수신 적용 수행

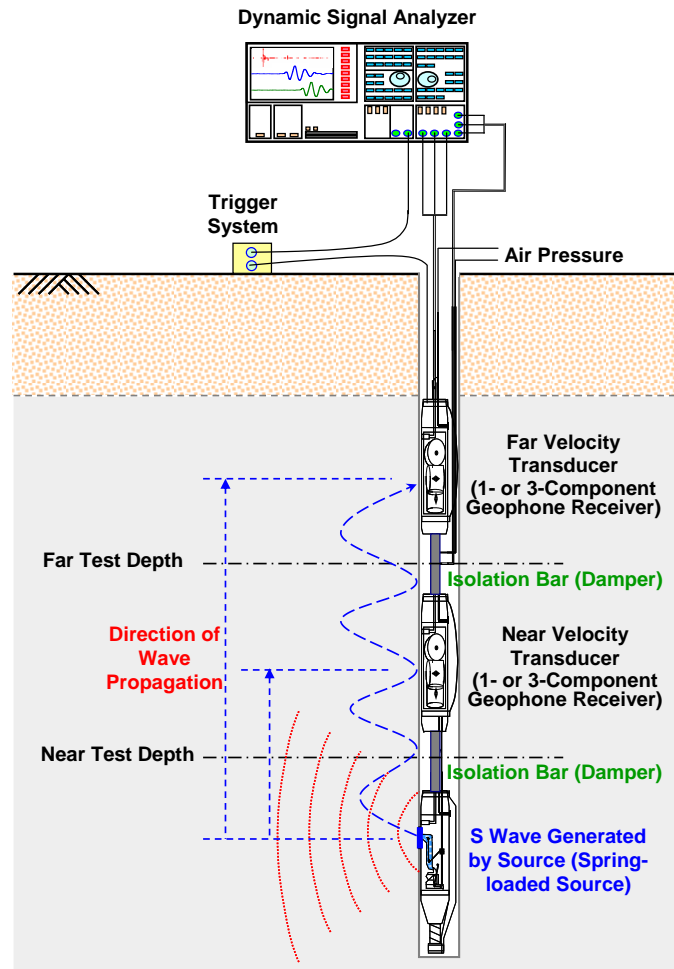


[선창국 등, 2005]

# 인홀(Inhole) 탄성파 시험 및 완전파형 음파 검층

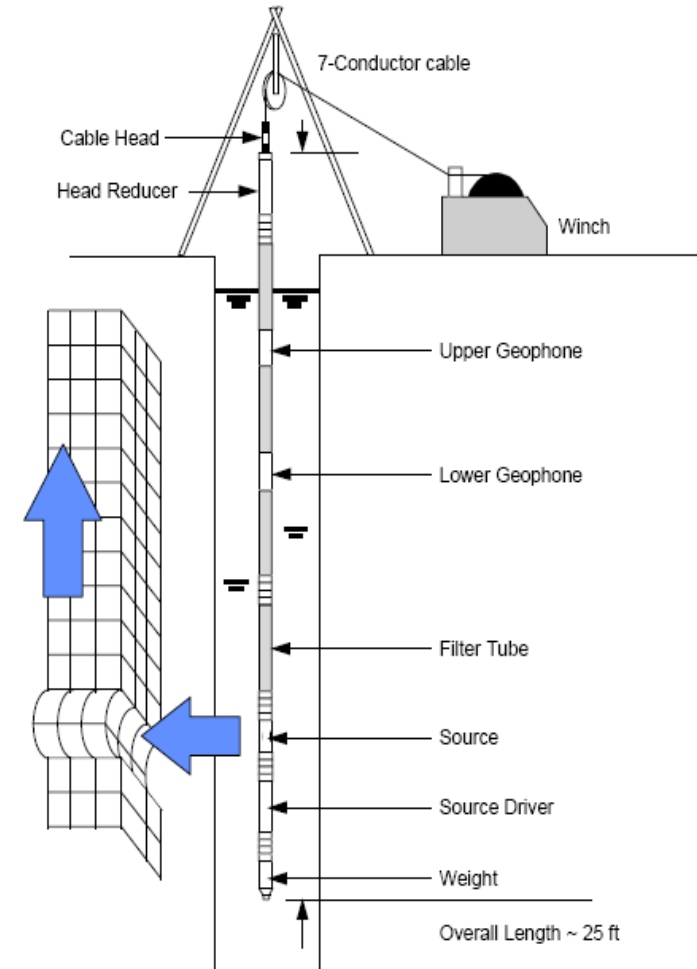
## 단일 시험공 내 발진 및 수신 적용 수행

- 인홀 탄성파 시험



[선창국 등, 2005]

- 완전파형 음파 검층

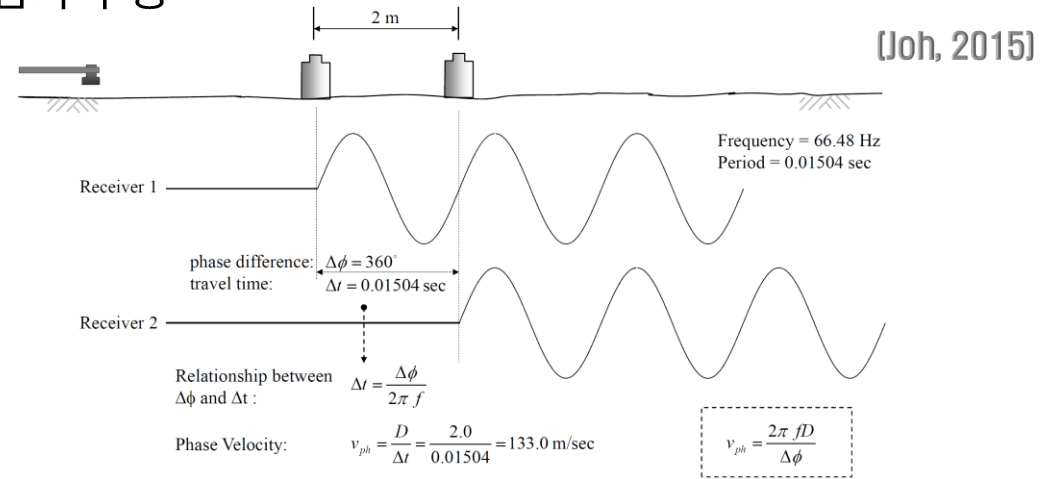
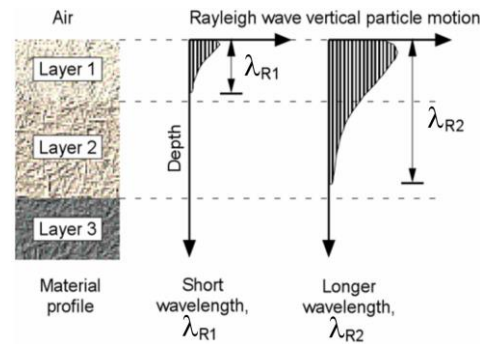




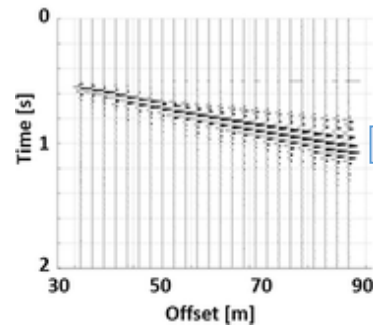
# 비파괴 표면파 (Surface waves) 탐사 기법

## 지표면 부근 지반 표면파 분산특성 이용 분산곡선 획득 수행

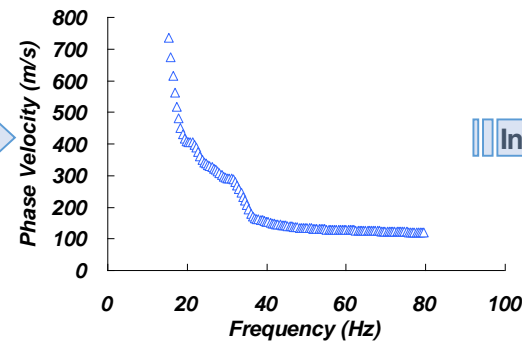
- 표면파 분산 위상속도 측정 탐사 수행



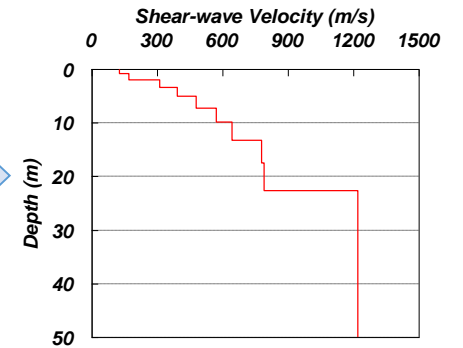
- 자료 처리 및 역산 분석



Processing



Inversion



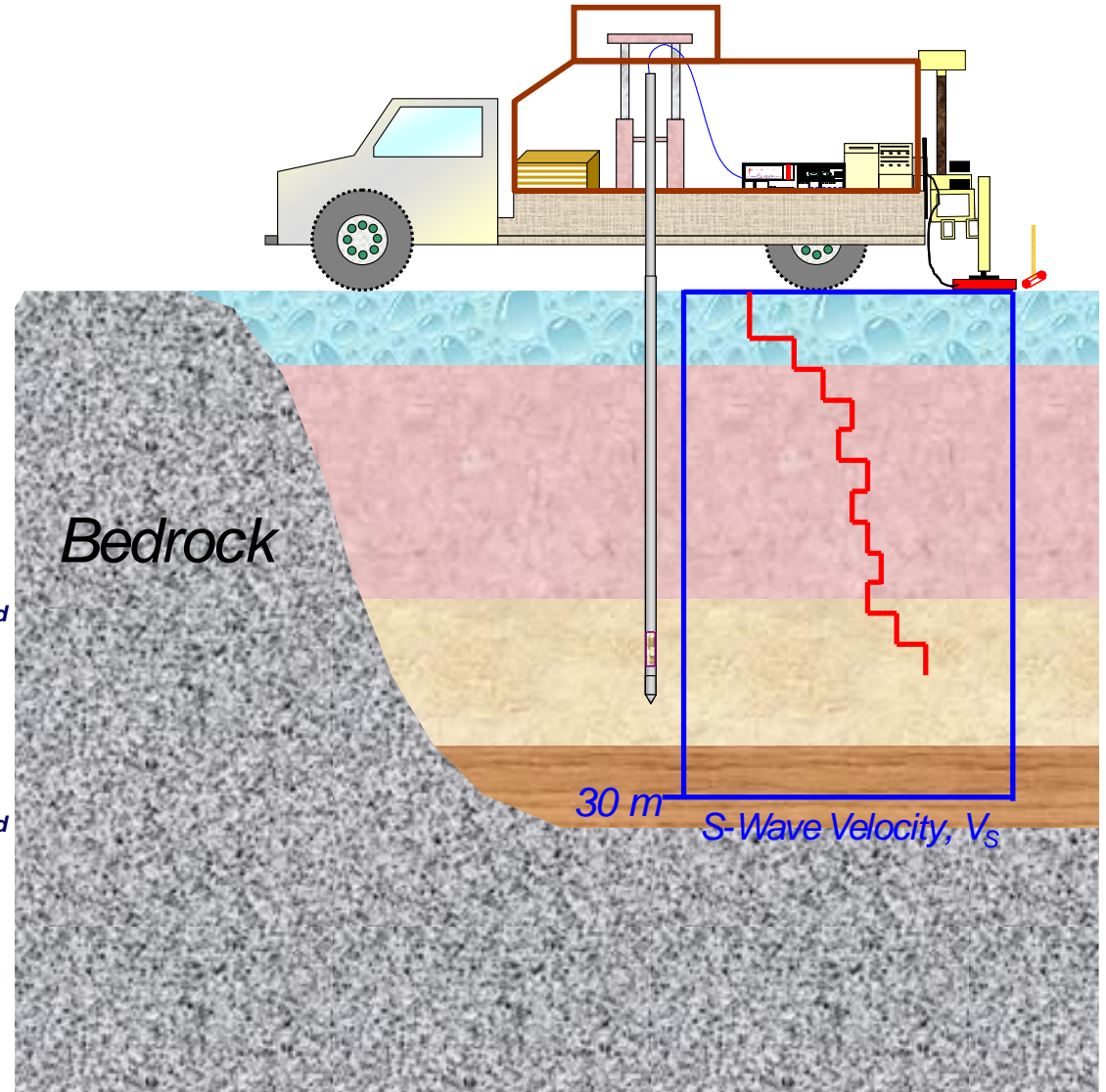
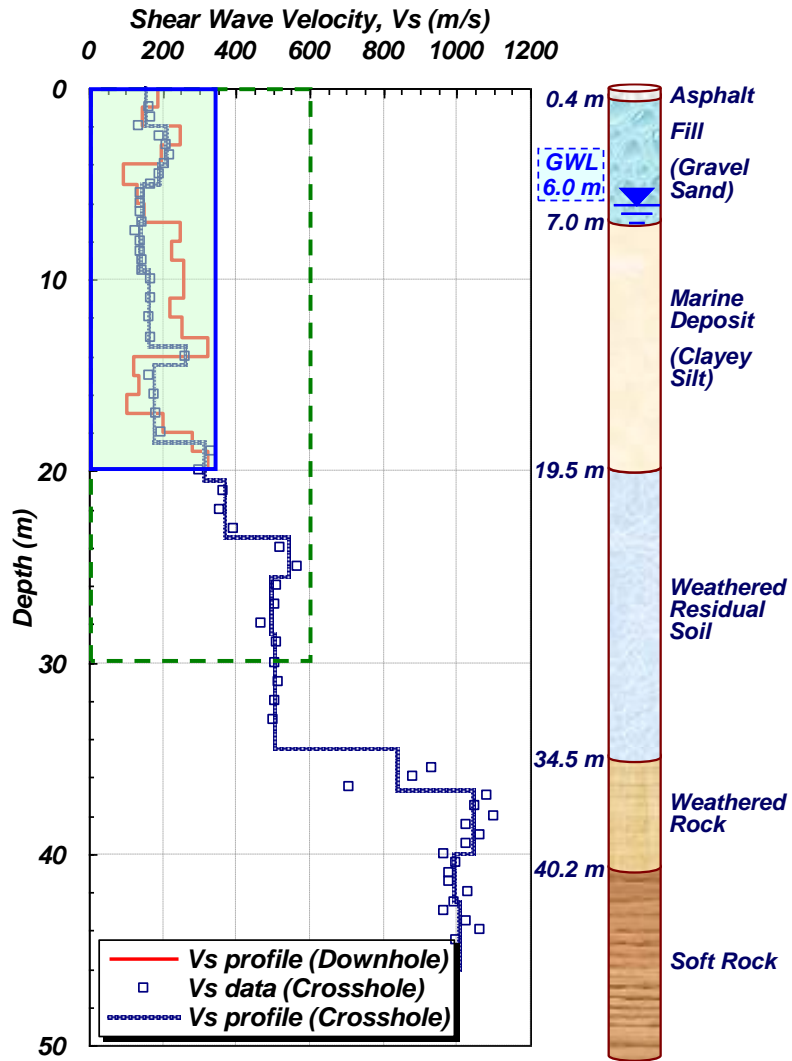
# 시험 기법별

## $V_s$ 분포

### (주상도)

### 획득 제한 및

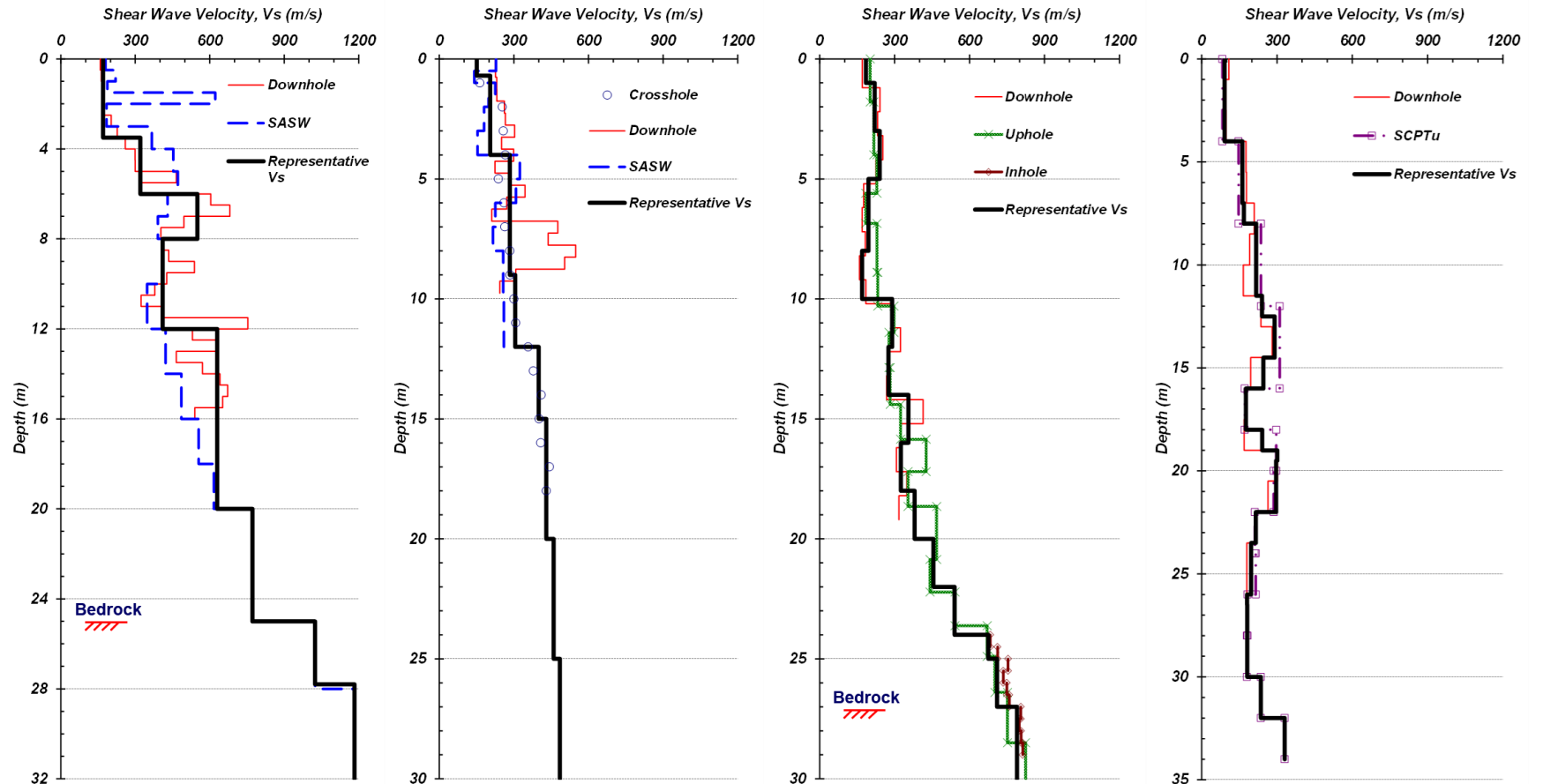
### 상호 보완



# 지반지진공학 관점 대표 $V_s$ 분포(주상도) 결정 활용

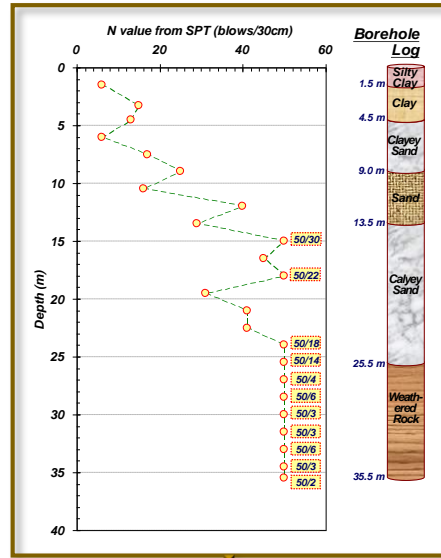
## 부지고유 지반동적 특성으로서의 대표 전단파속도 분포 결정

- 시험 기법별 일반적/전문가적 신뢰도 및 현장 고유여건 포괄적 고려
- 부지고유 지진응답해석 수행 및 지반지진공학 매개변수( $H$ ,  $V_{S30}$ ,  $V_{S,soil}$ ,  $T_G$  등) 결정 활용

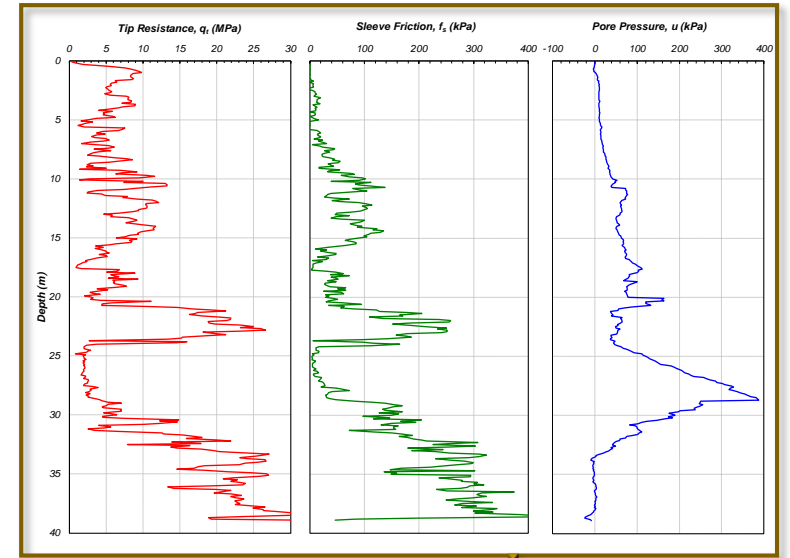


(탄성파 시험  
미수행)  
시추/관입시험  
자료 이용  
 $V_s$  분포  
경험적 산정  
(제한적 수준  
신뢰도)

(Sun et al., 2013)

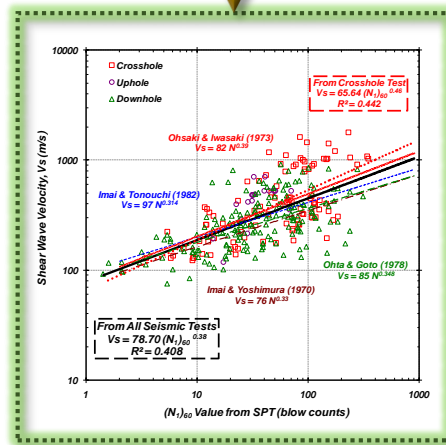


Borehole log and SPT-N values

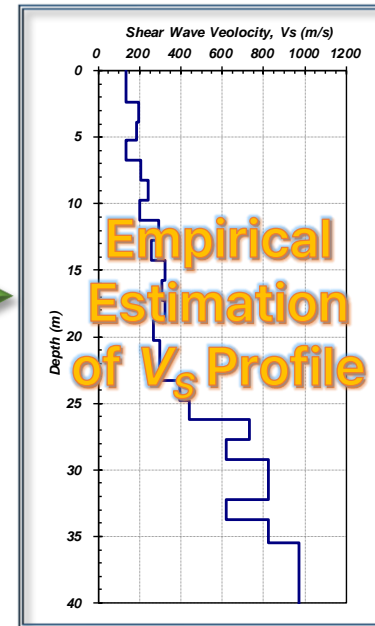


CPTu data

Region-Specific

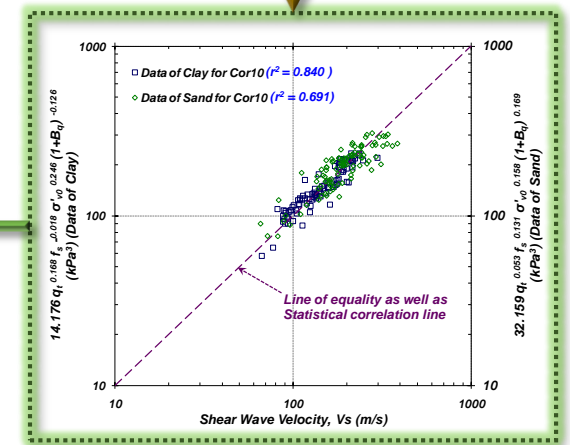


N- $V_s$  Correlation



Empirical Estimation of  $V_s$  Profile

Region-Specific

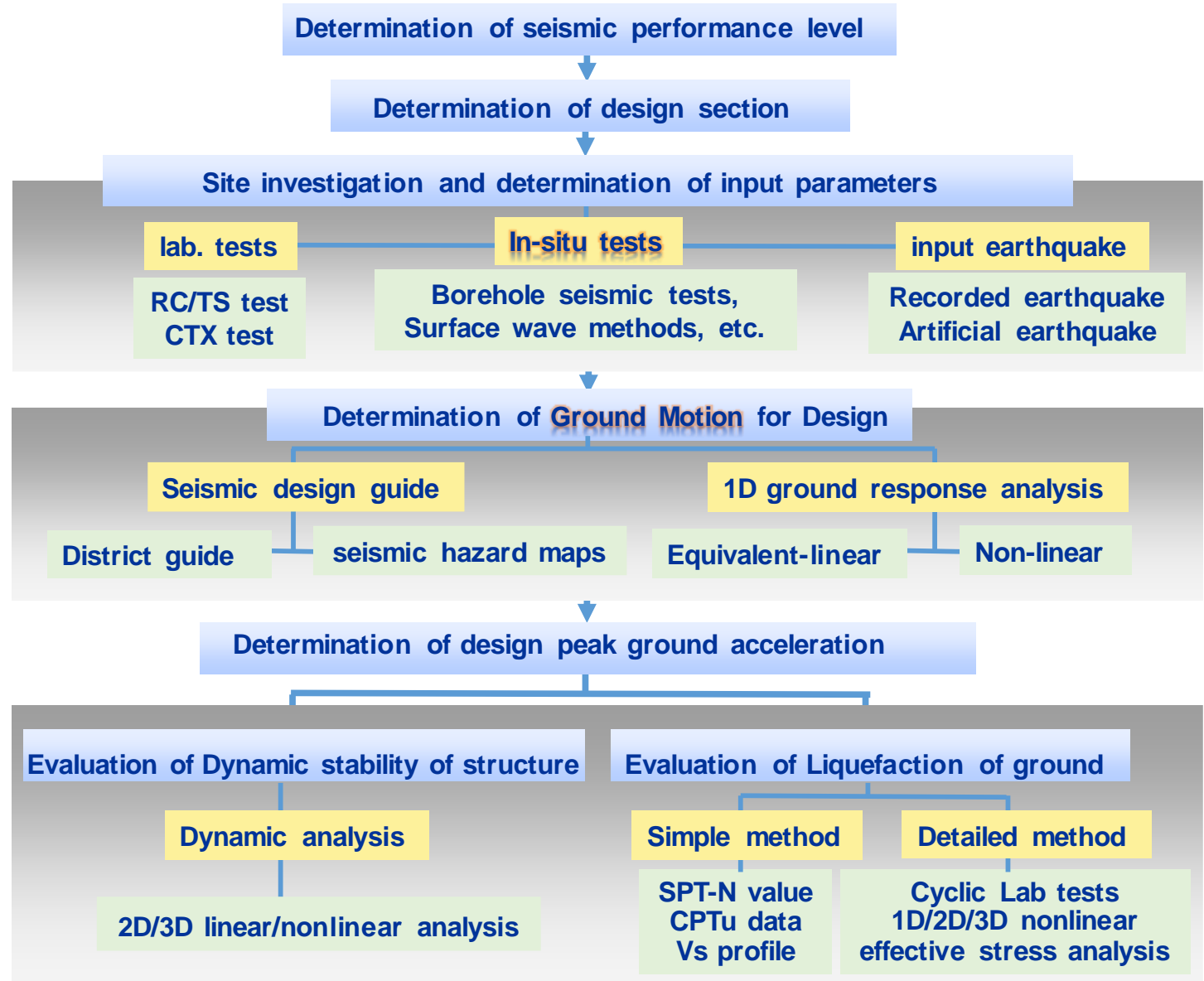


CPTu data- $V_s$  Correlation

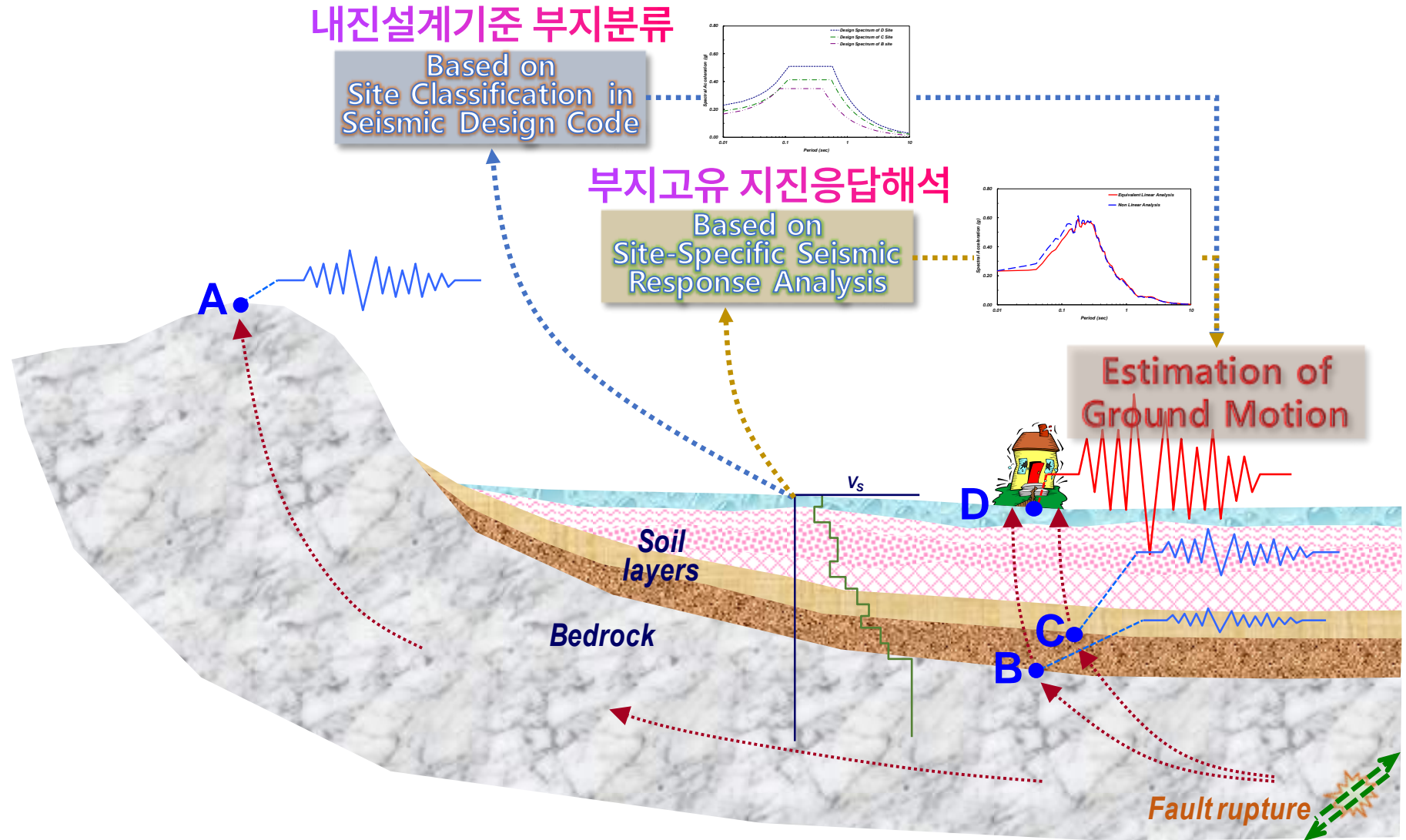
(Sun et al., 2013)

# 지역 지진지반운동 평가 및 활용

# 지반지진공학 관점 내진설계 일반적 흐름



# 원위치 부지 지반동적 특성 ( $V_s$ ) 이용 지진지반운동 평가

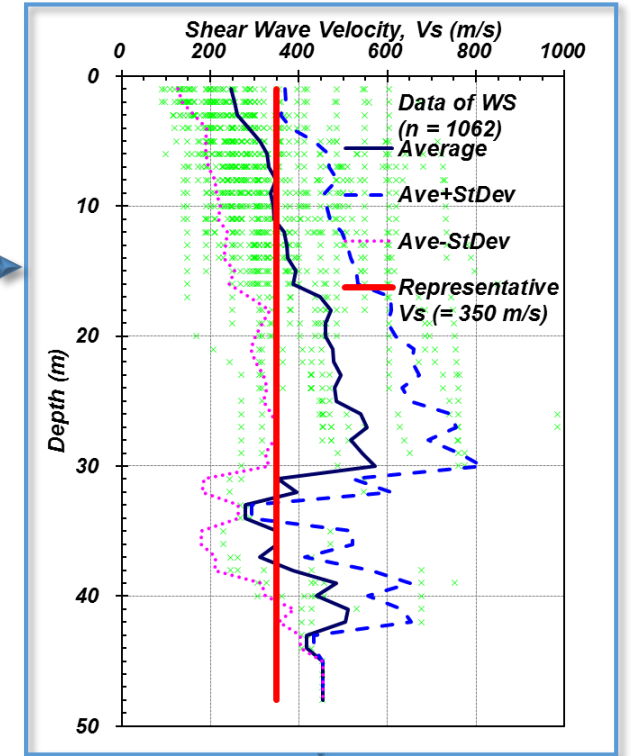
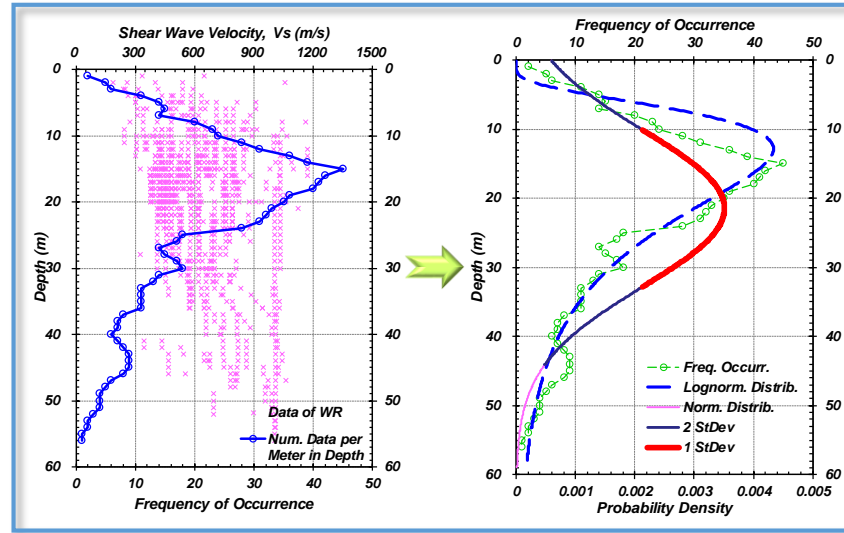


(대안적 활용)  
 국내 지반지층  
 대표  $V_s$  제안  
 (신뢰성 확보  
 자료 축적 지속  
 보완 필요)

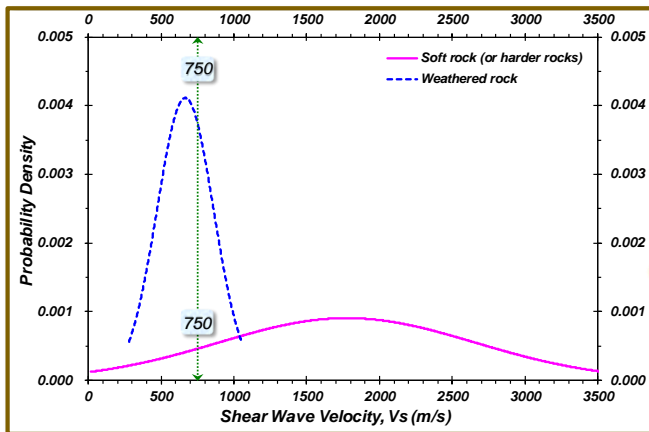
[선창국 등, 2012]

지반지진공학 관점 매립토, 퇴적토, 풍화토, 풍화암, 기반암 구분 및 자료 통계 분석

풍화토 지층  $V_s$  자료 분석 예시



[Sun et al., 2014]



지반지층  
 대표  $V_s$   
 도출 제안

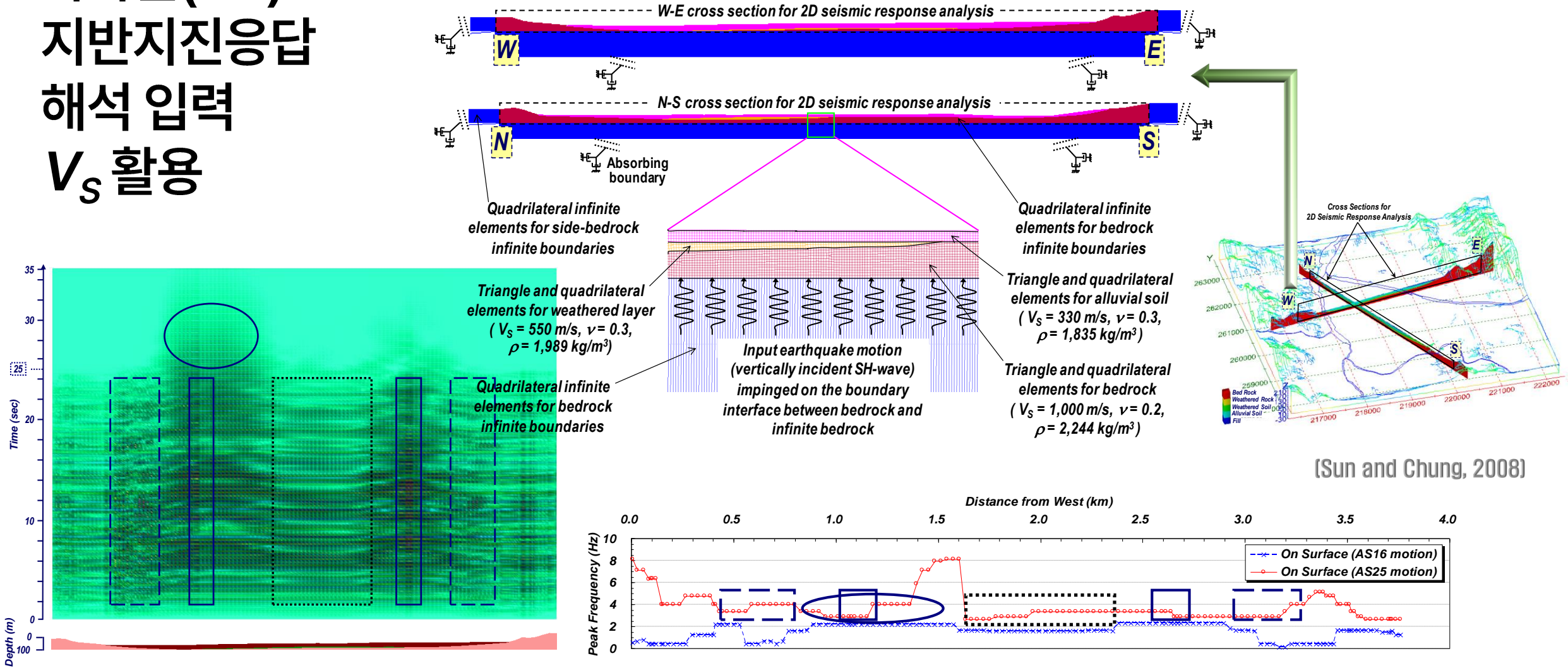
[선창국, 2014]

Name of Layer	Representative $V_s$	Average of $V_s$	Stand. Dev. of $V_s$
Fill	190 m/s	(186 m/s)	(99 m/s)
Alluvial Soil	280 m/s	(283 m/s)	(149 m/s)
Weathered Soil	350 m/s	(353 m/s)	(151 m/s)
Weathered Rock	650 m/s	(651 m/s)	(202 m/s)
(Bed Rock)	(1300 m/s)	(1289 m/s)	(543 m/s)



# 다차원(2D) 지반지진응답 해석 입력 $V_S$ 활용

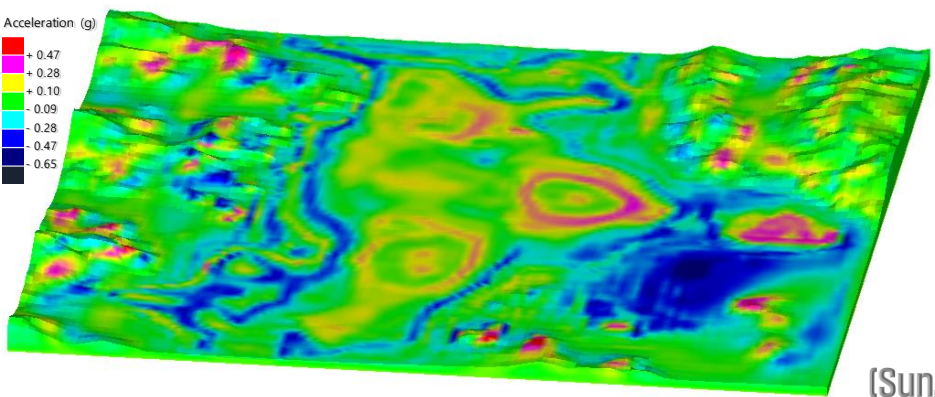
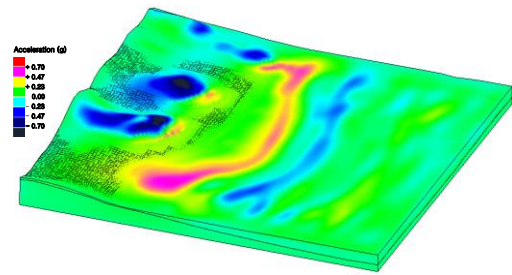
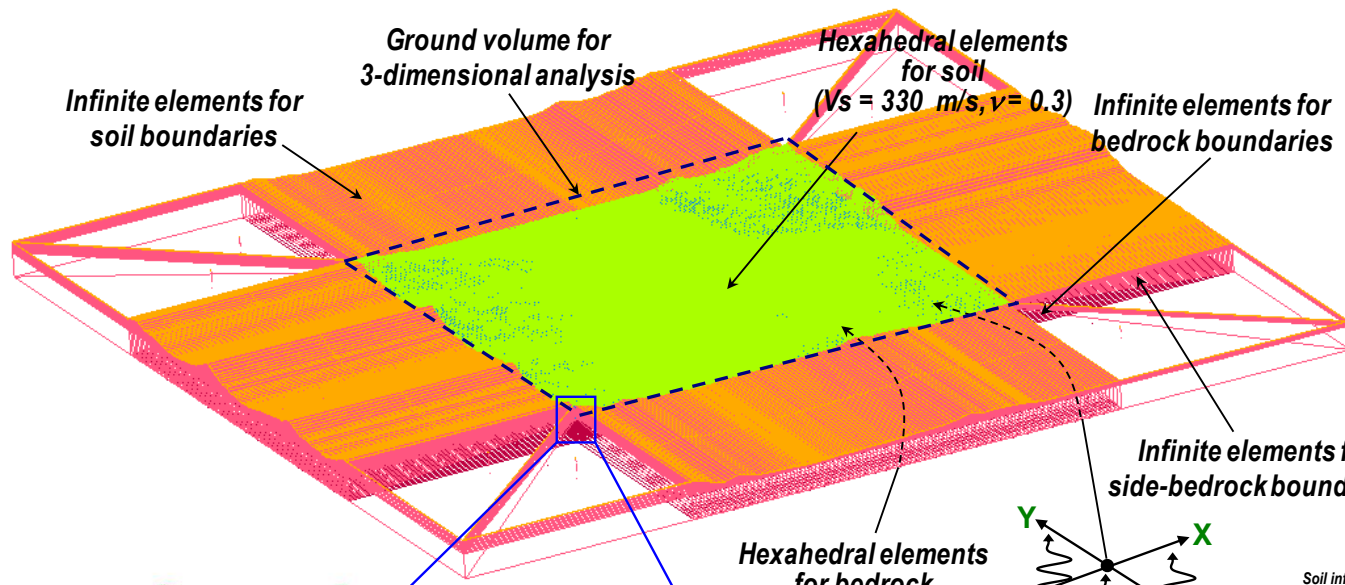
## 관심 영역 3D 공간 지반정보 기반 2D 주요단면 FE 모델링 지진지반운동 평가



(Sun and Chung, 2008)

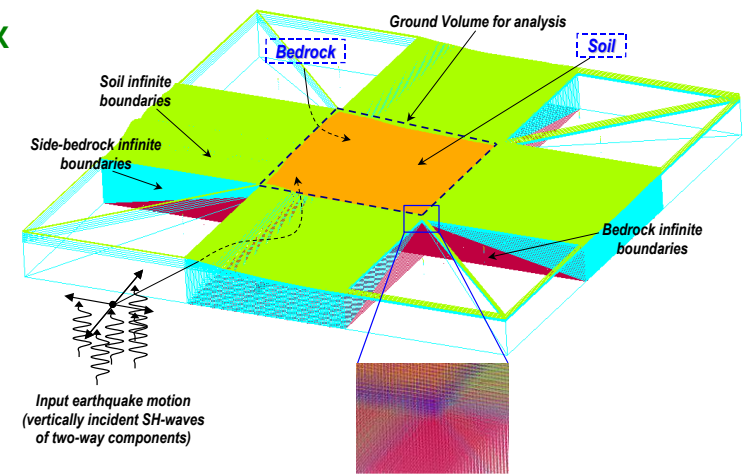
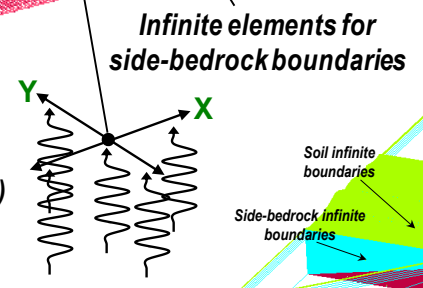
# 다차원(3D) 지반지진응답 해석 입력 $V_s$ 활용

## 관심 영역 3D 공간 지반정보 기반 3D FE 모델링 지진지반운동 예비평가

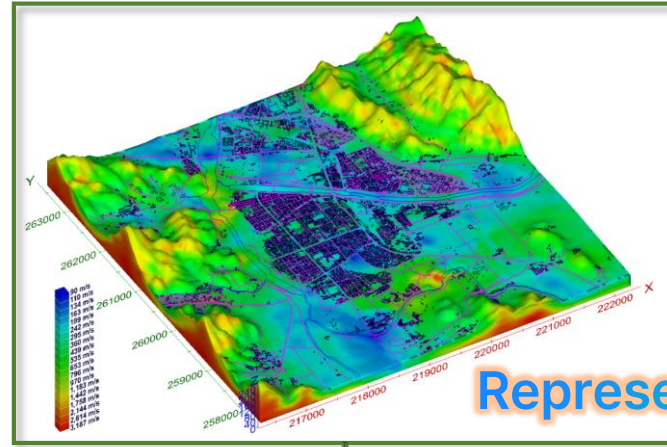
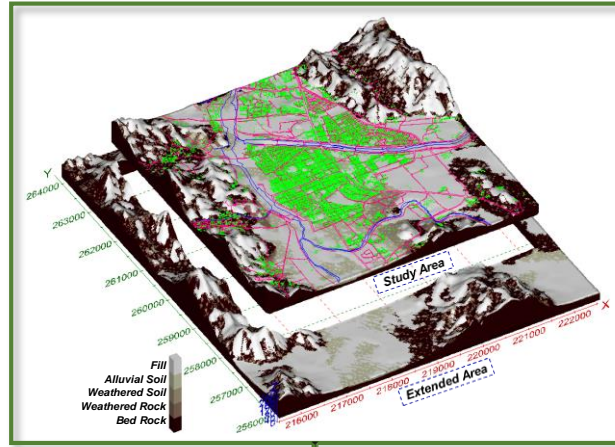


(Sun, 2012)

Hexahedral elements for bedrock ( $V_s = 1,000 \text{ m/s}, \nu = 0.2$ )



# 3D 공간 지반 지진공학 정보 구현 기반 지역적 지진 지반운동 결정



Geo-Layer	$V_s$ (m/s)
FL	190
AS	280
WS	350
WR	650

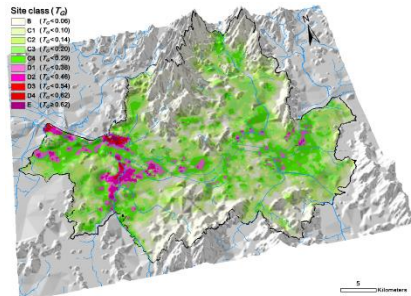
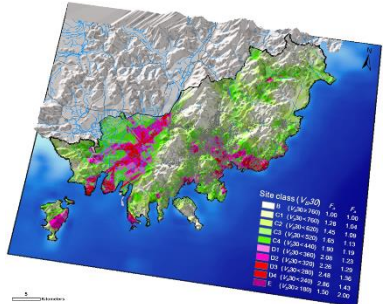
Representative  $V_{s30}$

$$H = \sum_{i=1}^n D_i$$

$$V_{S,Soil} = \sum_{i=1}^n D_i / \sum_{i=1}^n \frac{D_i}{V_{Si}}$$

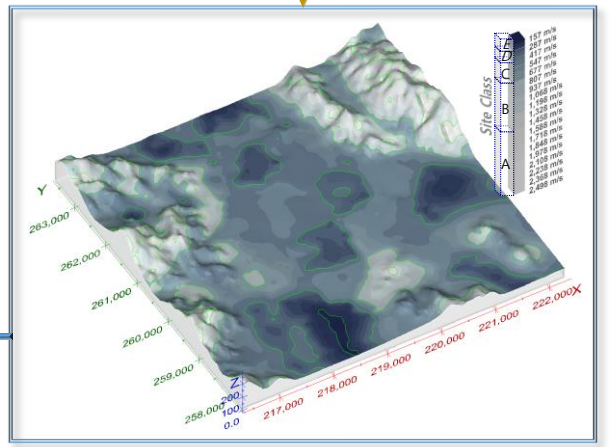
$$V_{S30} = 30 / \sum_{i=1}^n \frac{d_i}{V_{Si}}$$

$$T_G = 4 \sum_{i=1}^n \frac{D_i}{V_{Si}}$$



(Sun and Kim, 2017)

## Site Classification (Site Effects)



Regional Estimation  
of Earthquake Ground  
Motions with Various  
Seismicity Levels

Regional Evaluation  
and Quantification  
of Site Amplification  
Characteristics

# 참고문헌

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감사합니다.