Evaluation of Dynamic Soil Properties

June 3, 2008

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- Introduction

1) Seismic testing methods from exploration geophysics for dynamic soil properties

A variety of geophysical methods have been widely applied to geotechnical engineering for determining various subsurface soil properties. In particular, seismic methods such as borehole seismic testing methods and surface wave methods are recently applied to obtain dynamic soil properties, to require primarily for seismic design and seismic performance evaluation. From the geotechnical perspective, shear wave velocity (V_S) which were usually emphasized as a seismic design parameter could be determined only from in-situ seismic tests.

2) Determination of shear modulus from in-situ tests

Seismic field tests measure the small strain response of a relatively large volume of ground (ref., Fig. 1).

$$G_{\max} = G_0 = \rho V_S^2$$

Where, $G_{\max}$, G_0 : maximum shear modulus at small strain level,

ρ : total mass density, V_S : shear wave velocity

$$G = \frac{E}{2(1+\nu)}$$

Where, G : shear modules, E : elastic modulus, ν : Poisson's ratio

$$\nu = \frac{\frac{1}{2}(V_P / V_S)^2 - 1}{(V_P / V_S)^2 - 1}$$

Where, V_P : compression wave velocity, V_S : shear wave velocity

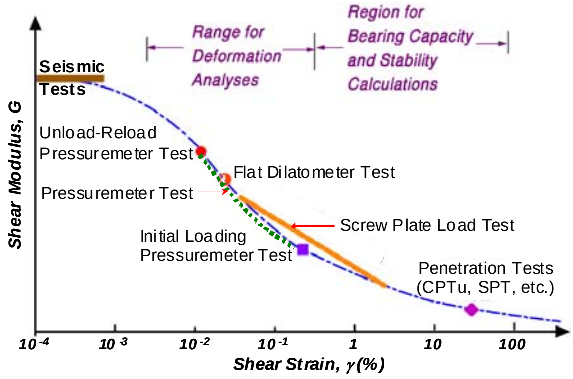

Fig. 1. Shear modulus with strain determined from various in-situ tests

3) Importance of in-situ tests for seismic design of geotechnical structures

For the reliable seismic design and seismic performance evaluation of both geotechnical structures and super structures, dynamic soil properties should be determined from in-situ tests and laboratory tests. The V_S profiles from the field seismic tests are very important to reflect the site-specific characteristics (ref., Fig. 2).

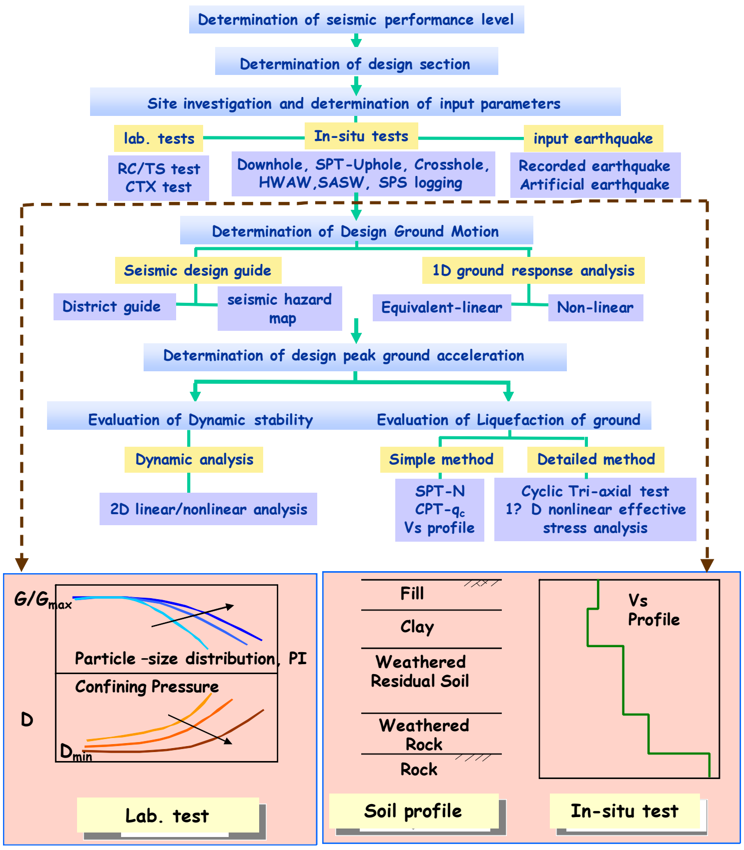

Fig. 2. Importance of dynamic soil properties for seismic design

- Conventional Field Tests

Since the beginning of geotechnical engineering, a good number of different geotechnical in-situ tests have been developed and, nowadays, several methods are available for site investigation in soil deposits with the most common being the SPT, CPTu (also CPT), flat dilatometer test (DMT), pressuremeter test (PMT) and vane shear test (VST). Besides these geotechnical in-situ investigation tests, the recent site investigation program could include various geophysical methods for obtaining the V_S profile. Among the common in-situ tests, the most widely used dynamic and static penetration testing methods coupled with the geophysical seismic methods are the SPT with borehole drilling and sampling and the CPTu.

1) Standard penetration test (SPT) with borehole drilling investigation (ref., Fig. 3)

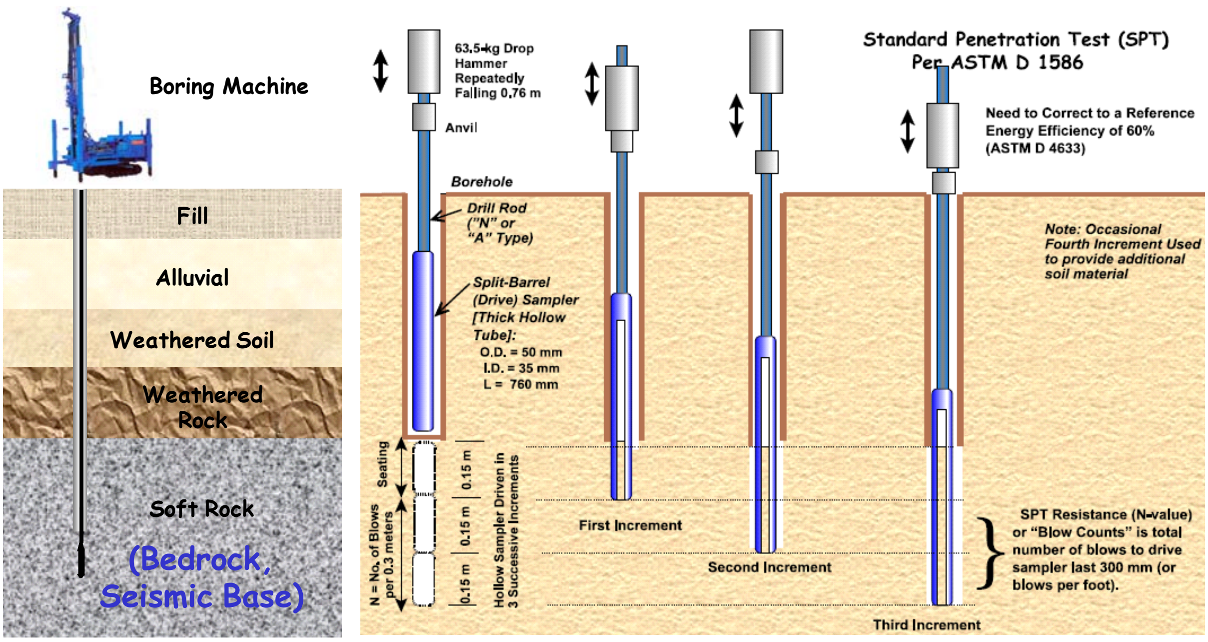

Fig. 3. Schematic of borehole drilling and SPT (modified from Mayne et al., 2001)

2) Piezocone penetration test (CPTu) (ref., Fig. 4)

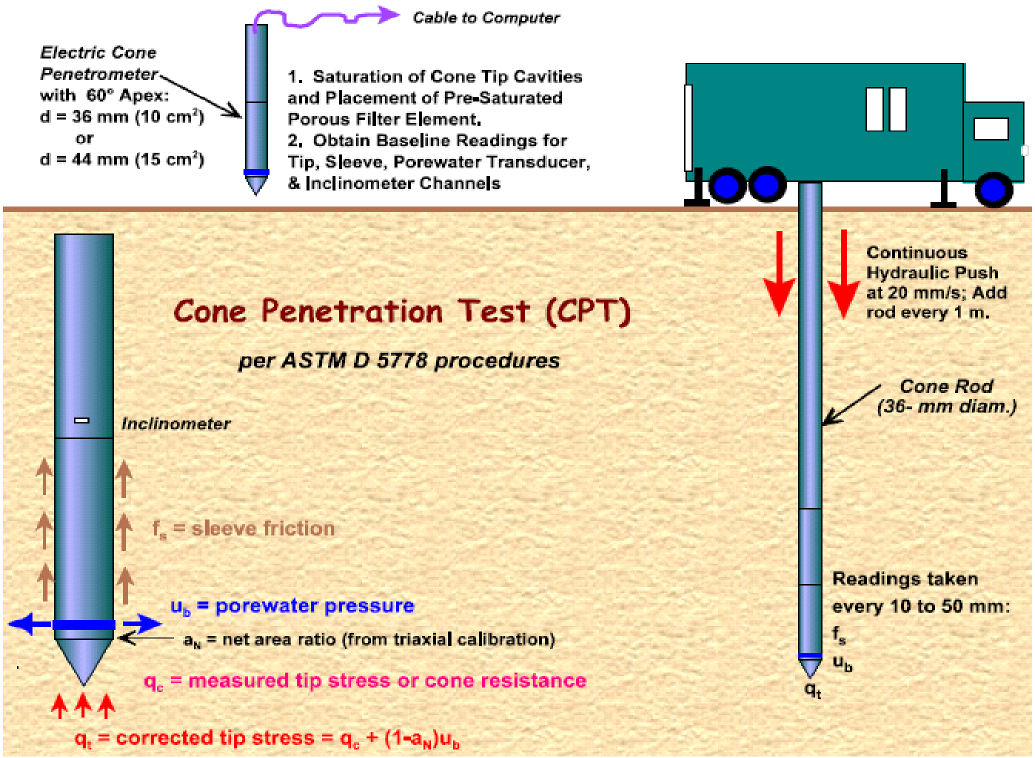

Fig. 4. Schematic of CPTu (after Mayne et al., 2001)

- Outline of Seismic Field Tests

The testing methods for measurement of V_S are divided as in-situ tests and laboratory tests (ref., Fig. 5). The in-situ tests are composed of non-intrusive methods such as surface seismic tests and intrusive methods such as borehole seismic tests. The surface seismic tests are often less expensive and can be performed relatively quickly, whereas the borehole seismic tests are usually more accurate and have generally the information gained directly from the boring investigation. Typical surface seismic tests include spectral analysis of surface waves (SASW) test, multi-channel analysis of surface waves (MASW) test, harmonic wavelet analysis of waves (HWAW) test, seismic reflection test, seismic refraction test and steady-state vibration (or surface wave) test. And representative borehole seismic tests are crosshole test, downhole test, uphole test, inhole test, suspension logging test and seismic cone test.

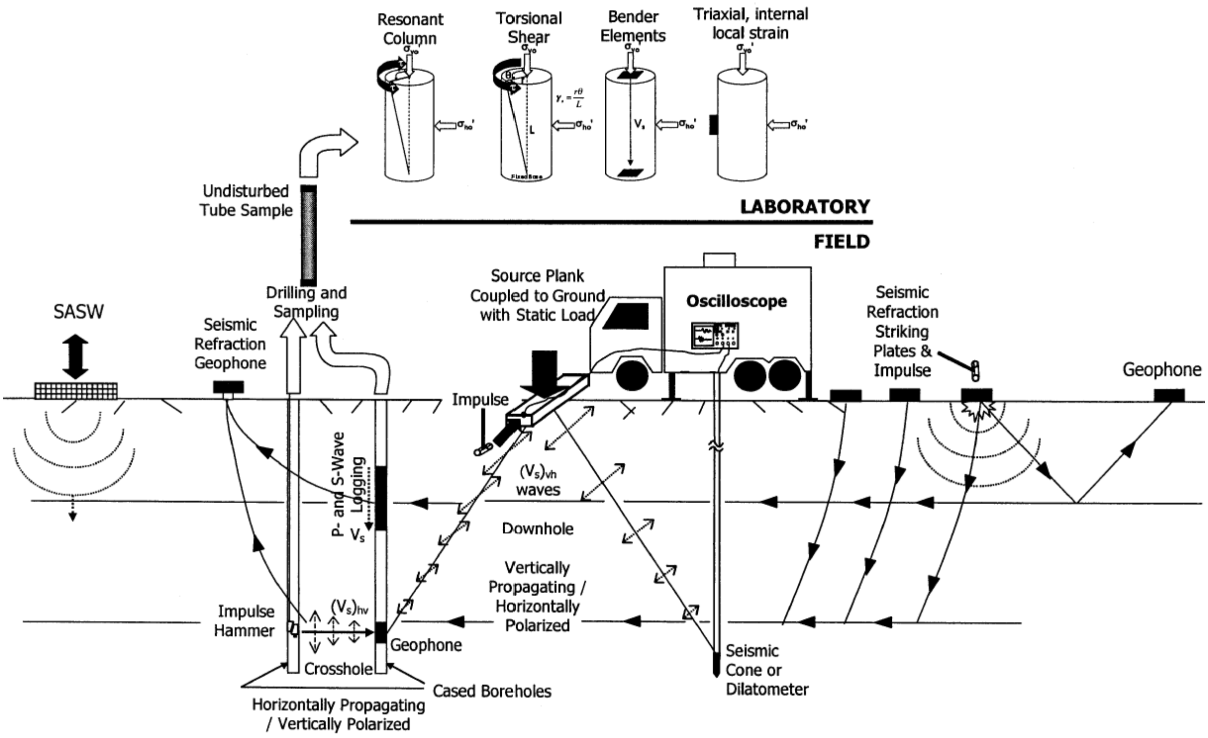

Fig. 5. Field and laboratory tests for obtaining V_S (after Schneider et al., 2001)

- Crosshole Seismic Test

- Need more than two boreholes: one for source and the others for receivers
- Generation of body wave within a borehole and its detection at another borehole at the same depth (ref., Fig. 6)
- More reliable than other seismic testing methods and more simple for interpretation.

$$V_S = \text{(Distance from Source to Receiver) / (Travel Time of Shear Wave)}$$

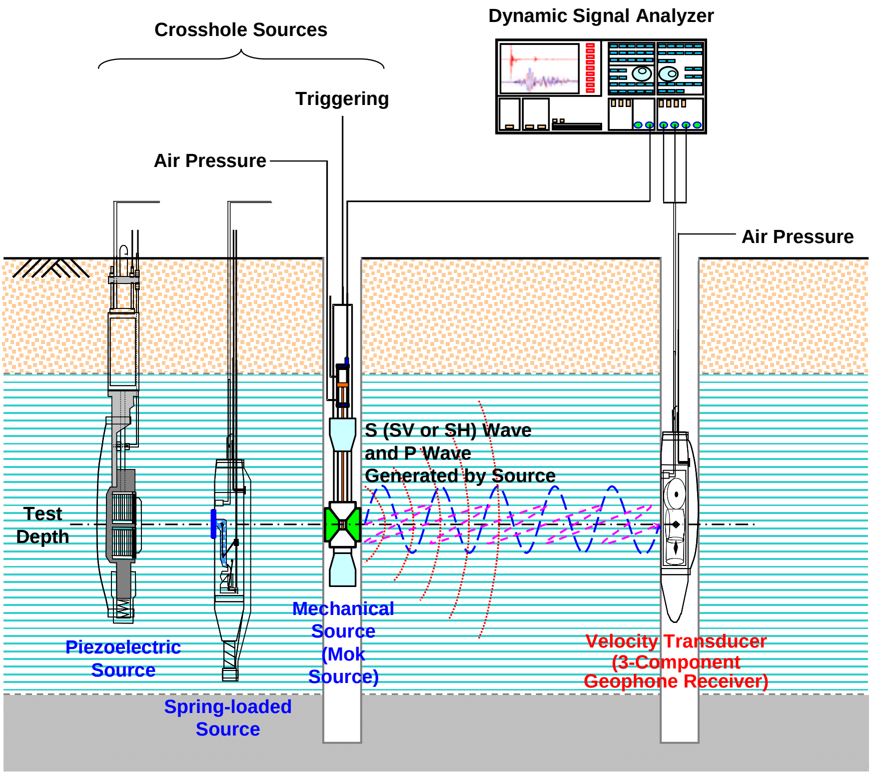

Fig. 6. Schematic of crosshole seismic test

- Downhole Seismic Test

- Need only one borehole: use surface source (ref., Fig. 7)
- Limitation of exploration depth due to use surface source
- Rigorous interpretation method is required considering refracted ray path
- After obtaining waveforms with depth from the downhole seismic test in a field, wave arrival times with the testing depth should be first picked by means of several picking methods: cross-over method, peak-to-peak method, and cross-correlation method.
- After picking the wave arrival times or time differences, the V_S profile is deduced by means of several downhole interpretation methods: direct method, interval method, modified interval method, and refracted ray path method.

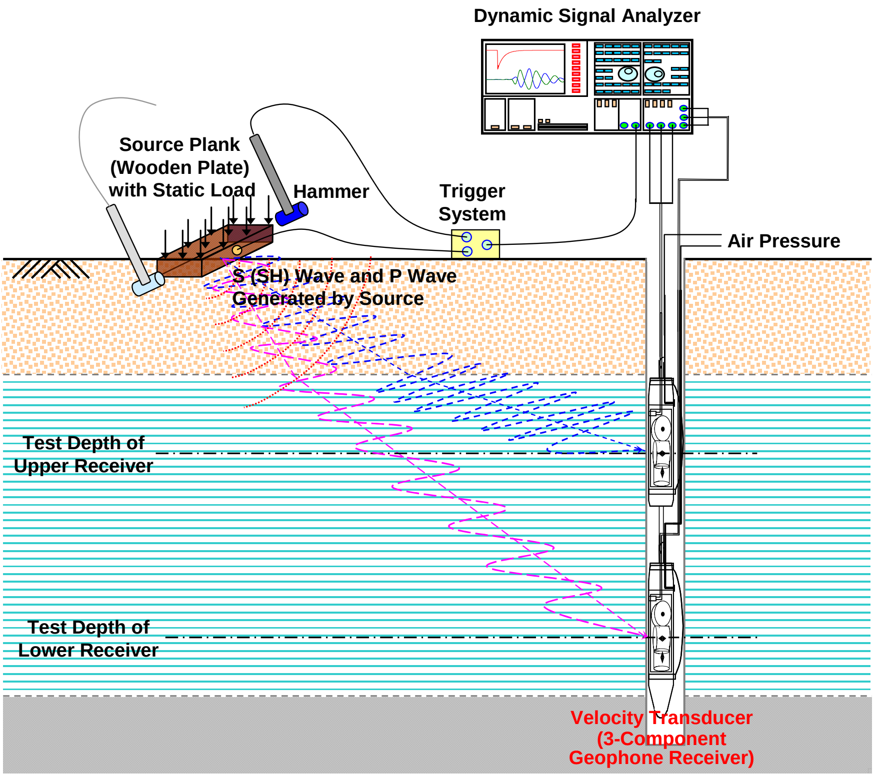

Fig. 7. Schematic of downhole seismic test

1) Wave arrival time picking method

a) Cross-over method (ref., Fig. 8)

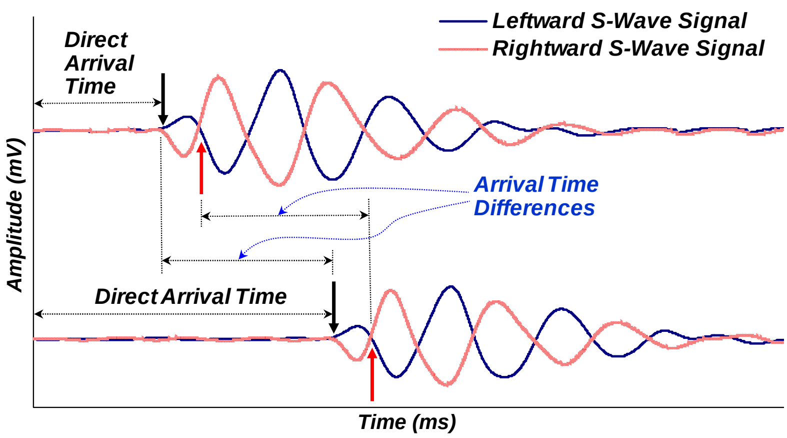

Fig. 8. Concept of cross-over method

b) Peak-to-peak method (ref., Fig. 9)

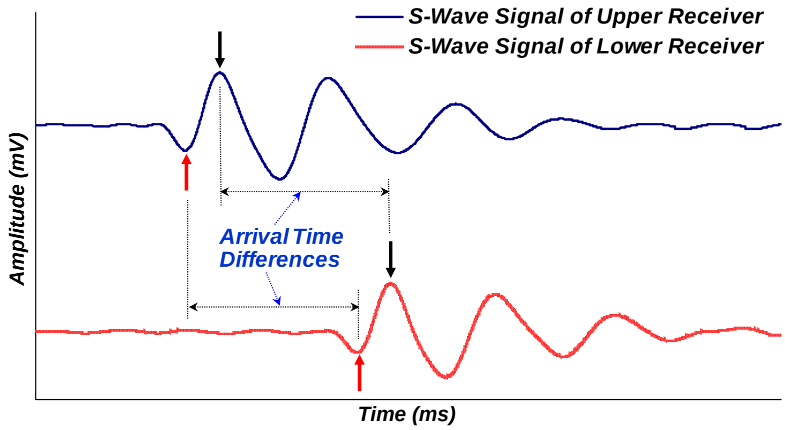

Fig. 9. Concept of peak-to-peak method

c) cross-correlation method (ref., Fig. 10)

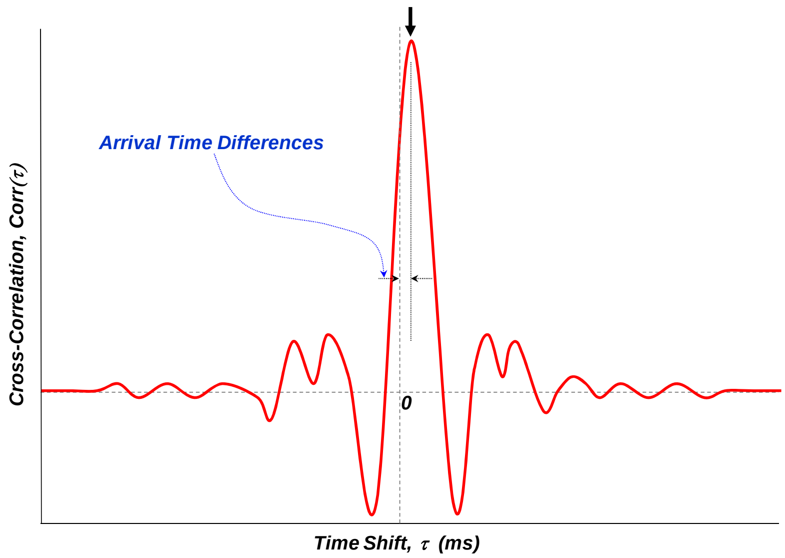

Fig. 10. Function of cross-correlation for selected waveform windows

2) Downhole interpretation method

a) Direct method

- Determination of mean velocity profile using direct (corrected) travel time

- Corrected travel time (t_c) (ref., Fig. 11)

$$t_c = D\frac{t}{R}$$

Where, D : depth of receiver, t : measured travel time,

R : Inclined travel path

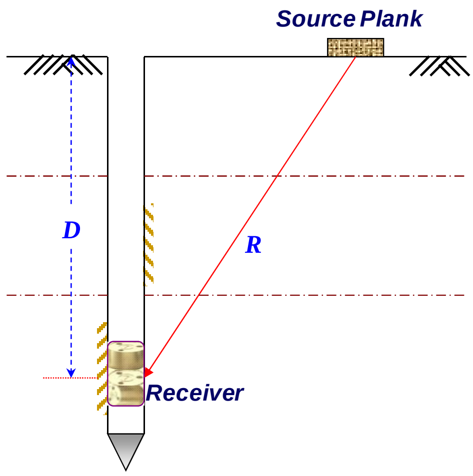

Fig. 11. Concept of direct method

- Shear wave velocity (V_S) of each soil layer having similar travel time

$$V_S = \frac{\Delta D}{\Delta t_c}$$

b) Interval method

- Using travel time (T_l or T_u) delay between two receivers
- Shear wave velocity (V_S) between two receivers (or adjacent testing depth) (ref., Fig. 12)

$$V_S = \frac{R_l - R_u}{T_l - T_u}$$

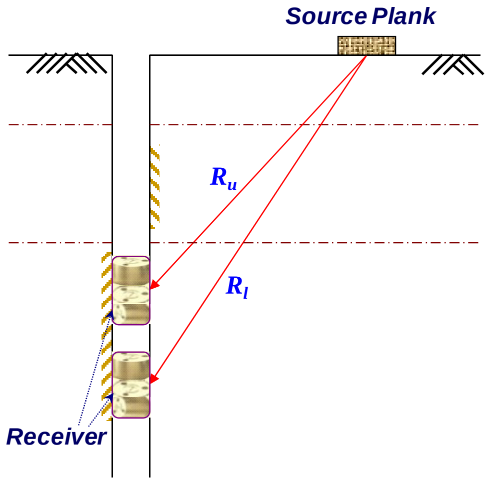

Fig. 12. Concept of interval method

c) Modified interval method

- Considering the stiffness of upper layers and straight ray path (ref., Fig. 13)

$$V_S = \frac{L_{ii,l}}{T_{i,l} - \sum_{j=1}^{i-1} \frac{L_{ij,l}}{V_{S\,j}}}$$

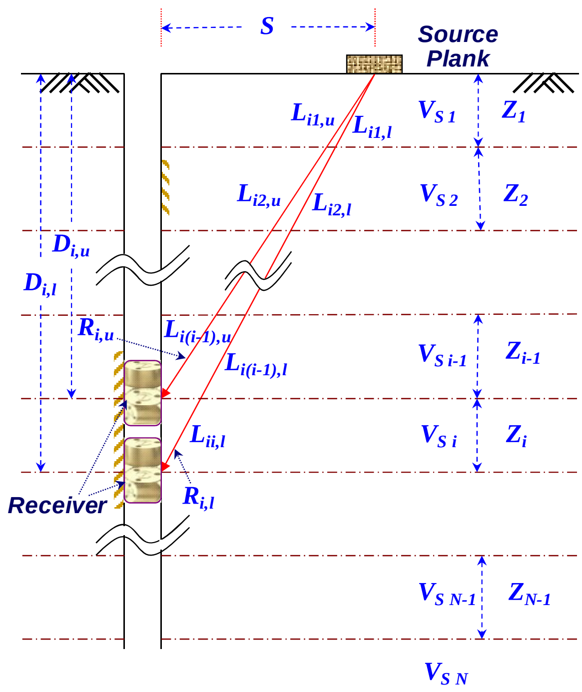

Fig. 13. Concept of modified interval method

d) Refracted ray path method

- Considering refracted ray path due to the stiffness differences between layers (ref., Fig. 14)
- Adopt Snell's law and the equation same as the modified interval method

$$\frac{\sin\theta_{i1}}{V_{S1}} = \frac{\sin\theta_{i2}}{V_{S2}} = \cdots = \frac{\sin\theta_{ij}}{V_{S\,j}} = \cdots = \frac{\sin\theta_{ii}}{V_{S\,i}}$$

$$V_S = \frac{L_{ii.l}}{T_{i,l} - \sum_{j=1}^{i-1}\frac{L_{ij,l}}{V_{S\,j}}}$$

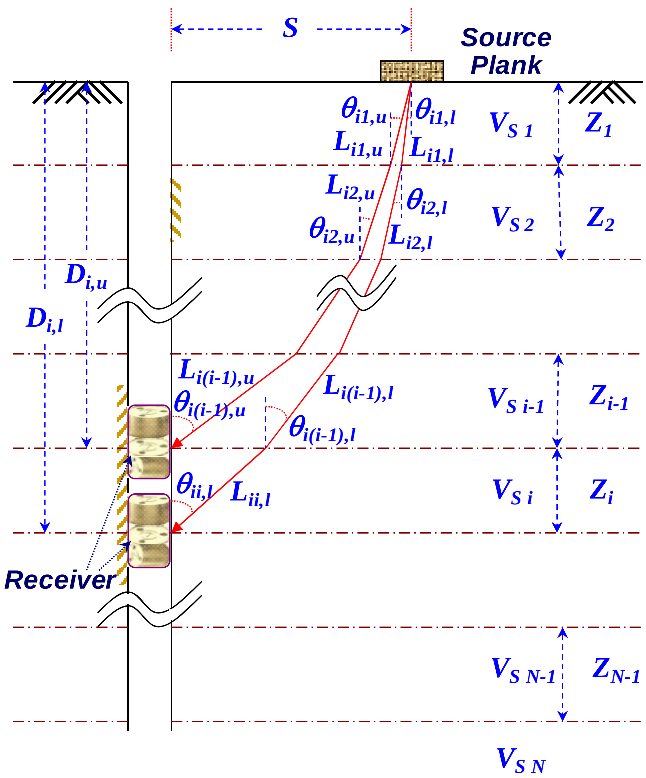

Fig. 14. Concept of refracted ray path method

3) Other field testing technique coupled with the downhole seismic test

a) Seismic piezocone penetration test (SCPTu)

- Use the seismic cone which is an ordinary CPTu probe with a built-in geophone (or accelerometer)
- Perform the downhole seismic test during the CPTu (ref., Fig. 15)

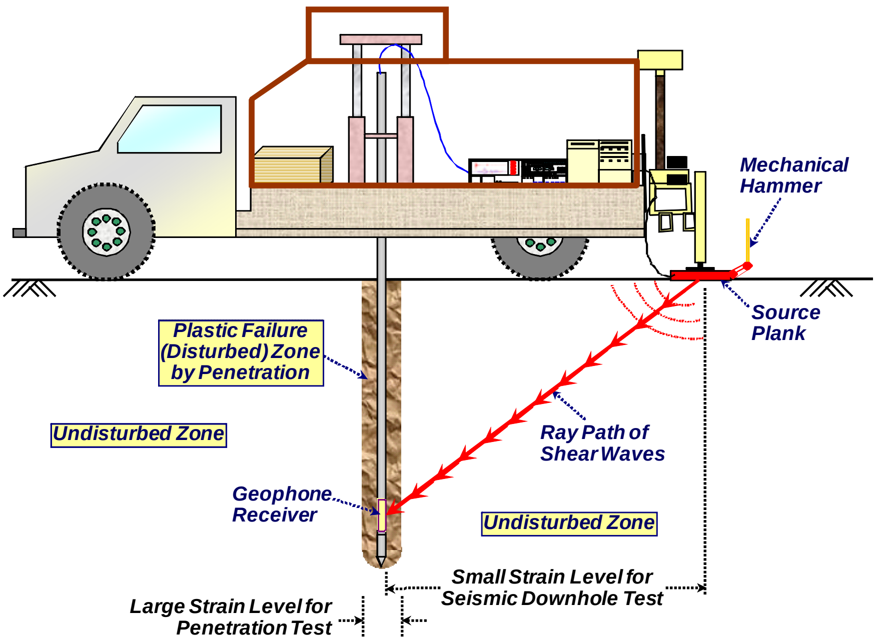

Fig. 15. Procedure and dual strain levels of the SCPTu

b) Seismic dilatometer penetration test (SDMT)

- Use the seismic dilatometer probe which is an ordinary DMT probe with a built-in geophone (or accelerometer)
- Perform the downhole seismic test during the DMT

● Uphole Seismic Test

- Need one borehole: use several sources within the borehole (SPT, blasting and so on) and surface geophones (ref., Fig. 16)
- Rigorous interpretation method is required considering refracted ray path similar to the downhole test with inverse geometry

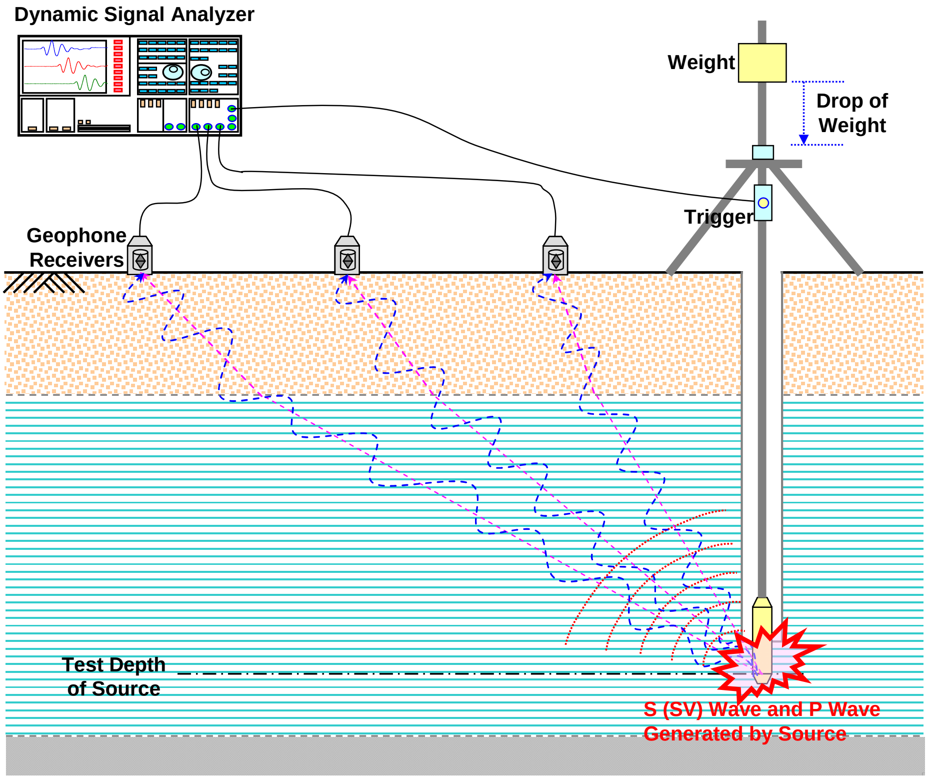

Fig. 16. Schematic of uphole seismic test

- Inhole Seismic Test

  - Need one borehole: locate source and receivers in the same borehole
  - Conduct the Inhole seismic technique mostly for open-hole typed rock formation (ref., Fig. 17)
  - Perform the suspension PS logging for the ground usually lower than ground water level adopting for PVC casing or open-hole filled with bentonite slurry (ref., Fig. 18)

V_S = (Distance from Source (Receiver) to Receiver) / (Travel Time of Shear Wave)

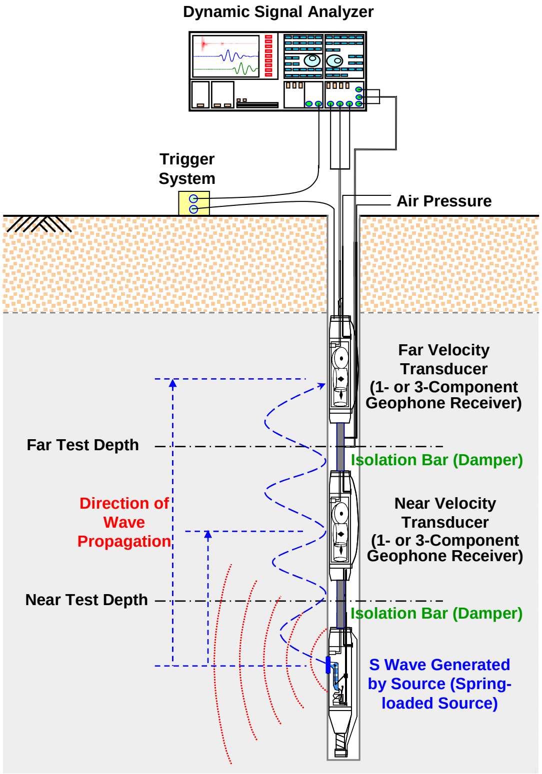

Fig. 17. Schematic of inhole seismic test

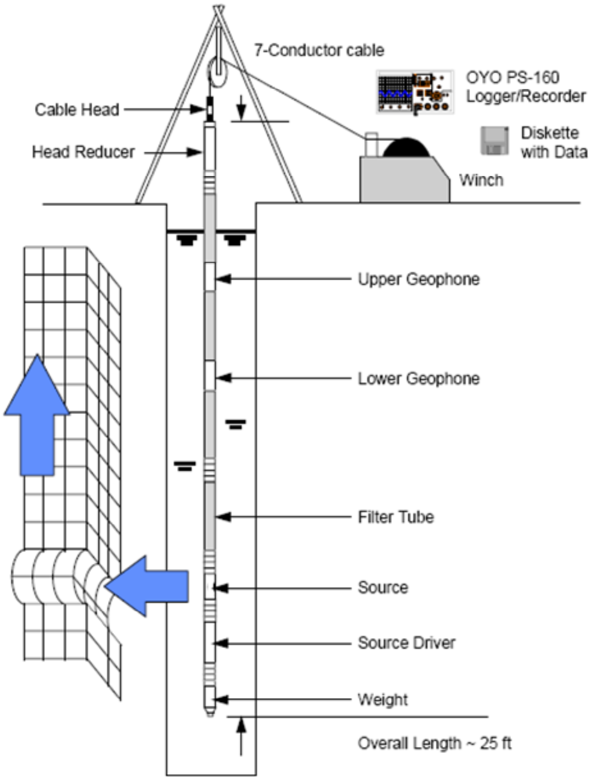

Fig. 18. Schematic of suspension PS logging

- Surface Wave Methods

Surface or Rayleigh waves are distortional stress waves that propagate near to the boundary of an elastic half space, in this case the ground surface. The propagation velocity of surface waves is controlled by the stiffness of the ground within one half and one third wavelength of the surface and so measurements therefore need to determine their wavelength as well as their velocity. The VS profile can be determined by using the inversion of the experimental dispersion curve obtained based on the signals in the field (ref., Fig. 19).

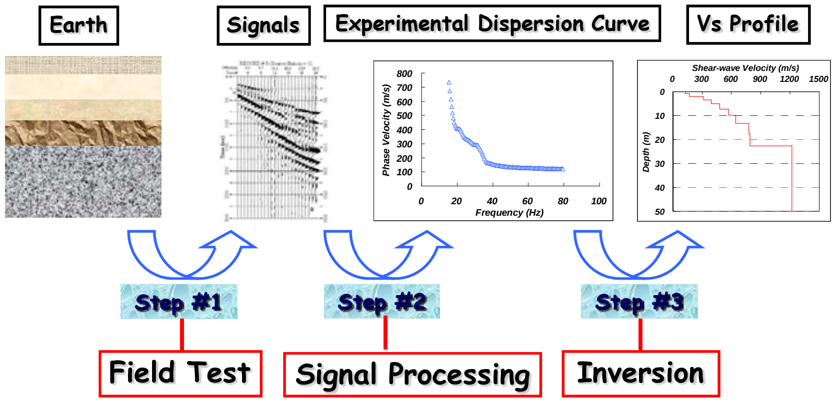

Fig. 19. Three steps of surface wave methods

1) Spectral analysis of surface waves (SASW) method

- A variety of sources: impact sources (sledge hammer or drop weight) and continuous source (heavily equipment with caterpillar or massive vibrator)
- Use two geophone (generally 1 Hz) receivers
- Perform with several receiver spaces mostly with 1 m, 2 m, 4 m, 8 m, 16 m, 32 m, and more (ref., Fig. 20)

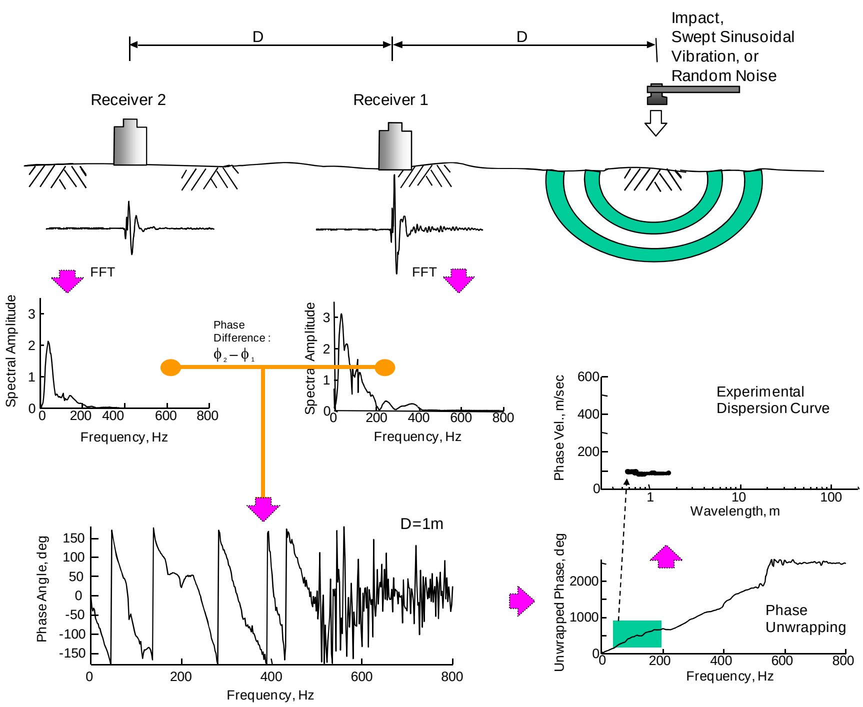

Fig. 20. Basic configuration and phase velocity calculation for SASW method

2) Muti-channel analysis of surface waves (MASW) method

- Use simply impact source (sledge hammer) and a series of twelve geophones (4.5 Hz) receivers (ref., Fig. 21)

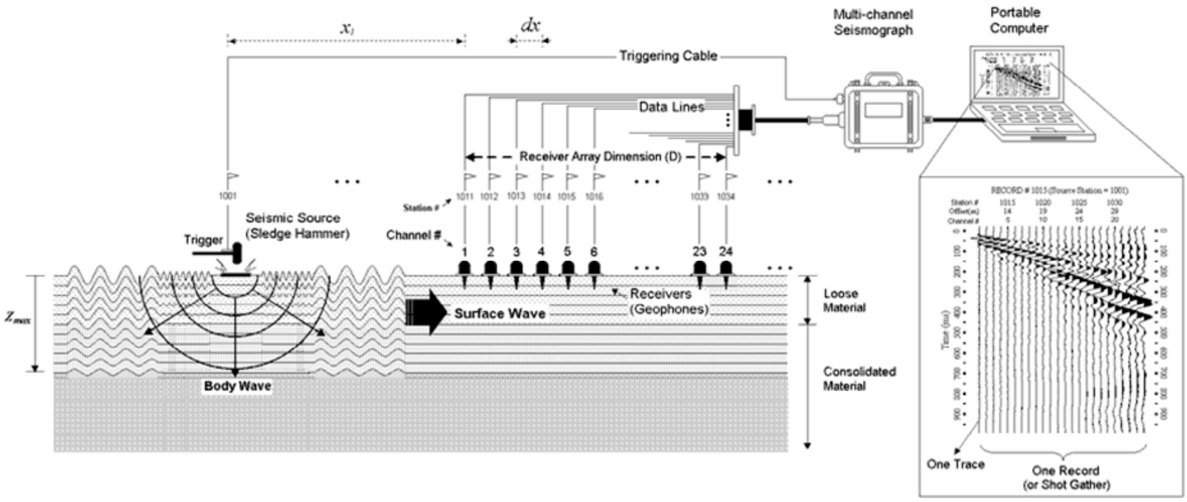

Fig. 21. Overall setup and obtaining of signals for MASW method

3) Harmonic wavelet analysis of waves (HWAW) method

- Use simply impact source (sledge hammer) and two geophone (1 or 4.5 Hz) receivers
- Perform with only 2 m receiver space and 4 m source offset from near receiver (ref., Fig. 22)

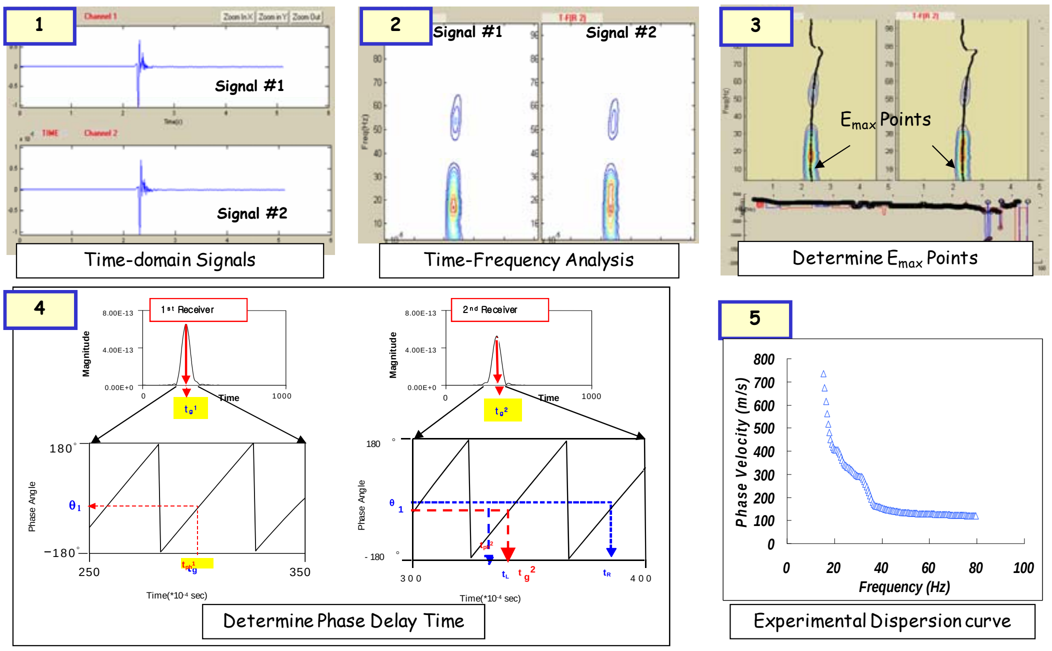

Fig. 22. Determination of experimental dispersion curve by HWAW method

- Evaluation of Representative V_S profile

- Deduce V_S profile from ground free surface to bedrock depth based on several types of filed seismic tests
- Consider different reliability of test results according to site conditions and test methods
- Need to combine results of each test properly (ref., Fig. 23)
- Evaluation of representative V_S profile considering reliability region

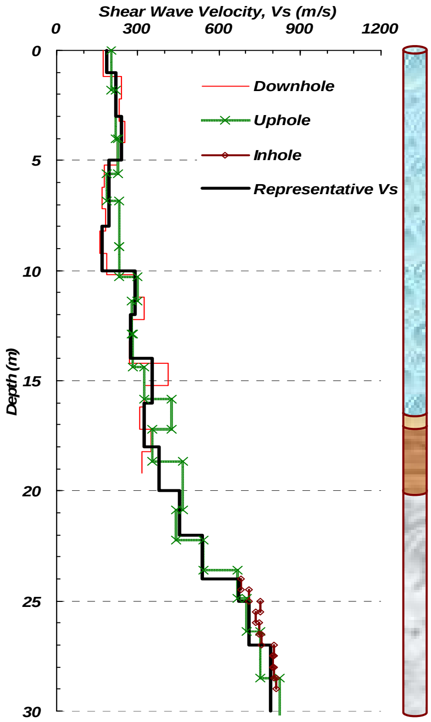

Fig. 23. Typical example of evaluation of representative V_S profile

- References

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