CYCLIC BEHAVIOUR of SOILS

Atilla Ansal
Ground Motion Characterization

Proper design of earthquake-resistant structures requires estimation of the level of ground shaking to which they will be subjected.

Level of ground shaking depends on the characteristics of the source, the path and the site.
Field Testing in Geotechnical Engineering
LOCAL SITE CONDITIONS

- Soil Stratification
- Geological Structure
- Ground water table level
- Bedrock Depth
- Properties of soil layers
SOILS

- Fine grained soils, silts and clays
- Coarse grained soils, sands and gravels
### Unified Soil Classification and Symbol Chart

#### Coarse-Grained Soils
- **Clean Gravels** (Less than 5% fines)
  - GW: Well-graded gravels, gravel-sand mixtures, little or no fines
  - GP: Poorly-graded gravels, gravel-sand mixtures, little or no fines

- **Gravels** with fines (More than 12% fines)
  - GM: Silty gravels, gravel-sand-silt mixtures
  - GC: Clayey gravels, gravel-sand-clay mixtures

- **Clean Sands** (Less than 5% fines)
  - SW: Well-graded sands, gravely sands, little or no fines
  - SP: Poorly graded sands, gravely sands, little or no fines

- **Sands** with fines (More than 12% fines)
  - SM: Silty sands, sand-silt mixtures
  - SC: Clayey sands, sand-clay mixtures

#### Fine-Grained Soils
- **Silt and Clays**
  - ML: Inorganic silts and very fine sands, rock flour, silty of clayey fine sands or clayey silts with slight plasticity
  - CL: Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays
  - OL: Organic silts and organic clay silts of low plasticity

- **Silt and Clays**
  - MH: Inorganic clays of high plasticity, fat clays
  - CH: Inorganic clays of high plasticity, fat clays
  - OH: Organic clays of medium to high plasticity, organic silts

#### Highly Organic Soils
- **PT**: Peat and other highly organic soils

### Laboratory Classification Criteria

- **GW**:
  \[ C_u = \frac{D_{60}}{D_{10}} \] greater than 4; \[ C_c = \frac{D_{30}}{D_{10} \times D_{60}} \] between 1 and 3

- **GP**: Not meeting all gradation requirements for GW

- **GM**: Afterberg limits below "A" line or P.I. less than 4

- **GC**: Afterberg limits above "A" line with P.I. greater than 7

- **SW**:
  \[ C_u = \frac{D_{60}}{D_{10}} \] greater than 4; \[ C_c = \frac{D_{30}}{D_{10} \times D_{60}} \] between 1 and 3

- **SP**: Not meeting all gradation requirements for GW

- **SM**: Afterberg limits below "A" line or P.I. less than 4

- **SC**: Afterberg limits above "A" line with P.I. greater than 7

### Plasticity Chart

- **ML & OL**: Peat and other highly organic soils

- **CH**: Inorganic clays of high plasticity, fat clays

- **CL**: Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays

- **OH**: Organic clays of medium to high plasticity, organic silts

- **MH & OH**: Inorganic clays of medium to high plasticity, organic silts

- **A LINE**: PI = 0.73(LL-20)

- **PI**: Plastics Index

- **LL**: Liquid Limit (%)
Plasticity Chart

Liquid limit (LL) vs. Plasticity Index (PI)

- Low plastic inorganic clays; sandy and silty clays
- Silty clays; clayey silts and sands
- Medium plastic inorganic clays
- Inorganic clays of high plasticity
- Micaceous or diatomaceous fine sandy and silty soils; elastic silts; organic silts, clays, and silty clays
- Inorganic and organic silts and silty clays of low plasticity; rock flour; silty or clayey fine sands

U-line: PI = 0.9(LL - 8)
A-line: PI = 0.73(LL - 20)
Why do we want to know dynamic soil properties?

Characteristics of the soil can greatly influence the nature of shaking at the ground surface. Soil deposits tend to act as ‘filters’ to seismic waves by attenuating motion at certain frequencies and amplifying it at others.

One major uncertainty: dynamic soil properties and their dependency on the excitation level (i.e. nonlinear behavior of soil with increasing strain amplitude).

One of the most important aspects of geotechnical earthquake engineering practice involves evaluation of the effects of local soil conditions on strong motion. Evaluation of the effects of local soil conditions requires quantification of the soil behavior under dynamic loading. The behavior of soil subjected to dynamic loading is governed by what have come to be known as ‘dynamic soil properties’.
CHARACTERISTICS of DYNAMIC BEHAVIOUR

SOIL BEHAVIOUR UNDER DYNAMIC LOADING

STRESS – STRAIN RELATIONS
• Shear Modulus
• Damping Ratio
• Strain Dependent Modulus and Damping

SHEAR STRENGTH PROPERTIES
• Number of Cycles
• Cyclic Stress Ratio

During earthquake
After earthquake
Cyclic Stress-Strain Behaviour of Soils

- Dynamic shear modulus
- Damping Ratio

1. Definition of
   - Dynamic Shear Modulus
   - Damping Ratio
   A. Empirical
   B. Not a material property
   C. Modeling Cyclic Behavior
   D. Single phase model

2. Determination
   A. Stress Controlled Tests
   B. Strain Controlled Tests

\[ D = \frac{1}{4\pi} \frac{\Delta W}{W} \]
Factors Affecting Cyclic Behaviour Of Soils

- Shear Strain
- Void ratio
- Effective confining pressure
- Plasticity
- Overconsolidation ratio
- Saturation
- Number of cycles
- Frequency
LABORATORY TESTS

Soil element tests: Classified into two categories considering the shear strain levels at which they are able to measure accurately of these properties:

- Low-strain element tests:
  - Resonant column test
  - Piezoelectric bender element test
- High-strain element test:
  - Cyclic direct simple shear test
  - Cyclic triaxial test
  - Cyclic torsional shear test.

Model tests: Use a small-scale physical model of a full-scale prototype structure and aim to simulate the boundary conditions of a geotechnical problem. Shaking table tests and centrifuge tests are among the most referred model tests in these studies.
Laboratory Measurement of Dynamic Soil Properties

Laboratory Methods in General

1. Reproduction of Initial In Situ Conditions
A specimen typically sized ~38-50 mm in diameter with similar moisture content, density and structure as in the field is consolidated under estimated in situ stress

2. Stress- or Strain-Controlled Loading
Earthquake Loading in the Field  Harmonic Loading in the Laboratory

3. Measurement of Soil Response
   Load  ➔  Stress
   Deformation  ➔  Strain
   Pore Pressure  ➔  Excess Pore Pressure
Cyclic Triaxial Test (CTT)
• cylindirical specimen placed between top and bottom loading plates sealed by a rubber membrane
• confined in a triaxial chamber subjected to radial stress through pressurized cell fluid
• axial stress applied on top through loading rod

Testing procedure:
1. saturation and consolidation to reproduce initial in situ conditions
2. cyclic loading under undrained conditions by applying sinusoidally varying axial load
3. axial load, axial deformation, and porewater pressure development with time are monitored.
The cyclic loading generally causes an increase in the pore-water pressure in the specimen, resulting in a decrease in the effective stress and an increase in the cyclic axial deformation of the specimen.
for a given hysteresis loop;

1. calculate the Young's Modulus (E)
2. calculate the material damping ratio (D)
   \[ D = \frac{A_L}{4 \pi A_T} \]
3. calculate the shear modulus (G)
   \[ G = \frac{E}{2(1+\nu)} \]
4. calculate the shear strain (\( \gamma \))
   \[ \gamma = \varepsilon_a (1+\nu) \]
Cyclic Triaxial Test (CTT)

Limitations

• **Measurement of shear strain is indirect**

*Typically obtained through the normal strain and an assumed value of Poisson’s ratio*

• **Stress concentrations at the top and bottom platens.**

*Nonuniform stress conditions within the test specimen are imposed by the specimen end platens. This can cause a redistribution of void ratio within the specimen during the test.*

• **Stress path is not representative of those in the field.**

*A 90° change in the direction of the major principal stress occurs during the two halves of the loading cycle on isotropically consolidated specimens.*

• **System compliances such as membrane penetration effects, piston friction etc.**

The interaction between the specimen, membrane, and *confining fluid has an influence on cyclic behavior. Changes in pore-water pressure can cause changes in membrane penetration in specimens of cohesionless soils. These changes can significantly influence the test results.*

• **Usually can not measure strains below 10^-2%**.

*Typically $G_{\text{max}}$ is measured at strains less than 0.001%*
Cyclic Simple Shear Test (CSST)
Cyclic Simple Shear Test (CSST)

- The cyclic loading generally causes an increase in the pore-water pressure in the specimen, resulting in a decrease in the effective stress and an increase in the cyclic shear deformation of the specimen.

for a given hysteresis loop;
- calculate the shear modulus \((G)\)
- calculate the material damping ratio \((D)\)

\[
D = \frac{A_L}{4 \pi A_T}
\]
Cyclic Simple Shear Test (CSST)

**Limitations**
Significant nonuniformity in the stress distribution at the specimen boundaries. 
Shear stress is only applied to the top and bottom surfaces of the specimen and since no complimentary shear stresses are imposed on the vertical sides, the moment caused by the horizontal shear stresses must be balanced by non uniformly distributed shear and normal stresses.

**Advantages**
A better representation of the idealized field stress conditions (plane strain conditions) 
Principle stresses continuously rotate due to the application of shear stress as similar to those imposed on the soil element in the field subjected to vertically propagating shear waves.
Direct measurement of shear stress and shear strain
Cyclic Torsional Shear Test (CTST)
• A cylindrical or hollow cylindrical soil specimen is enclosed in rubber membrane and confined in a triaxial chamber where it is subjected to in situ confining pressure.
• Axial load and torque is applied to the top of the specimen.
• Axial load, torque, axial deformation, angular rotation and porewater pressure development with time are monitored.
Cyclic Torsional Shear Test (CTST)

for a given hysteresis loop;

- calculate the shear modulus \( G \)
- calculate the material damping ratio \( D \)

\[
D = \frac{A_L}{4 \pi A_T}
\]
Cyclic Torsional Shear Test (CTST)

**Limitations**

- Equipment not so common.
- Specimen preparation can be difficult for hollow cylinder specimens.
- Cylindrical specimens suffers from stress nonuniformity.

*Shear strain varies radially within the specimen, from zero at the center to a maximum at the perimeter for a solid specimen.*

**Advantages**

- A better representation of the idealized field stress conditions (plane strain conditions).
- *Cyclic shear stresses on horizontal planes with continuous rotation of principal stresses*
- Can measure properties over a wider range of strains.
Resonant Column and Torsional Shear Test (RCTS)

- A cylindrical soil specimen placed in a confining chamber and pressurized to the in situ confining pressure
- Specimen is vibrated in harmonic torsional motion using a coil-magnet drive system and the response to torsional loading is measured.
- Combination of two tests can be performed on the same specimen
  1. Resonant Column Test
  2. Torsional Shear Test
Switching from one type of test to the other is done outside of the chamber by changing, *excitation frequency used to drive the specimen and the motion monitoring devices used to record the specimen response*
Resonant Column and Torsional Shear Test (RCTS)

Material damping is evaluated using either
1. Free-vibration decay curve is recorded by shutting off the driving force after specimen is vibrating in steady-state motion at the resonance frequency.
2. Half-power bandwidth method is based on measurement of the width of the dynamic response curve around the resonance peak.
Disturbance caused by sampling and sample preparation alters soil properties such as:

- fabric and structure (geometric or spatial arrangement of individual soil particles and voids, organization of soil constituents into larger compound particles)
- stress history
- strain history
- density
- degree of saturation

all of these adversely effect the ability of laboratory tests to accurately measure dynamic soil properties …
\[
\left( \frac{G_{\text{maks}}}{p_a} \right) = 321 \left( 2.97 - e \right)^2 \frac{AKO^M}{1 + e} \left( \frac{\sigma'_c}{p_a} \right)^N
\]

\[
\frac{G}{G_{\text{maks}}} = \frac{35.09}{1 - 0.99 \exp\left( -18.97 PI^{-1.27} \right)} + 34.74
\]

**Elastic threshold:**

\[
\gamma_e = \frac{0.035}{1 + 11.92 \exp(-0.1 PI)}
\]

**Plastic threshold:**

\[
\gamma_p = \frac{1}{1.39 - 0.33 PI^{0.28}}
\]

- **Cyclic Behaviour:** Elastic and Plastic threshold
- **Thresholds are functions of Plasticity Index**
Shear Strength Properties

- Shear Stress Amplitude
- Number of Cycles
GOLDEN HORN CLAY
Normally consolidated, organic, fat clay (CH/OH)

- Uniform Cyclic Shear Stresses
- Static Shear Tests Following Uniform Cyclic Shear Stresses
- Uniform Cyclic Loading Under Sustained Shear Stresses
- Simultaneous Application of Cyclic and Static Shear Stresses
BEHAVIOUR DURING UNIFORM CYCLIC LOADING

Cyclic Shear Stress Ratio - Shear Strain Amplitude Relationship

cyclic yield strength

for different number of cycles
TEKRARLI KAYMA GERİLİMİ ORANI

BİRİM KAYMA (%)

0,2 0,3 0,4 0,5 0,6 0,7 0,8 0,9

0 0,5 1 1,5 2 2,5 3

10 50 100 500
Shear Strength Ratio =

\[
\frac{\text{Post Cyclic Shear Strength}}{\text{Static Undrained Shear Strength}}
\]

Cyclic Shear Strain Ratio =

\[
\frac{\text{Maximum Shear Strain Amplitude}}{\text{Failure Strain in Static Shear Test}}
\]
POST EARTHQUAKE BEHAVIOUR

- Decrease in Effective Stresses
- Particle Structure Breakdown

Softening
Shear Strength Reduction
Additional Settlements
Soil Layers modify Earthquake Characteristics and Earthquake Excitations modify Engineering Characteristics of Soil Layers
TEKRARLI BİRİM KAYMA GENLİĞİ (%)

DINAMİK KAYMA MODÜLÜ (MPa)

STATİK KAYMA GERİLMESİ OLMADAN

STATİK KAYMA GERİLMESİ ALTINDA

**Numune özellikler:**

- AKO=1-1.5
- w=%26-51
- PI=%10-33
- sc=70-400 kPa (çevre basıncı)
Birim kayma genliği, $\gamma$ (%)

Birim şekil değiştirme, $\varepsilon$ (%)

Kayma modülü oranı, $G/G_{\text{maks}}$

Sonum oranı, $D$ (%)

$N=10$

$G_{\text{maks}}=34.8$ Mpa

$G/G_{\text{maks}}=\%100$

$D=\%2.82$
Birim kayma genliği, $\gamma$ (%)

Sönüm oranı, $D$ (%)

Birim şekil değiştirme, $\varepsilon$ (%)

Tekrarlı gerilme oranı, $\sigma_d/\sigma_c$

N=65

G=27.9 Mpa

$G/G_{\text{maks}}=82.1$

D=4.4

N=65-70
Tekrarlı gerilme oranı, \( \sigma_d/\sigma_c \)

Birim kayma genliği, \( \gamma(\%) \)

Sönüm oranı, \( D(\%) \)

N=145-150

G=1.5 Mpa

G/G_{maks}=\%5-3

D=\%17-19
Çevrim sayısı, $N$

Gerilme oranı genliği, $\varepsilon_d/2\varepsilon_c$

Boşluk suyu basıncı oranı, $u_c/\varepsilon_c$
FIELD TESTS

• **Low-strain tests:**
  - Seismic Reflection / Refraction Test
  - Seismic Cross-Hole / Down-Hole / Up-Hole Test
  - Steady-State Vibration (Rayleigh Wave) Test
  - Spectral Analysis of Surface Waves (SASW)
  - Suspension PS Logging
  - Seismic Cone Penetration Test (SCPT)

• **High-strain element test:**
  - Standard Penetration Test, SPT
  - Cone Penetration Test, CPT
  - Dilatometer Test, DMT
  - Pressuremeter Test, PMT
Measurement of Dynamic Soil Properties

**Laboratory** methods involve testing small specimens of soil samples (~38-70 mm in diameter) that are assumed to be representative of the soil in the field.

**Field** methods involve testing soil in place by measuring seismic wave propagation.

Factors such as testing procedure, testing errors and interpretation errors affect measurements.

**Laboratory Testing Methods**

(+ Pros.) conditions can be controlled
wide range of strains
can do parametric studies

(- Cons.) sample disturbance
specimen size
reproduction of actual field conditions (stress, chemical, thermal and structural)

**Field Testing Methods**

(+ Pros.) properties measured in existing state
do not require sampling
testing relatively large volume of soil

(- Cons.) conditions cannot be controlled
indirect measurement
limited strain range
Field Testing in Geotechnical Engineering

Standard Penetration Test (SPT)

- Quantifies penetration resistance of soils
- Provides some correlation with in-place (in-situ) soil properties

2-in. (51mm) split-spoon sampler is driven into the undisturbed soil by using 140-lb (63.6kg) weight falling 30 in. (0.76m) until 18-in penetration is achieved. Blow counts for driving the sample for each 6-in. (152mm) of penetration is recorded separately. Number of blow counts required for the last 12-in (0.3m) of driving is reported as the SPT result at that depth ($N_{SPT}$). Repeat at regular depth intervals (typically 1-2m) to obtain $N_{SPT}$ with depth.
## Standard Penetration Test (SPT)

### Table 1: Standard Penetration Test Data

<table>
<thead>
<tr>
<th>SPT</th>
<th>Sample Type</th>
<th>SPT Borehole D1</th>
<th>SPT Borehole D2</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPT1</td>
<td>1.50</td>
<td>1.95</td>
<td>1.75</td>
</tr>
<tr>
<td>SPT2</td>
<td>3.00</td>
<td>4.00</td>
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<td>4.50</td>
<td>5.50</td>
<td>6.00</td>
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<td>5.00</td>
<td>7.50</td>
<td>8.45</td>
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<td>7.95</td>
<td>9.00</td>
<td>8.45</td>
</tr>
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<td>SPT6</td>
<td>9.00</td>
<td>10.90</td>
<td>10.50</td>
</tr>
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</tr>
<tr>
<td>SPT11</td>
<td>16.00</td>
<td>16.00</td>
<td>16.00</td>
</tr>
</tbody>
</table>

### Notes:
- **GRAVELLY SANDY CLAY**: Light brown, subangular-subrounded white gravelly of limestone, fine sandy, medium plasticity, hard clay. Sand content increases from 10.50m and includes shells.
- **LIMESTONE**: White, moderately weathered.
Standard Penetration Test (SPT)

Need to apply corrections to $N_{\text{SPT}}$ to have a standardized value ($N_{1,60}$)

Corrected $N_{1,60}$ values are calculated as

$$N_{1,60} = N C_N C_R C_S C_B C_E C_N$$

$N =$ measured standard penetration resistance,
$C_N =$ factor to normalize $N$ to a reference effective overburden stress,
$C_R =$ correction for rod length,
$C_S =$ correction for non-standardized sampler configuration,
$C_B =$ correction for borehole diameter,
$C_E =$ correction for hammer energy ratio.
Correlations between shear wave velocity, $V_S$ and $N_{SPT}$
Cone Penetration Test (CPT)

- Quantifies penetration resistance of soils
- Provides some correlation with in-situ soil properties

A cylindrical probe with a cone-shaped tip with different sensors that allow real-time continuous measurements by pushing it into the ground at a speed of 2 cm/s.

**Measures:**
1. cone resistance, $q_c$ at the tip
2. the sleeve friction, $f_s$
3. pore water pressure, $u$

Field computer displays the data in real-time and stores it at regular depth intervals.
Field Site – CPT Profile, May 2006
Cone Penetration Test (CPT)

Identification and classification of soil layers

(normalized net cone resistance $f_{s}/(q_{T}-\sigma_{v,\text{tot}})$ [%]

(normalized friction ratio $f_{s}/(q_{T}-\sigma_{v,\text{tot}})$ [%])
Cone Penetration Test (CPT)

**Advantages**
- Fast method,
- Gives detailed profiles,
- Relatively cheap,
- A lot of correlations exist,
- Allows measurements at in situ conditions, avoiding problems relating to sample disturbance.

**Limitations**
- Only usable in soft to medium stiff materials without boulders,
- No samples are obtained for visual examination and laboratory testing.
**PENETRATION TESTS**

**SPT**

SPT-N

\[ V_s = 51.5N^{0.516} \]

Shear Wave Velocity

**CPT**

Point resistance

\[ V_s = 55.3q_c^{0.377} \]

Shear Wave Velocity

(İYİSAN, 1996)
Wave Propagation and Geophysical Methods

Seismic Test Method in General
1. Creation of transient and/or steady state stress waves using an energy source
2. Monitoring of particle motion with transducers (i.e. receivers) located at one or more locations away from the source
3. Times of wave arrivals are determined from the waveforms recorded at receiver locations and wave velocity is calculated from

\[ V = \frac{\Delta x}{\Delta t} \]

should take into account:
- The size of the receivers that are used to monitor wave motions should be much smaller than the wavelength
- Receivers should be at least two to four wavelengths away from the source
Seismic Reflection Test

- Useful for investigation of large-scale and/or very deep stratigraphy
- Many source and receiver locations must be used to produce meaningful images
- Interference between the reflected waves and surface waves requires careful signal processing and usually restrict the use of this method at shallow-depths
Seismic Refraction Test

An active source and a series of receivers are placed on the ground surface in a linear array
- Output of all receivers are recorded when the source is triggered
- Arrival times of the first waves to reach each receiver is determined and plotted as a function of source-receiver distance

The method is based on the ability to detect the arrival of wave energy that is critically refracted (traveling parallel to the boundary) from a higher velocity layer which underlies lower velocity sediment.
Spectral-Analysis-of-Surface-Waves-Test (SASW)

- Rayleigh wave energy is created at one point and resulting vertical surface motions at two or more measurement points (receiver points) away from the source are monitored.
- Measurements are performed at multiple source-receiver spacings along a linear array placed on the ground surface.
Spectral-Analysis-of-Surface-Waves-Test (SASW)

- Variation of $V_R$ with different $\lambda$ or $f$ is called the 'dispersion curve'
- An initial estimate of the $V_s$ profile is made and iteratively changed to match the theoretical dispersion curve with the experimental dispersion curve to obtain the best estimate for $V_s$ profile
Spectral-Analysis-of-Surface-Waves-Test (SASW)

**Advantages**
- Quick and easy to perform
- Does not require drilling
- Can measure $V_s$ profile up to 100 m depth

**Limitations**
- Resolution decreases with depth
- Thin layers are hard to detect
- Provides ‘global measurements’

Determines averaged properties over the lateral measurement distance
Crosshole Seismic Test (CST)

- Source and receivers are placed at the same depth in adjacent boreholes.
- P and S waves are generated using the source mechanism and waves propagating along horizontal path are measured at the receiver boreholes.
- Travel time from the source to receivers (direct travel time) and the travel time between the receivers (interval travel time) are measured.
- By testing at various depths variation of velocity with depth is obtained.
Crosshole Seismic Test (CST)

- A wedged source is used to generate P and S waves at depth inside the source borehole,
- The wedging mechanism operates with compressed air to lock the hammer against the casing in the borehole,
- A sliding hammer that moves vertically produces impulses of reversed polarity.
Crosshole Seismic Test (CST)

- Wave propagation velocities are calculated from difference in arrival times at adjacent pairs of boreholes
- Arrival times can be determined by eye using points of common phase (first arrival, first peak, first trough)
Field Measurement of Dynamic Soil Properties

Crosshole Seismic Test (CST)

Advantages
• Resolution is high since source and receivers are placed close to the material to be evaluated
• Direct measurement of wave velocities are performed
• Individual soil layers can be tested
• Can detect thin layers
• Reliable data up to 100 m

Limitations
• Requires two or three boreholes, expensive and time consuming
• Requires vertical deviation survey for the boreholes
• Provides ‘local measurements’
Downhole Seismic Test (DST)

- An impulse source is located on the ground adjacent to a single borehole and one or more receivers are placed in the borehole.
- P and S waves are generated from the source on the surface and waves propagating along a direct path between the source and the receivers are measured.
- Travel time from the source to receivers (direct travel time) and the travel time between the receivers (interval travel time) are measured.
- Travel distances are typically based on assuming straight ray paths between the source and the receivers.
- By testing at various depths variation of velocity with depth is obtained.
Field Measurement of Dynamic Soil Properties

Downhole Seismic Test (DST)

A plot of travel time with depth can be generated using the arrival times identified on the waveforms recorded at various depths.

- Slope of travel-time curve at any depth represents the wave propagation velocity at that depth.
Seismic Cone Penetration Test (SCPT)

- A cone penetrometer that measures tip and side resistances on a probe pushed into the soil that allows measurement of shear wave velocities in a downhole testing arrangement.
- SH waves are generated at the surface near the insertion point of the cone by applying a horizontal impact on an embedded beam and travel times of the shear wave energy are measured at one or more locations above the cone tip. Travel time-depth curves can be generated and interpreted in the same way as for downhole tests.
- By testing at various depths variation of velocity with depth is obtained.
Downhole Seismic Test (DST)

**Advantages**

- Direct measurement of wave velocities are performed
- Reliable data up to 50 m
- Less expensive than CST *(requires one borehole)*

**Limitations**

- Energy that can be generated by the source on the ground surface limits the testing depth
- Provides ‘local measurements’
PS-Logging Test

- Measurements are made in a single, cased/uncased fluid-filled borehole.
- An acoustic wave is generated in the borehole fluid by activating a solenoid source which is located at the end of the suspending probe.
- The impact of this wave on the borehole wall creates both P and S waves which travel radially away from the borehole. A portion of the wave energy travels along the soil as a head wave and transmits energy back into the fluid.
- These waves are detected with two 2-D geophones on the probe. The vertical and horizontal components of the geophone correspond to P- and S-wave energies, respectively.
- By testing at various depths variation of velocity with depth is obtained.
PS-Logging Test

- The travel time differences between horizontal and vertical receivers of the two 2-D geophones on the probe are used to calculate the interval S- and P-wave velocities, respectively, over the 1-m interval.
- The results of a suspension logging test consist of a Vs and a Vp profile, with data points as many as measurement intervals.
PS-Logging Test

Advantages
• Effective at greater depths (up to 1 km)
• Source travels with the receivers down the borehole

Limitations
• Frequencies generated by the source are too high (500 to 2000 Hz for S wave)
• Indirect measurement of S waves
• Can be significantly affected from grouting around the casing
Comparison of CST, DST and PS

Silty Clay
N=20
I_p=41%

Silty Sand / Sandstone
N>50

Siltstone / Sandstone

Claystone

7.6 m

0.00 200 400 600

V_s (m/s)

CH
DH
PS