National Workshop on

Importance of Disaster Risk Reduction and Resilience

Mizoram University, 10 April 2023

Geotechnical Investigations for Landslide Studies

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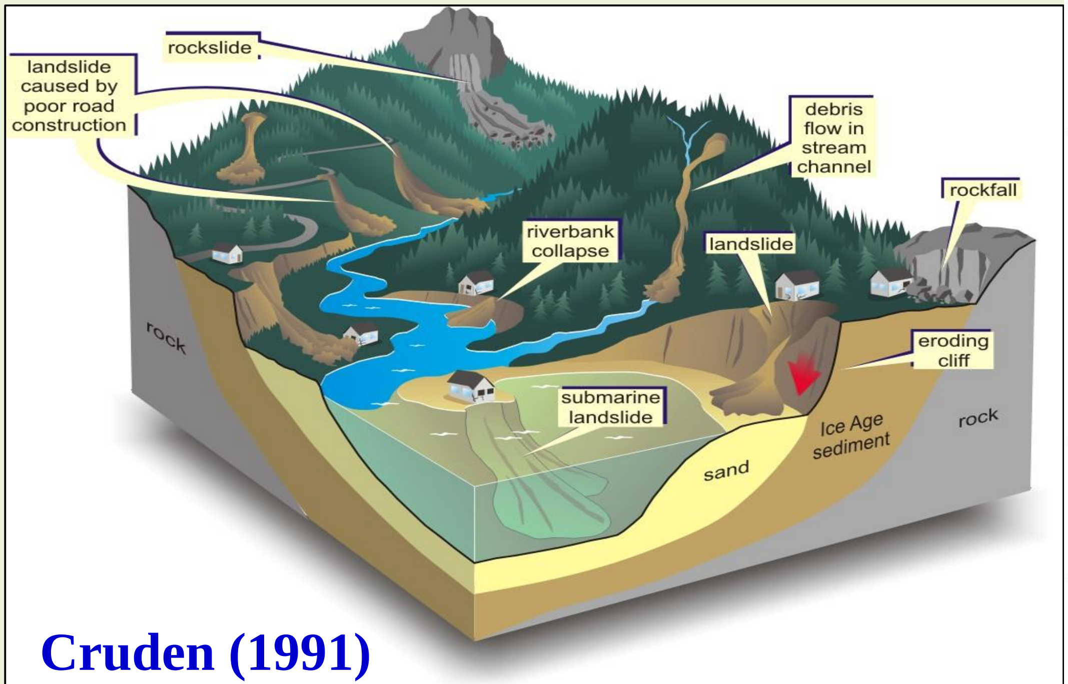
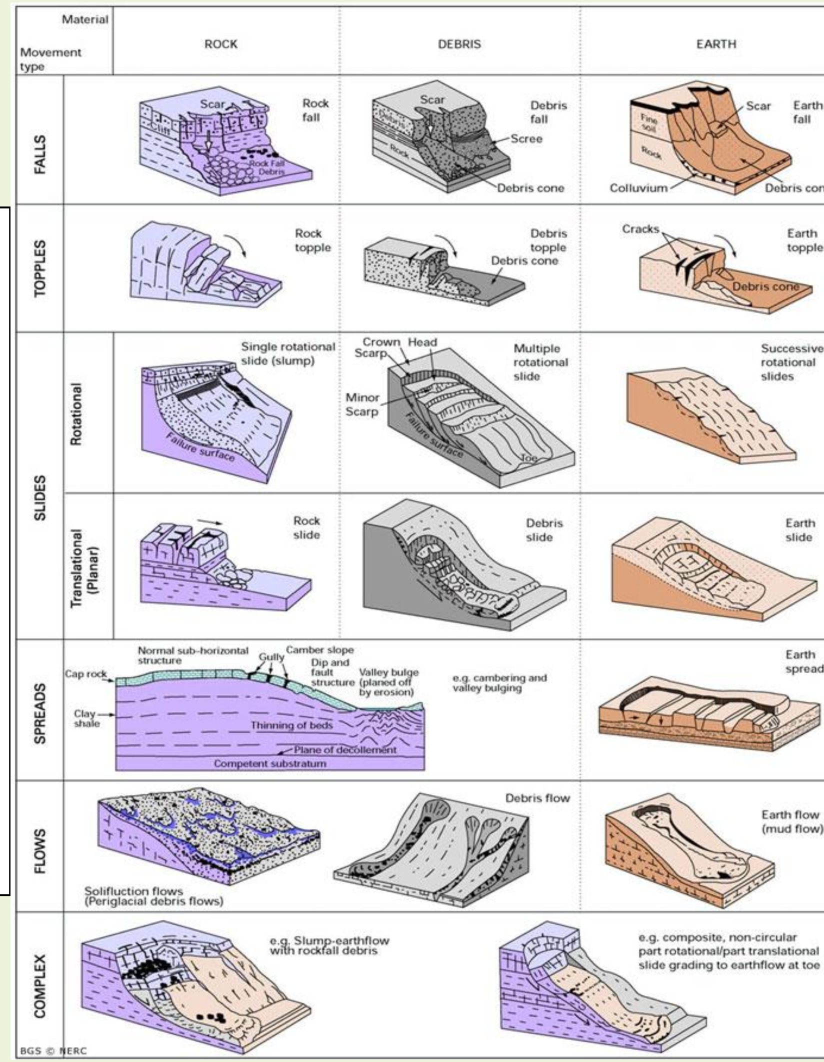
IIT Guwahati

Landslides

Movement of mass of rock, debris or earth down a slope



Cruden (1991)



Landslides: Various types – Various Reasons

Banderdewa, AP

Saiphum, Mizoram

Guwahati, Assam

Ghorafam, IIT Mandi

Sonapur, Assam

Tawang, AP

Landslides: CAUSE and TRIGGER

Stable Slope

Causal Factors

Marginally Stable Slope

Triggering Factors

Slope Failure

- Triggers
  - *Rainfall*
  - *Seismicity*
  - *Toe cuts*

Causes of Landslide

Natural Causes

Geological Causes

- Weathering
  - Chemical
  - Physical
  - Biological
- Structure
  - Stratification
  - Orientation

Morphological Causes

- Topography
- Surface Cover
- Slope inclination
- Erosion
  - Toe erosion
  - Gully erosion
- Subterranean
  - Solution
  - Piping
- Deposition
  - On slope face
  - On crest
- Tectonic activities
  - Uplift

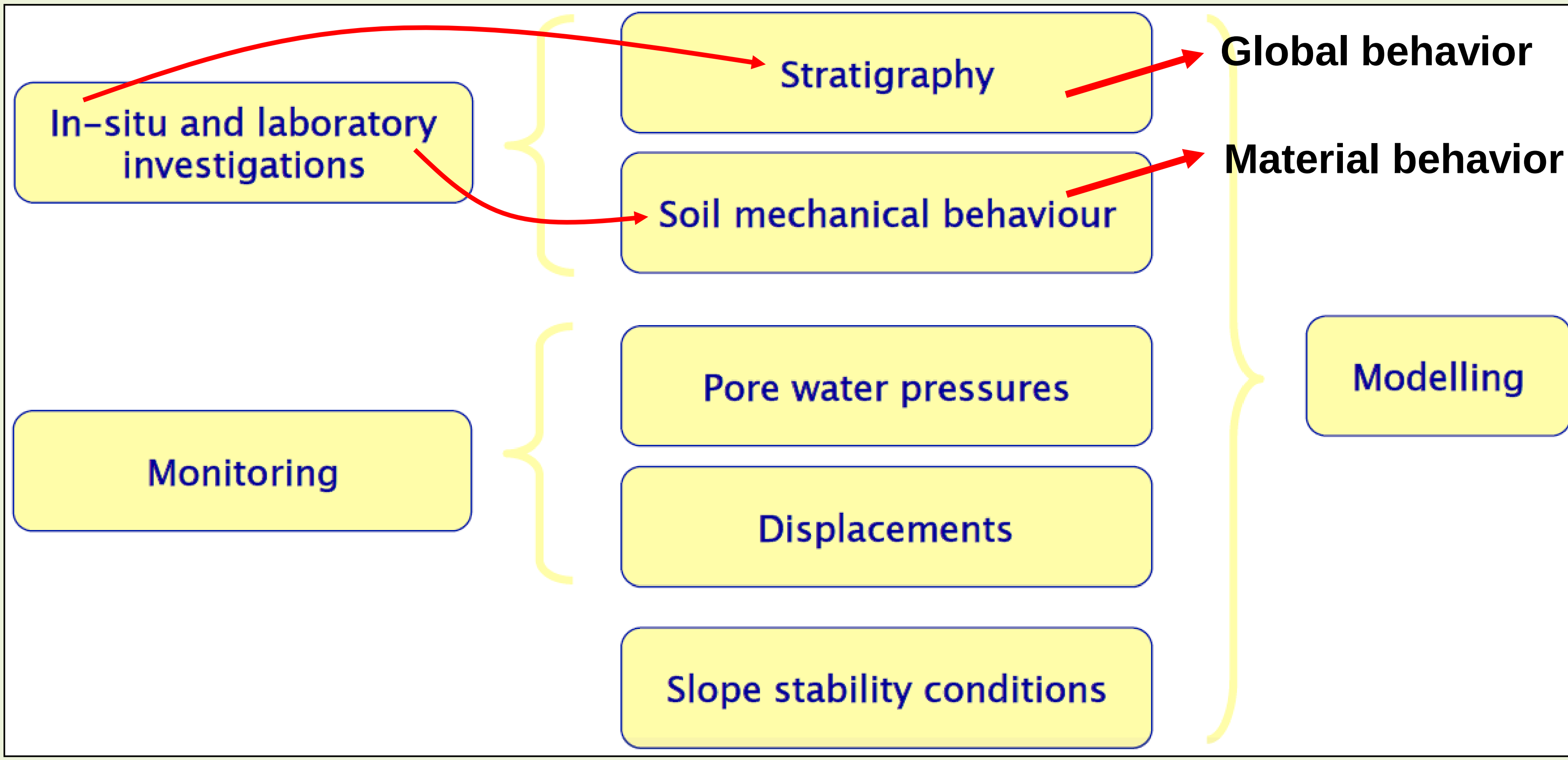
Hydrological Causes

- Rainfall
- Runoff
- Infiltration
- Percolation
- Seepage

Anthropogenic Causes

- Encroachment
- Unscientific cutting of hill slopes
- Deforestation
- Unplanned drainage and Sewerage system
- Unplanned construction of roads

Components of Landslide Studies



Pertinent Laboratory Investigations

- Water content
- Particle Size Gradation
    - *Dry sieving, Wet sieving, Hydrometer*
- Field Density and Relative Density for granular soils
- Atterberg Indices (Consistency and Swelling) for fine-grained soils
- Saturated Hydraulic Conductivity and Infiltration Tests
- Consolidation characteristics
- Unsaturated Hydraulic Conductivity
    - *Soil-Water Characteristic Curve (SWCC)*
- Shear Strength Tests
    - *Direct Shear Test (Suction controlled for unsaturated samples)*
    - *Triaxial Shear Test (Suction controlled for unsaturated samples)*
    - *Monotonic and Cyclic Triaxial Shear Test (to simulate seismic effects)*
    - *Torsional Ring Shear test (to simulate landslide movement)*
- Model tests and Centrifuge tests (when necessary)

Pertinent Field Investigations

- Landslide Reconnaissance
- Exploratory borings
- Characterization of in-situ soil shear strength
  - *SPT, In-situ CPT, Field VST, In-situ DST/BST*
- Geophysical investigations
  - *GPR, ERT, SRS, MASW*
- Ariel and Geodetic Surveys
  - *LIDAR and GIS platforms*
- Hydro-Geological Surveys
  - *In-situ Infiltration and Permeability tests using Infiltrometers/Permeameters*
  - *Ground water measurements using Piezometers*
  - *Soil suction measurements using Tensiometer*
  - *Precipitation Records over time using Raingauges*
  - *Geological variation and classification of soils*

Laboratory Investigations

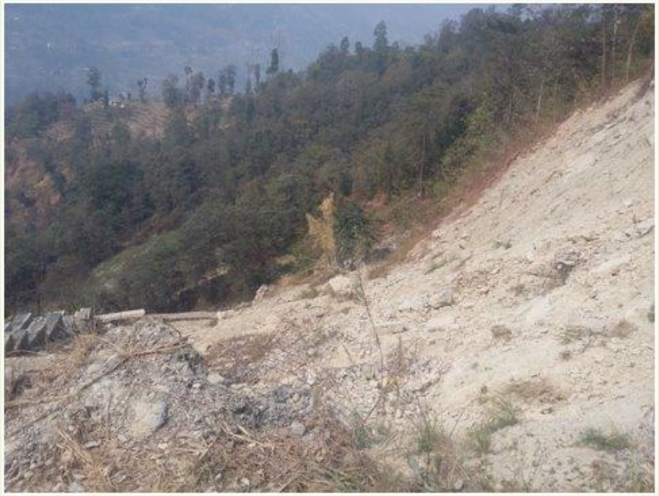
Water Content

- Laboratory results for water content may be intriguing
    - *Can provide misinformation about the natural moisture content of soil*

Sl. No.	State of water content determination	Water content (%)	
		Sirwani	Tumin
1	Just after in-situ sample collection	11.07	7.2
2	After 15 days	8.8	4.63

Sirwani Slide Sikkim

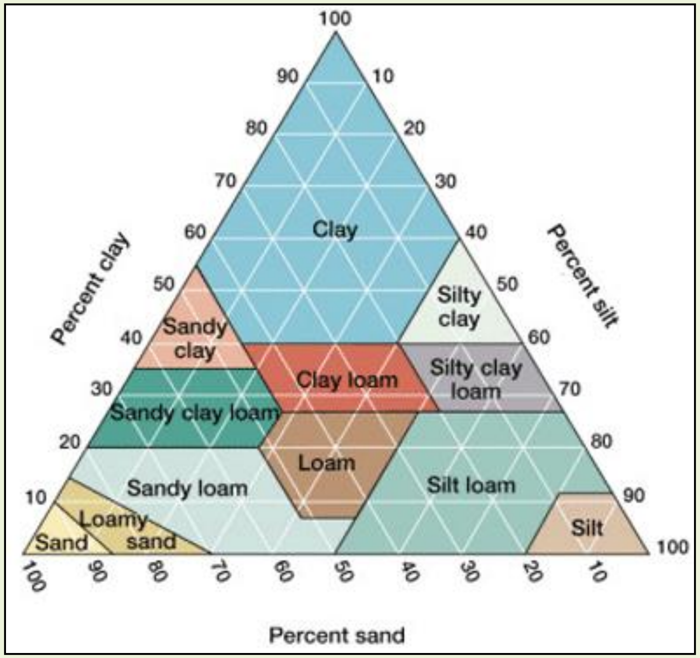
Tumin Slide Sikkim

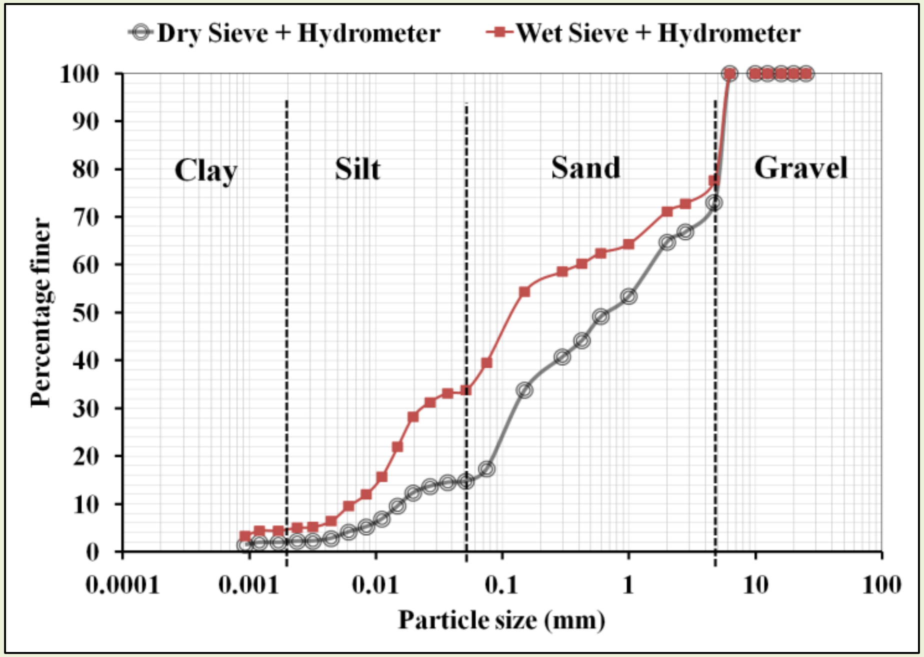


Proper preservation of the collected in-situ soil samples are necessary before commuting them to the laboratory so that there is no loss in moisture content and change in shear strength estimations

Particle Size Gradation

- Proper fractionation from the most coarse to very fine contents
  - ❖ *Adopt wet sieving wherever the soil has fine content*
    - Dry sieving of such soils can be erroneous
      - Change in the particle size characteristics





Field Density and Relative Density

- Field Density
  - ❖ *Sand replacement method*
  - ❖ *Core cutter method*

Field Density Testing Method

	Sand Cone	Balloon Dens meter	Shelby Tube	Nuclear Gauge
Advantages	• Large sample • Accurate	•Large sample • Direct reading obtained • Open graded material	•Fast • Deep sample • Under pipe haunches	• Fast • Easy to redo • More tests (statistical reliability)
Disadvantages	• Many steps • Large area required • Slow • Halt Equipment • Tempting to accept flukes	• Slow • Balloon breakage • Awkward	•Small Sample • No gravel • Sample not always retained	•No sample • Radiation • Moisture suspect • Encourages amateurs
Errors	• Void under plate • Sand bulking • Sand compacted • Soil pumping	• Surface not level • Soil pumping • Void under plate	• Overdrive • Rocks in path • Plastic soil	• Miscalibrated • Rocks in path • Surface prep required • Backscatter
Cost	• Low	• Moderate	• Low	• High

- Relative density

$$D_r = \frac{[(G\gamma_w/\gamma_{d\,min}) - (G\gamma_w/\gamma_d)]}{[(G\gamma_w/\gamma_{d\,min}) - (G\gamma_w/\gamma_{d\,max})]}$$

$$\Rightarrow D_r = \frac{(1/\gamma_{d\,min}) - (1/\gamma_d)}{[(1/\gamma_{d\,min}) - (1/\gamma_{d\,max})]}$$

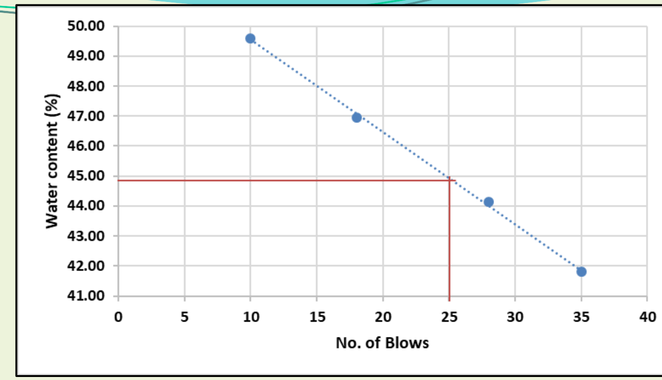
$$\Rightarrow D_r = \frac{(\gamma_d - \gamma_{dmin}/\gamma_{dmin}\cdot\gamma_d)}{(\gamma_{d_{max}} - \gamma_{dmin}/\gamma_{dmin}\cdot\gamma_{d\,max})}$$

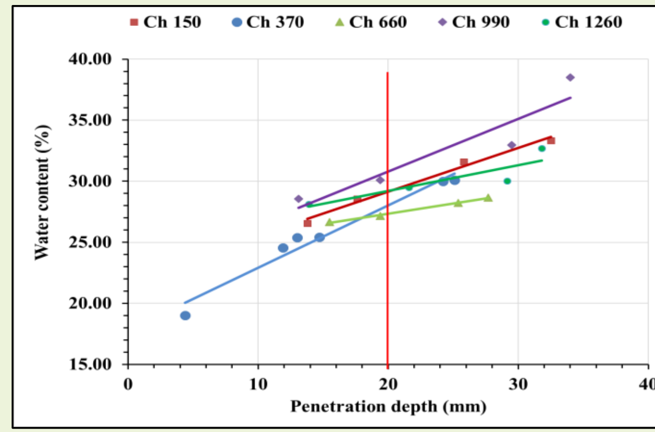
$$\Rightarrow D_r = \frac{\gamma_{dmax}}{\gamma_d}\left[\frac{\gamma_d - \gamma_{dmin}}{\gamma_{dmax} - \gamma_{dmin}}\right]$$

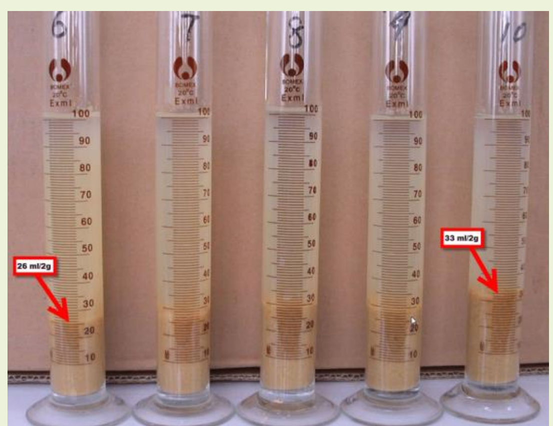
Relative Density (%)	Descriptive Term
0–15	Very loose
15–35	Loose
35–65	Medium
65–85	Dense
85–100	Very dense

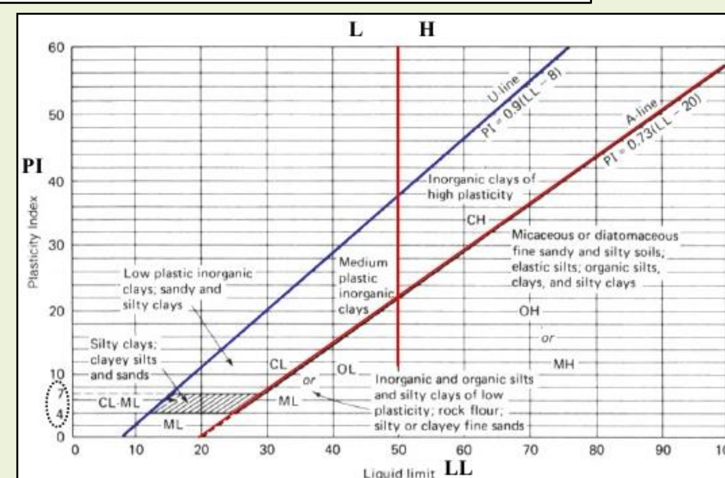
Atterberg's Indices

- Fine grained soils
  - *Consistency indices*
    - Atterberg limits
      - Plastic Limit
      - Liquid limit
        - Atterberg apparatus
        - LL Cone Penetrometer
      - Shrinkage limit
    - Activity
    - Thixotropy
    - Toughness
    - Sensitivity
  - *Swelling indices*
    - Free swell index
    - Swelling potential



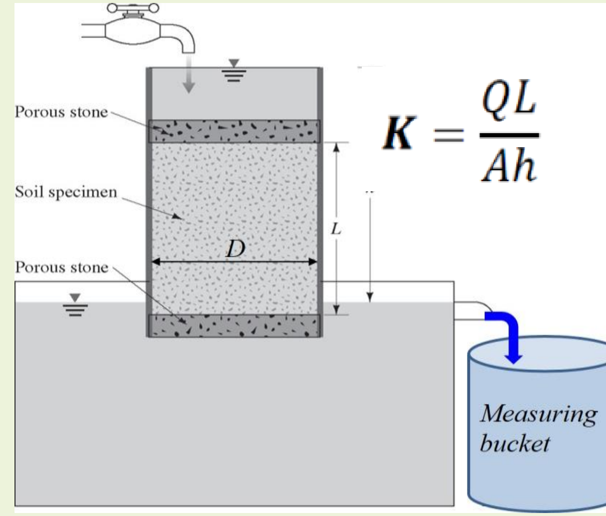




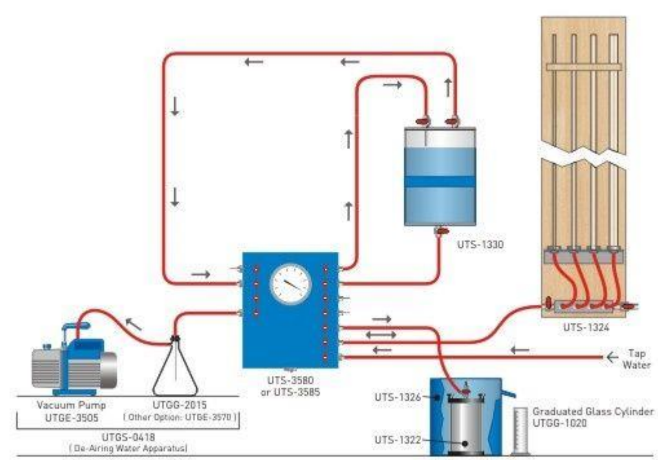


Saturated Hydraulic Conductivity

- Hydraulic conductivity for saturated flows
  - *Constant Head Test (Granular soils)*
  - *Falling Head Test (Fine-grained soils)*
    - Suggestion: Repeat with various tube diameters



L is length of sample
A is the cross sectional area of soil core
h is the constant head



Falling Head Permeability Test with De-Airing Water System

$$k = \frac{a \cdot L}{A \cdot t} \cdot \ln \cdot \frac{h_0}{h_t}$$

k = coefficient of permeability (cm / sec)

a = area of burette standpipe (cm^2)

L = length of specimen (cm)

A = area of specimen (cm^2)

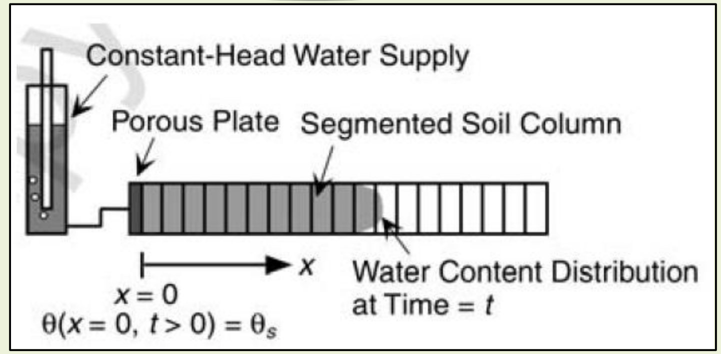
t = elapsed time of test (sec)

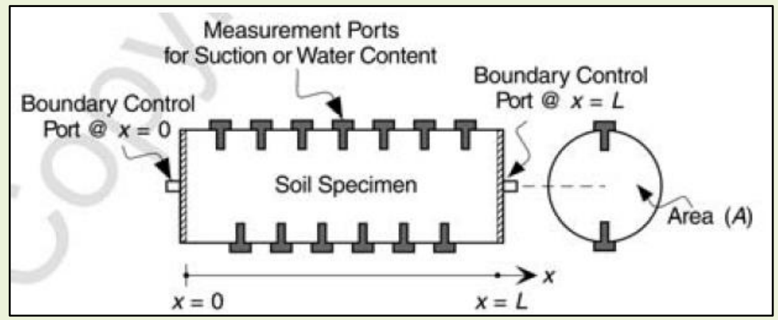
h_0 = head at beginning (time = 0) of test (cm)

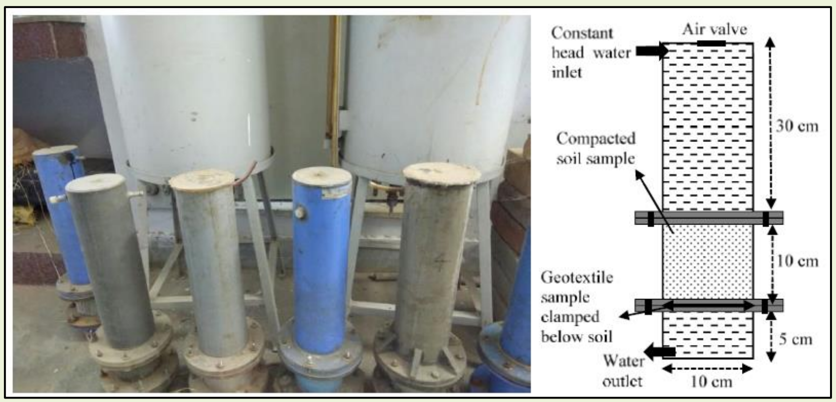
h_t = head at end (time = t) of test (cm)

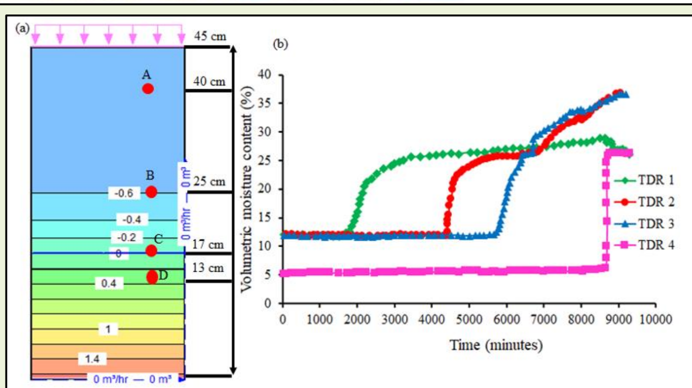
Infiltration Tests

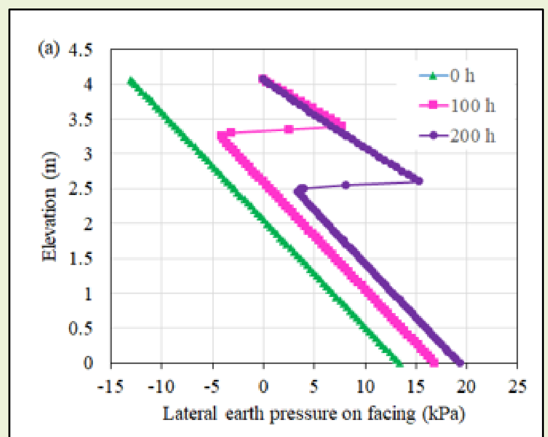
- Migration of saturation fronts
  - ❖ *Horizontal infiltration method*
  - ❖ *Instantaneous Profile lab*
  - ❖ *Column infiltrations tests*

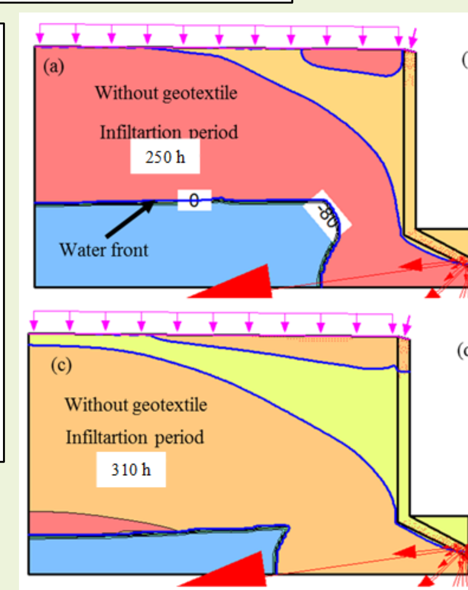






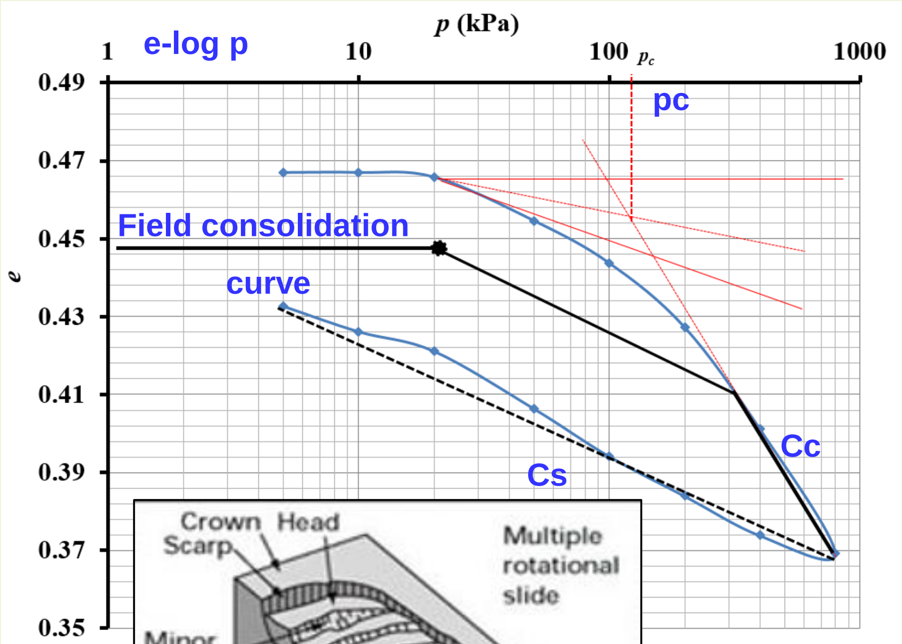


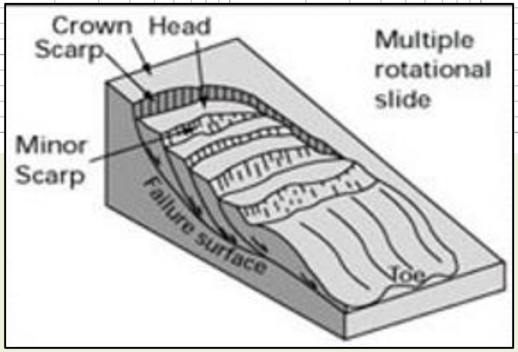


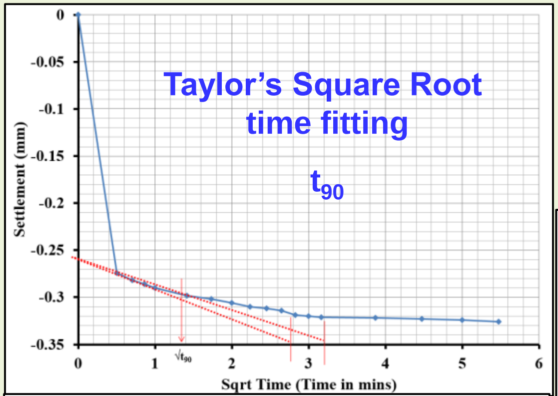


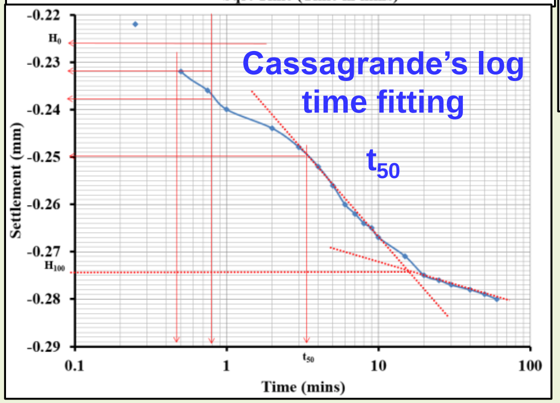
Progression of saturation front in backfill behind retention system

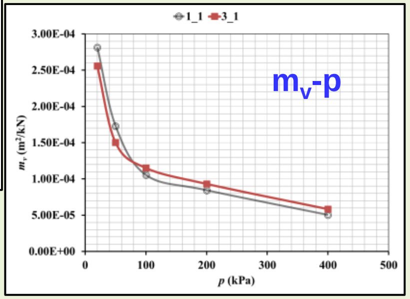
Consolidation Characteristics

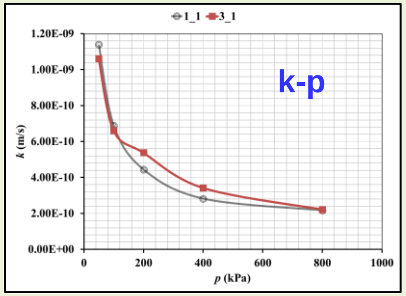


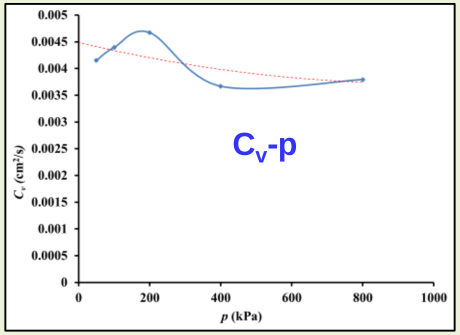


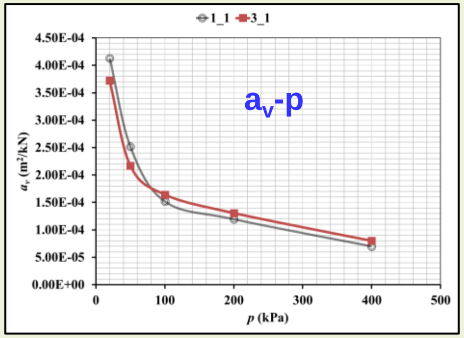




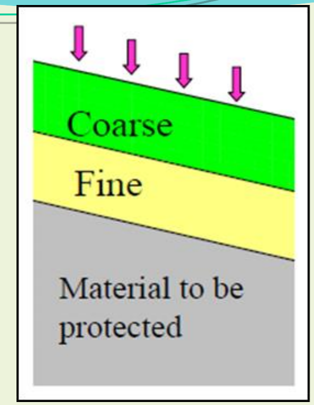


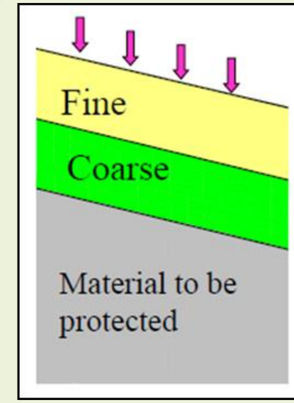




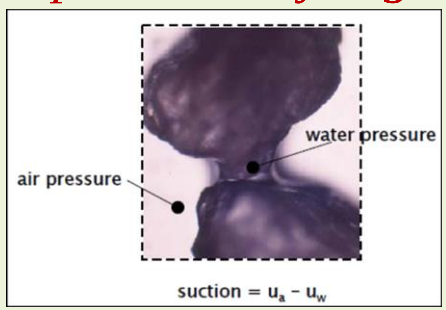


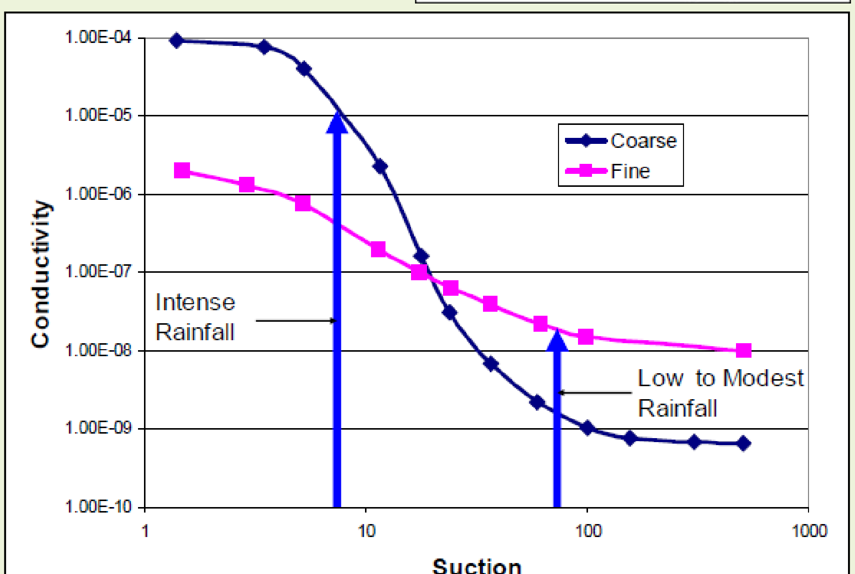
Unsaturated Hydraulic Conductivity

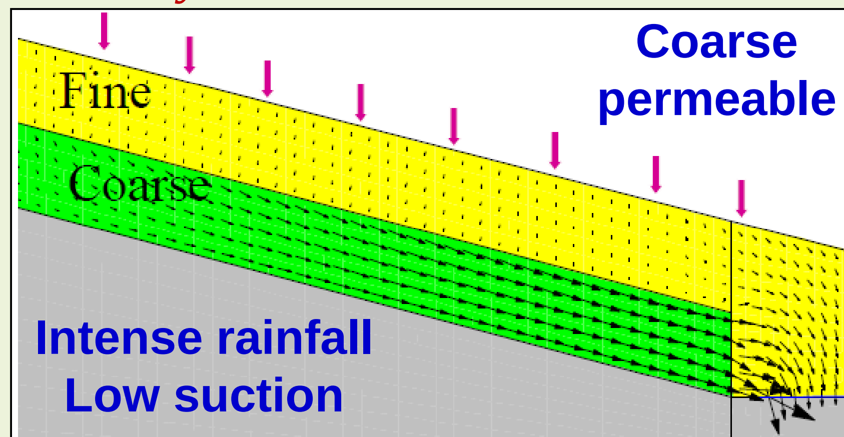


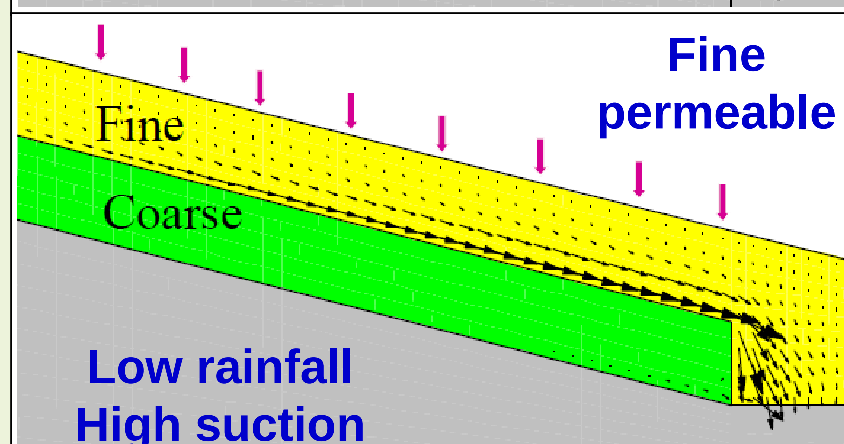


- Hydraulic conductivity for unsaturated flows
  - ❖ *Which is more permeable – Coarse or Fine soil????*
  - ❖ *For unsaturated flows, permeability is governed by*
    - Suction
    - Intensity of Rainfall
    - Aridity







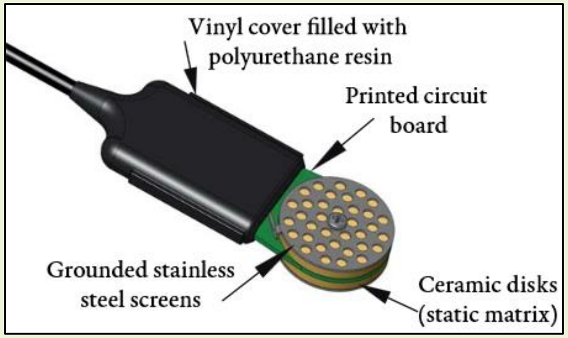


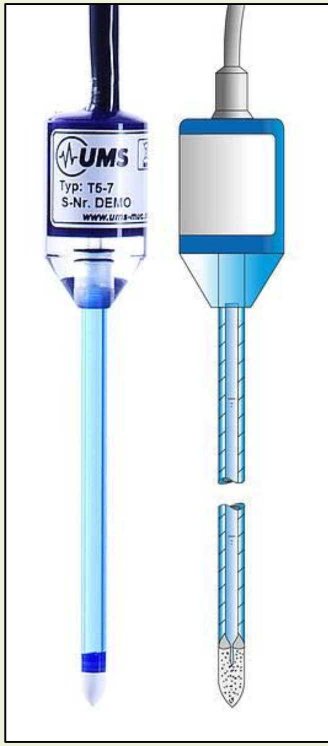
Unsaturated Soil Characteristics

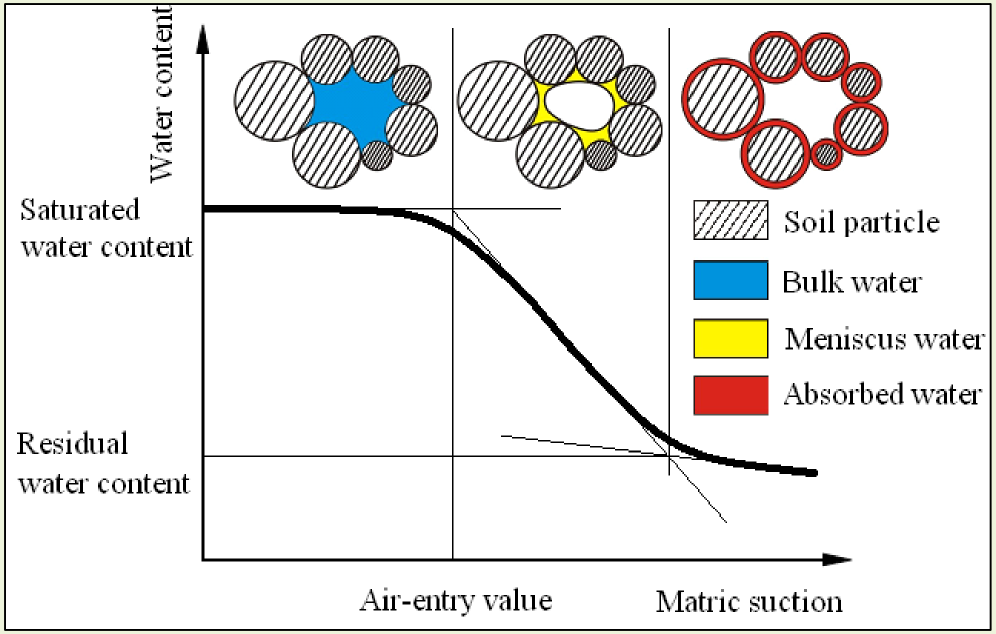
- Measurement of soil suction
  - *Variety of techniques: Cost, Complexity and Range*
  - *Either laboratory or Field based*
    - Matric suction
      - Tensiometers: 0-100 kPa
      - Axis translation techniques: 0-1500 kPa
      - Electrical/Thermal conductivity sensors: 0-400 kPa
      - Contact paper filter method: Entire range?
    - Total Suction (Highly specialized requirements)
      - Thermocouple psychrometer: 100-8000 kPa
      - Chilled mirror hygrometer: 1000-150000 kPa
      - Resistance/Capacitance sensors: Entire range?
      - Isopietic humidity control: 4000-400000 kPa
      - Two pressure humidity control: 10000-600000 kPa
      - Noncontact filter paper method: 1000-500000 kPa

Unsaturated Soil Characteristics

- Determination of soil-water characteristic curve (SWCC)
  - ❖ *Laboratory Tensiometer*
  - ❖ *Manifold Pressure Sensor*
    - Dielectric water potential sensor
  - ❖ *Dew-point Potentiometer*

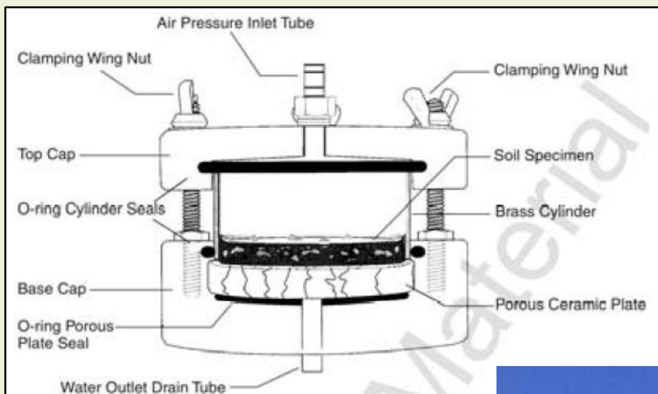






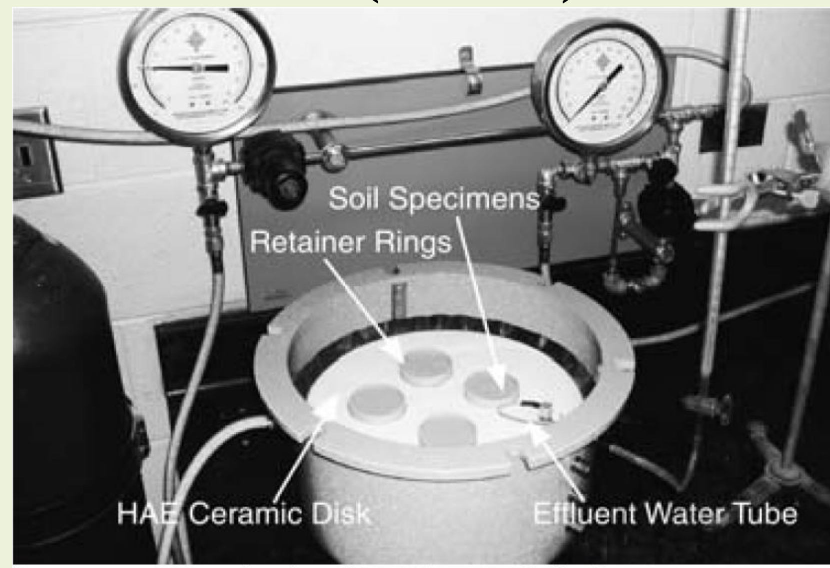
Unsaturated Soil Characteristics

- Determination of soil-water characteristic curve (SWCC)
  - ❖ *Pressure plate: 0-1500 kPa*
  - ❖ *Tempe Cell: 0-100 kPa*



[Source: Unsaturated Soil Mechanics by Lu and Likos]

[Source: Soilmoisture Equipment Corporation]



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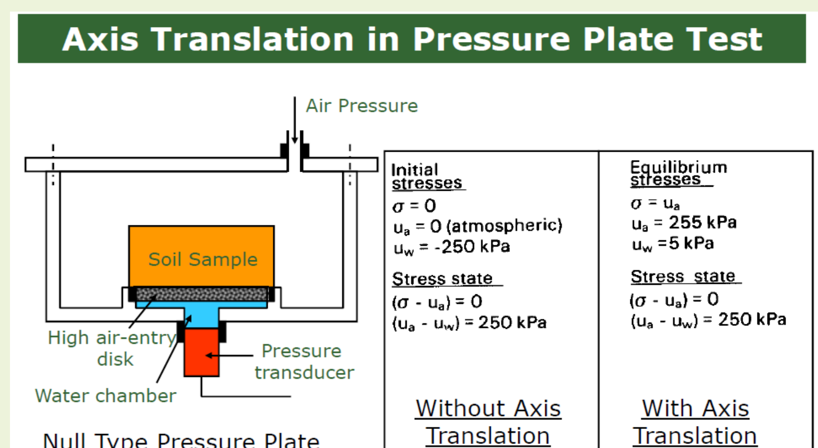
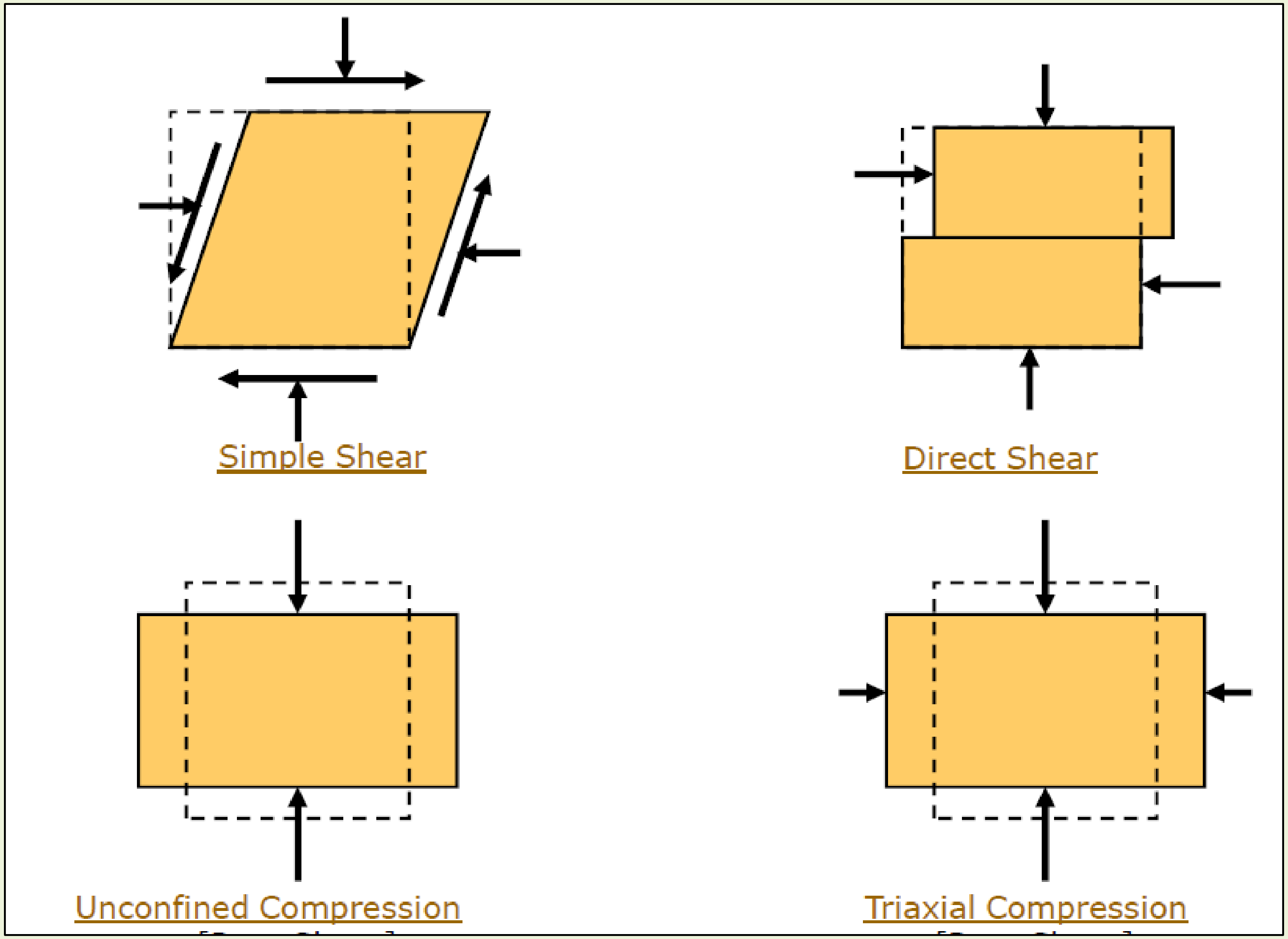


Laboratory Tests for Shear Strength Estimation

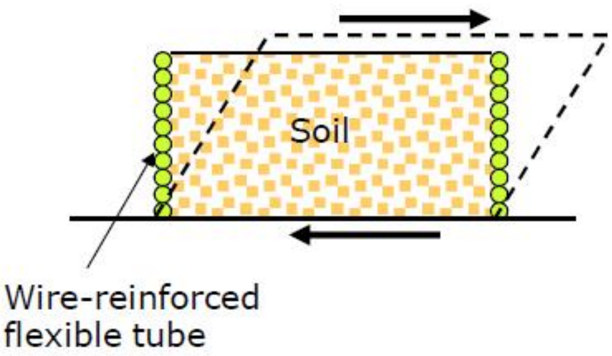
- Shear strength parameters control the failure mechanism of landslides

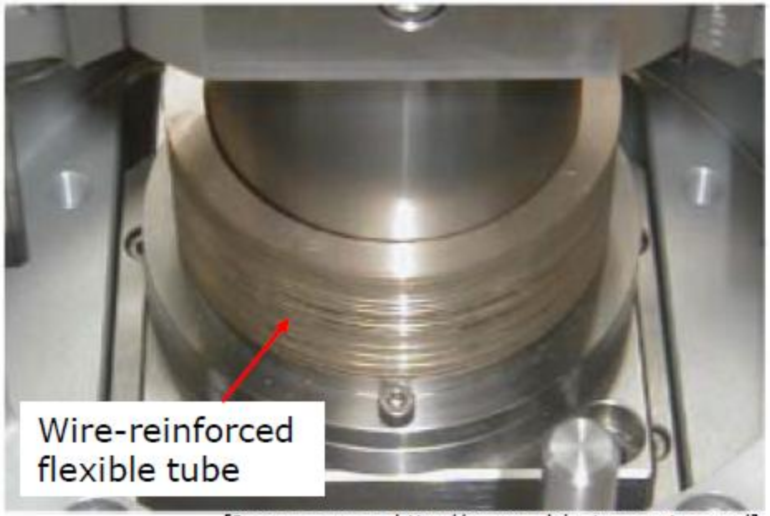


Shear Strength

Simple Shear Test

- Soil sample is contained in a wire-reinforced flexible tube.
- Shear force is applied at the top of the sample while keeping the bottom of the sample restrained.
- Rotation and vertical movement of the sample are recorded using dial gauges.
- Not normally used in day-to-day geotechnical practice.

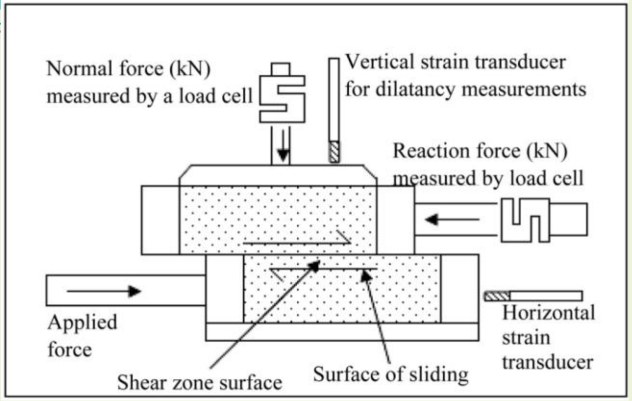


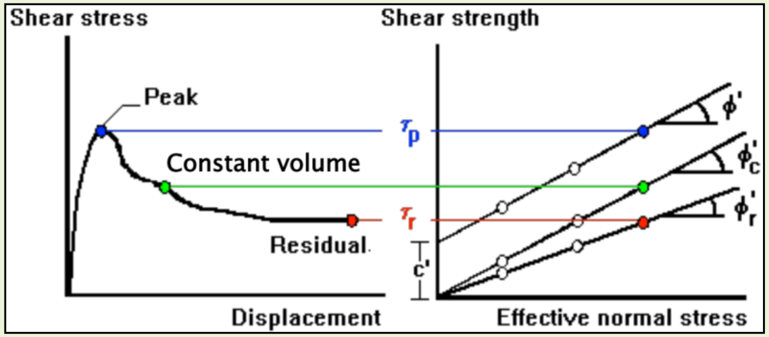


[Image source: http://www.gdsinstruments.com/]

Shear Strength

- Direct Shear test with varying strain rates
  - ❖ *Suction controlled for unsaturated samples*
    - Small and Large Box DS Tests





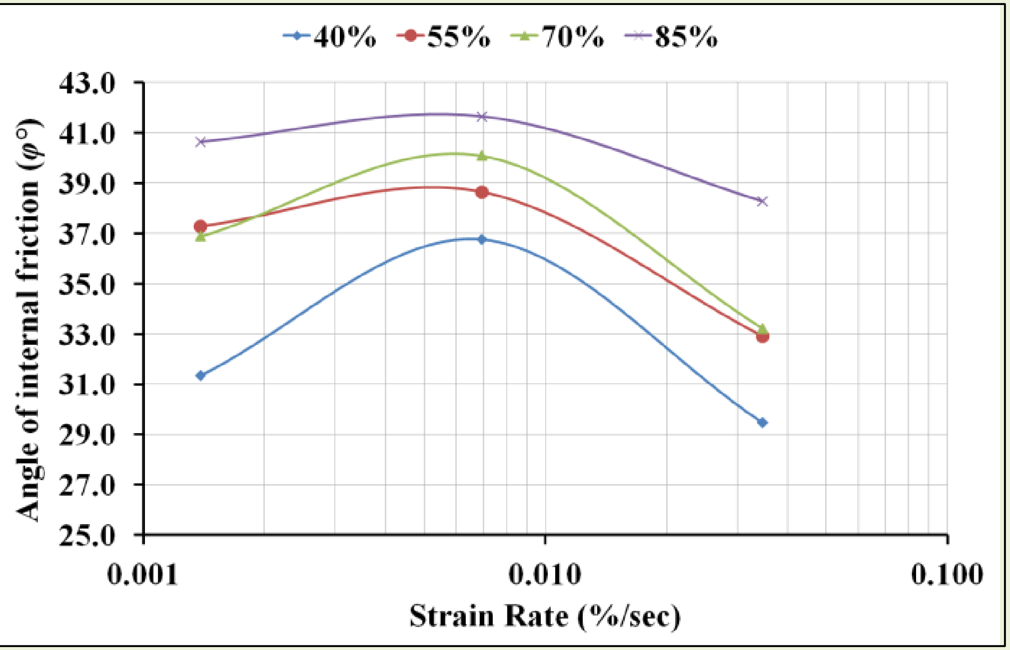
Classification of Landslides as per their Velocity

Velocity Class	Description	Velocity (mm/sec)	Typical Velocity	Probable Destructive Significance
7	Extremely Rapid			Catastrophe of major violence; buildings destroyed by impact of displaced material; many deaths; escape unlikely
		5×10^{3}	5 m/sec	
6	Very Rapid			Some lives lost; velocity too great to permit all persons to escape
		5×10^{1}	3 m/min	
5	Rapid			Escape evacuation possible; structures; possessions, and equipment destroyed
		5×10^{-1}	1.8 m/hr	
4	Moderate			Some temporary and insensitive structures can be temporarily maintained
		5×10^{-3}	13 m/month	
3	Slow			Remedial construction can be undertaken during movement; insensitive structures can be maintained with frequent maintenance work if total movement is not large during a particular acceleration phase
		5×10^{-5}	1.6 m/year	
2	Very Slow			Some permanent structures undamaged by movement
		5×10^{-7}	15 mm/year	
1	Extremely SLOW			Imperceptible without instruments; construction POSSIBLE WITH PRECAUTIONS

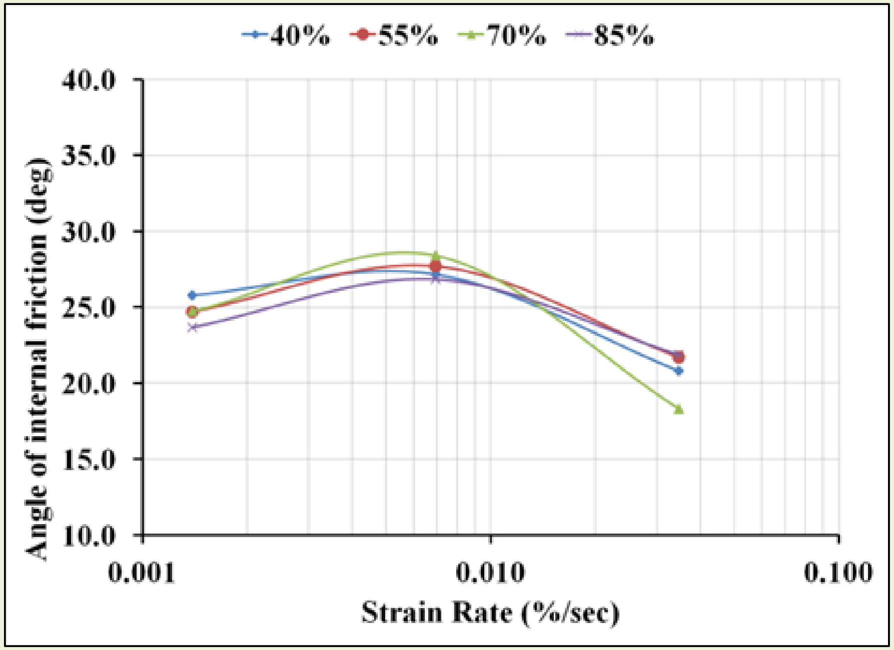
Cruden and Varnes, 1996

Effect of Strain Rate in DS Test

Peak angle of internal friction

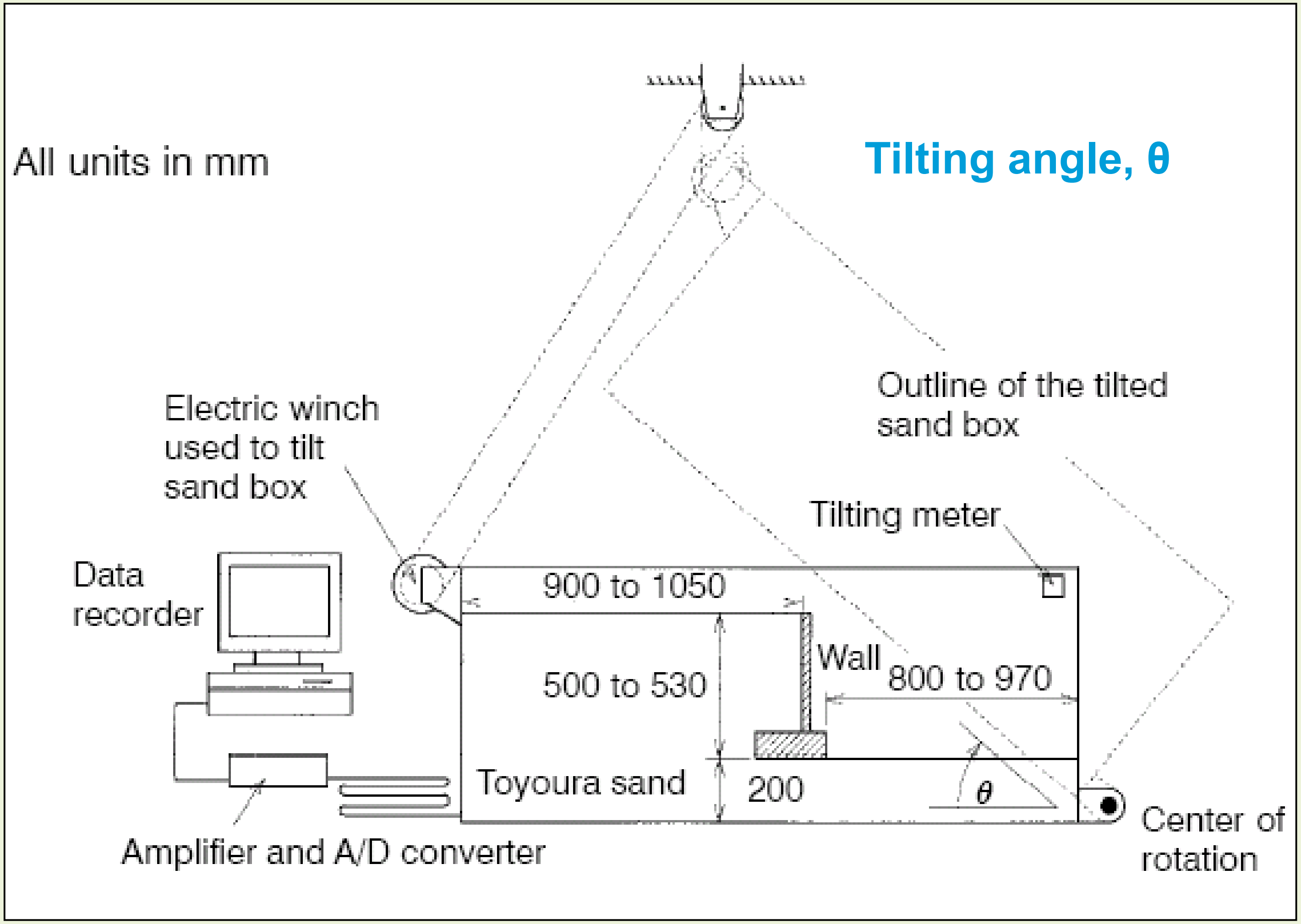


Critical angle of internal friction



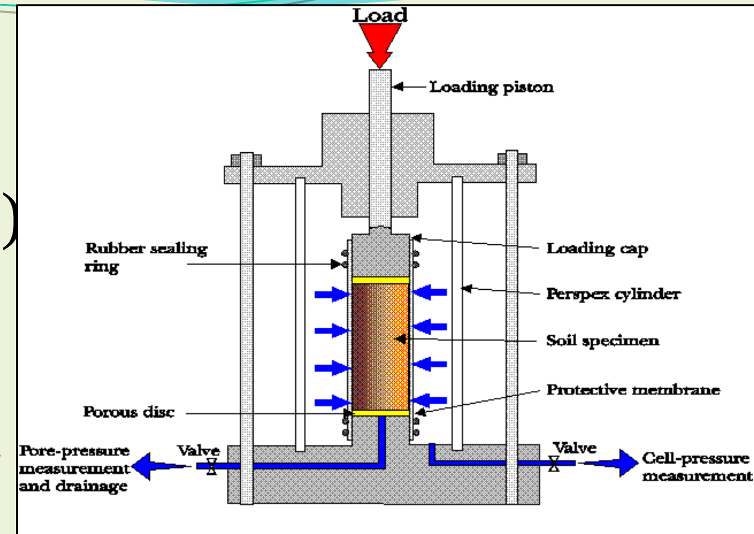
Shear Strength

- Tilt Table Test for friction of slides comprising large sized particles

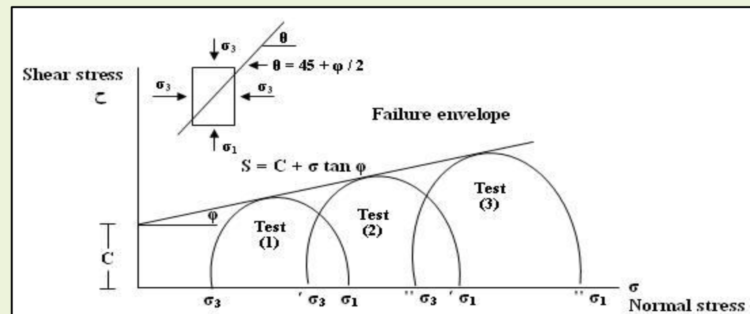


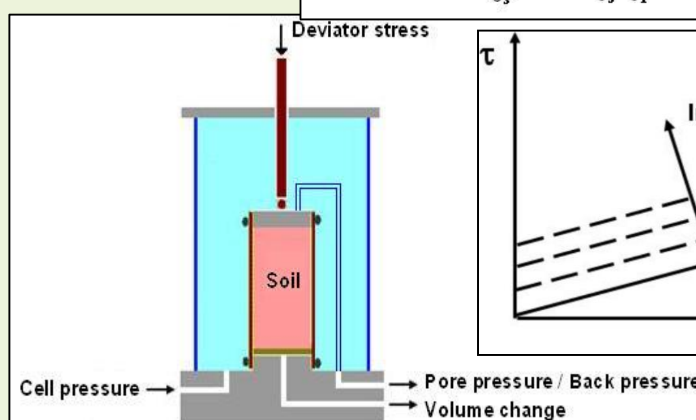
Shear Strength

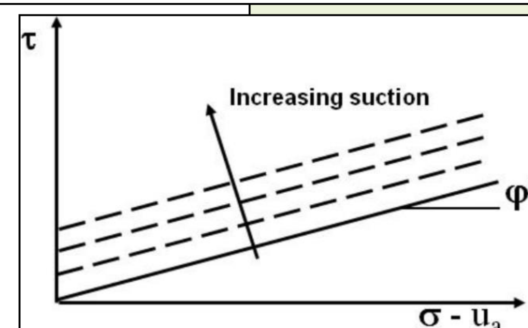
- Triaxial Shear test (UU, CU, CD, UCS)
  - ❖ *Saturated samples*
  - ❖ *Dry samples*
  - ❖ *Suction controlled for unsaturated samples*



Triaxial apparatus

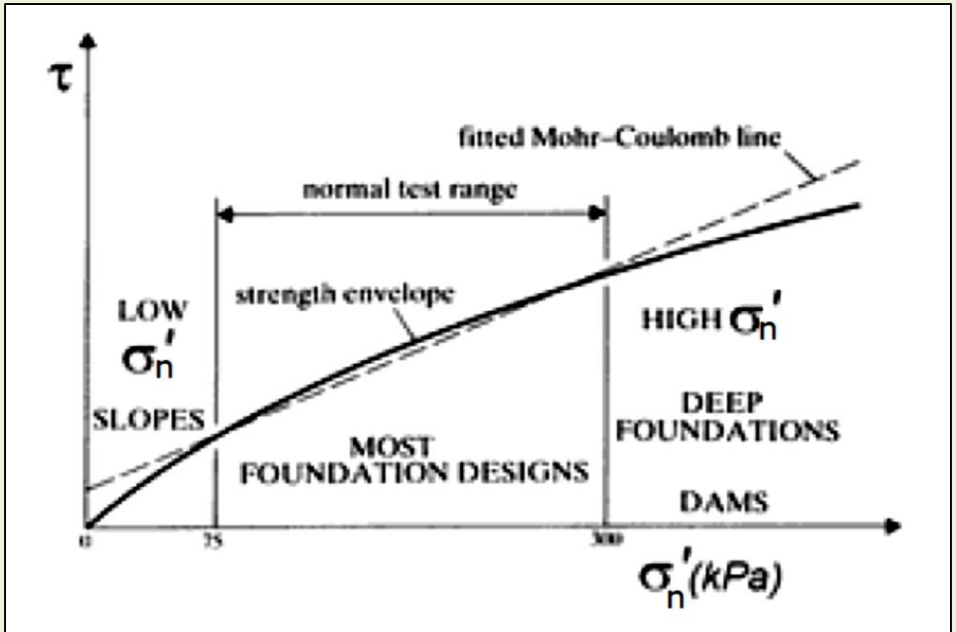




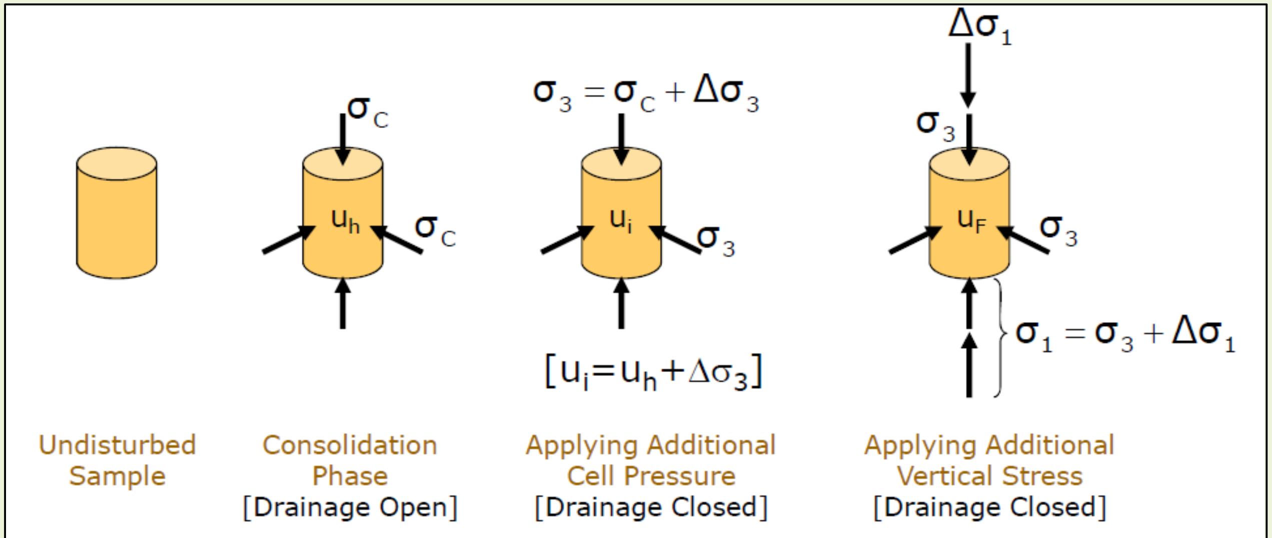


Triaxial Shear Test Conditions

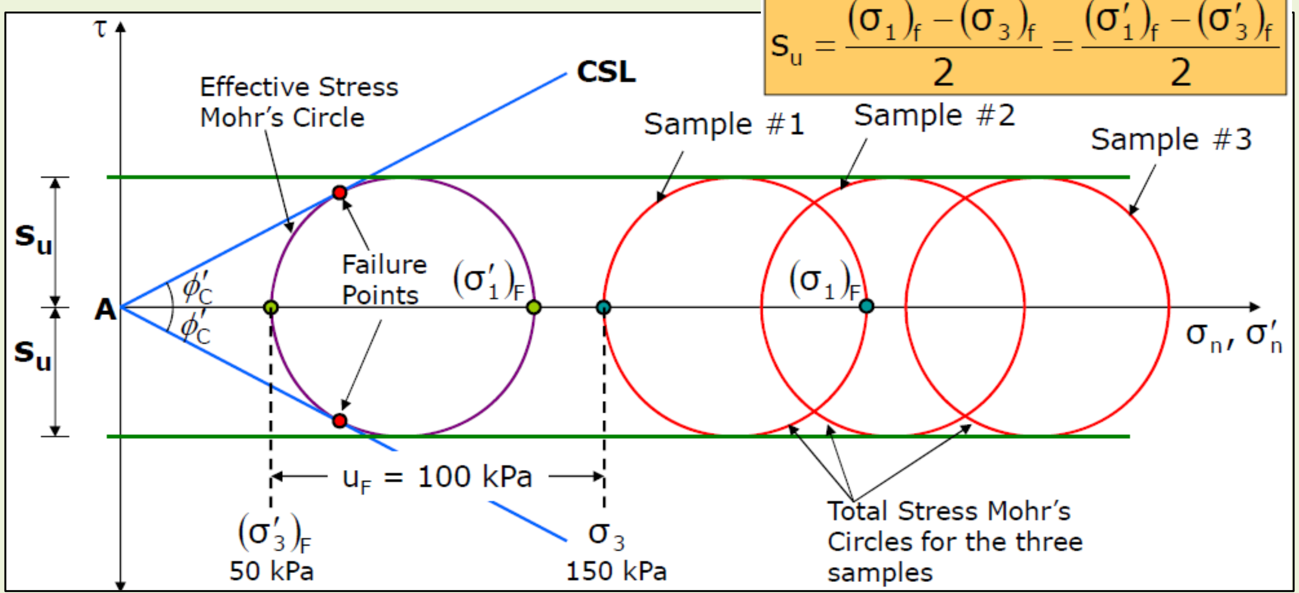
- Appropriate consideration of confining stress range
  - *50, 100, 150, 200 kPa – Foundation design problems*
  - *< 75 kPa – Slope stability problems*
  - *> 300 kPa – Dam amd Deep foundation problems*
- Appropriate fitting on curvilinear failure envelope
  - *Proper estimation of shear strength parameters*



Consolidated Undrained Test

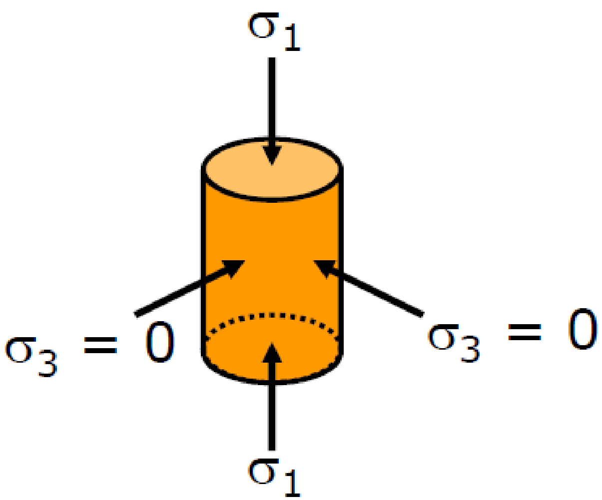


$$s_u = \frac{(\sigma_1)_f - (\sigma_3)_f}{2} = \frac{(\sigma'_1)_f - (\sigma'_3)_f}{2}$$

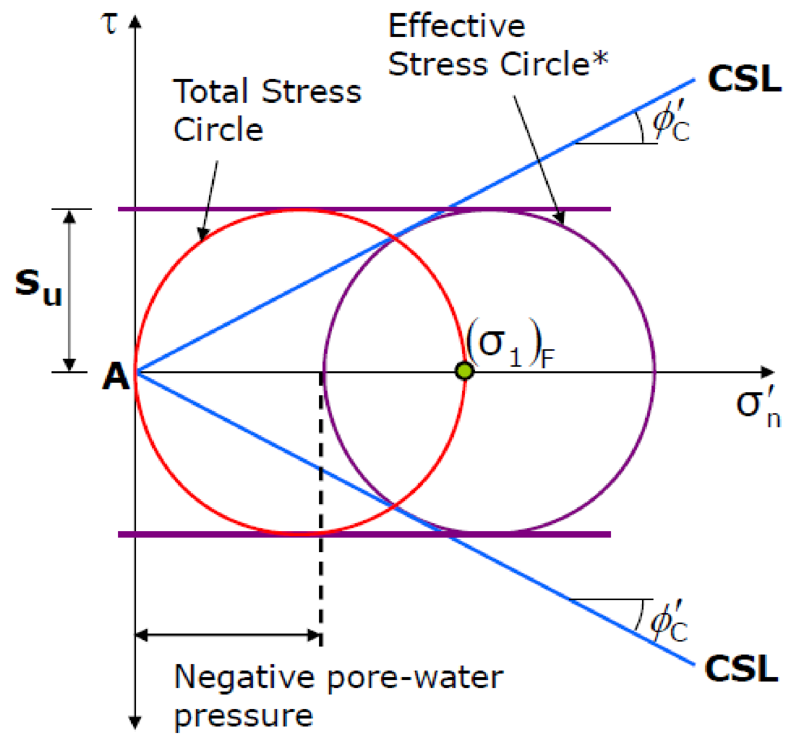


Unconfined Compression Test

s_u from Unconfined Compression Test

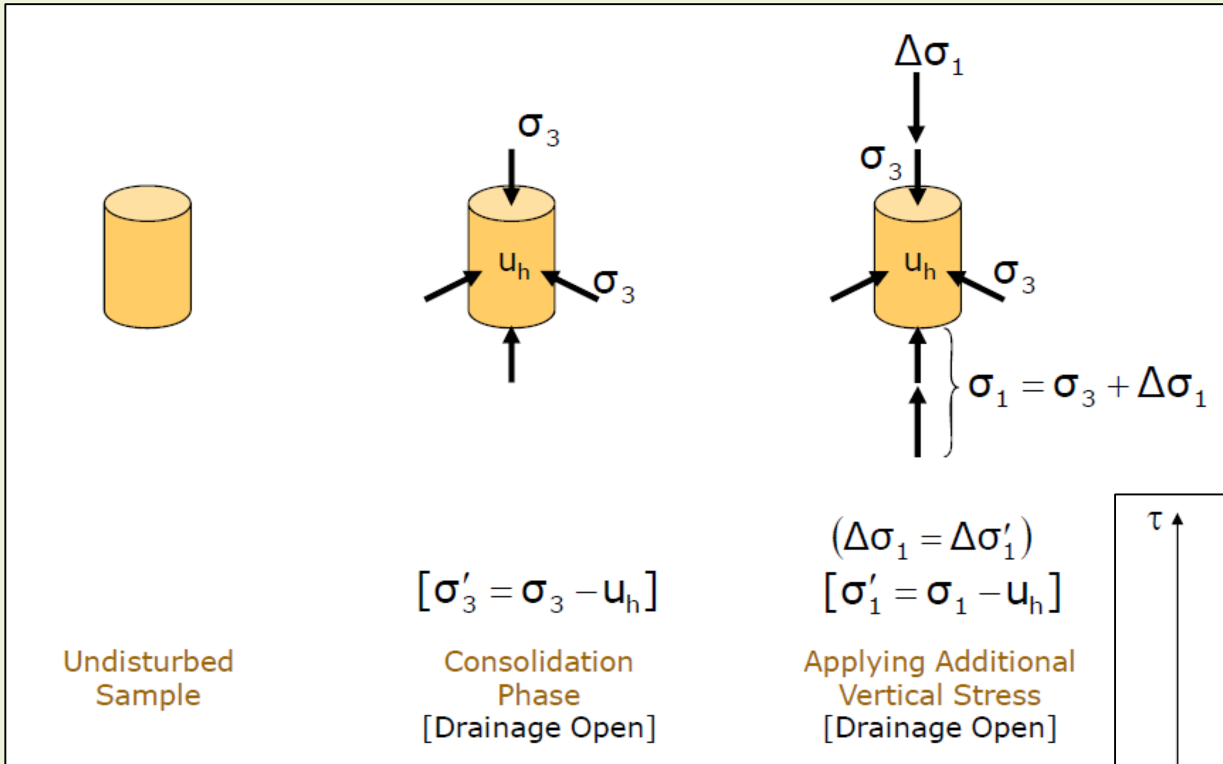


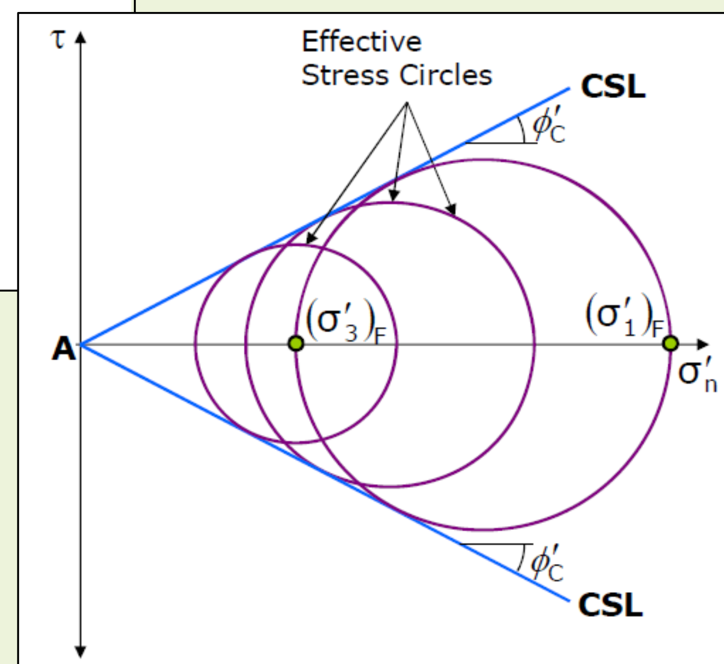
$$s_u = \frac{1}{2}(\sigma_1)_F$$



[* Shown for the purpose of illustrating negative pore-water pressures in fine-grained soils. In case of unconfined compression test, it is not possible to plot Mohr's Stress Circle in terms of effective stress.]

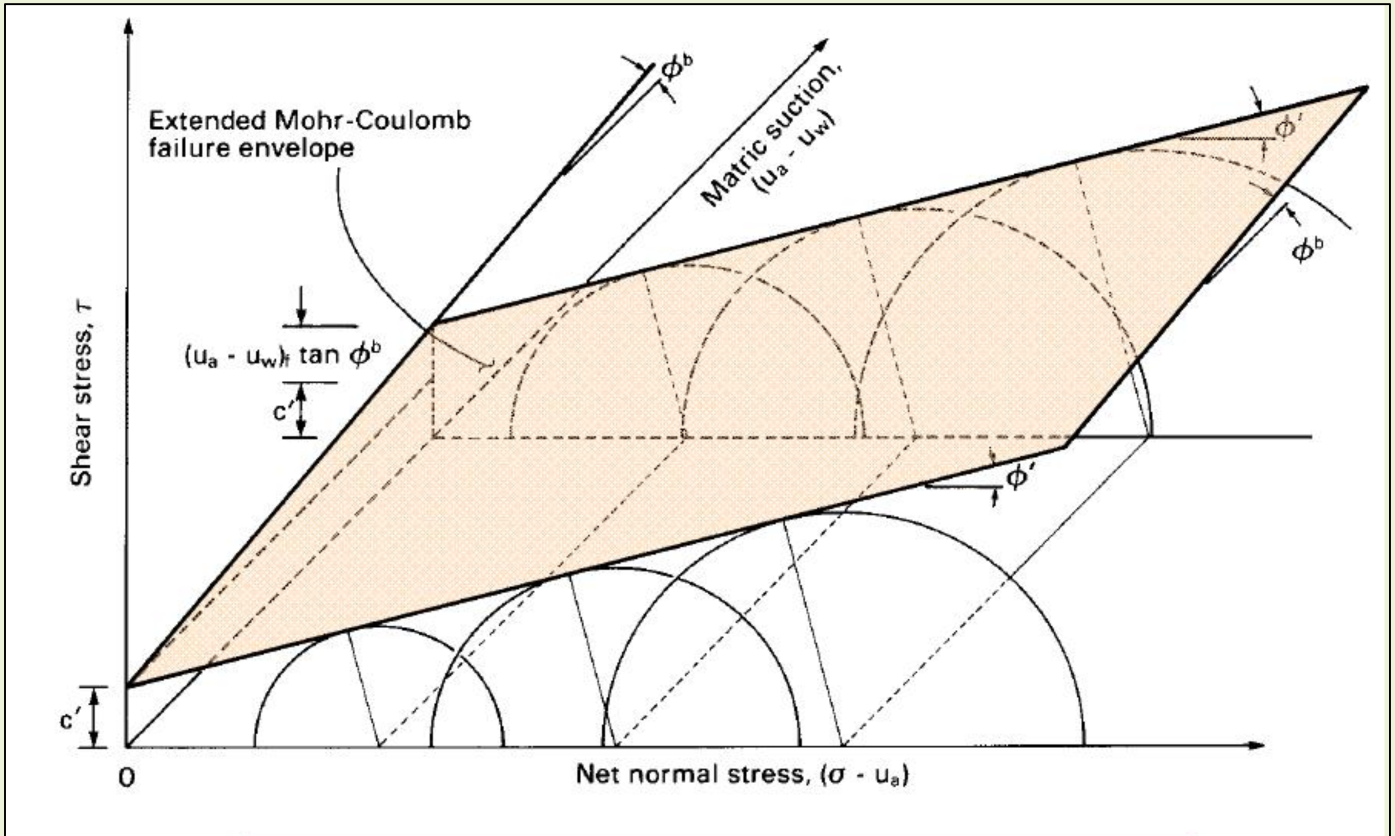
Consolidated Drained Test





Unsaturated Triaxial Strength Test

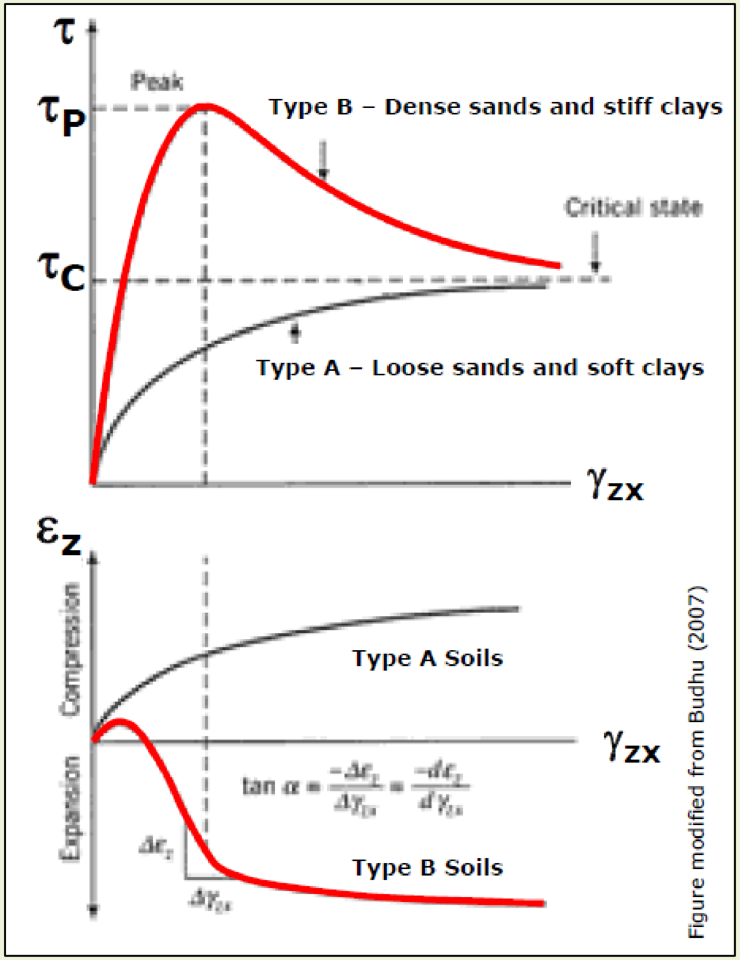
- Extended Mohr-Coulomb Failure Envelope
  - *Fredlund and Rahardjo (1993)*

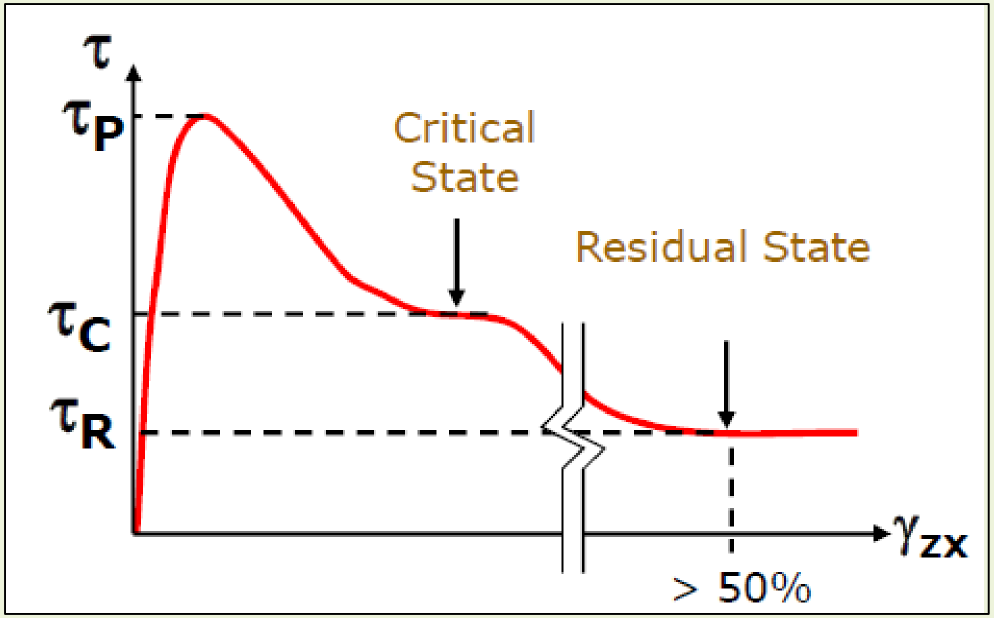


$$\tau_f = c' + (\sigma - u_a)_f \cdot \tan\phi' + (u_a - u_w)_f \cdot \tan\phi^b$$

Residual Shear Strength

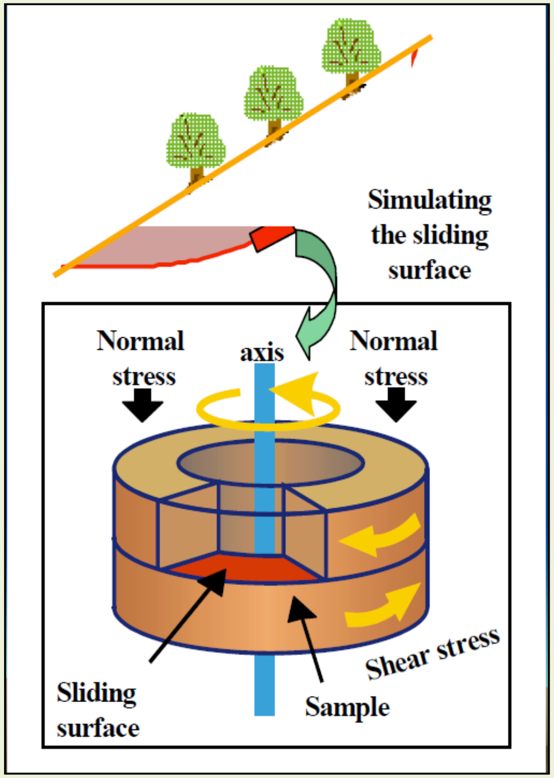
- Response of saturated fine grained or very soft soil to shearing





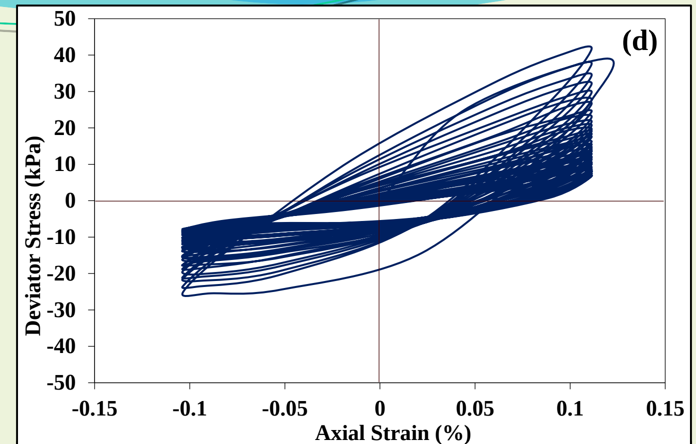
Residual Shear Strength

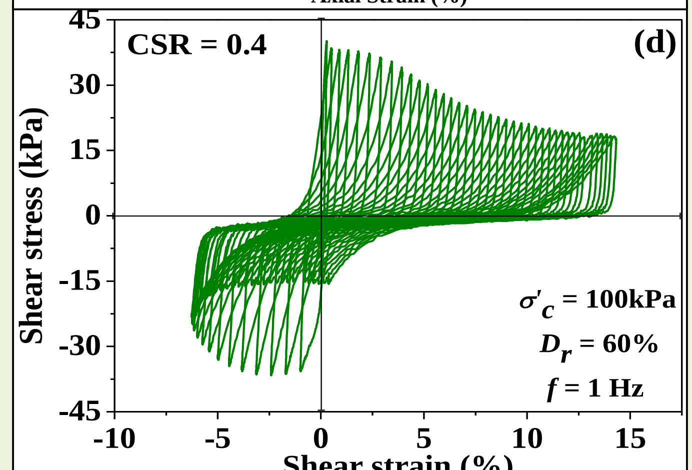
- Torsional Ring Shear test
  - *Simulation of landslide strains*
    - One-directional or cyclic
    - Large deformation problem

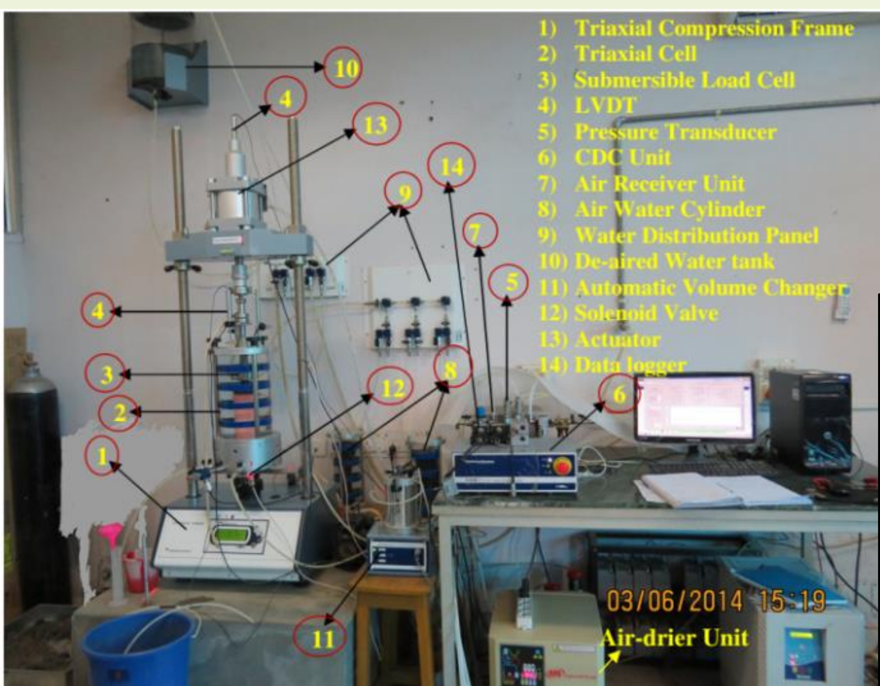


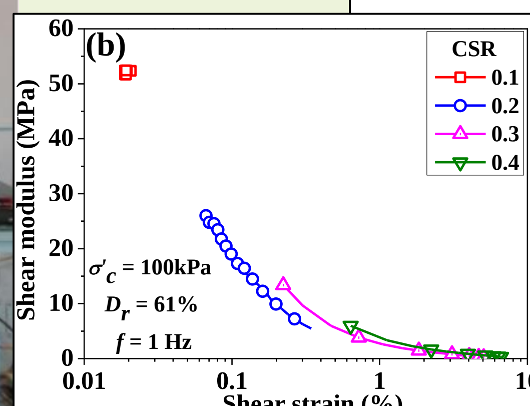
Cyclic Shear Strength

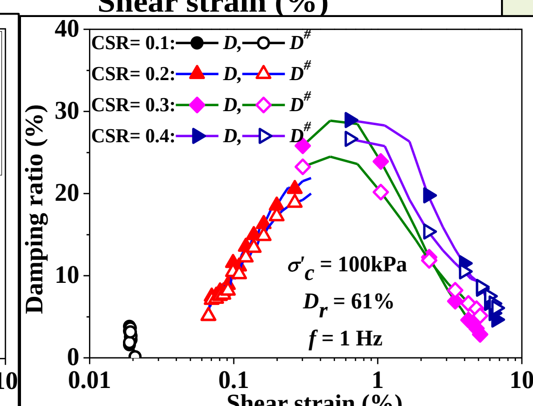
- Cyclic Triaxial Shear test
  - ❖ *Stress-controlled and Strain-controlled tests*
    - Simulation of seismicity induced failures
    - Determination of dynamic behavior of soil
      - Shear modulus degradation
      - Damping ratio





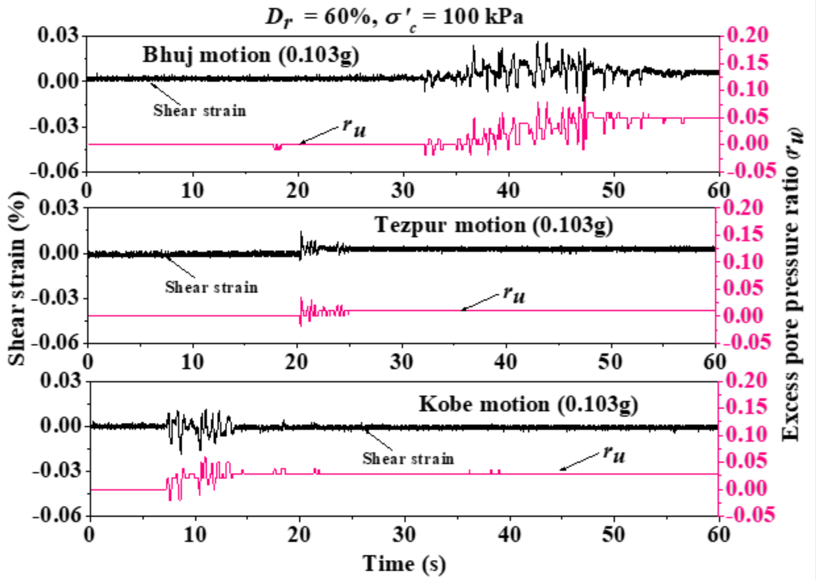


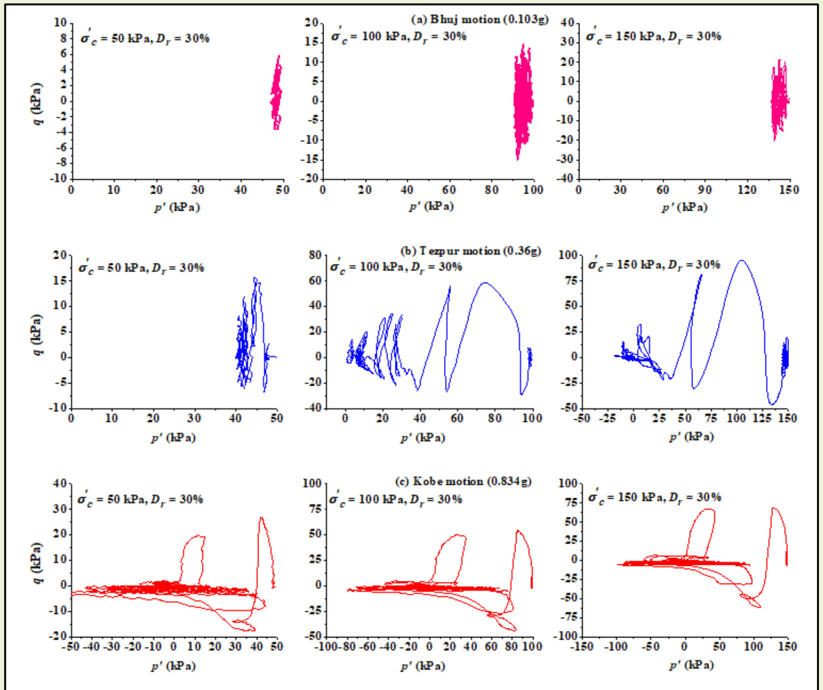


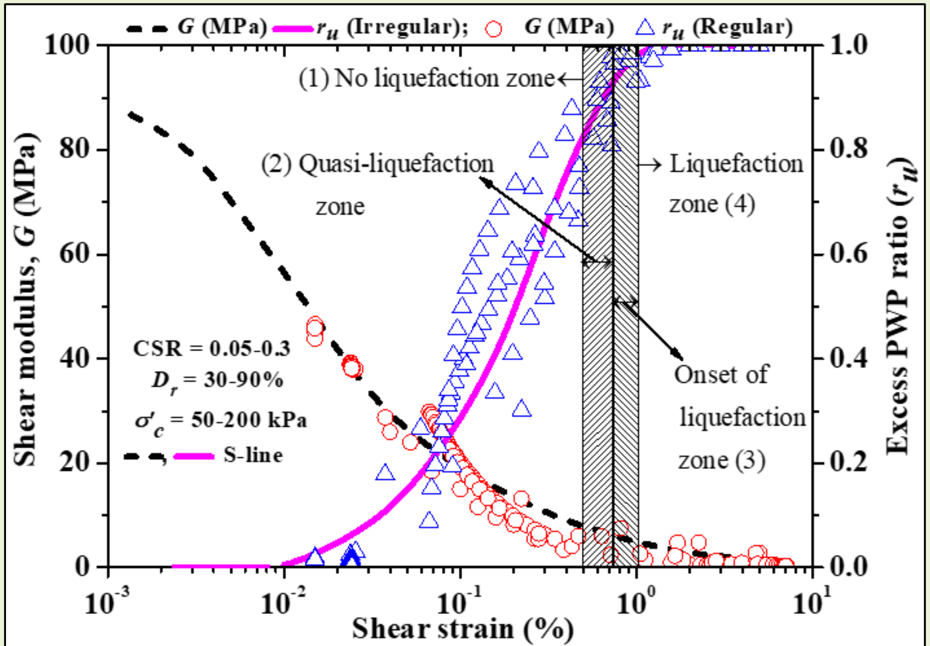


Cyclic Shear Strength

- Cyclic Triaxial Shear test
  - *Stress-controlled and Strain-controlled tests*
    - Simulation of seismicity: Regular and irregular excitations
    - Liquefaction scenarios and parameters
      - Evolution of Liquefaction induced landslides

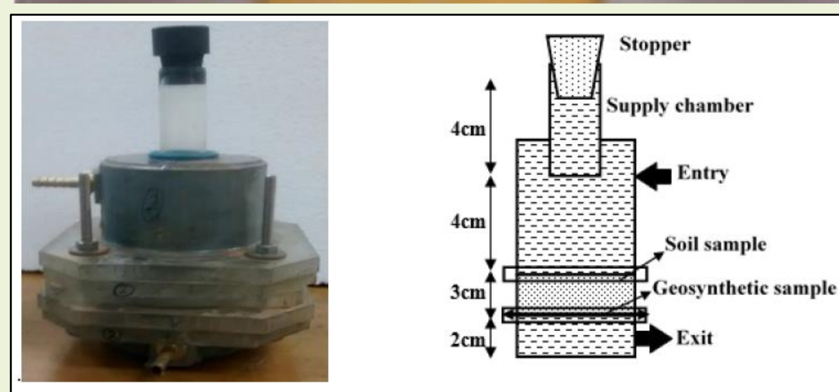




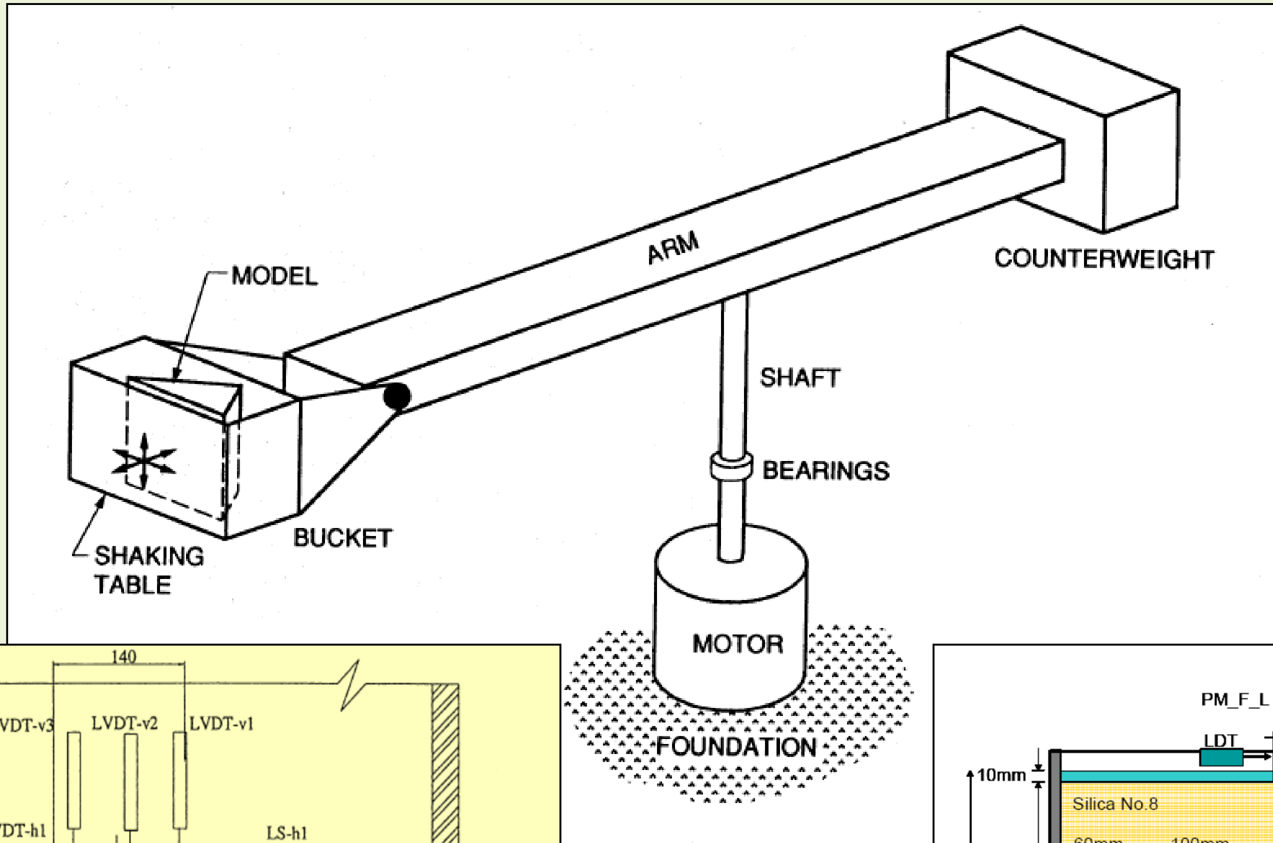


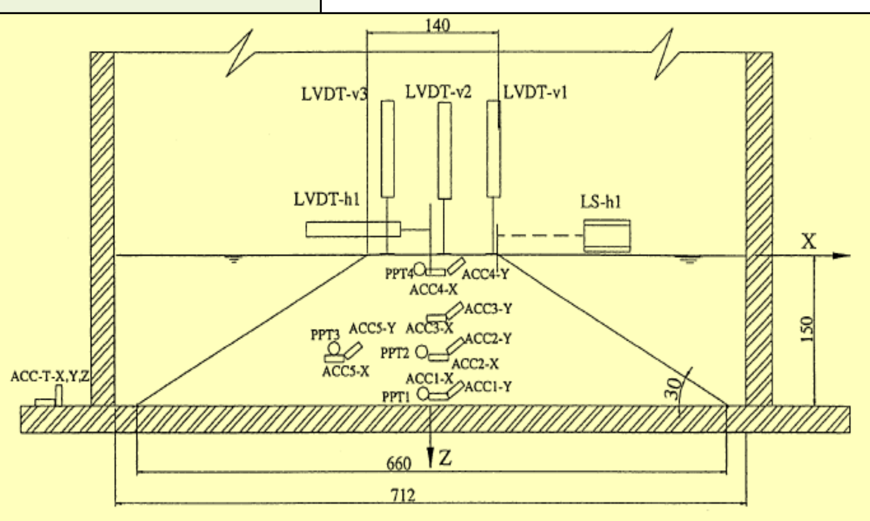
Centrifuge Test

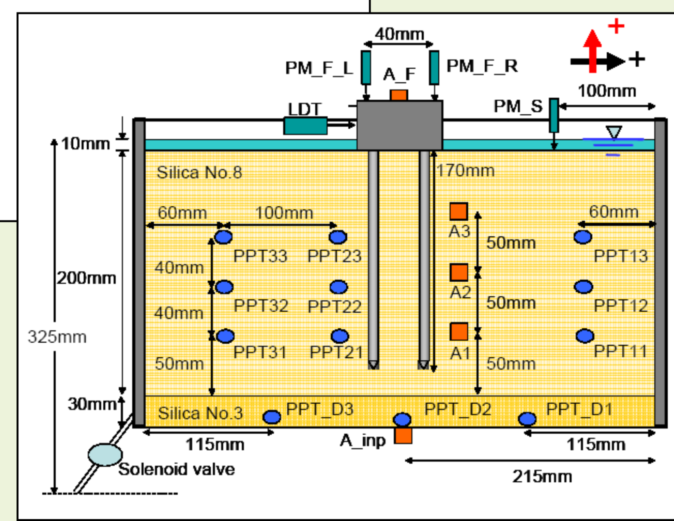
- Miniaturization tests simulating field scenarios
  - ❖ *Miniature centrifuge in the IIT Guwahati Geotechnical laboratory*
  - ❖ *Huge centrifuge of 9 m radius at UC Davis, California*



Representation of Centrifuge Testing Scheme





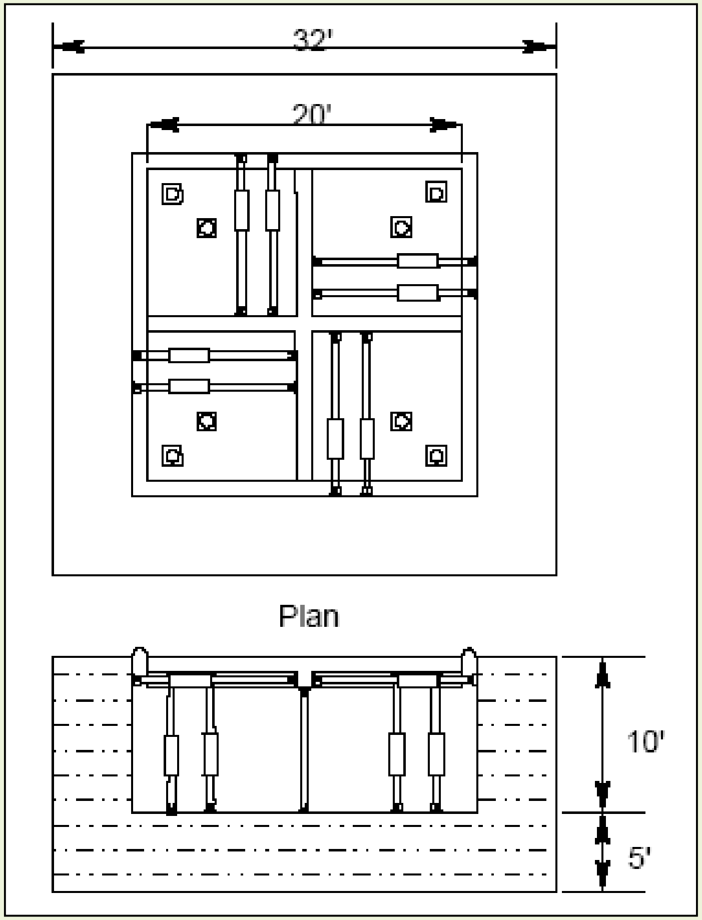


Shaking Table Tests

- *1-g model tests for liquefaction, settlement analysis, foundation response*
- *Uni-direction shake table: Simulates the most dominating feature of earthquake i.e., horizontal shaking*
  - Unidirectional Shake Table at IIT Guwahati

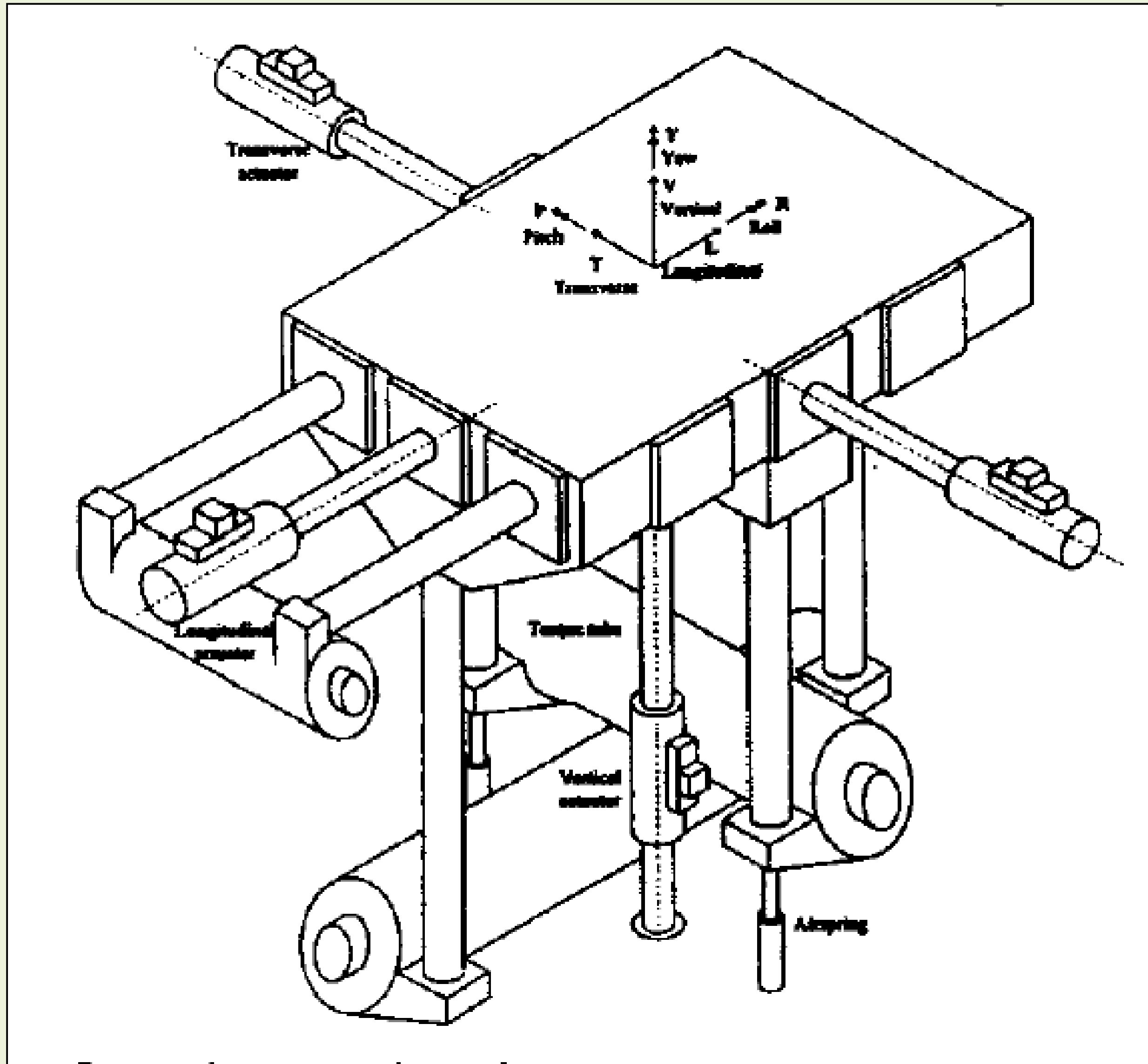
Shake Table at University of California Berkeley

- Biaxial → 8 vertical and 8 horizontal actuators



Schematic of a Shake Table

- Tri-axial shake table



Final Words

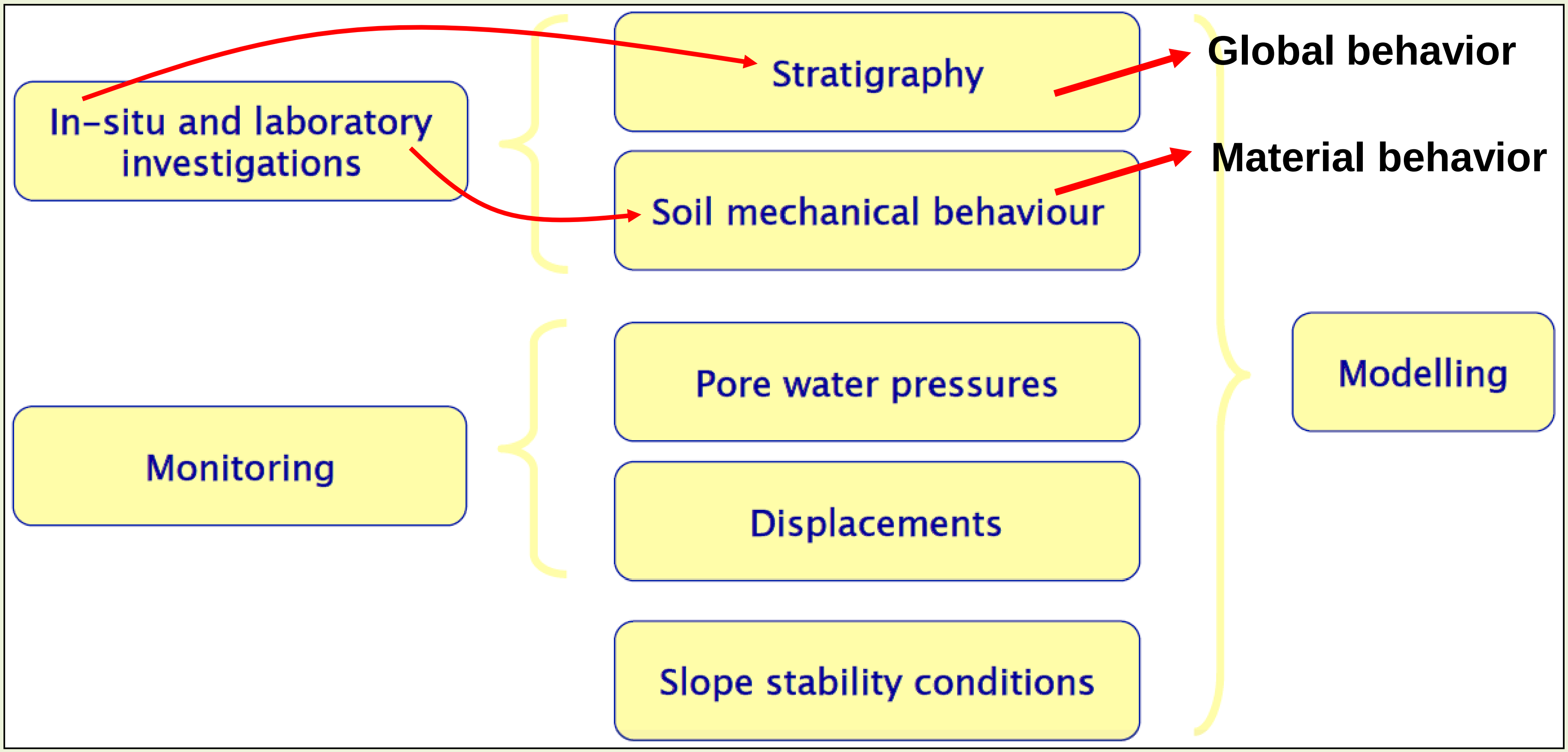
- Myriads of Laboratory Investigations
  - *Which to choose?*
    - What do we try to find out?
      - Index, Strength, Hydraulic or Deformation characteristics?
      - Saturated / Unsaturated characteristics
    - What time scenarios we are looking into?
      - Short-term or long-term characteristics?
    - What are the influential factors?
      - Rainfall, Seismicity, Water, Excavation … etc.
    - What are the mechanism we are looking to?
      - Slide, Flow, Spread etc.
      - Translational, Rotational, Progressive etc.
      - Rate of movement

SCIENTIFIC AND ENGINEERING JUDGEMENT

ACCOMPANIED BY PROPER INTERPRETATION

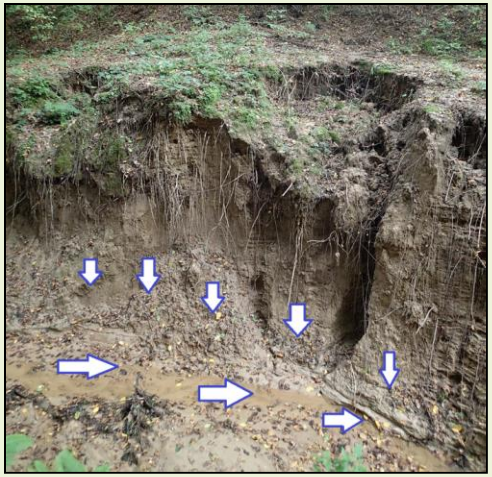
Field Investigations and Monitoring

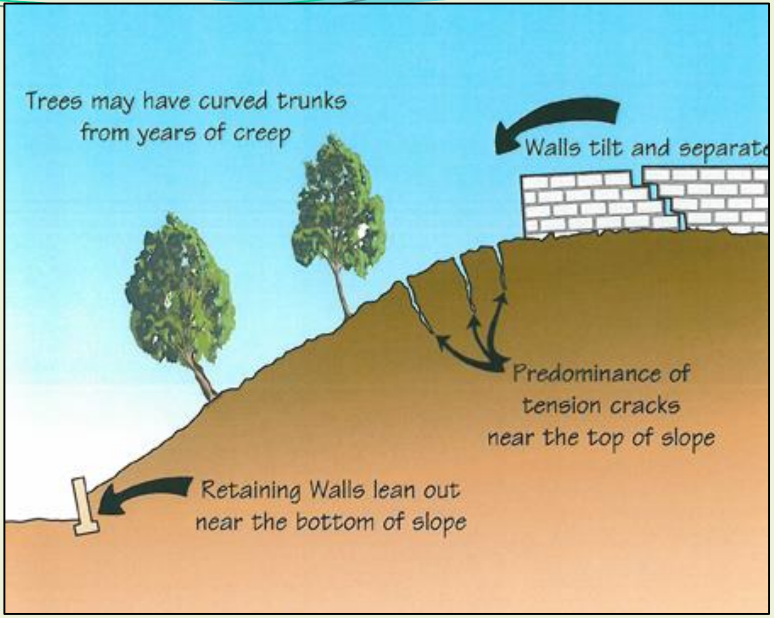
Components of Landslide Studies

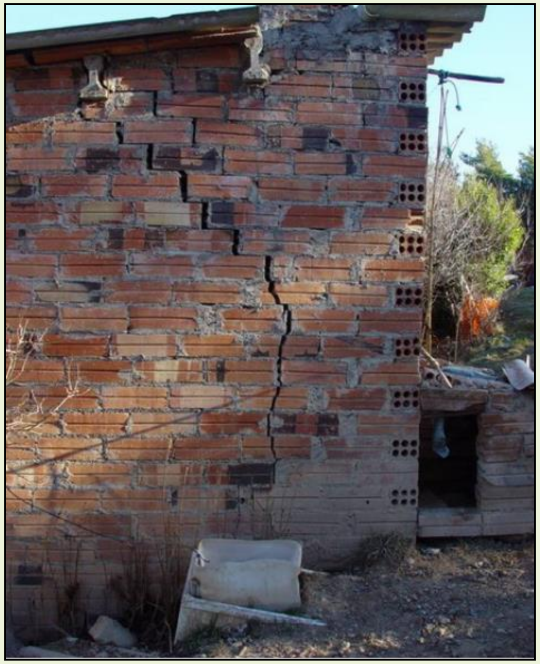


Landslide Reconnaissance

- Identification of potential/actual landslide through Geomorphological features





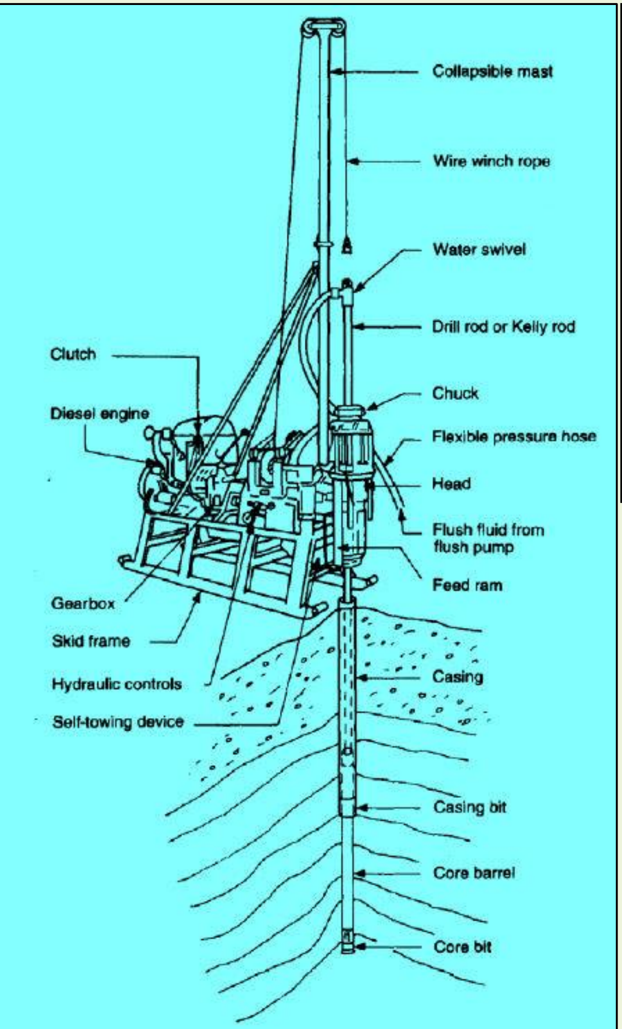


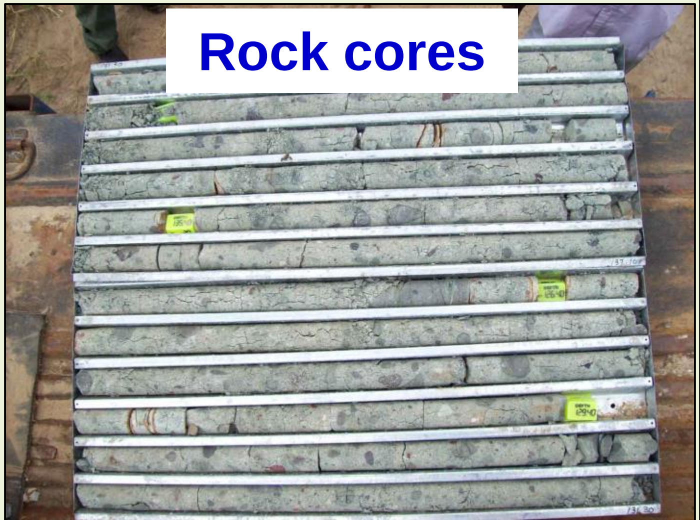
Landslide Reconnaissance

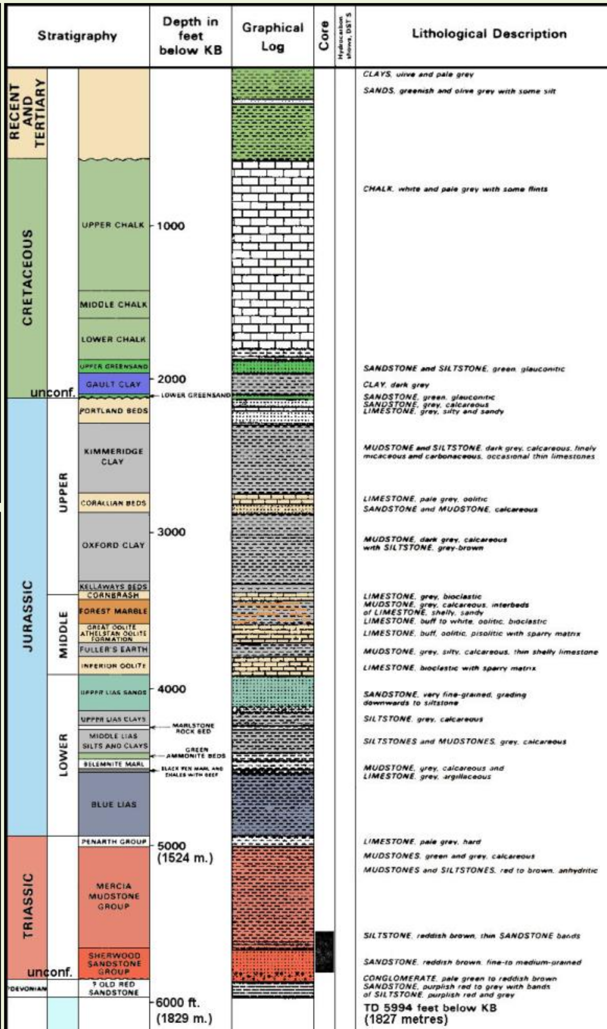
- Landslide behind Tawang Monastery

Exploratory Borings

- Core borings with continuous sample retrievals

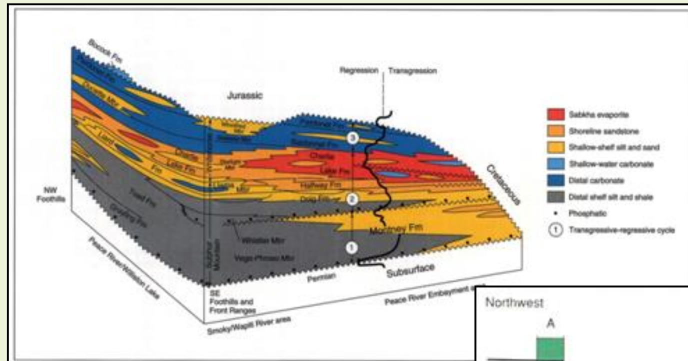


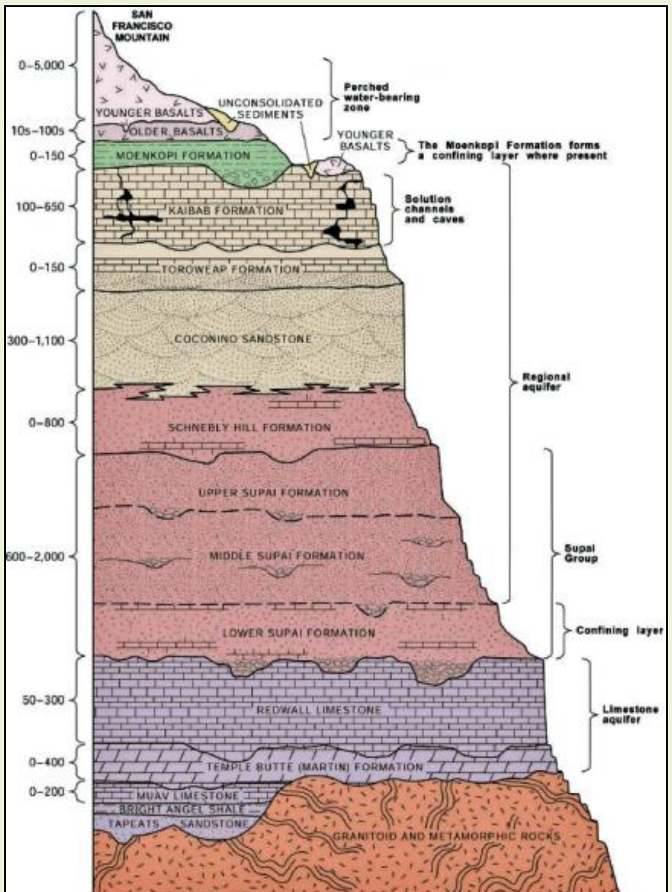


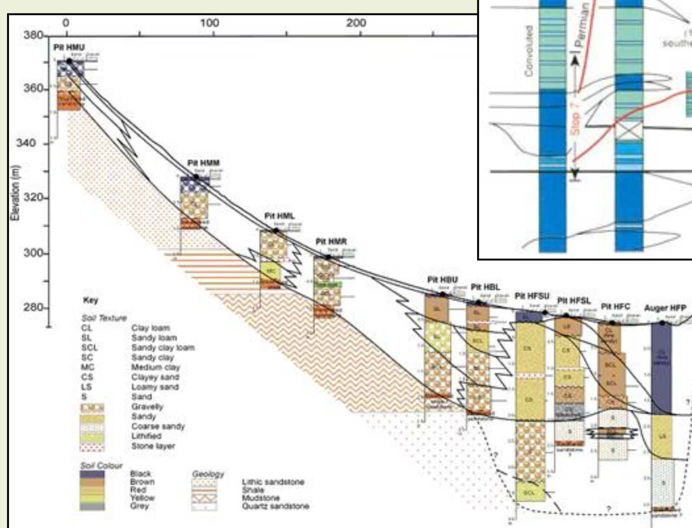


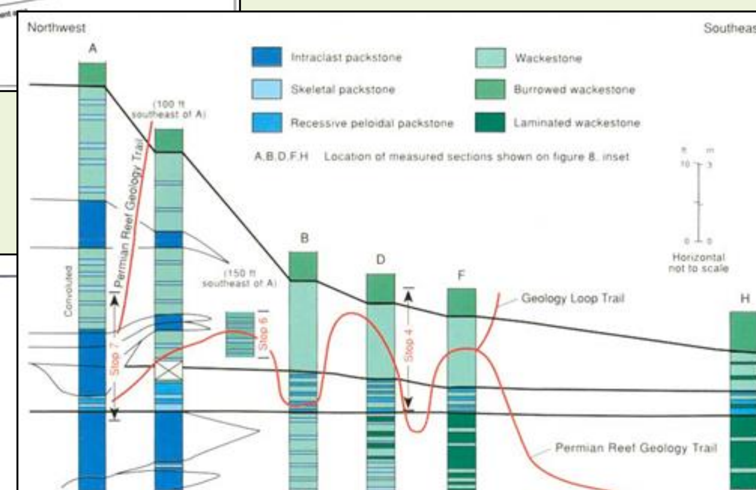
Exploratory Borings

- Achieve a good identification of geological profile and soil stratification









Exploratory Borings

- Representative BoreLog
  - ❖ *Necessary Information provided*
    - Method of boring
    - Drill-hole diameter
    - Boring inclination
    - RL of surface and Datum
    - SPT-N values
    - Sample nature
      - (Disturbed/Undisturbed)
    - Depth of SPT tests and sample collection
    - Soil material description with classification symbols
    - Location of water table
    - Moisture condition and index of density/consistency

Client : TasWater | Date : 29/8/13
Project : Proposed New Sewer Pipe | Logged By : MS
Location : Rosebery

Drill model : Drilltech | Easting: | Inclination: -90° | RL Surface :
Hole diameter : 130mm | Northing: | Bearing: - | Datum :

Method	Support	Penetration	Water	Notes Samples Tests	Depth (m)	Graphic log	Classification Symbol	Material Description	Moisture condition	Consistency density, index	Structure, additional observations
ADV	N				0.25, 0.50			FILL - Sandy Gravel, fine to coarse gravel (subangular, bluestone), grey	M	L MD	FILL
					0.75, 1.00		SM	SILTY SAND - fine grained, brown/ grey, with some clay and a trace of gravel	M	MD	NATURAL
					1.25		ML	SANDY GRAVELLY SILT - low plasticity, fine sand, light green/light brown	M	MD	
			▽		1.50, 1.75			Becoming light green, with a trace of clay	W		Water seepage at 1.5m
					2.00			Becoming light brown			
					2.25			Borehole terminated at 2.0m			

Depth scale: 0.25, 0.50, 0.75, 1.00, 1.25, 1.50, 1.75, 2.00, 2.25

Borelog cum Laboratory Test Result Datasheet

Boring method: Shell& Auger & Wash   Boring dia: 100mm   Date Commenced:11-06-08   Date completed:11-06-08

BH:1

Depth in meters below reference	Types of Sample	N-Value	Group symbols	Visual description of soil	% Gravel > 4.75mm	% Sand 4.75-0.075 mm	Silt 0.075-0.002	% Clay < 0.002 mm	Field density gms/cm³	Specific Gravity	Void Ratio	Natural moisture content	Unconfined compressive strength/cm² (U D)	Shear parameter: Cohesion 'c' Kg/cm²	Shear parameter: Angle of shearing resistance (Φ°)	Compression Index Cc	LL%	PL%	Passing 75 micron (%)
1.5-1.95	P	5		Brownish gray CLAY															
2.0	U			trace/some silt silty			15	85	1.91	2.67	0.75	28.1	0.51	0.25	5	0.13	40.6	24.4	
3.0-3.45	P	7		CLAY trace sand.															
3.5	U						10	90	1.95	2.67			0.72	0.35	4				
4.5-4.95	P	7	**CI**																
5.0	U						10	90											
6.0-6.45	P	11																	
6.5	U			6.5M		5	35	60	1.99	2.66			0.78	0.38	11				
7.5-7.95	P	18		Brownish gray fine															
8.0	D			SAND trace/some silt		65	25	10	1.94	2.67			0.22	0.12	26				
9.0-9.45	P	24	**SM**	trace clay.															
9.5	D					85	10	5											
10.5-10.95	P	27																	
11.0	D			12.0M		90	10		1.97	2.66					33-DS				

U: Undisturbed sample:: P: Standard Penetration test :.   D: Disturbed sample   DS:Direct Shear Test

In-Situ Soil Strength

- Characterization of in-situ soil properties
  - ❖ *Standard Penetration Test (SPT)*

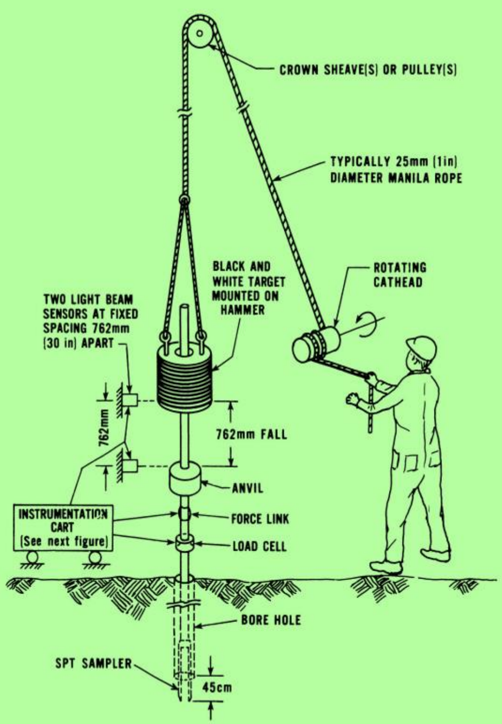
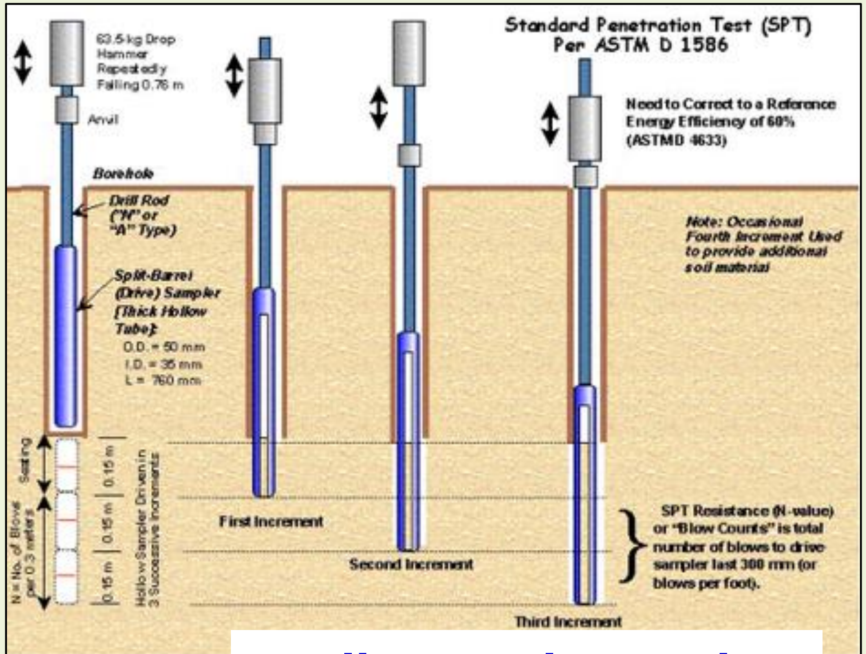
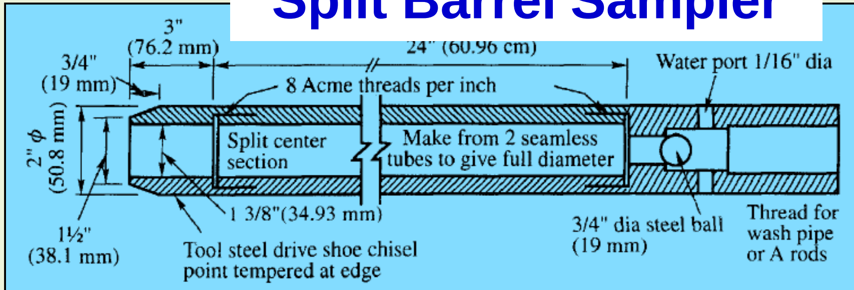


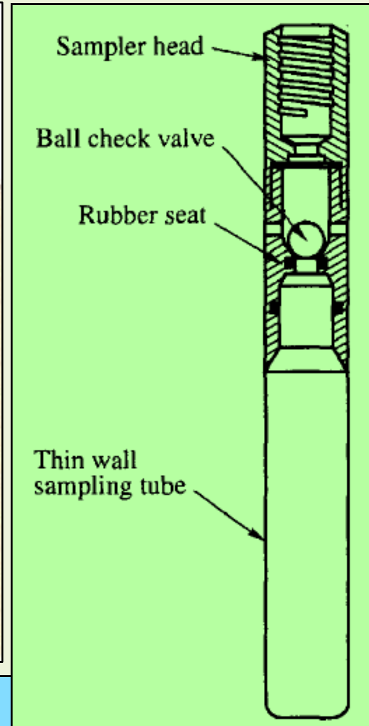
Figure 2-1. Sketch of instrumentation set up to measure fall height, velocity just before impact, and force in the drill stem.

12



Split Barrel Sampler



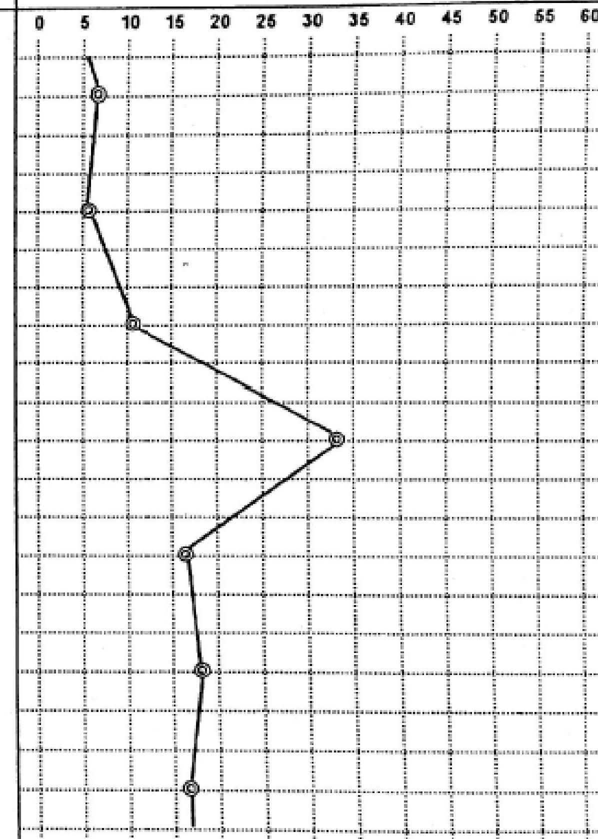


Thin Shelby Tube Sampler

Typical Borelog

Continued from previous sheet		BORE HOLE NO: 9							Sheet No: 2	
SUB SOIL PROFILE		**DEPTH**	**SPT**				**SAMPLE**		**GWL**	**REMARKS**
GEO FORMATION	**LOG**	**(M)**	**15 CM**	**15 CM**	**15 CM**	**TOTAL**	**TYPE & NO**	**FROM-TO**		
		7.00					U-5	7.00 - 7.35		
			2	3	4	7	D-5	7.50 - 7.95		
		8.00								
							U-6	8.50 - 8.85		
MEDIUM CLAY OF MEDIUM SPT VALUE, INORGANIC, HIGH PLASTIC		9.00	2	3	3	6	D-6	9.00 - 9.45		
		10.00					U-7	10.00 - 10.35		
			4	5	6	11	D-7	10.50 - 10.95		
STIFF CLAY OF HIGH SPT VALUE, INORGANIC, HIGH PLASTIC		11.00								
							U-8	11.50 - 11.85		
		12.00	7	15	18	33	D-8	12.00 - 12.45		
		13.00					U-9	13.00 - 13.35		
			4	7	10	17	D-9	13.50 - 13.95		
		14.00								
HARD CLAY WITH HIGH SPT VALUE							U-10	14.50 - 14.85		
		15.00	6	8	10	18	D-10	15.00 - 15.45		
		16.00					U-11	16.00 - 16.35		
			5	7	10	17	D-11	16.50 - 16.95		
		17.00								

GRAPHICAL REPRESENTATION OF SPT VALUE



D: DISTURBED SAMPLES // U: UNDISTURBED SAMPLES //
SPT: STANDARD PENETRATION TEST // GWL: GROUND WATER LEVEL

DISTURBED SAMPLE
UNDISTURBED SAMPLE

TYPE OF BORING: AUGUR AND WASH

Characterization of In-Situ Soil

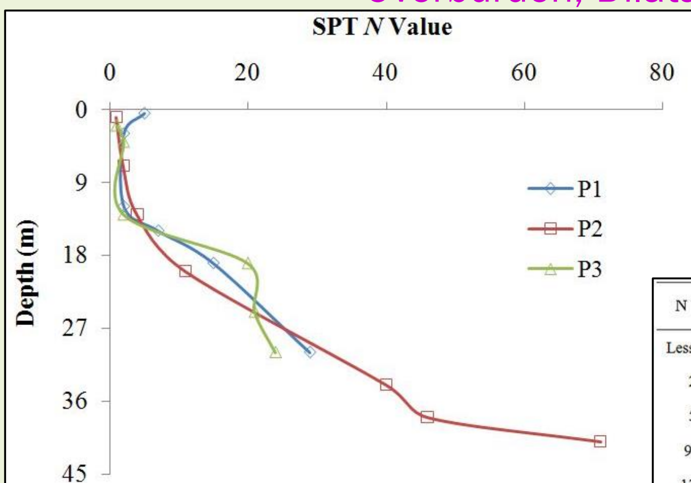
❖ *Standard Penetration Test (SPT)*

- *N*-value: Number of blows for 30 cm penetration (leaving the first 15 cm)
- Corrections applied
  - Overburden, Dilatancy, Hammer impact, fine-grains …

Stiffness

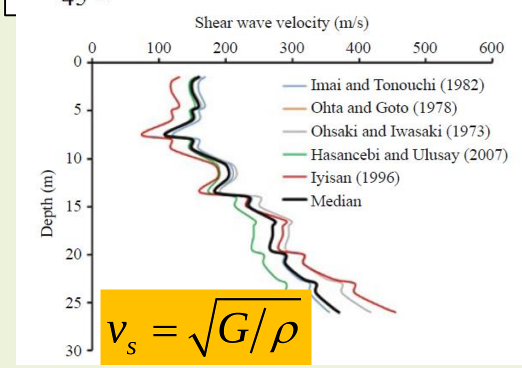
Strength

Index Properties

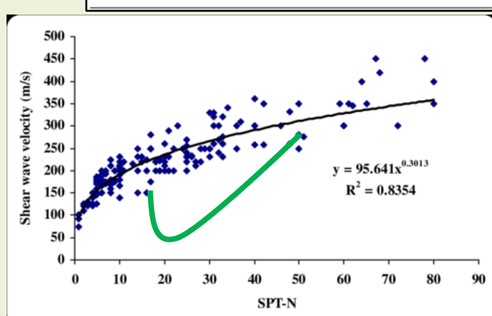


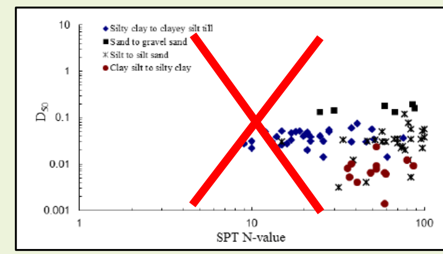
SPT N [Blows/0.3 m]	Soil packing	Relative Density [%]	Friction angle [°]
< 4	Very loose	< 20	< 30
4 -10	Loose	20 - 40	30 - 35
10 - 30	Compact	40 - 60	35 - 40
30 - 50	Dense	60 - 80	40 - 45
> 50	Very Dense	> 80	> 45

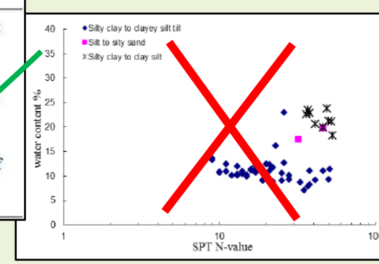
N Value	Unconfined Compression Strength (kg·cm⁻²)	Consistency
Less than 2	Less than 0.25	Very soft
2 - 5	0.25 - 0.50	Soft
5 - 9	0.50 - 1.00	Medium
9 - 17	1.00 - 2.00	Stiff
17 - 33	2.00 - 4.00	Very stiff
Over 33	Over 4.00	Hard

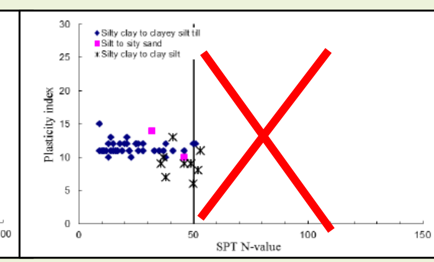


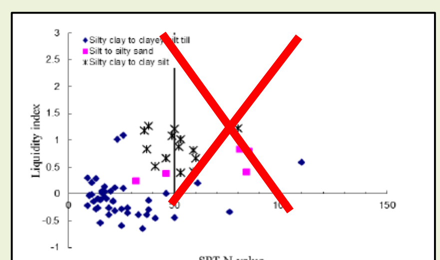
$$v_s = \sqrt{G/\rho}$$

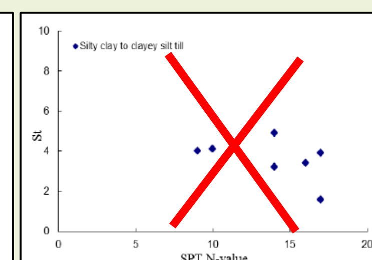






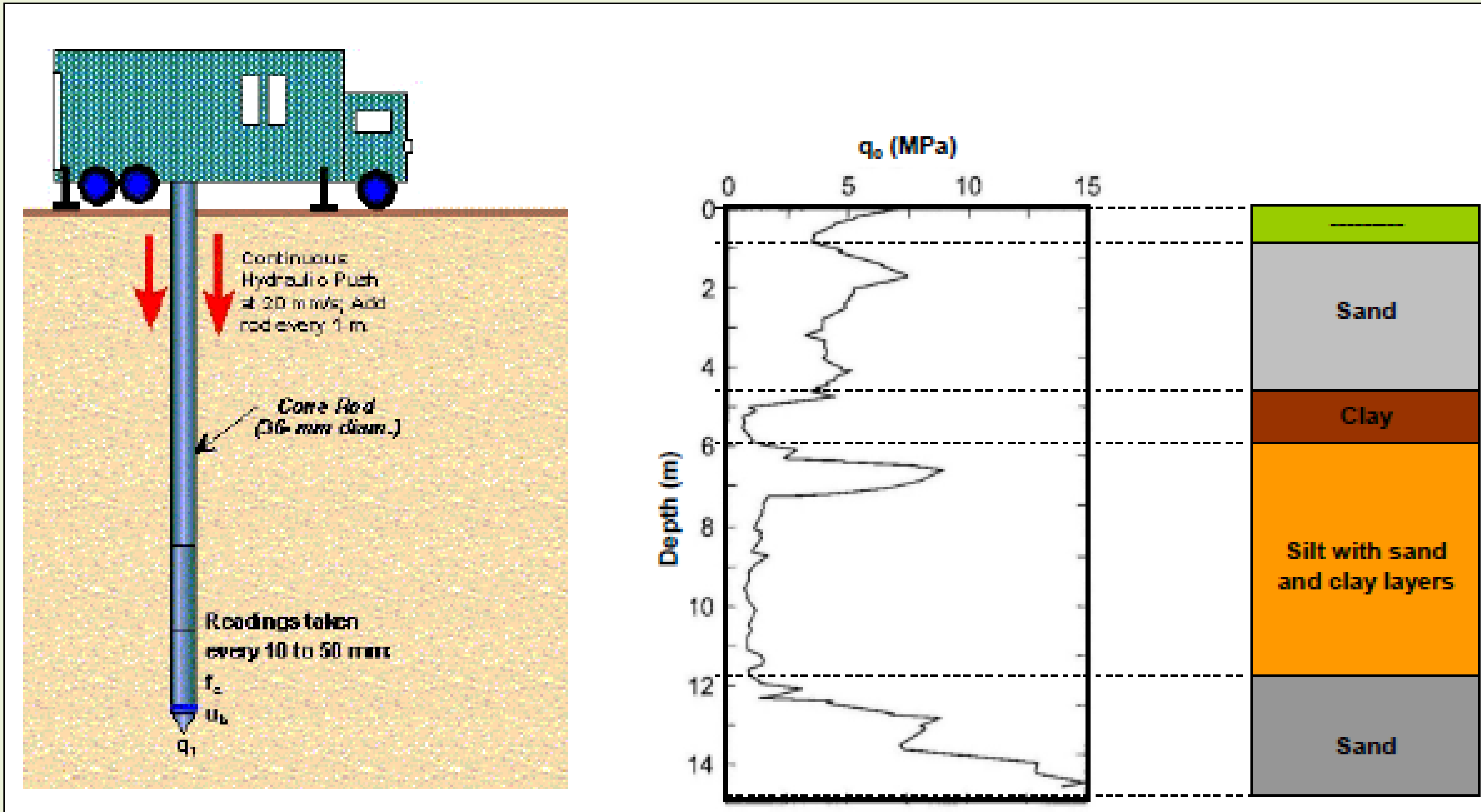






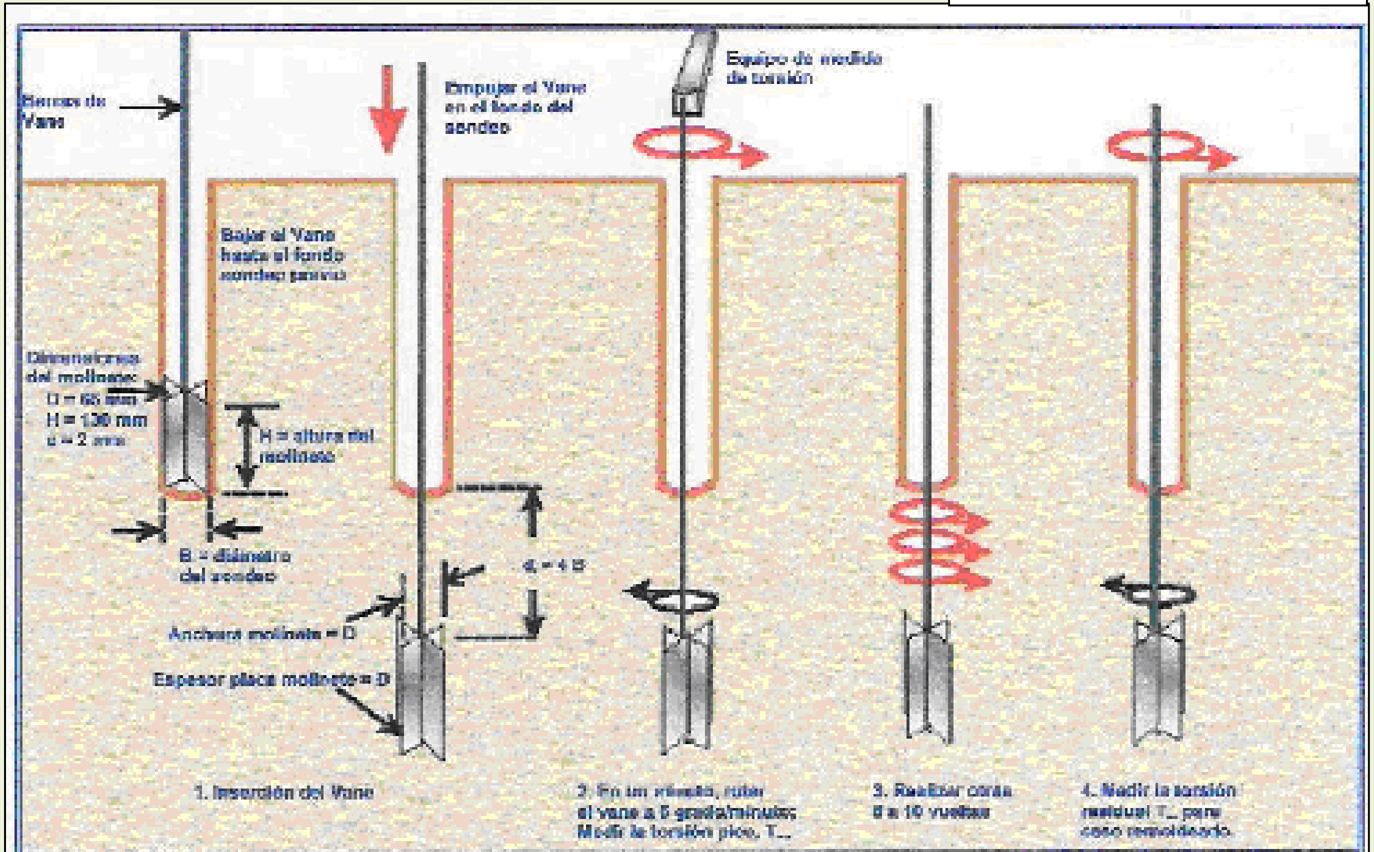
In-Situ Soil Strength

- Characterization of in-situ soil shear strength
    - ❖ *In-situ Cone Penetration Test (CPT) – Soils having fine contents*



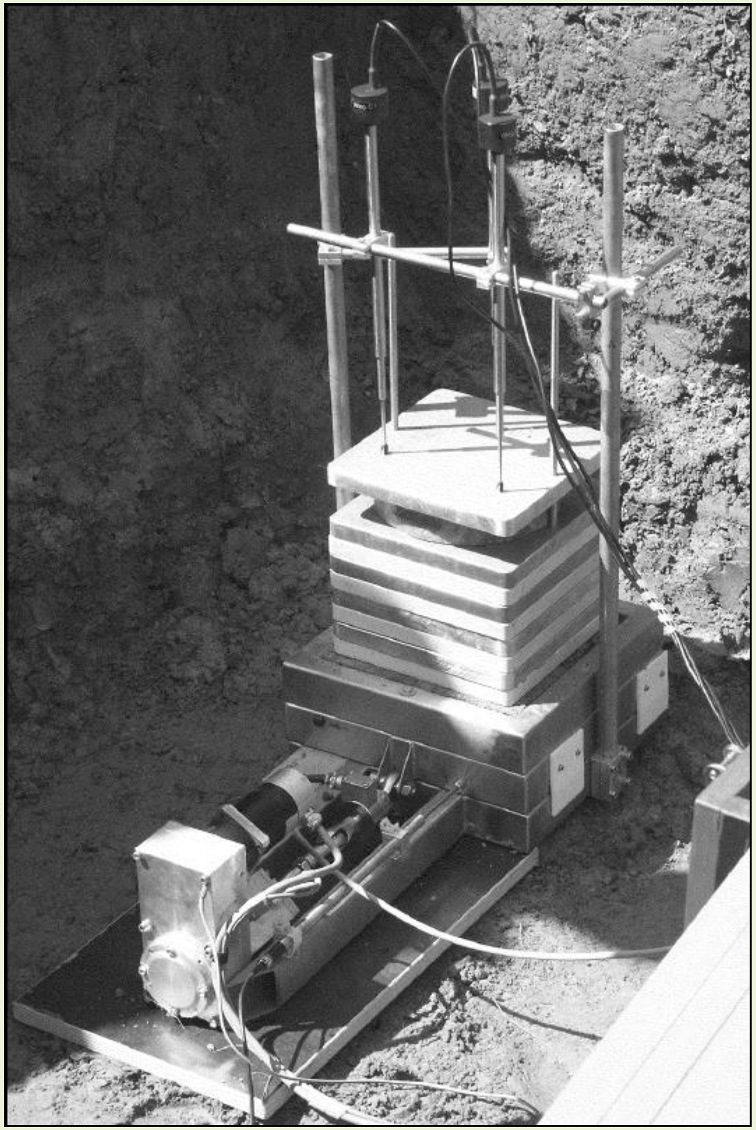
In-Situ Soil Strength

- Characterization of in-situ soil shear strength
  - ❖ *Soils with significantly low shear strength*
    - Field Vane Shear Test and Needle Penetration Test

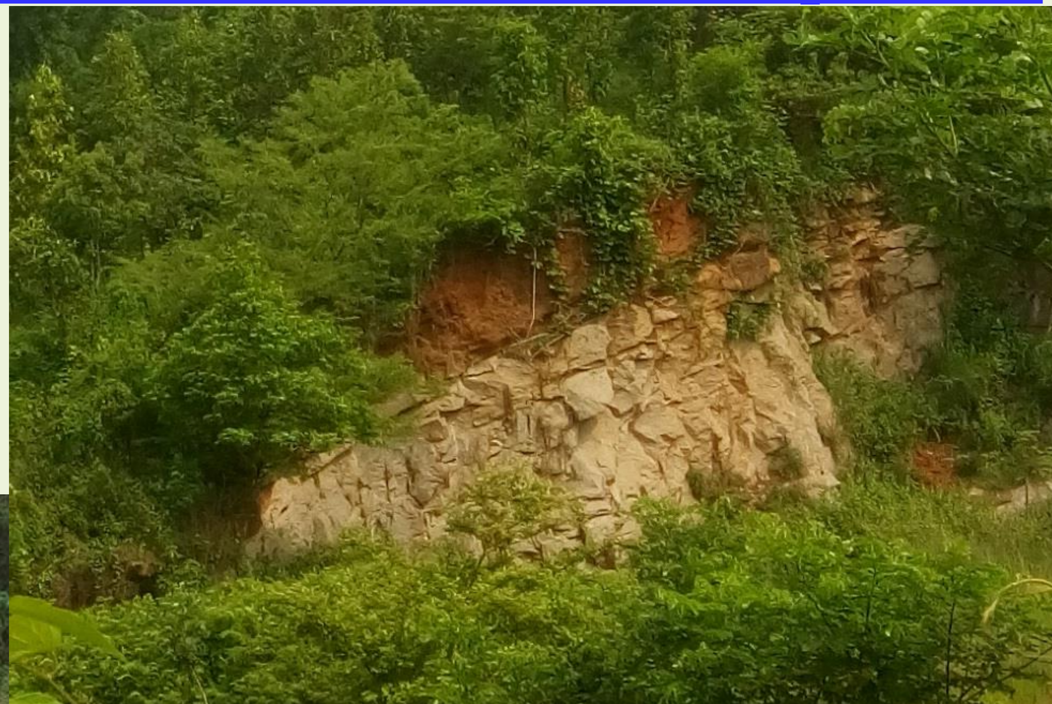


In-Situ Soil Strength

- Characterization of in-situ soil shear strength
  - *In-situ Box Shear Test*
    - Estimation of shear strength characteristics of soils right from the field with in-situ soil conditions



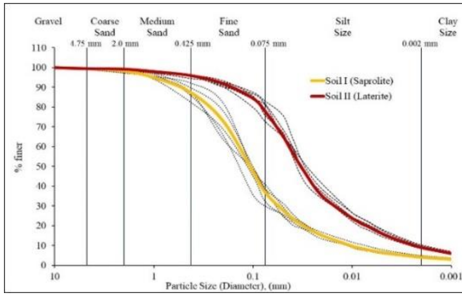
Characterization of Hillslope Soils

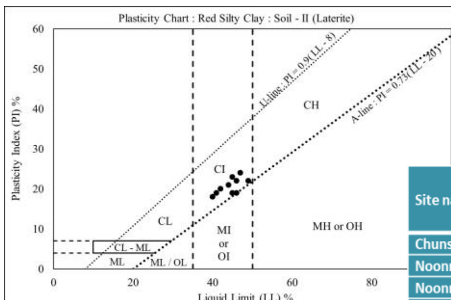


Characterization of Hillslope Soils

- Sample Collection

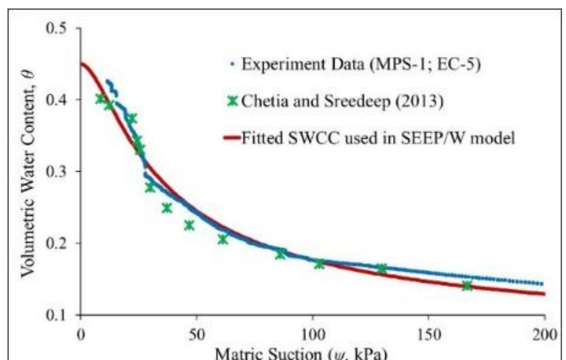
Characterization of Hillslope Soils

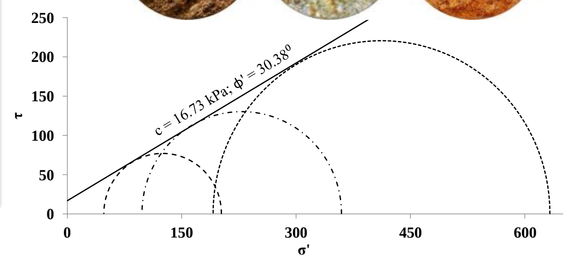


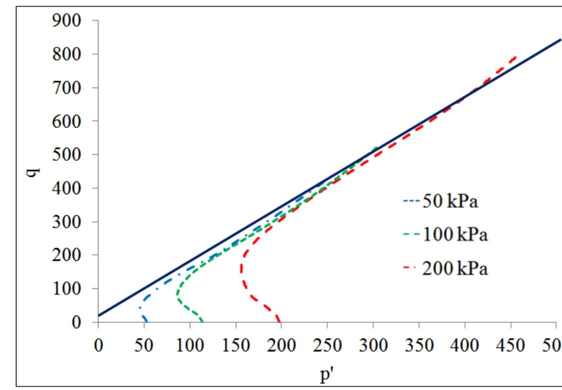


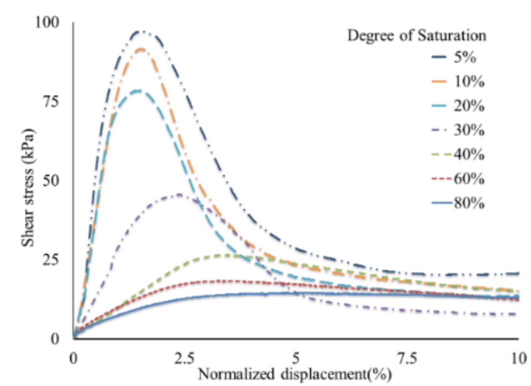
Soil Characteristics	Das and Saikia (2010; 2011) – SOIL 1	Das and Saikia (2010; 2011) – SOIL 2	Chetia and Sreedeep (2013)	Experimental Results – SOIL 1	Experimental Results – SOIL 2
Referred as	RSC	PGSS	RSC_CS	RSC_EXP1	PGSS_EXP2
Specific Gravity	2.44	2.64	2.62	2.68	2.68
In-situ bulk density	1.65	1.79	--	1.92	1.77
In-situ dry density	1.49	1.63	--	1.50	1.57
Liquid Limit	49	39	46	47	35*
Plastic Limit	27	Non – Plastic	27	27	Non – Plastic
Fines Content	72.7	7.45	74	77.8	36.75
Natural Moisture Content	11.00	10.00	--	27.72	12.69
In-situ Volumetric Water Content	16.60	16.52	--	41.68	15.39
Void Ratio	0.78	0.62	--	0.78	0.71
Porosity	0.44	0.38	--	0.44	0.41
In-situ degree of Saturation	38	43	--	95	47.79
Saturated Permeability (m/s)	1.86×10^{-7}	1.2×10^{-6}	--	10^{-6}	10^{-5}

Site name	Maximum infiltration rate $\times10^{-6}$(m/s)	Minimum infiltration rate $\times10^{-6}$(m/s)	Average infiltration rate $\times10^{-6}$(m/s)
Chunsali hill	0.955	0.867	0.911
Noonmati hill 1	1.75	0.160	0.955
Noonmati hill 2	7.36	6.70	4.02
Kailash nagar hill 1	2.12	1.83	1.97
Kailash nagar hill 2	0.828	0.614	0.721
Shree nagar Kailash nagar hill	0.566	0.462	0.514
Punnya nagar hill	4.59	4.48	4.53
Jyoti ban	17.5	11.1	1.43
Indupur kharghuli	113.0	9.00	10.1
Kamakhya hill	0.661	0.58	0.623
Shantipur hill	1.59	1.08	1.33



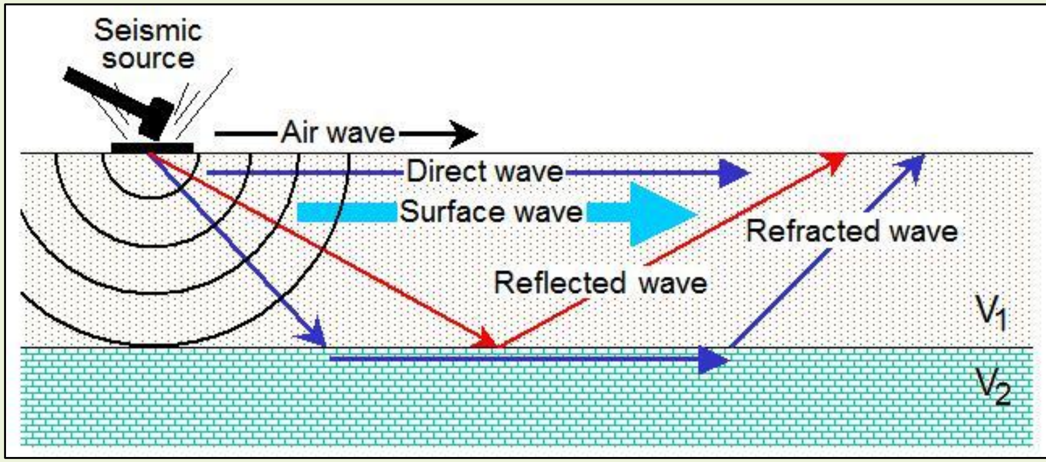


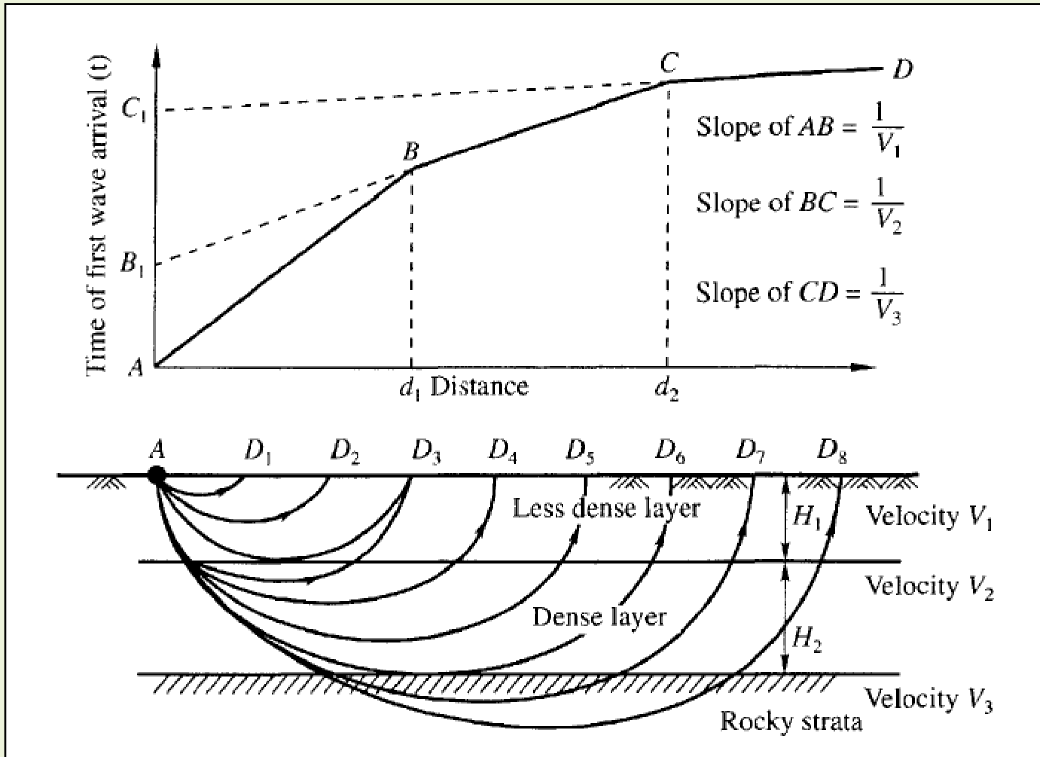




Geophysical Investigation

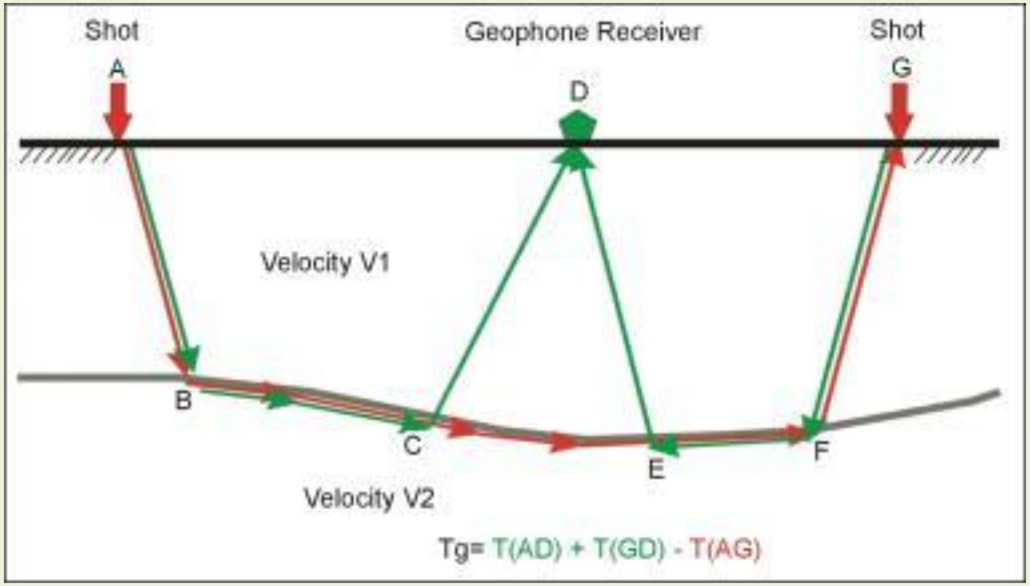
- Seismic Refraction Method (SRS)
  - *Operates on the velocity of wave propagation of the soil medium*
  - *Generates an array of reflected and refracted waves*
  - *Based on first arrival of waves in the receivers*
  - *Results*
    - Velocity of wave propagation in the medium
    - Thickness of the stratification

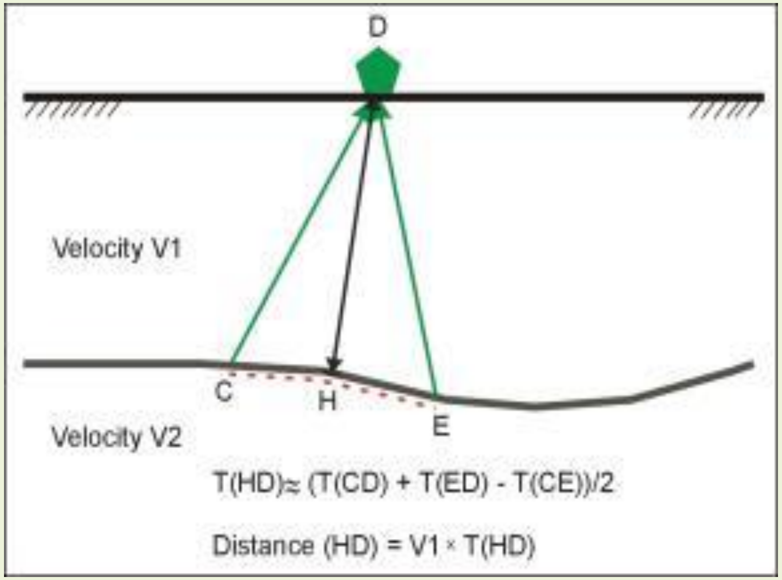




Geophysical Investigation

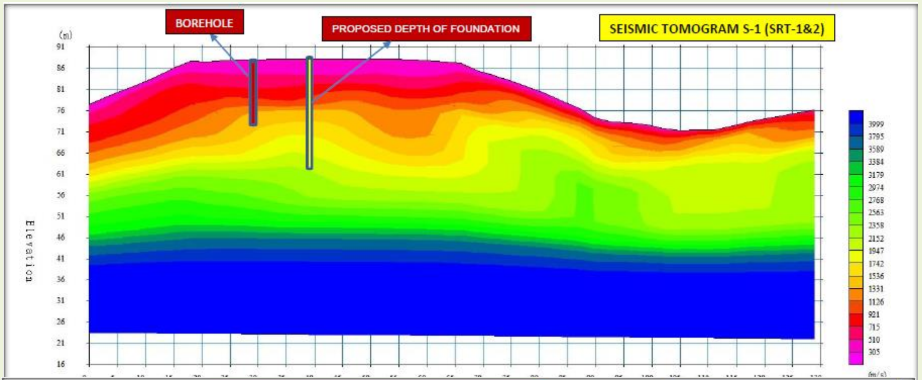
- Seismic Refraction Survey (SRS)
  - ❖ *Based on refraction of generated waves through various soil layers*
    - ▪ Restrictive limitation
      - Each of the successive soil layer should have higher velocity than the shallower layer
      - Improper for arbitrarily formed subsoil stratigraphy

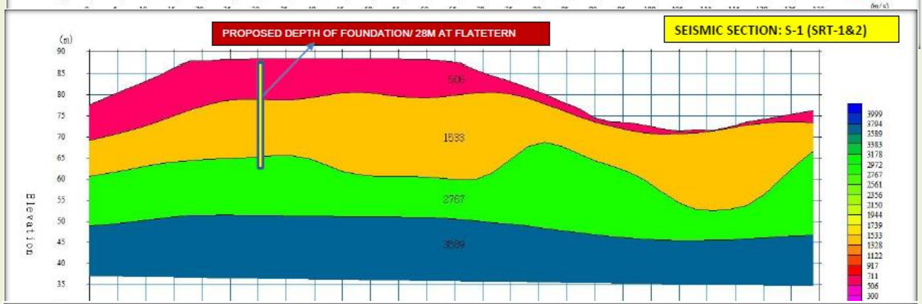


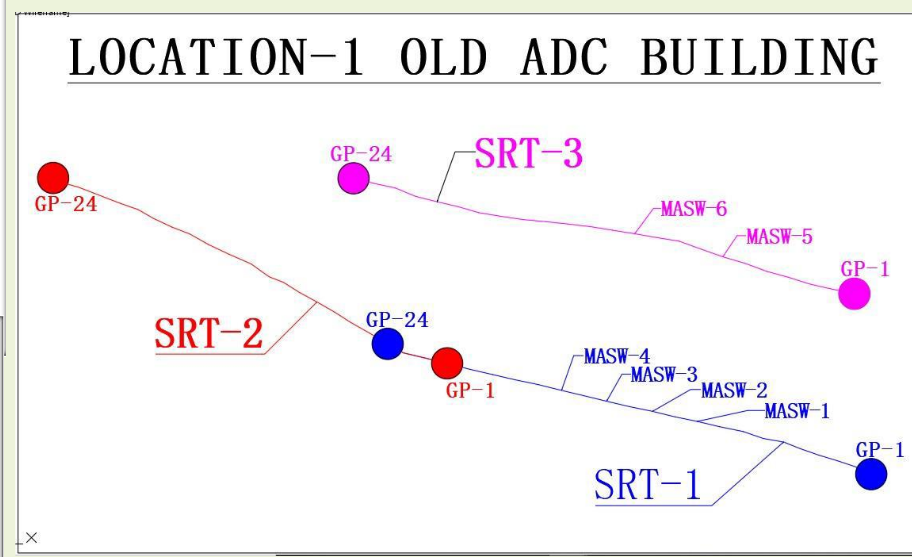


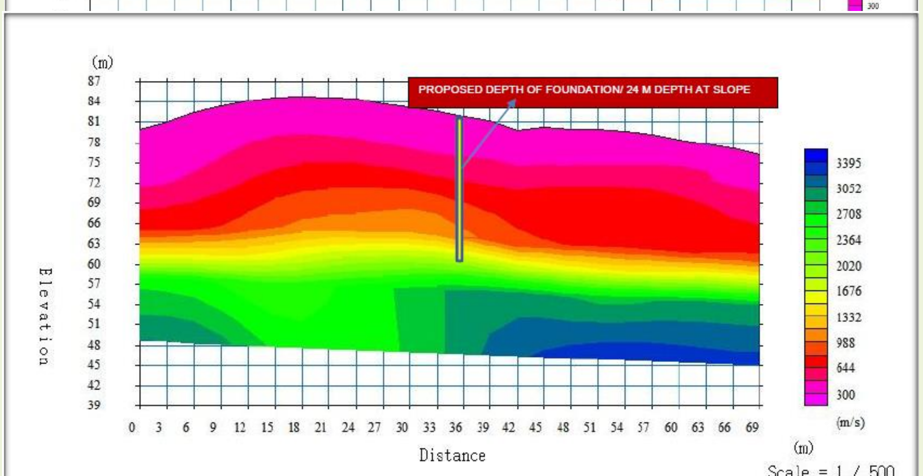
http://www.cflhd.gov

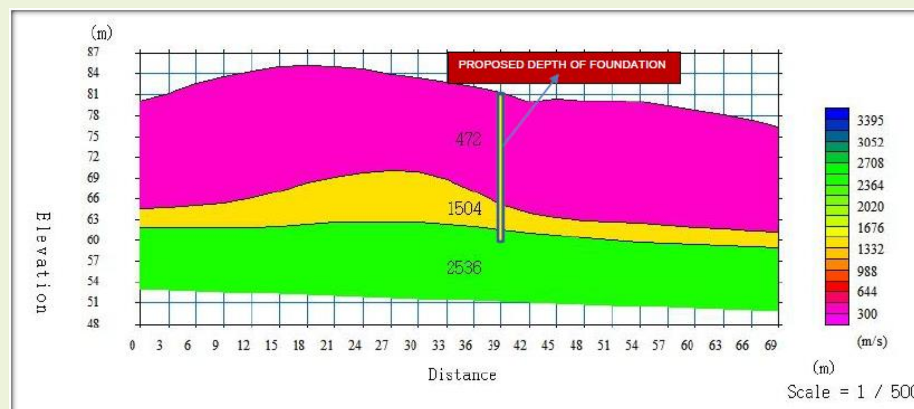
SRS at Failed RajBhawan Site, Assam





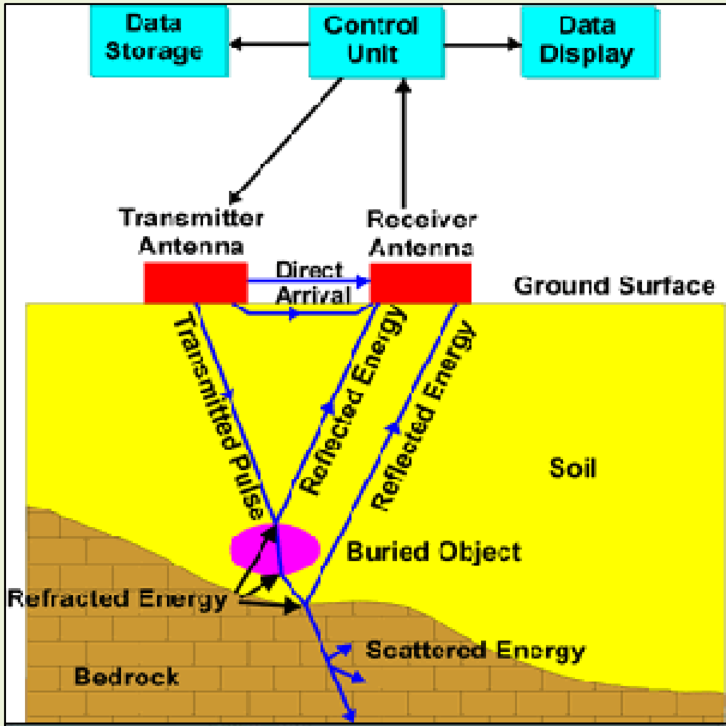


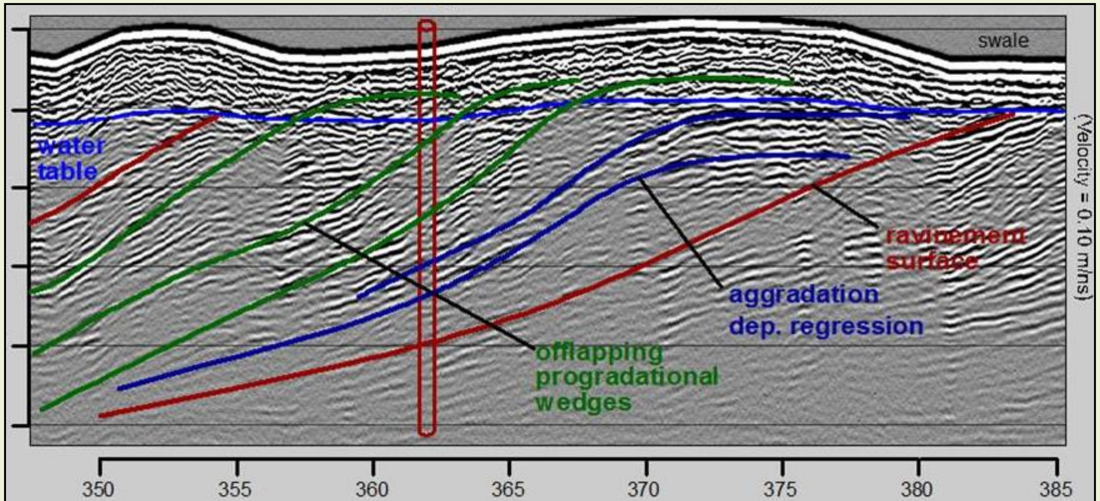


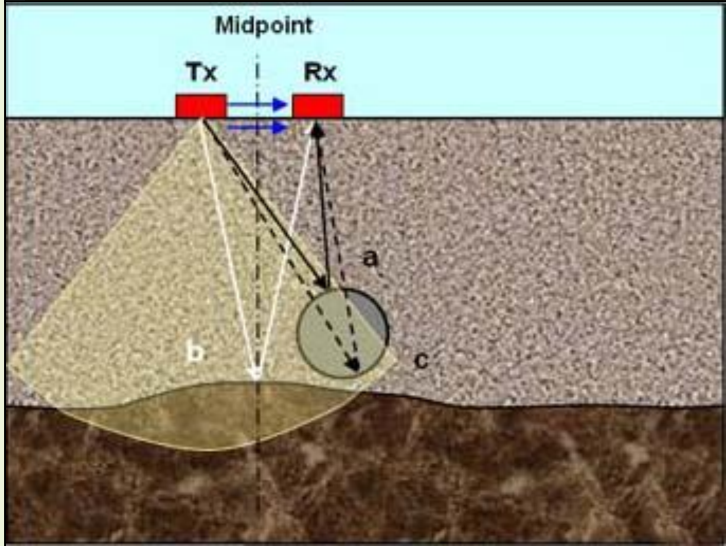


Geophysical Investigation

- Ground Penetrating Radar (GPR)
  - ❖ *Aids in the identification of underlying buried objects*
  - ❖ *Operates on the reflection of waves by an object*
  - ❖ *Identification of substrata based on the difference in stiffness at the interfaces*

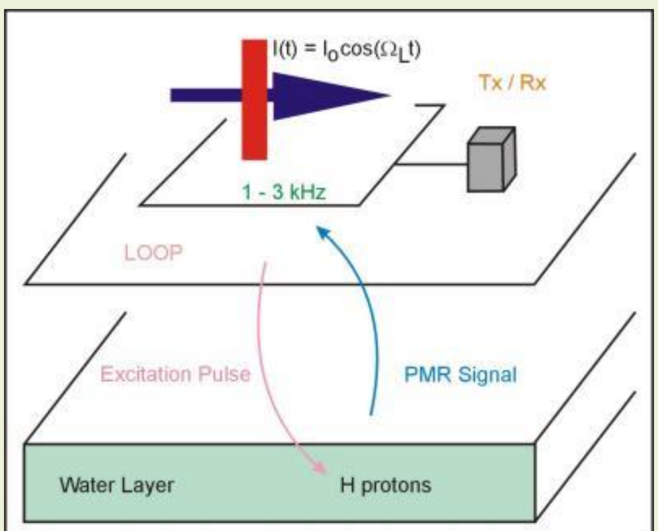


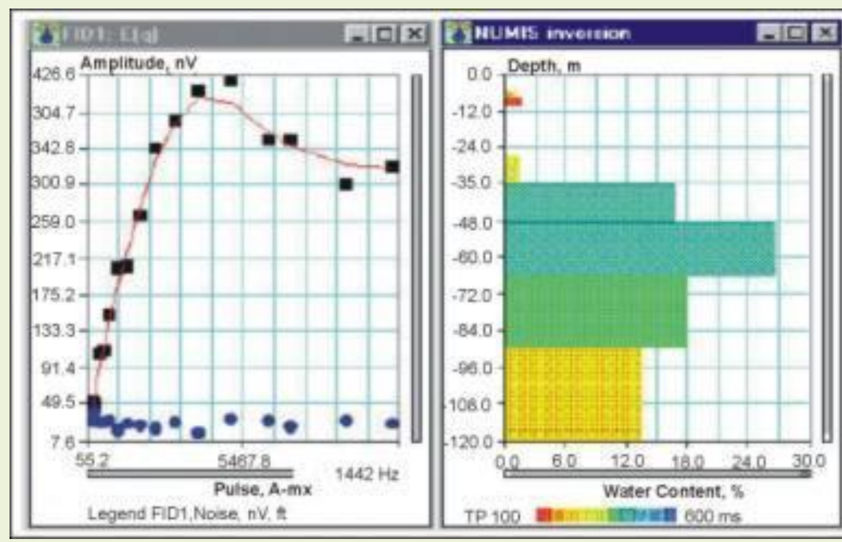




Geophysical Investigation

- Nuclear/Proton Magnetic Resonance (NMR/PMR)
  - ❖ *Based on the excitation of protons in subsurface water by earth's magnetic field*
    - Records variation of voltage in the receiver obtained from the transmitted signal
    - Restrictive limitation
      - Ineffective in the presence of magnetic minerals in the stratum

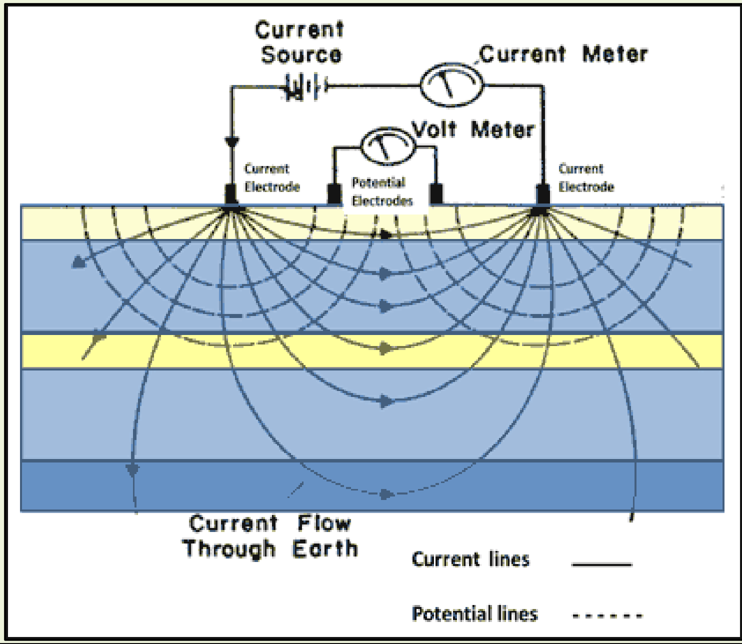


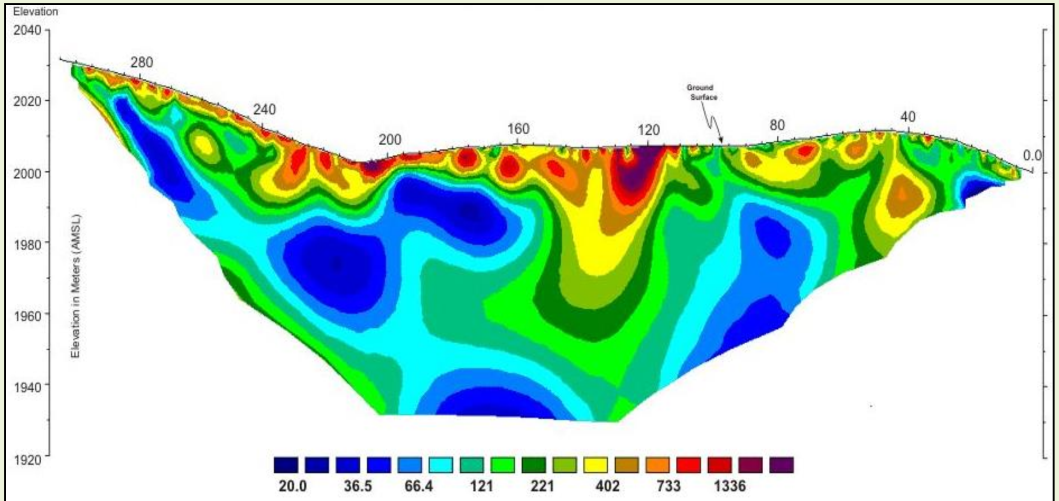


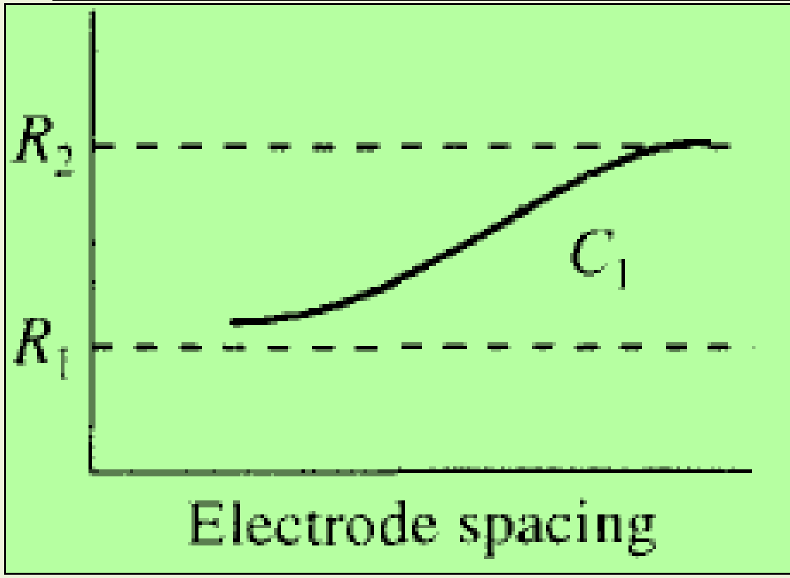
http://www.cflhd.gov

Geophysical Investigation

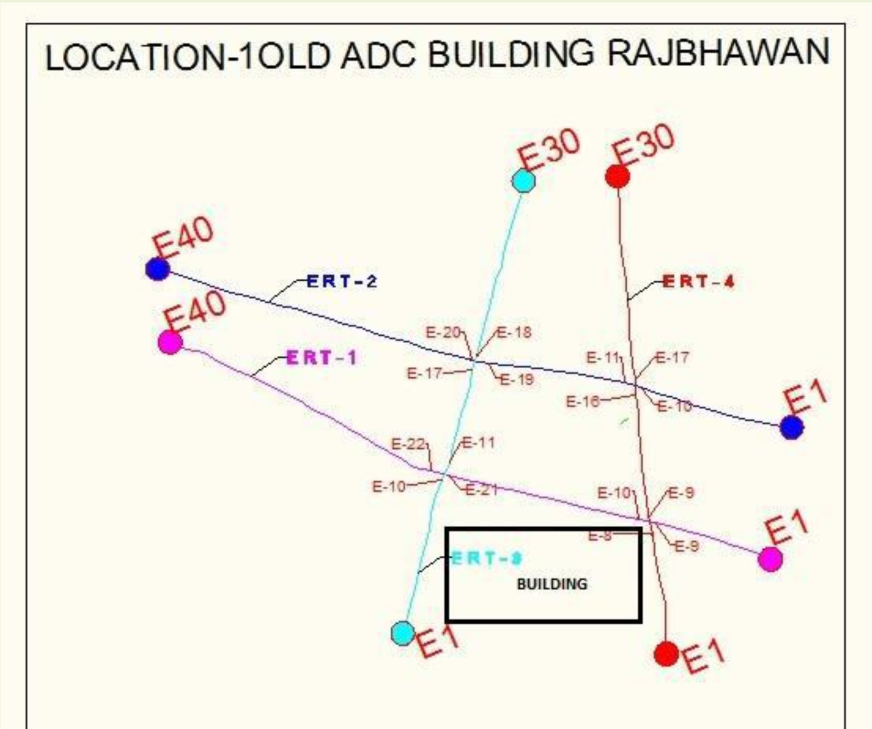
- Electrical Resistivity Tomography (ERT)
  - *Depends on the current flow generated due to the differences in the electrical resistance of different soils (dielectric constant)*
  - *Depends on salt concentration and water content of soils*
  - *Variation in apparent resistivity of soils*

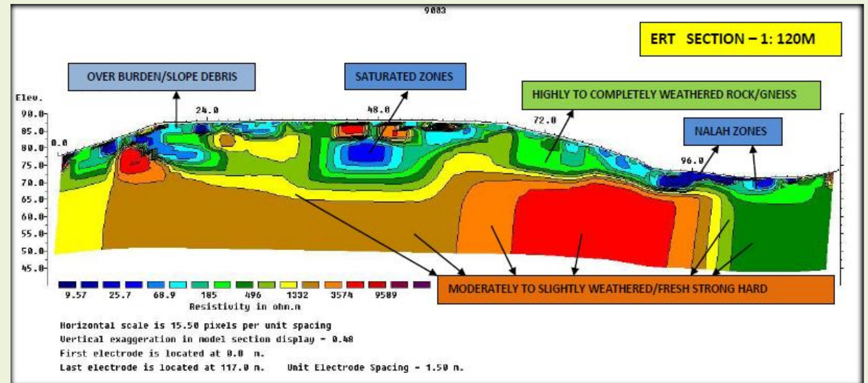


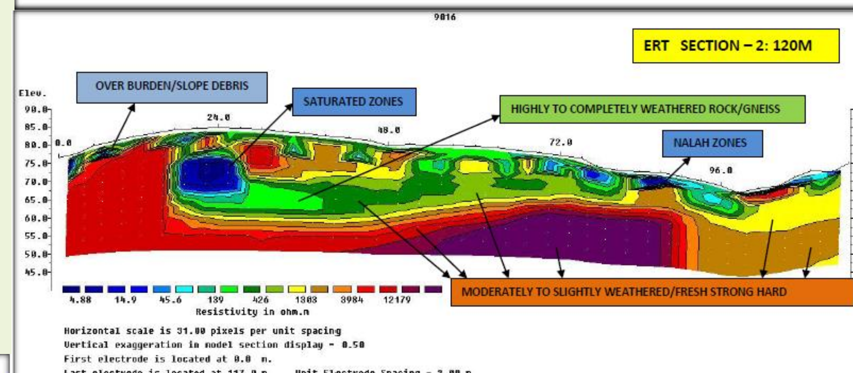


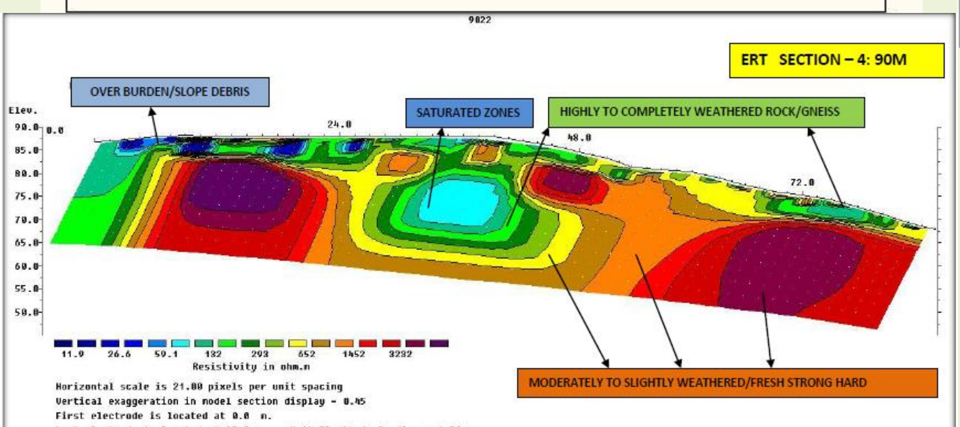


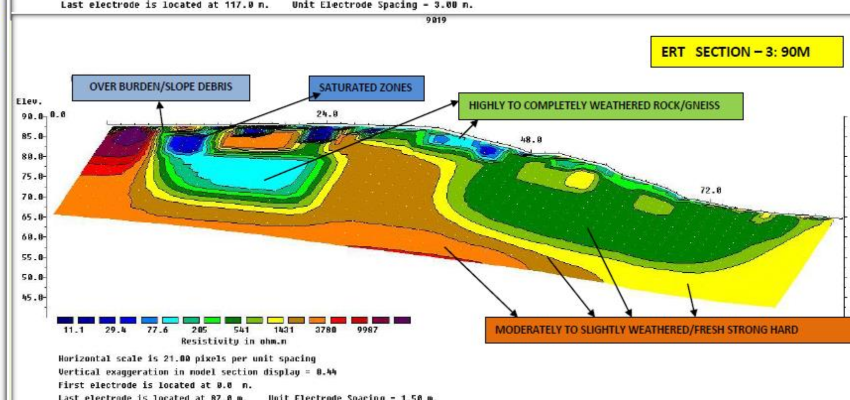
ERT at Failed RajBhawan Site, Assam





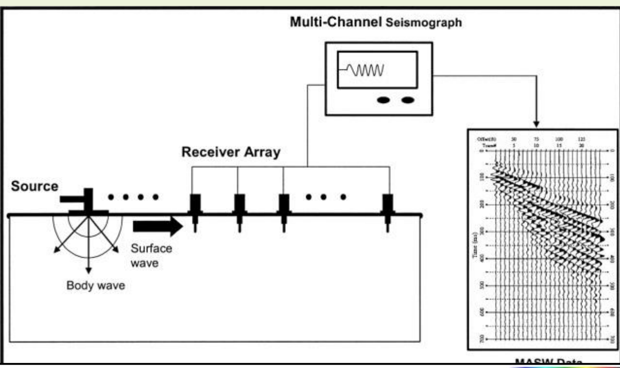


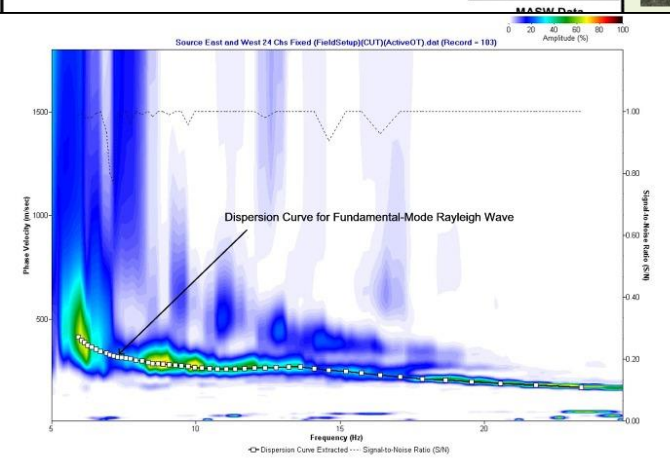


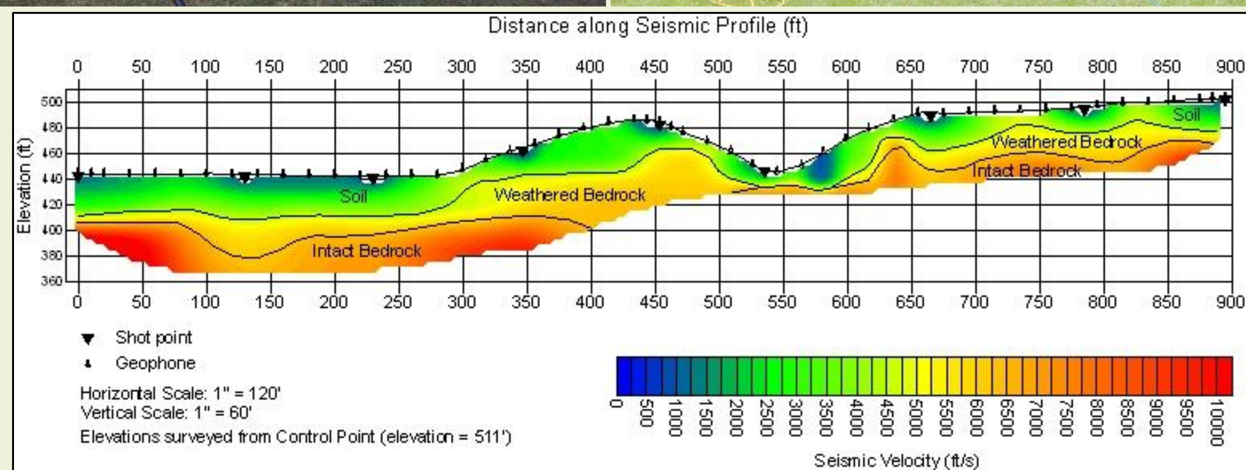


Geophysical Investigation

- Multichannel Analysis of Surface Waves (MASW) – Active and Passive Surveys
  - ❖ *Shear wave velocity profiling of soil substrata*
  - ❖ *Operates on the dispersive capacity of soils*

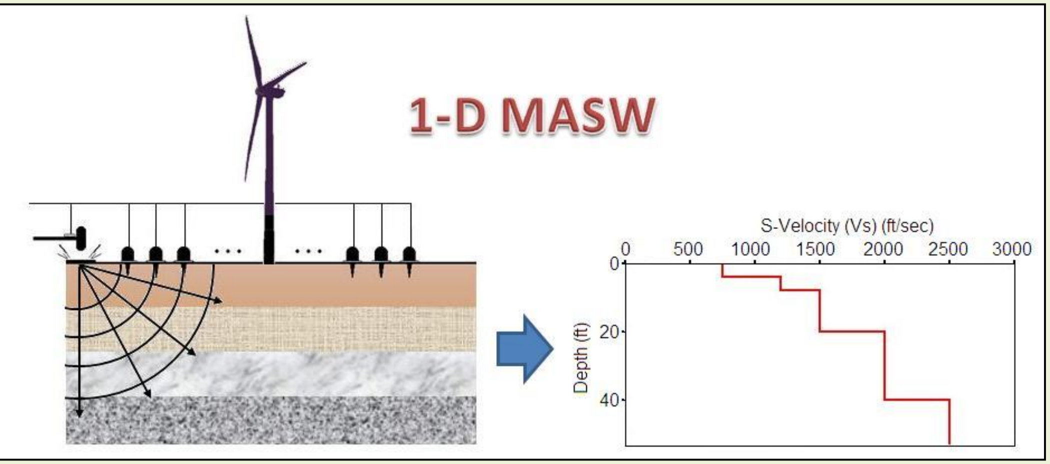


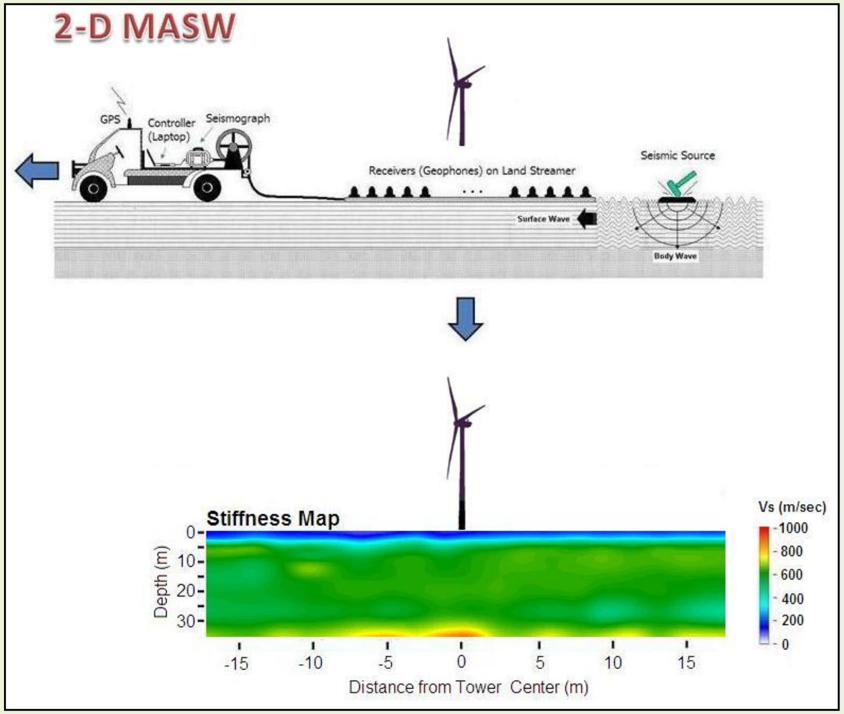


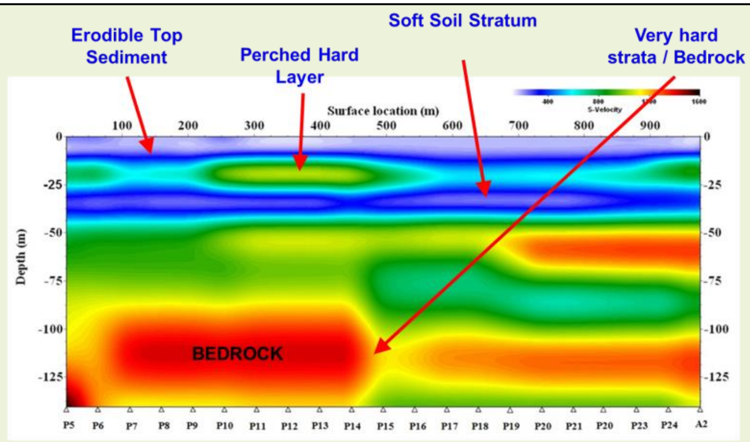


MASW

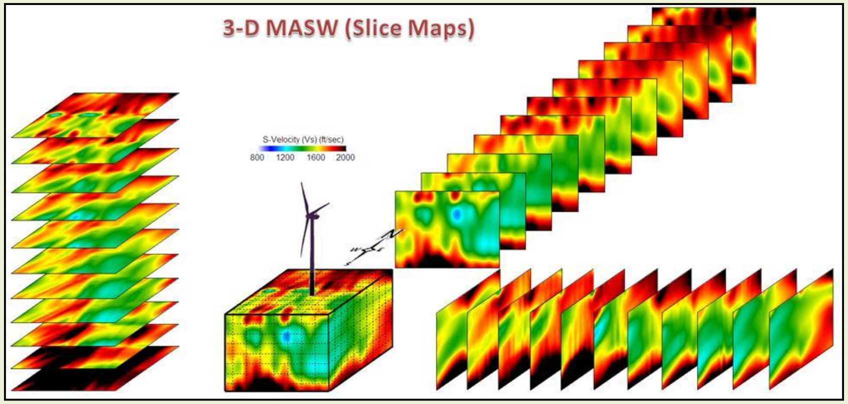
- *Evaluating ground stiffness*
- *1D, 2D or 3D formats*





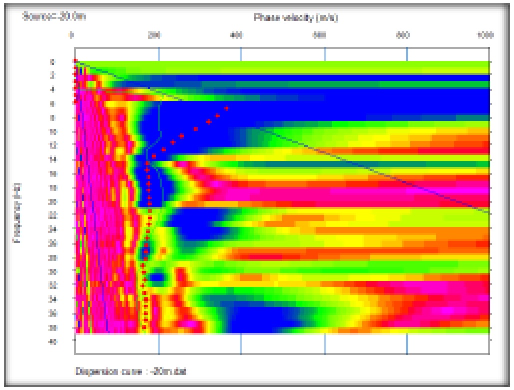


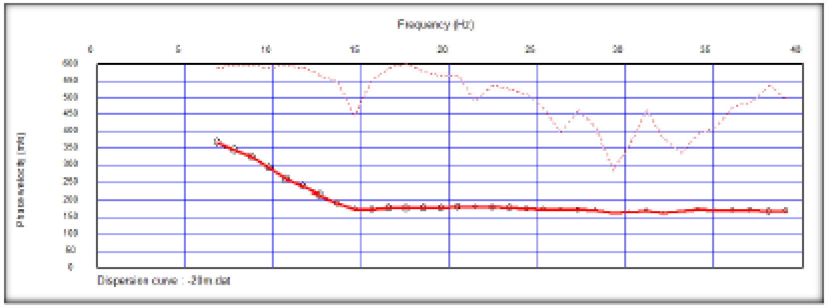
2-D shear wave velocity profile obtained from a roll-along active MASW conducted along the alignment of the proposed bridge over Jia-Bharali (P5-A2)

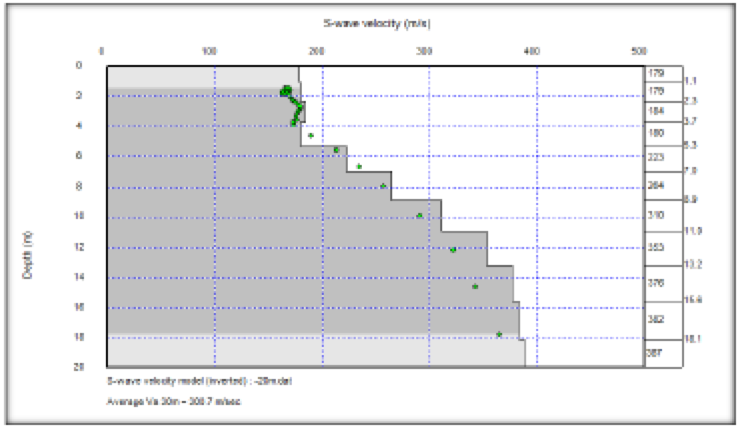


www.masw.com

MASW Survey at a Failed Rajbhavan Site

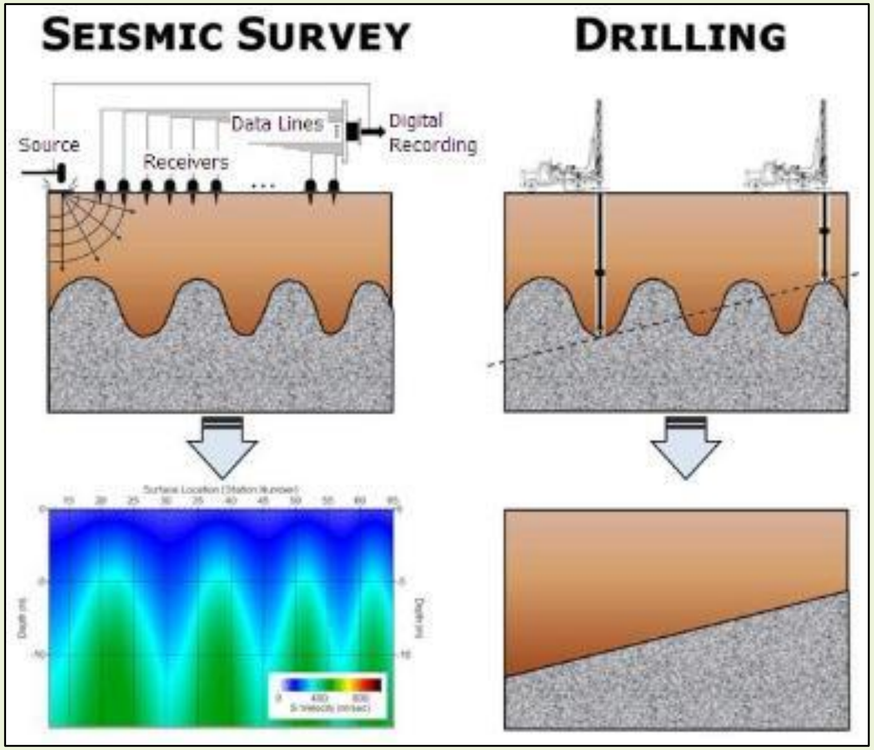






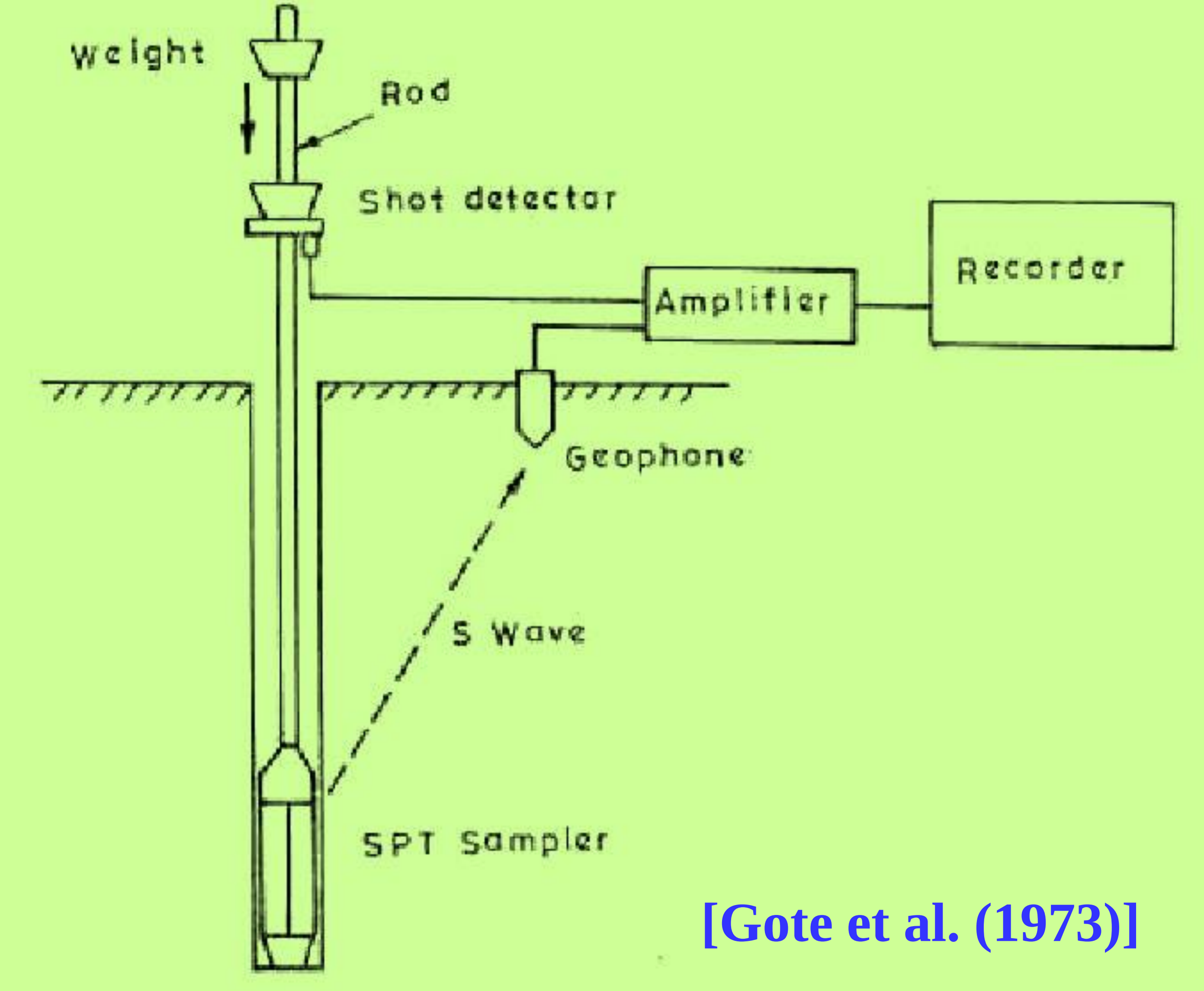
Advantages of NDT Geophysical Investigations

- Advantage over conventional boring and drilling method
  - *Drilling and boring technique is excessively costly*
  - *Spacing between boreholes have every possibility of missing the subsurface profile variation*
  - *Boring is till required to extract samples for actual strength and stiffness properties*



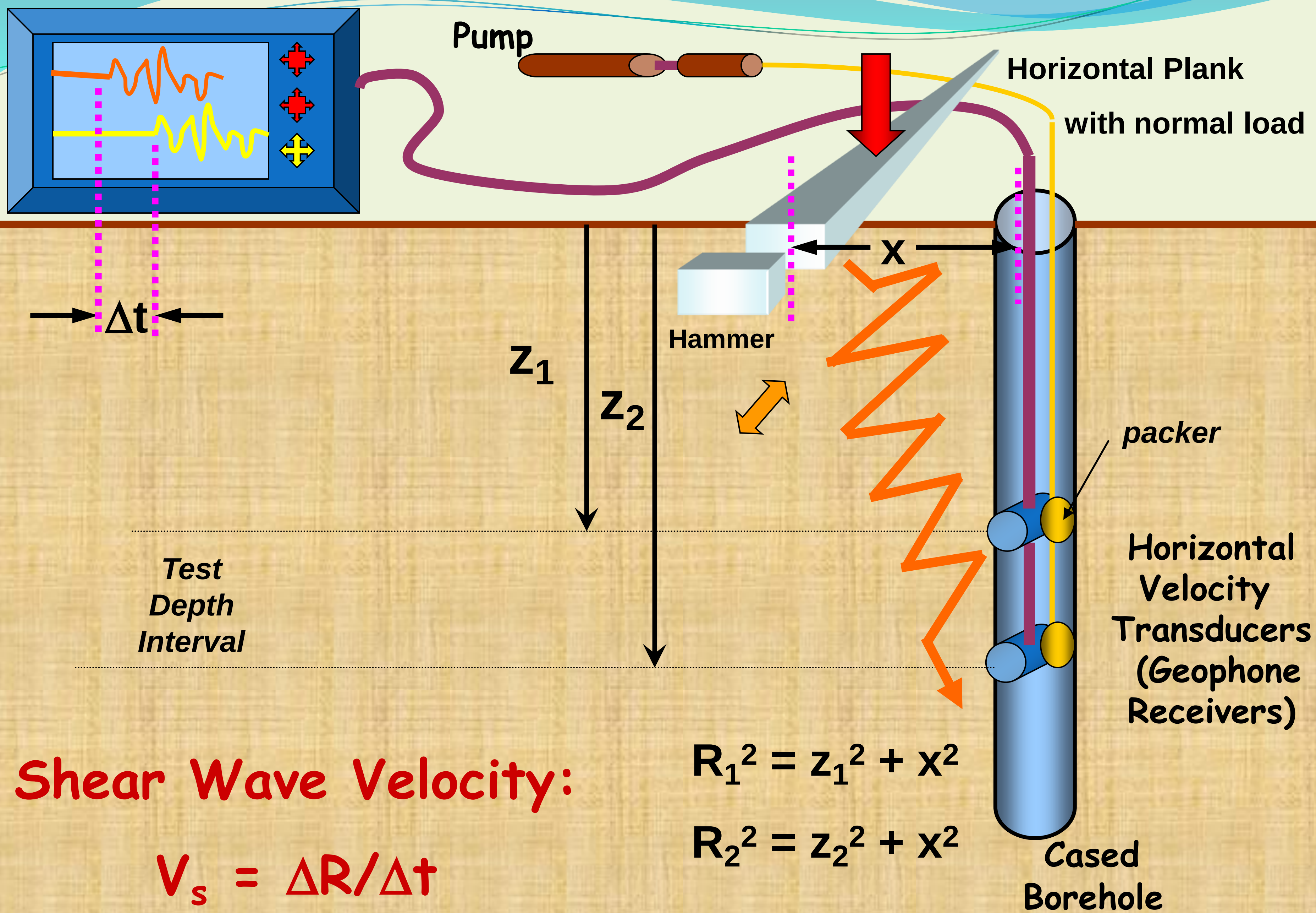
www.masw.com

Seismic Up-Hole Survey: Schematic



[Gote et al. (1973)]

Downhole Testing

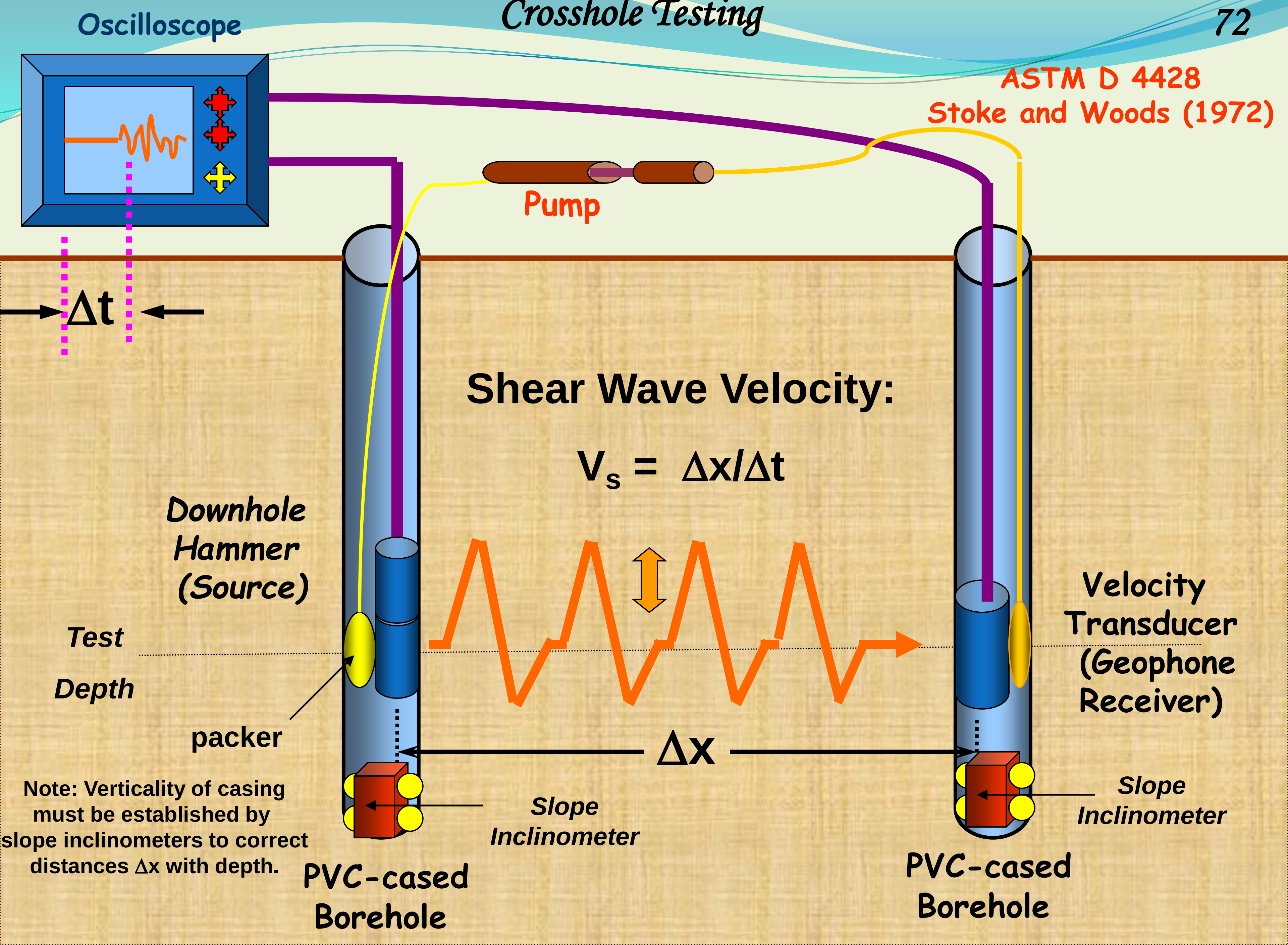


$$R_1^2 = z_1^2 + x^2$$

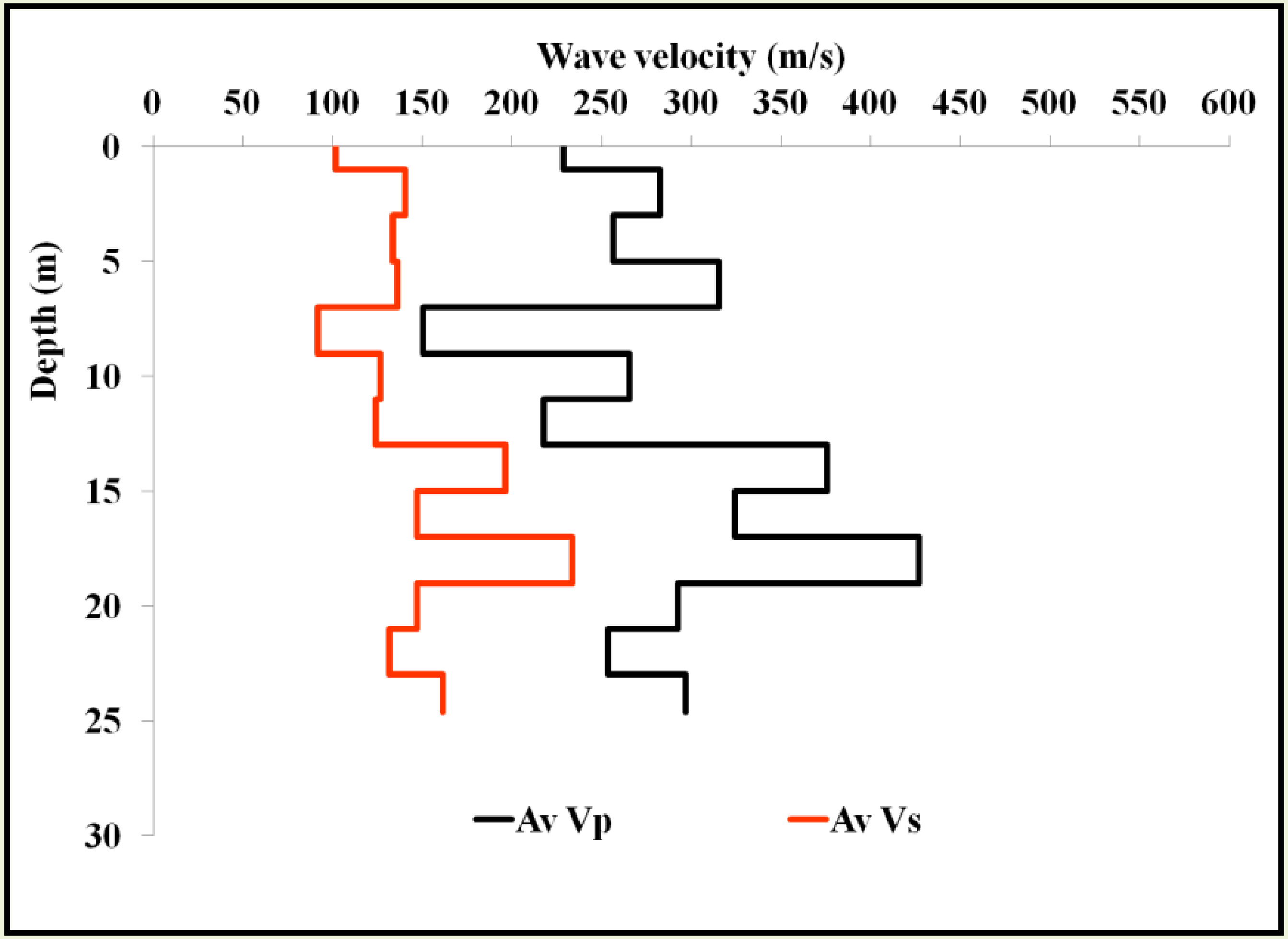
$$R_2^2 = z_2^2 + x^2$$

Shear Wave Velocity:

$$V_s = \Delta R / \Delta t$$

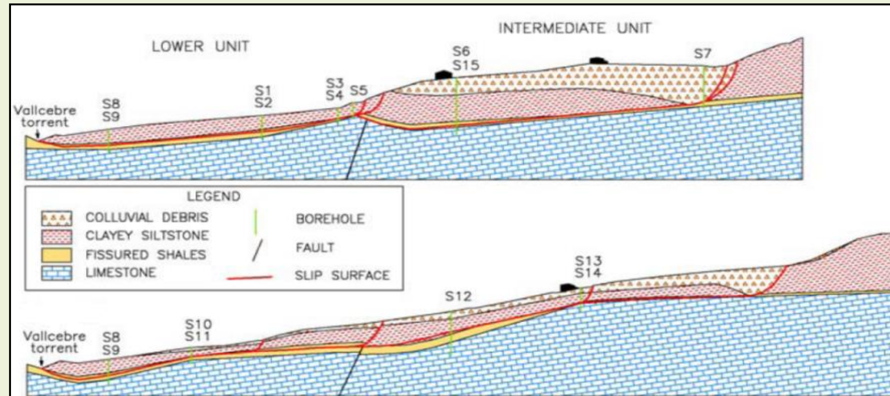

Oscilloscope
ASTM D 4428
Stoke and Woods (1972)
Pump
Δt
Shear Wave Velocity:
$V_s = \Delta x / \Delta t$
Downhole Hammer (Source)
Test Depth
packer
Velocity Transducer (Geophone Receiver)
Δx
Slope Inclinometer
Slope Inclinometer
Note: Verticality of casing must be established by slope inclinometers to correct distances Δx with depth.
PVC-cased Borehole
PVC-cased Borehole

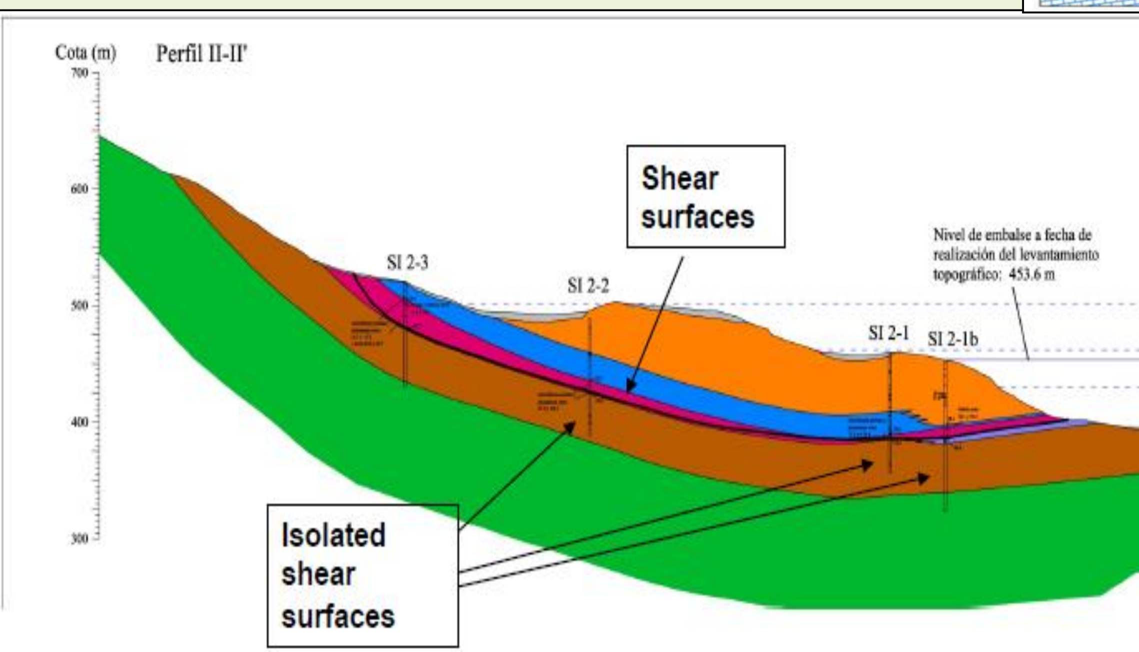
Subsurface Velocity Profile

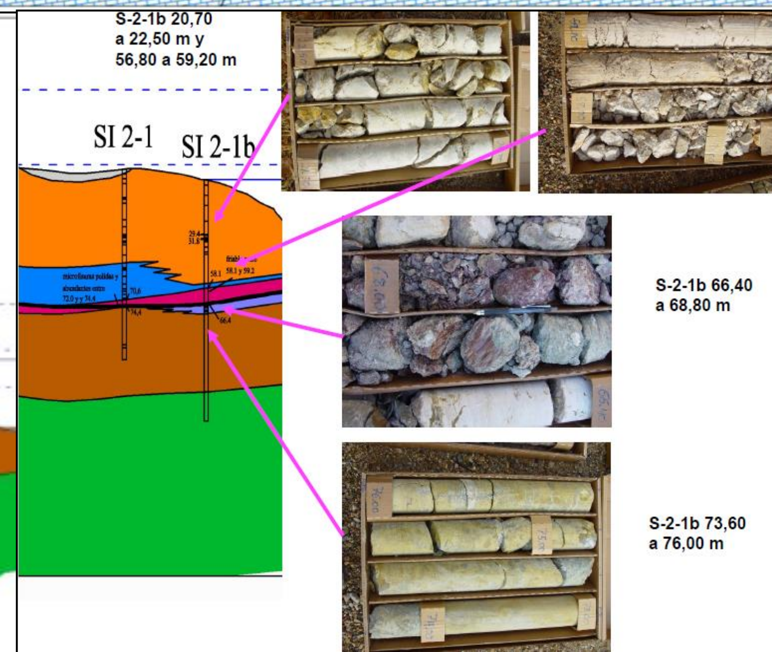


Target of Geophysical Investigations

- Understanding the characteristics of landslides
  - *Landslide characterization*
    - Subsurface imaging
    - Landslide boundaries
    - Depth of Rupture Surface
    - Location of Water Table

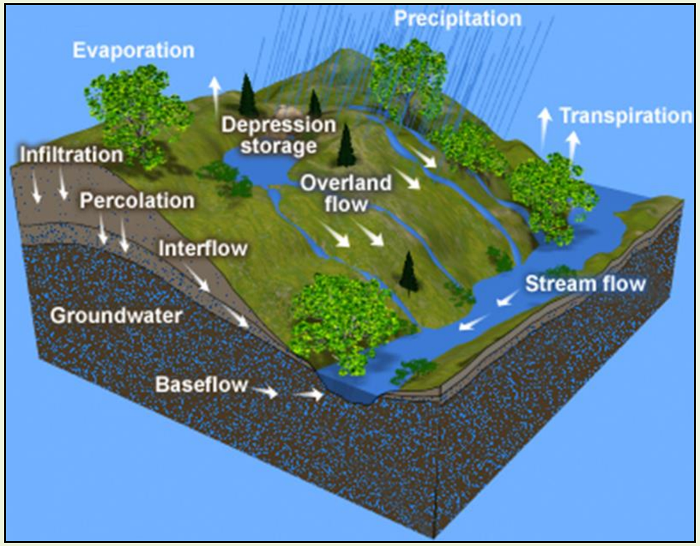


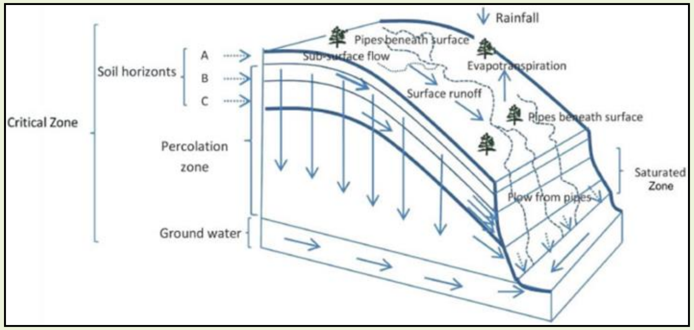


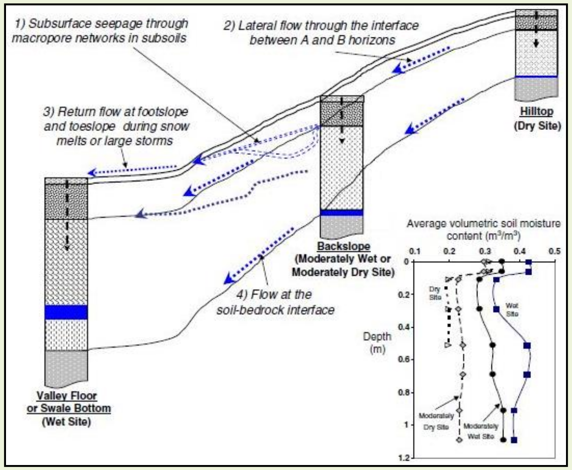


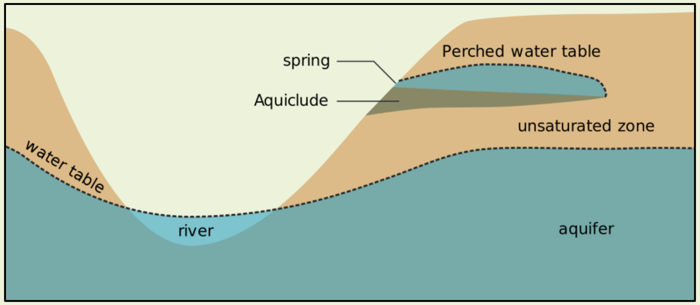
Hydro-Geological Surveys

- Identification of hydrological issues
  - *Ground water table*
  - *Suction capacity and Unsaturated zones*
  - *Perched water table*
  - *Infiltration*
  - *Surface runoff*
  - *Precipitation*
  - *Evapotranspiration*
  - *Seepage*
  - *Springs*
  - *Piping*



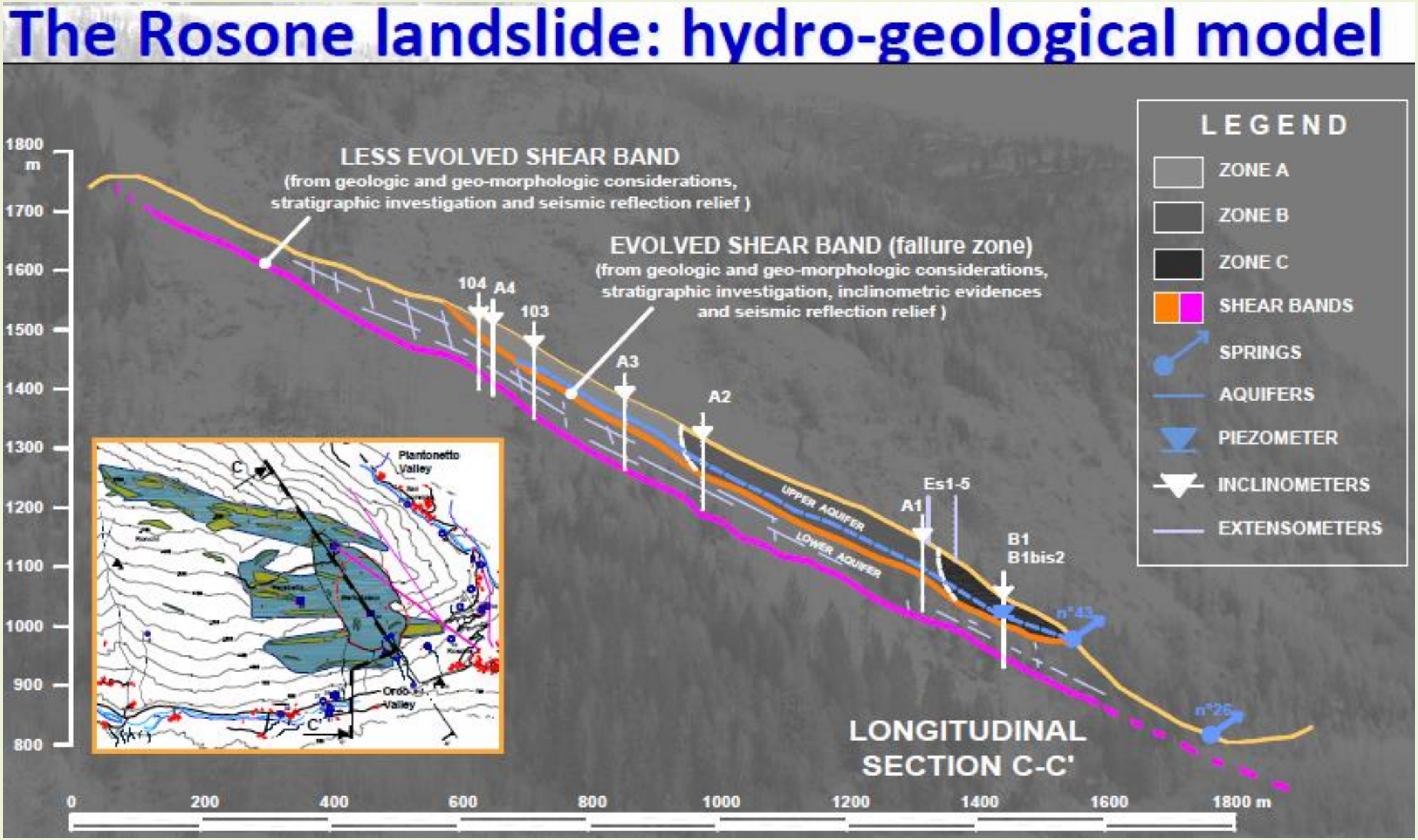






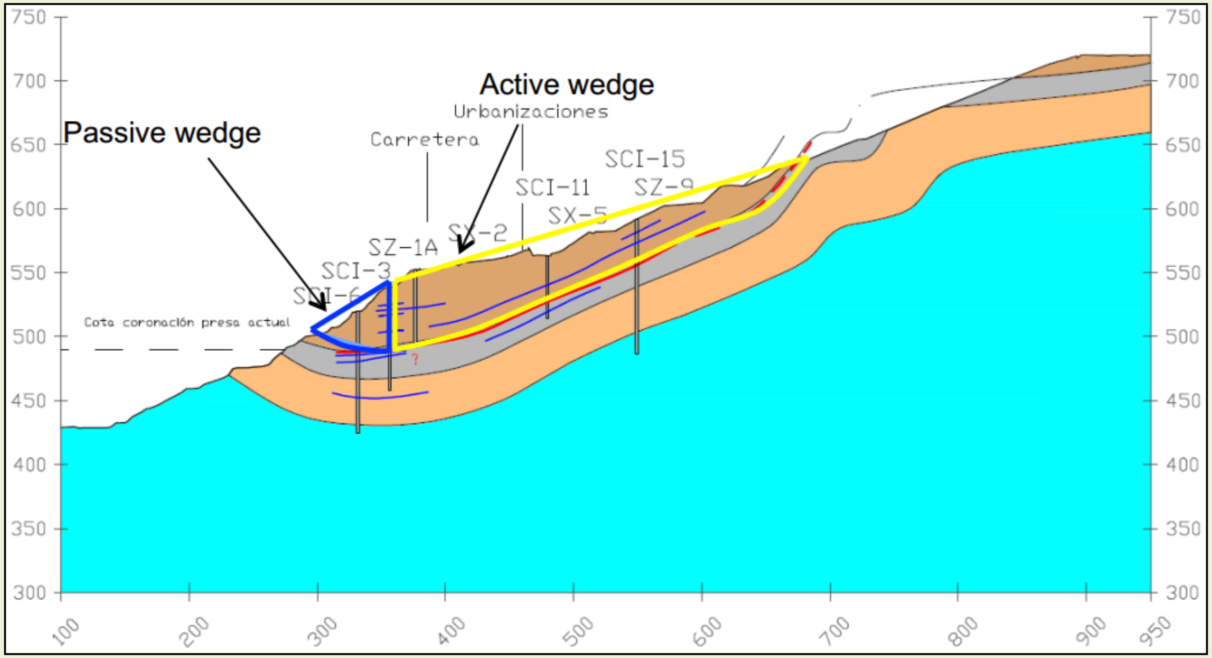
Hydro-Geological Surveys

- A typical Hydro-Geological Model: The Rosone Landslide



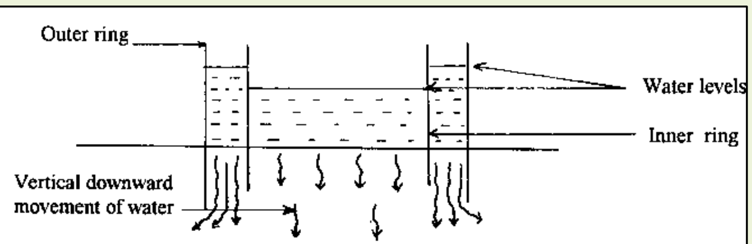
Continuous/Frequent/Intermittent Monitoring

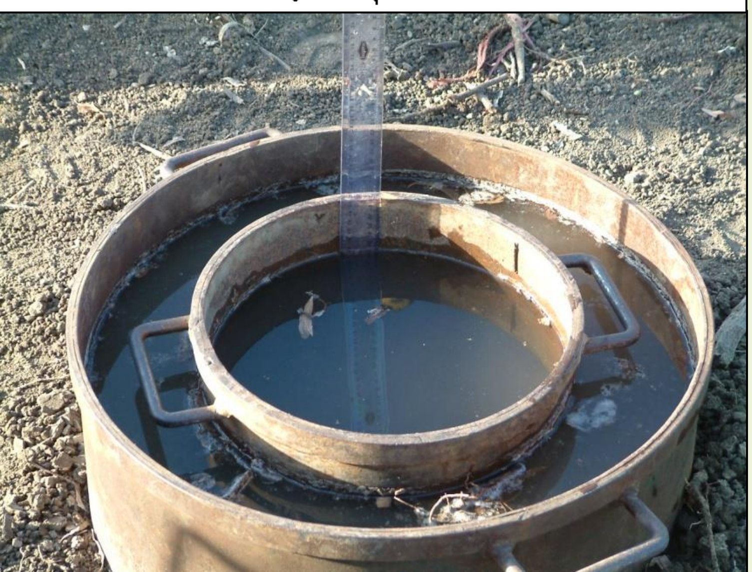
- Ground water monitoring
  - ❖ *Piezometers and In-situ Tensiometers*

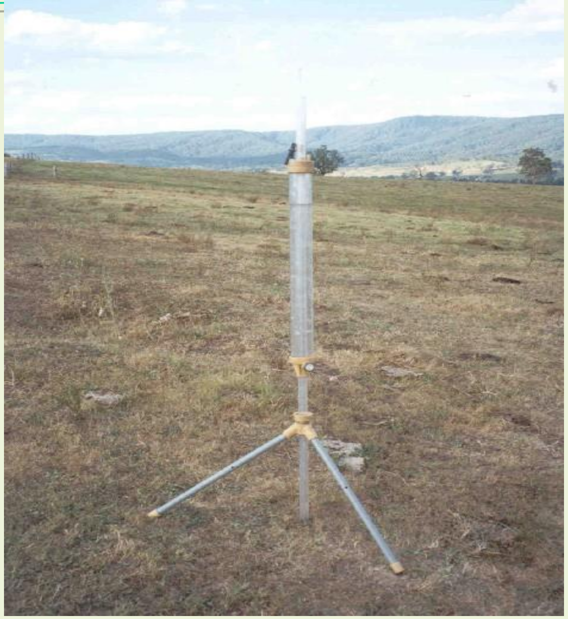


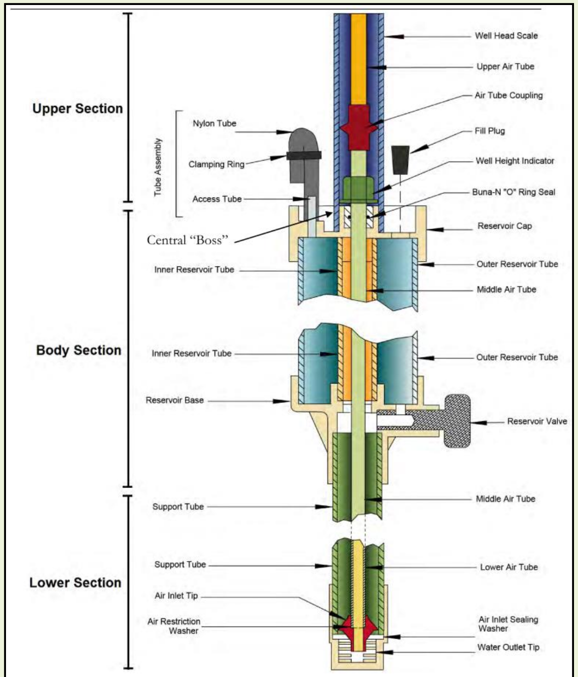
Hydro-Geological Surveys

- In-situ Infiltration and Permeability tests
  - ❖ *Double-ring Infiltrometer*
  - ❖ *Minidisk Infiltrometer*
  - ❖ *Guelph Infiltrometer/Permeameter*



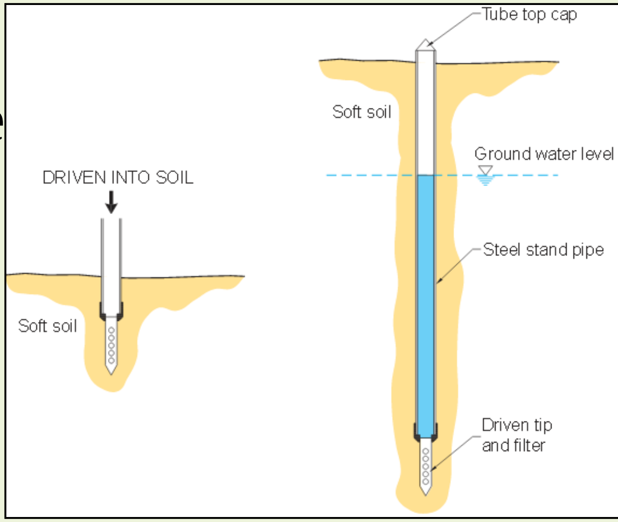


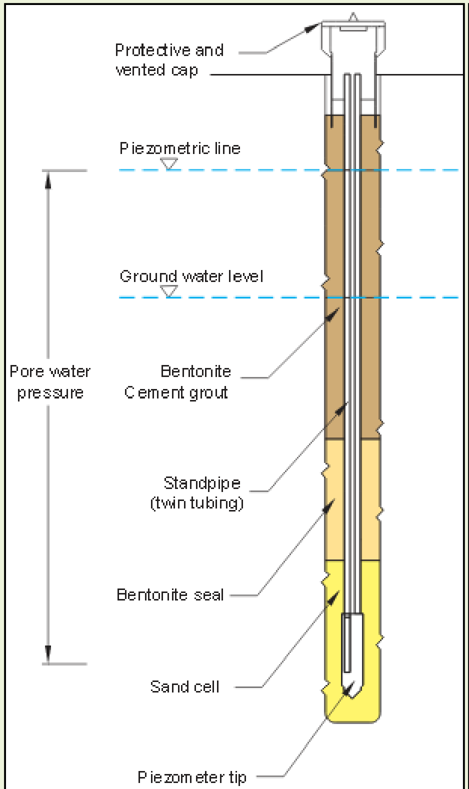


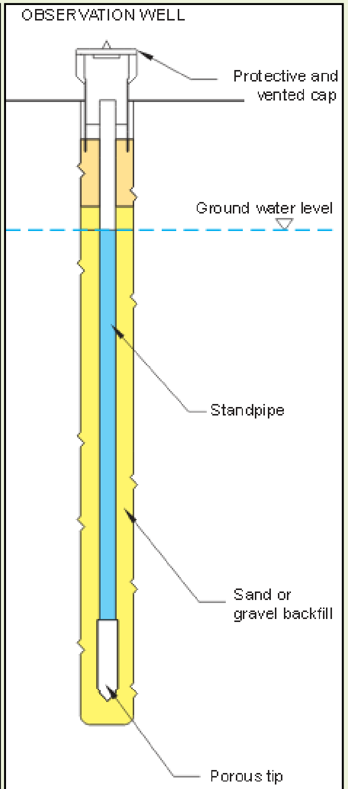


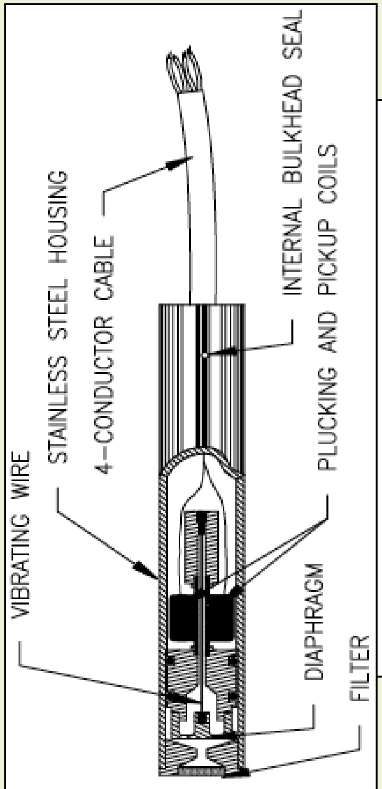
Hydro-Geological Surveys

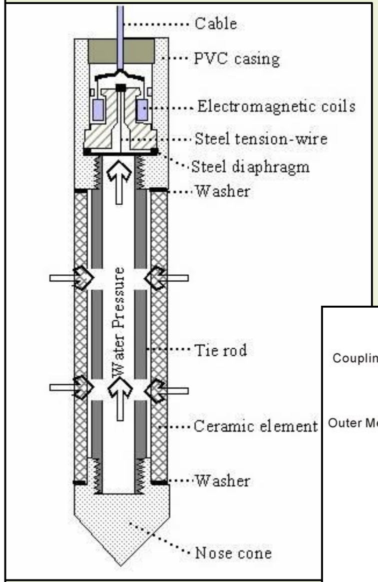
- Determination of GWT and pore-water pressure
  - ❖ *Hydraulic Piezometers (Stand Pipe, Casagrande)*
  - ❖ *Pneumatic Piezometers*
  - ❖ *Electric Piezometers (vibrating wire)*

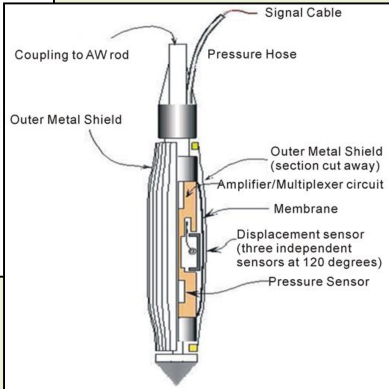






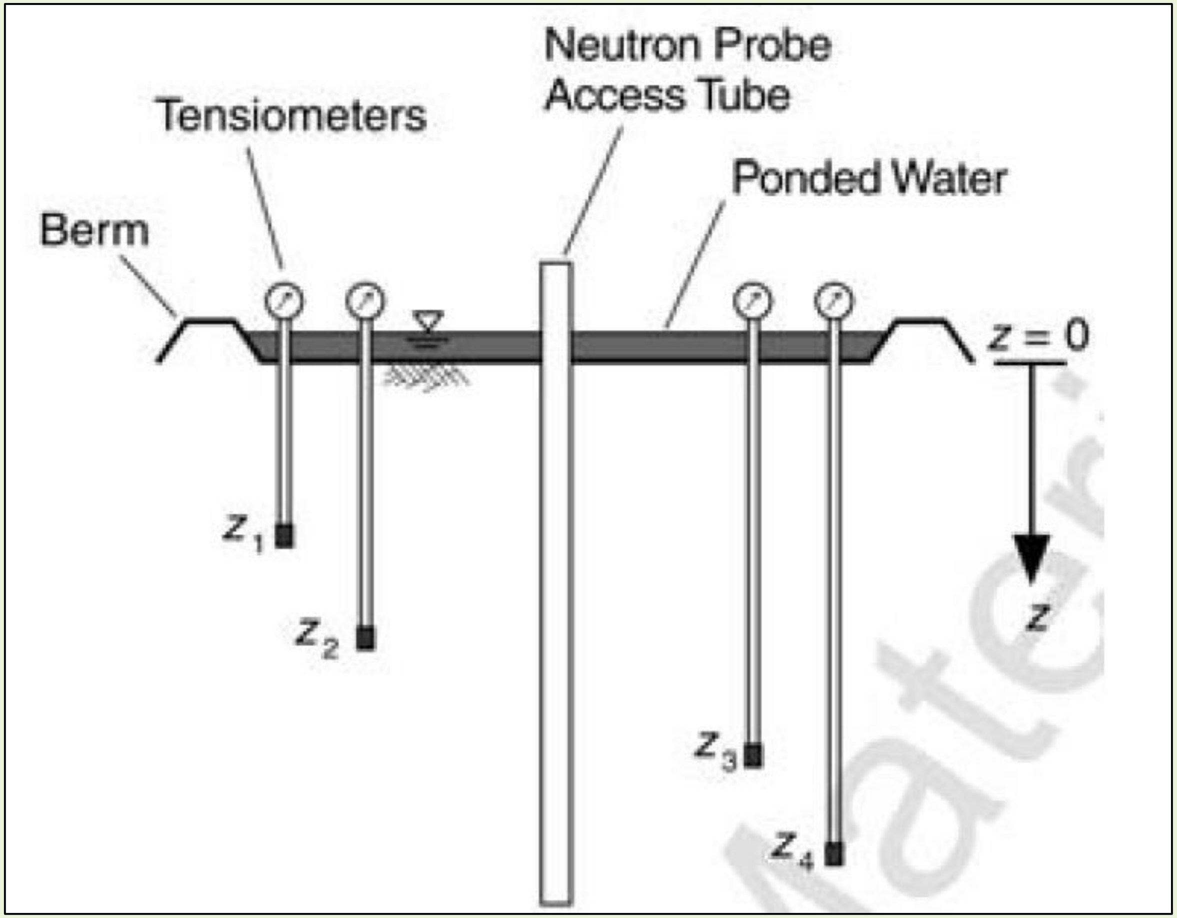






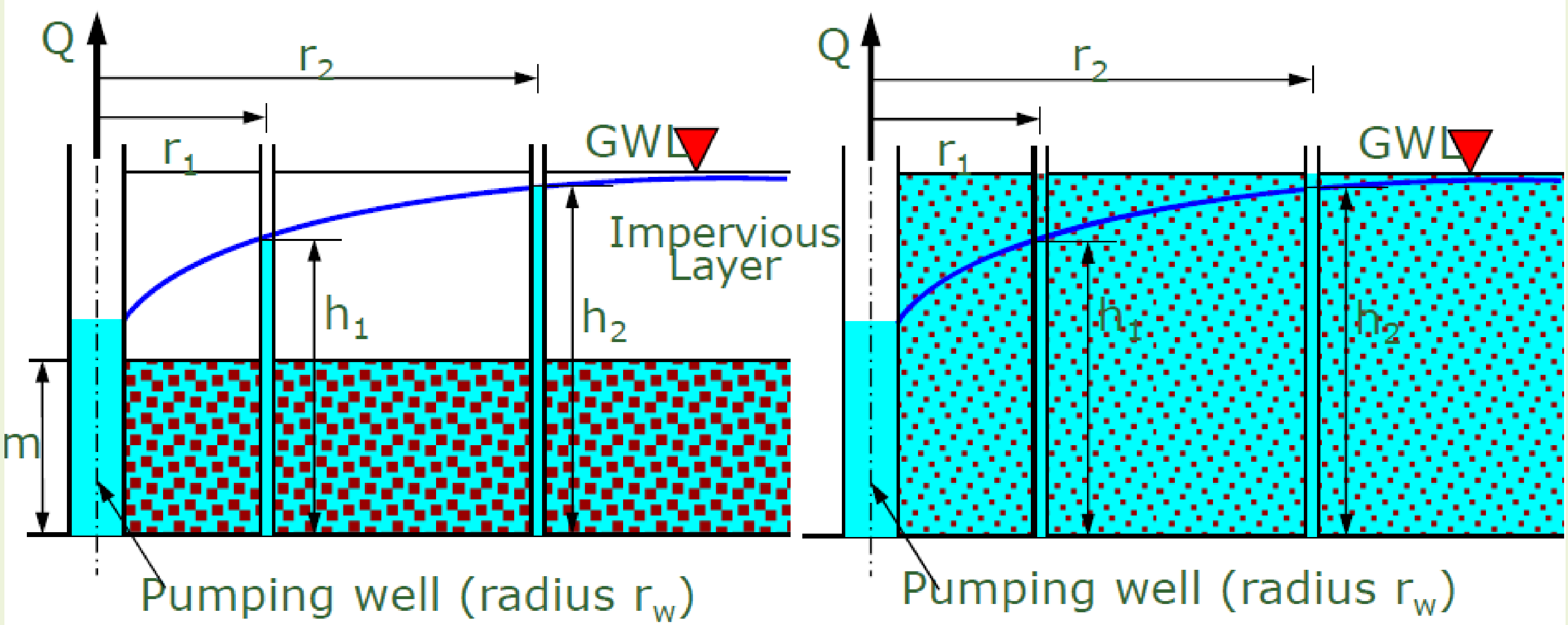
Hydro-Geological Surveys

- Determination of GWT and pore-water pressure
  - ❖ *Instantaneous Profile Method*



Hydro-Geological Surveys

Well Pumping Test



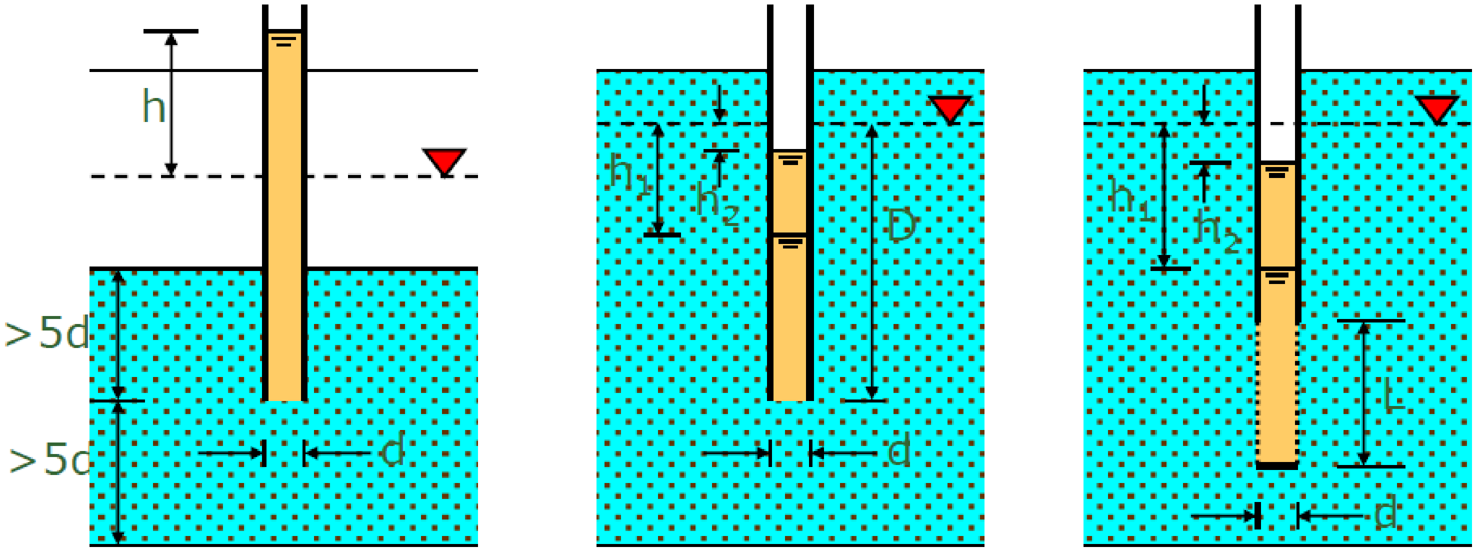
Confined Layer | Unconfined Layer

$$k = \frac{2.3Q\log\left(r_2/r_1\right)}{2\pi m\left(h_2 - h_1\right)}$$

$$k = \frac{2.3Q\log\left(r_2/r_1\right)}{\pi\left(h_2^2 - h_1^2\right)}$$

Hydro-Geological Surveys

Borehole Tests



[Spherical Tip]

[Cylindrical Tip]

Constant Head

Falling Head

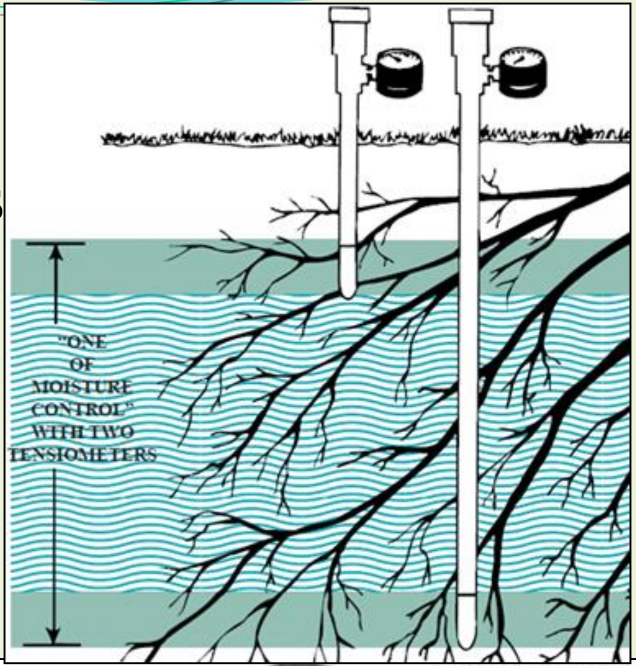
$$k = \frac{Q}{2.75\,(d \times h)}$$

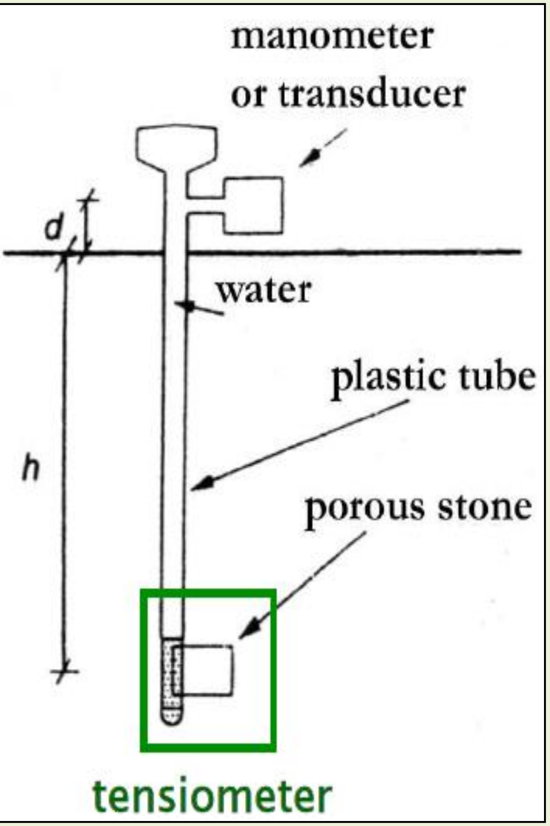
$$k = \frac{\pi d}{11t}\ln\left(\frac{h_1}{h_2}\right)$$

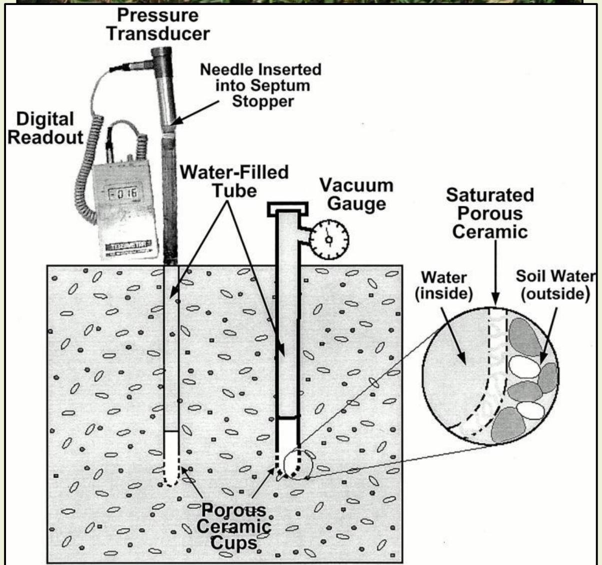
$$k = \frac{d^2}{8Lt}\ln\left(\frac{2L}{d}\right)\ln\left(\frac{h_1}{h_2}\right)$$

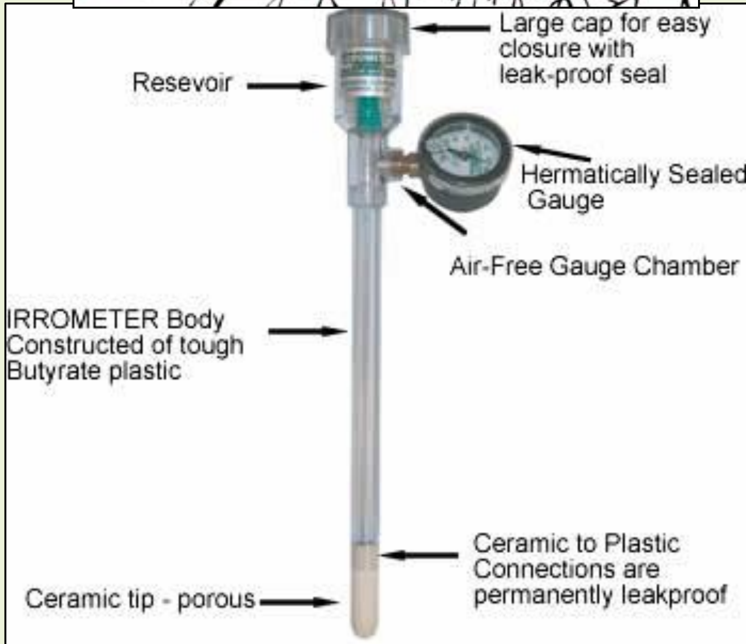
Hydro-Geological Surveys

- Soil suction measurement in unsaturated soils
  - ❖ *Identification of Vadose layers using Tensiometers*



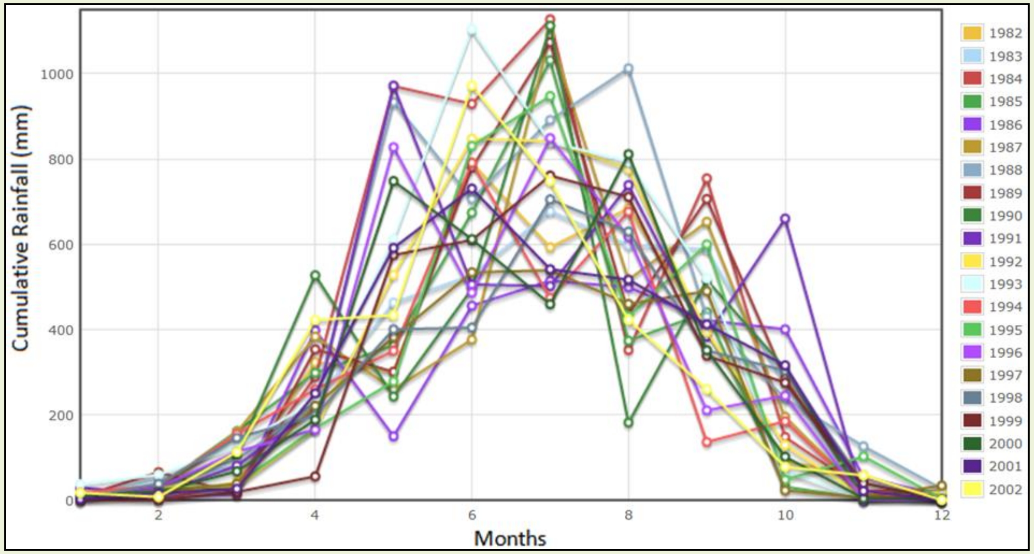


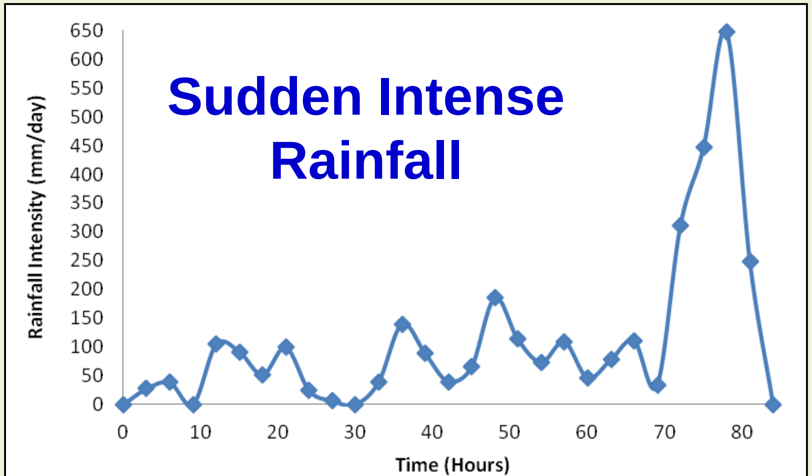




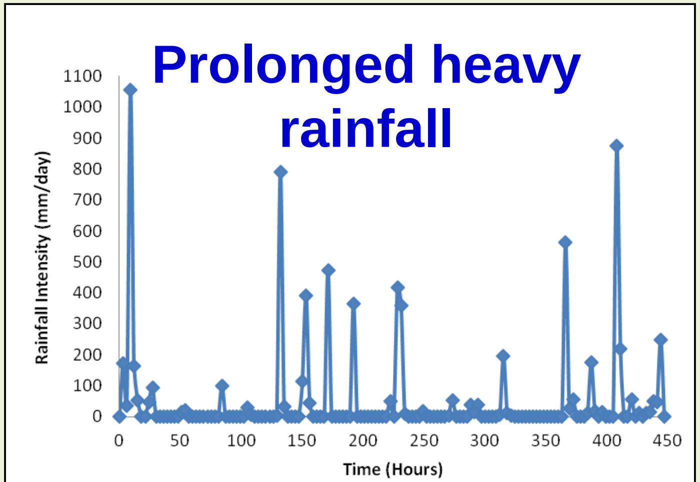
Hydro-Geological Surveys

- Precipitation/Rainfall records over time
  - ❖ *Provides the idea about the intensity and duration of rainfall*





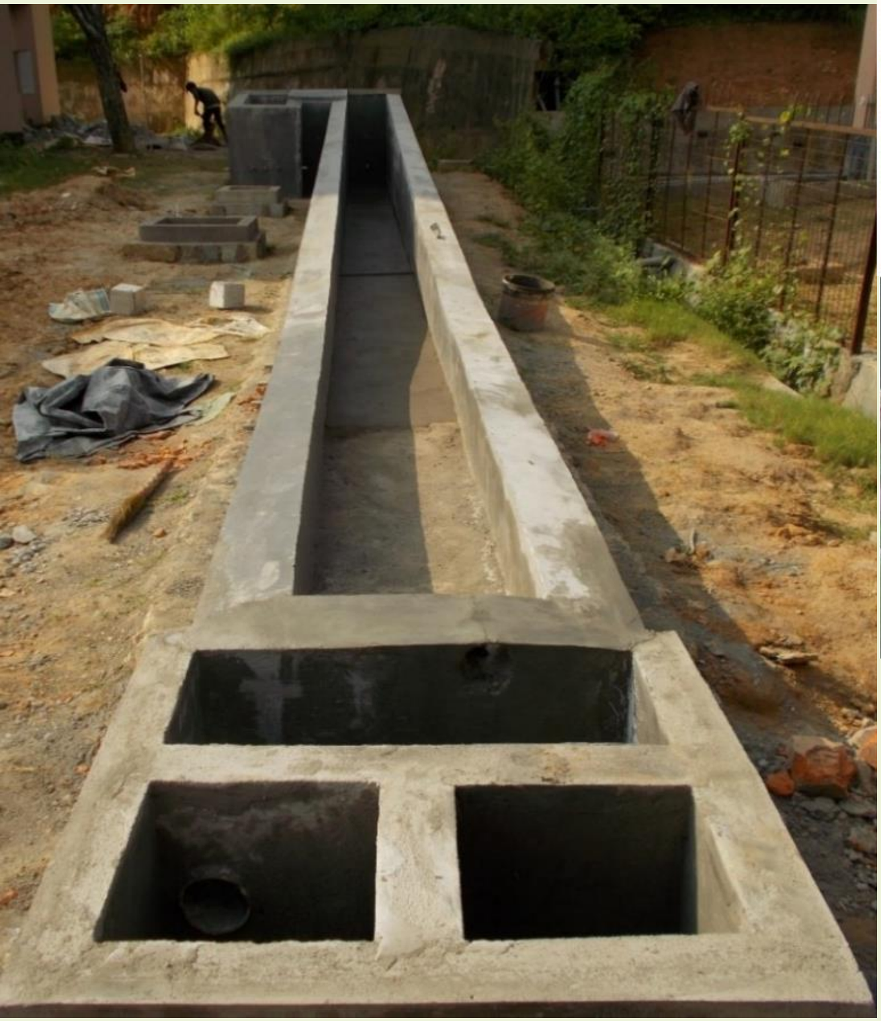
Rainfall Storm Event of October 2004

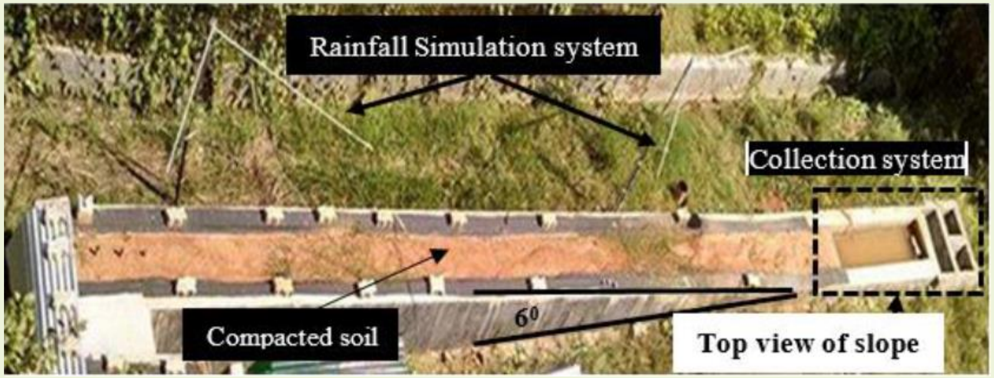


Rainfall in May - Aug, 2007

Hydro-Geological Surveys

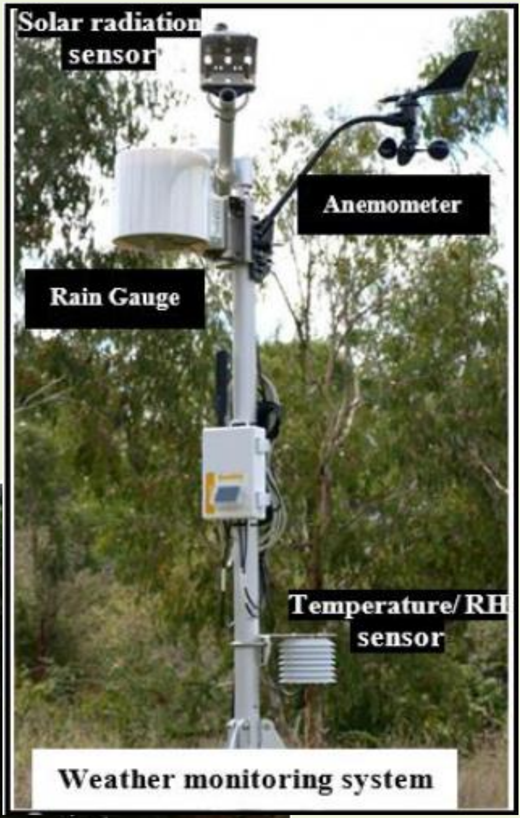
- Field setup





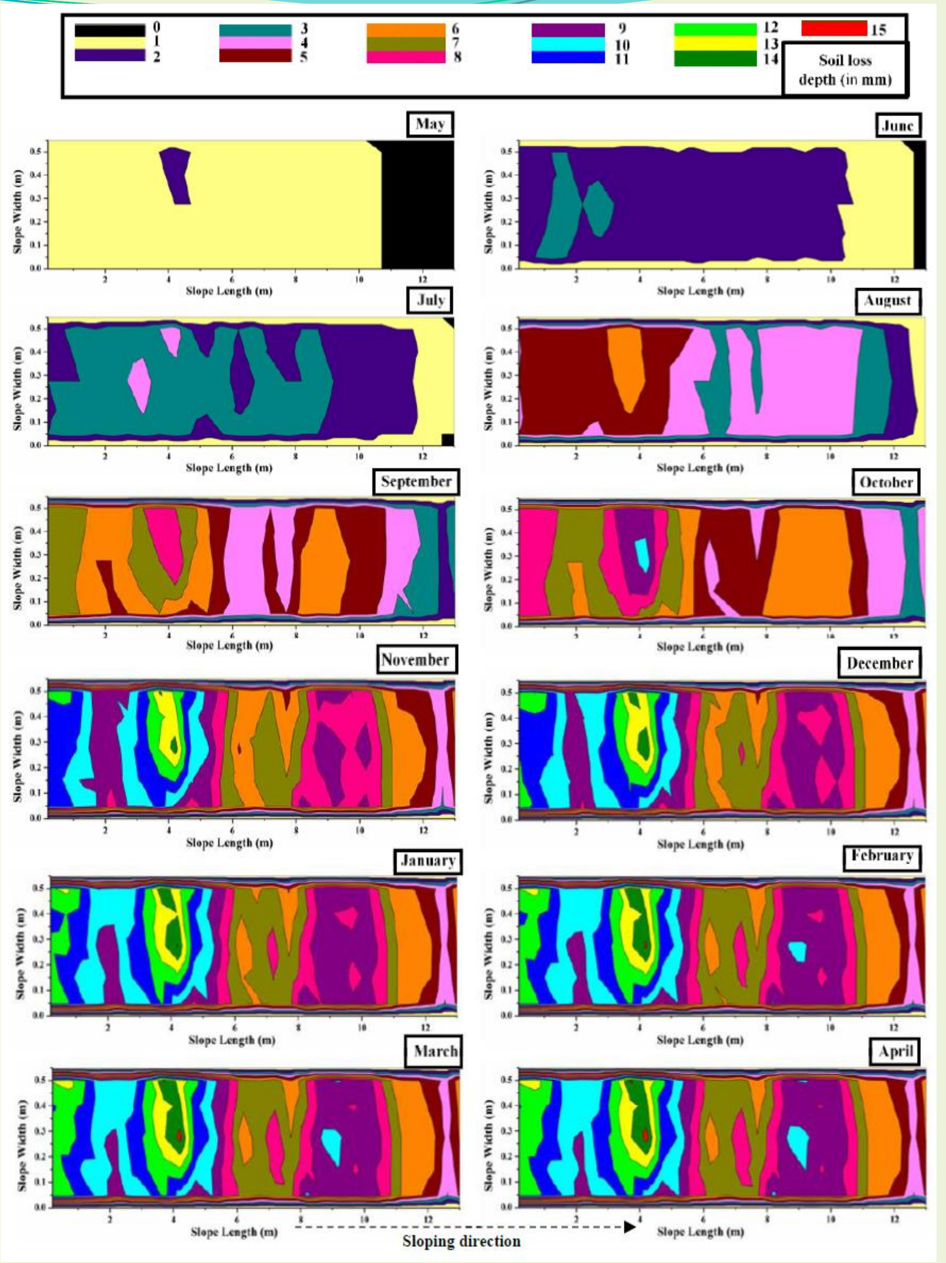
Hydro-Geological Surveys

- Rainfall simulator



Hydro-Geological Surveys

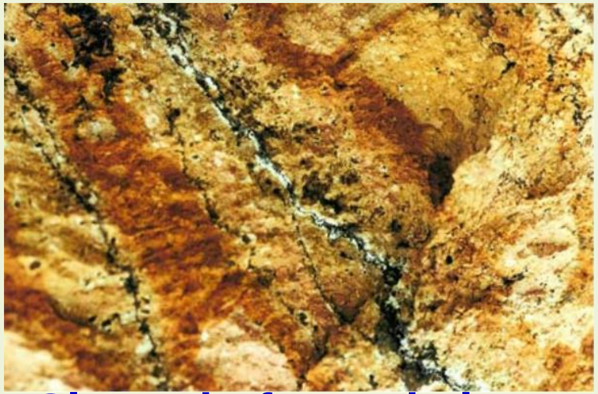
- Simulation of soil loss over time



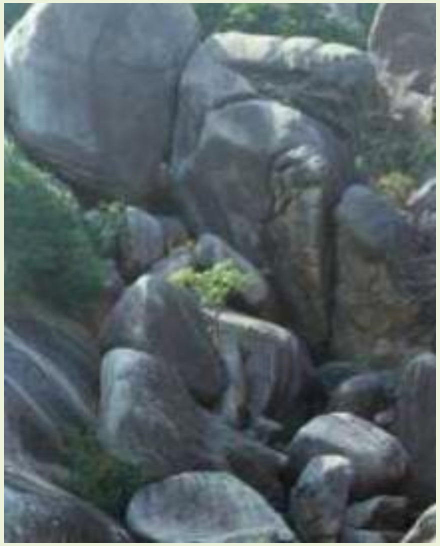
Hydro-Geological Surveys

- Geological characteristics of soils and their variation
  - *Results in uncertainty and heterogeneity in the field data*
    - Difficult to assess soil parameters

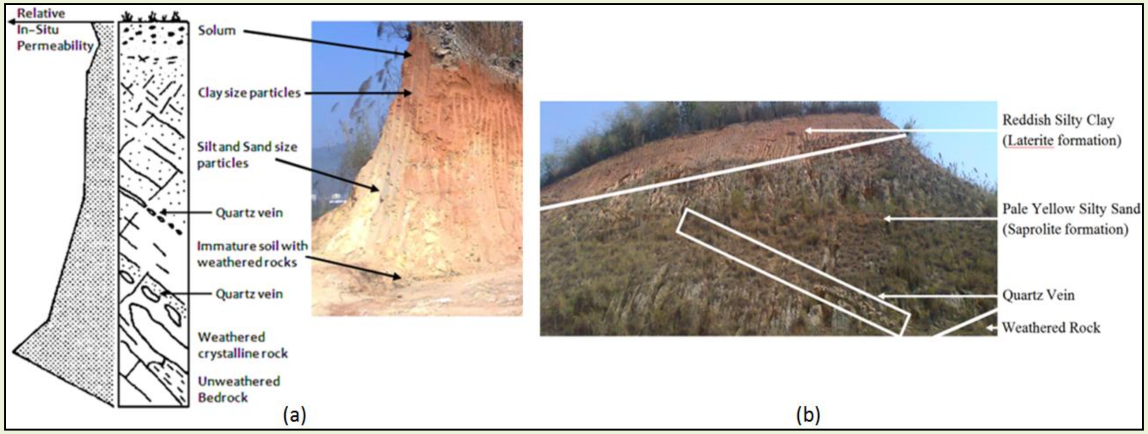
Development of a saprolite profile over weathered bedrock



Clay vein formed along a deformed relict joint plane



Granitic Boulders



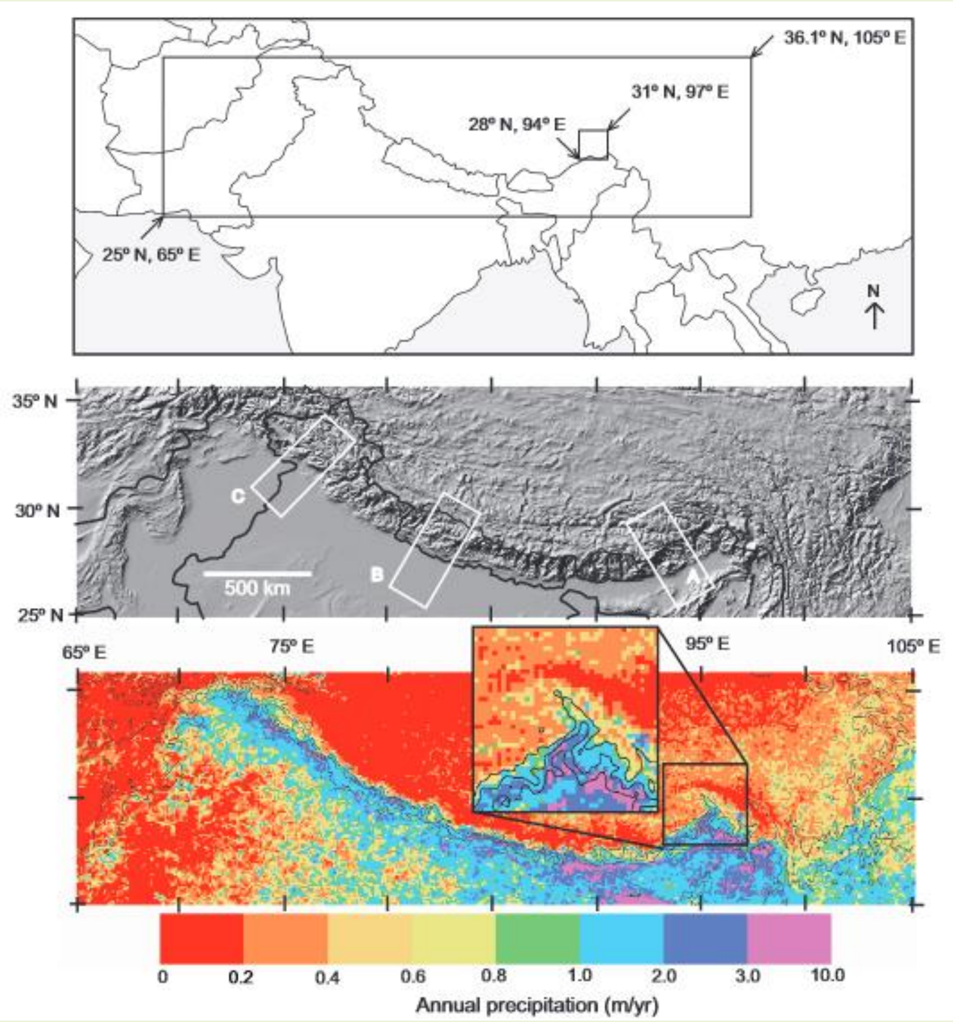
Investigating the Spatial Variability

- Spatial variability in properties
  - ❖ *Extremely important*

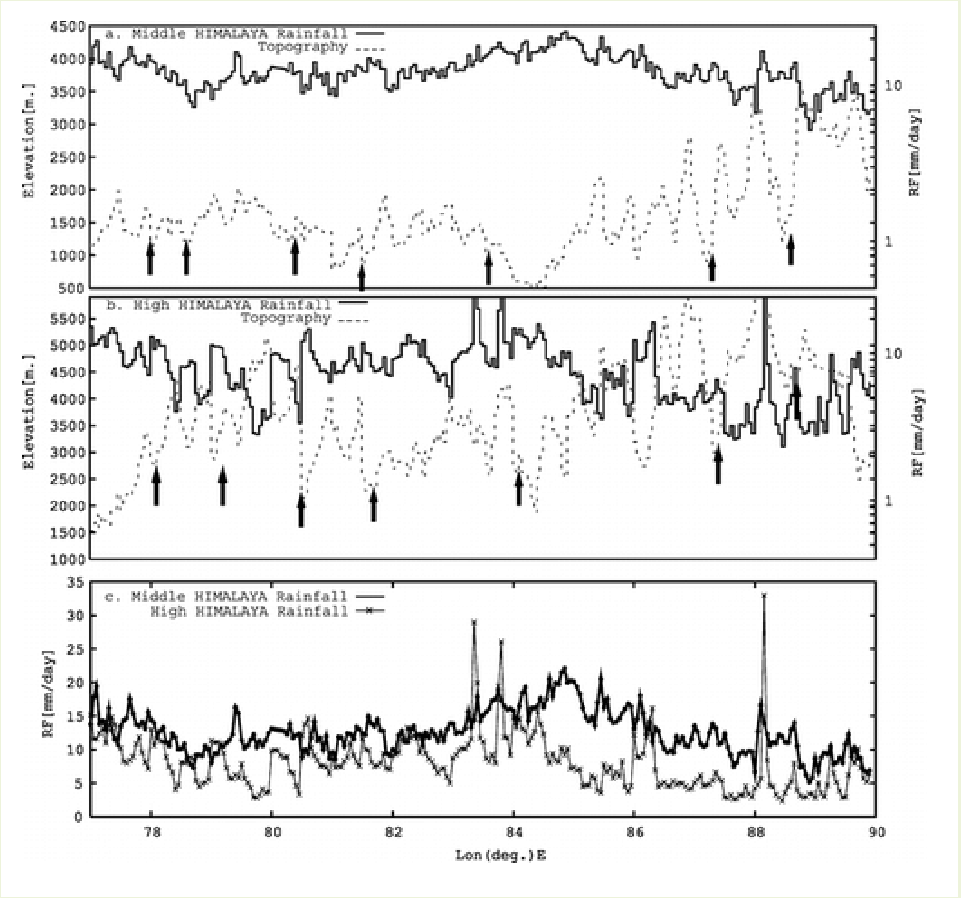
- Salient variable parameters
  - ❖ *Shear strength parameters*
  - ❖ *Permeability characteristics*
  - ❖ *Geological and geomorphological variability*
  - ❖ *Rainfall distribution*

Spatial and Temporal Variability of Rainfall

- Substantial spatial and temporal variation

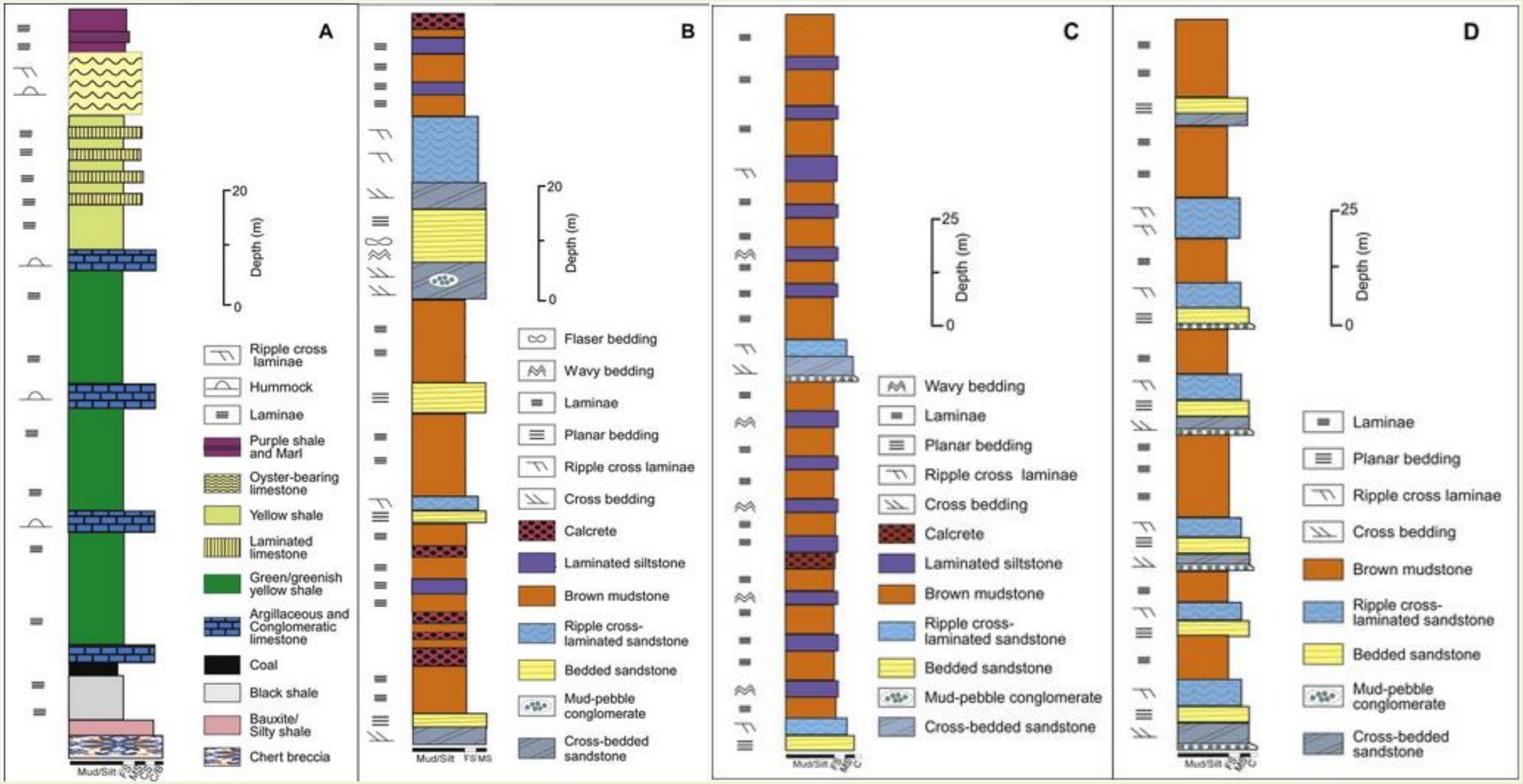


Bhatt and Nakamura (2005)



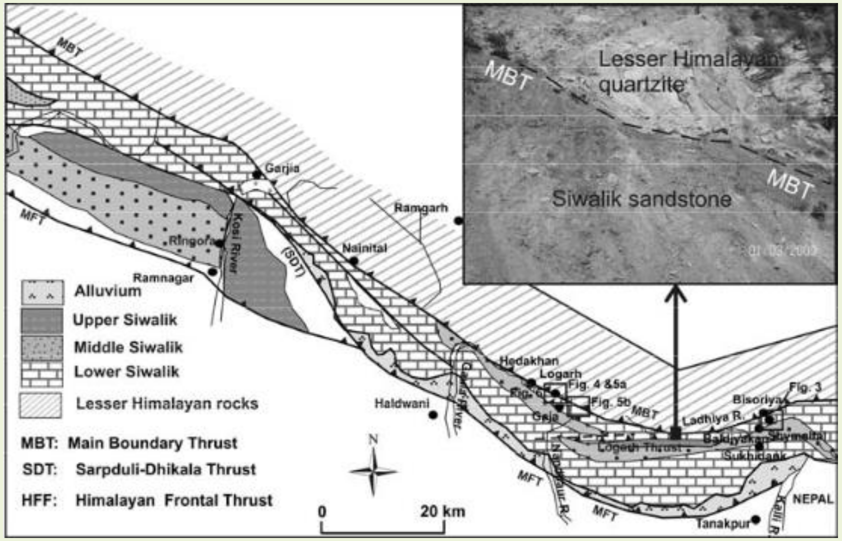
Anders et al. (2006)

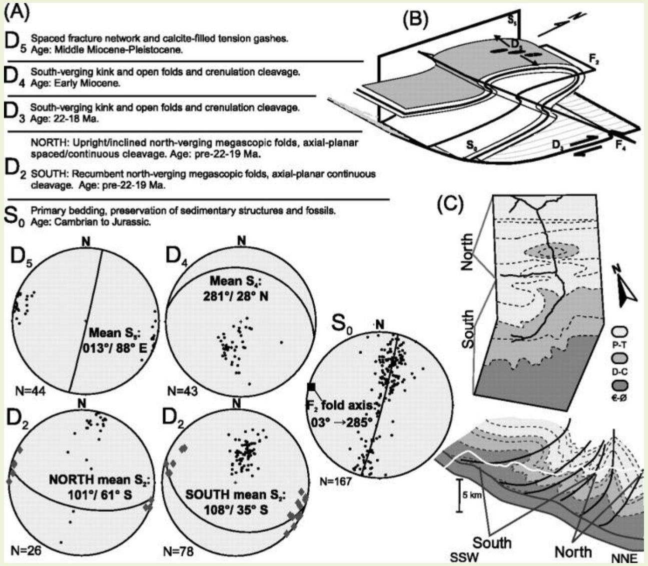
Spatial Variability in Soil Profiles



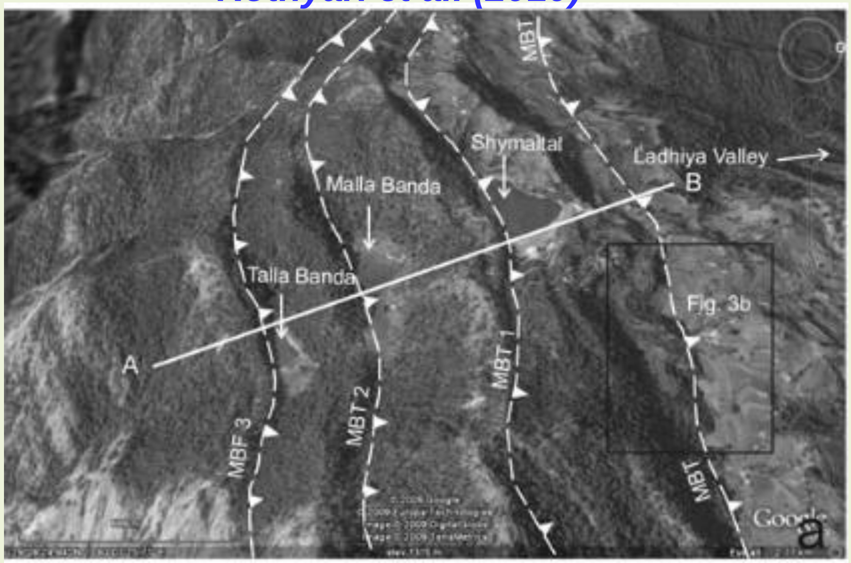
Singh (2013)

Spatial Variability in Geological Features



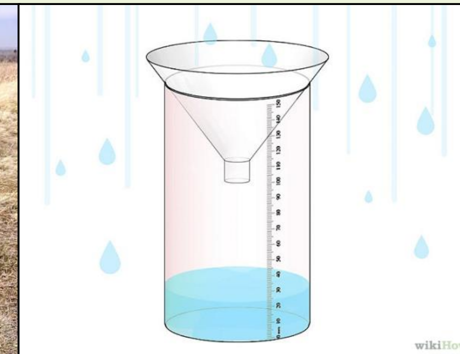


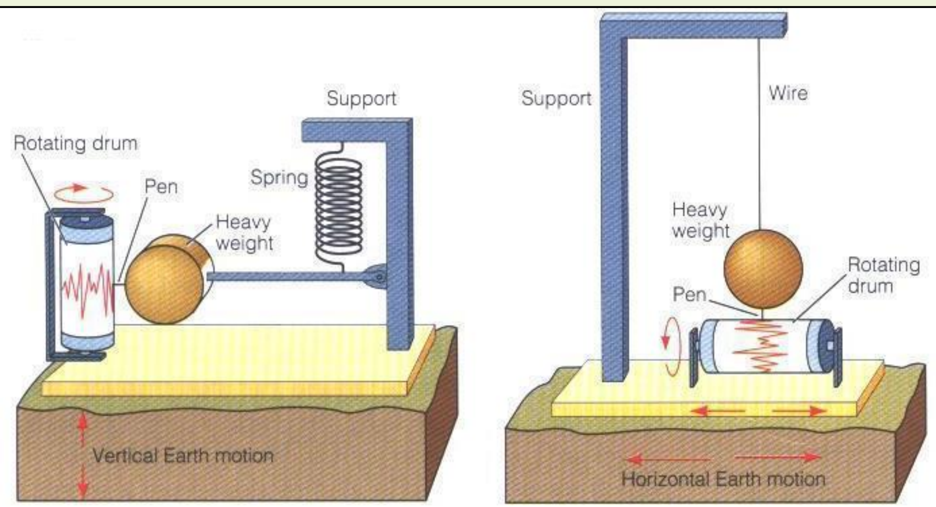
Kothyari et al. (2010)

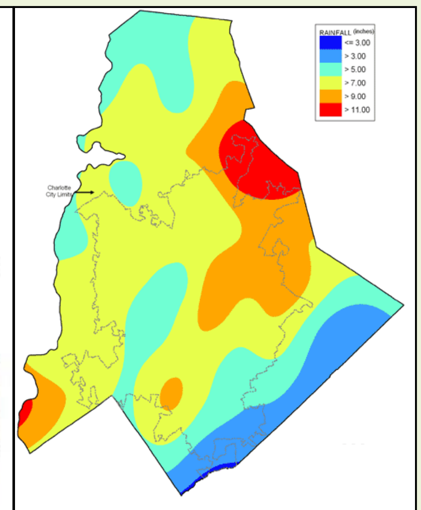
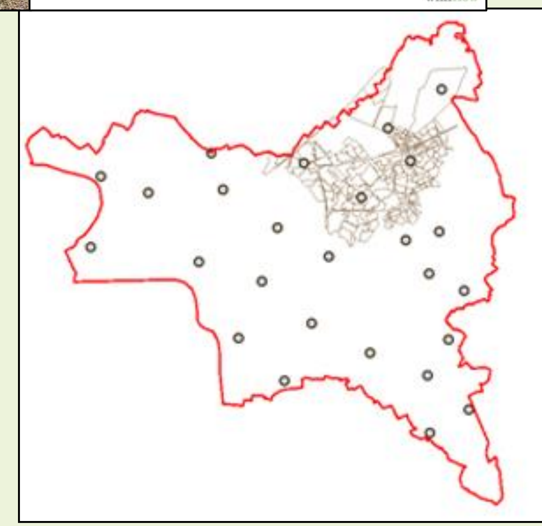


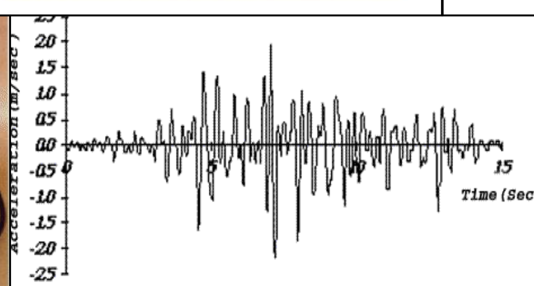
Investigation of Natural Triggering Events

- Rainfall event monitoring
  - ❖ *Strategically located Rain Gauges*
- Seismic event monitoring
  - ❖ *Accelerographs*

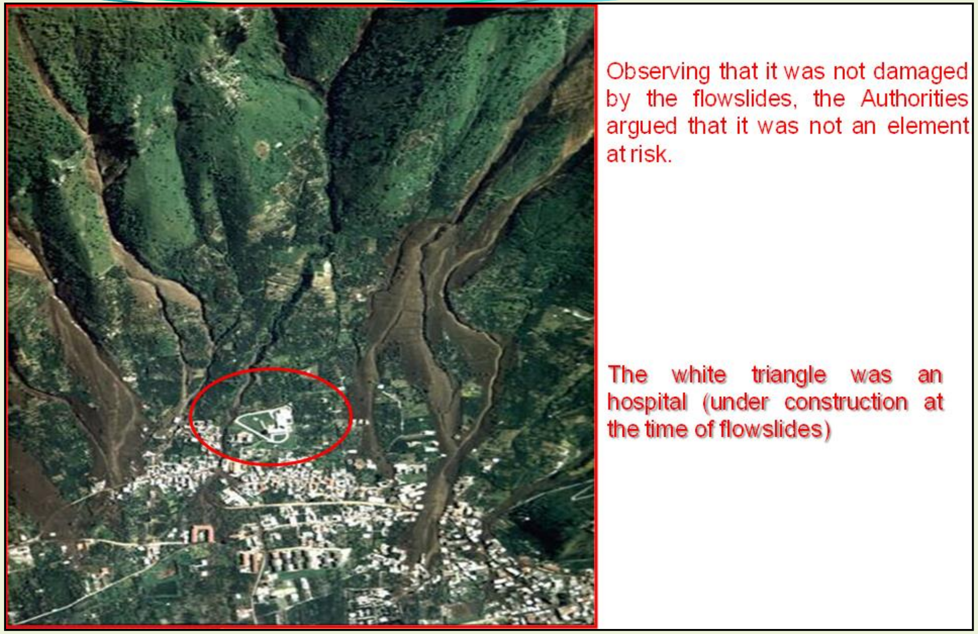


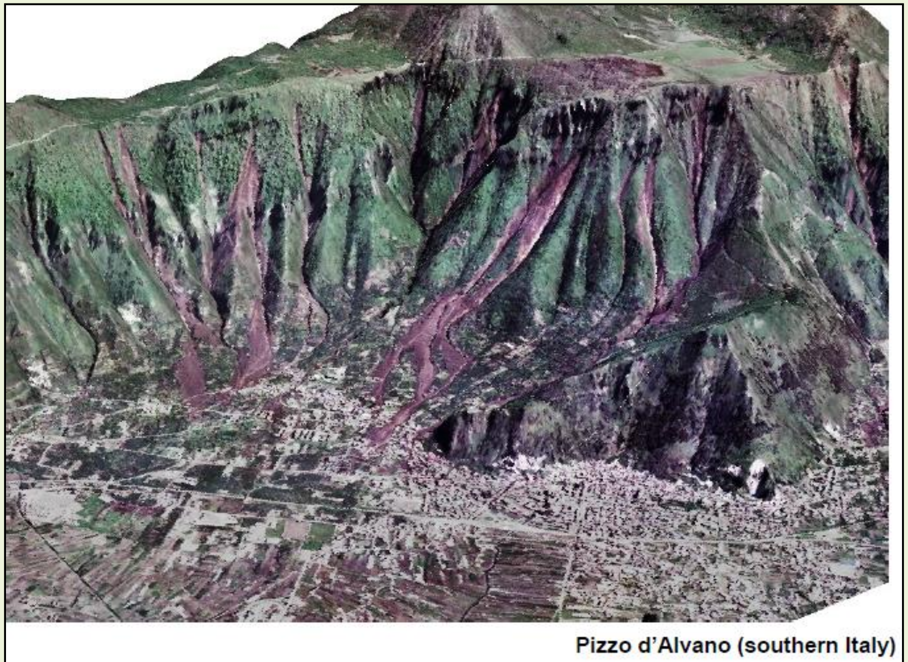





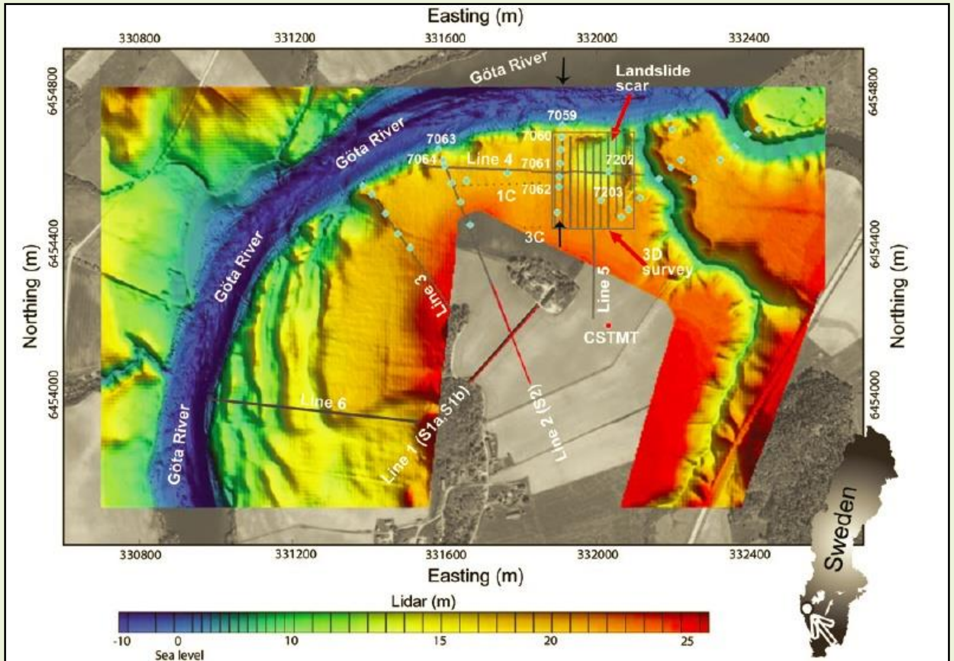
Ariel/Geodetic Surveys

- LIDAR Technique
  - *Velocity of soil movements*
  - *Type of movements – Rotational or Translational*
  - *Extent of damage*



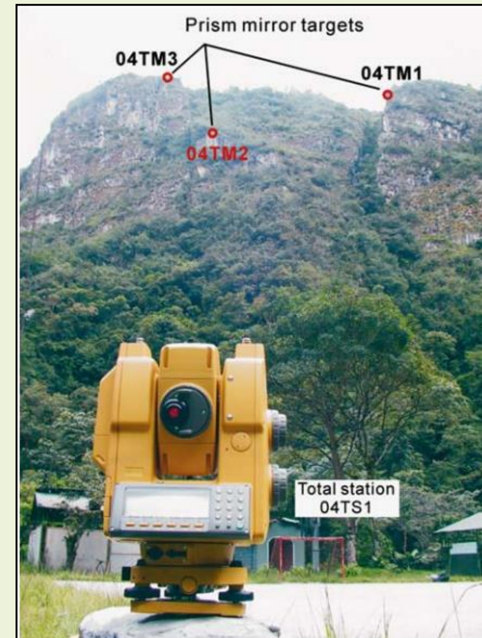


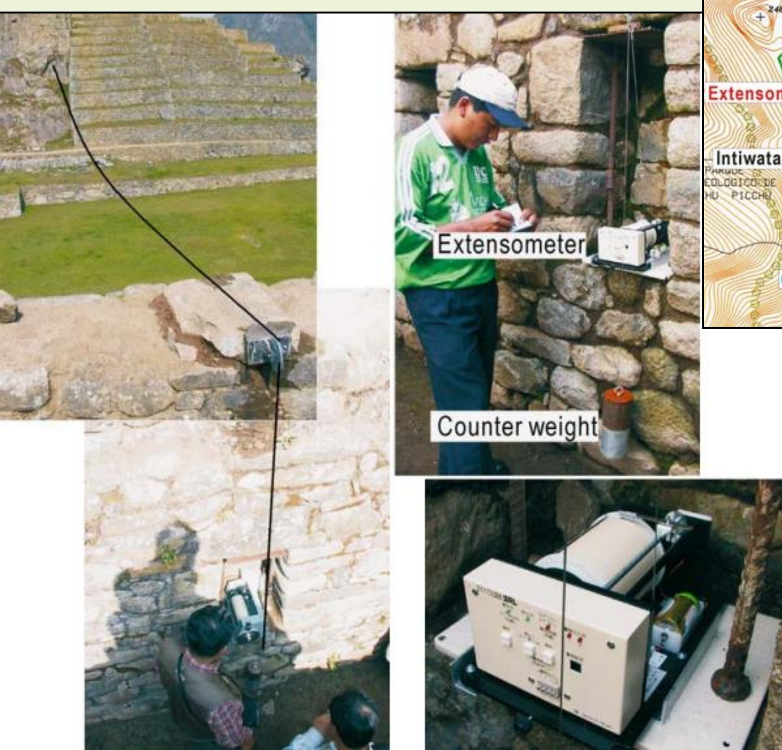
Pizzo d'Alvano (southern Italy)

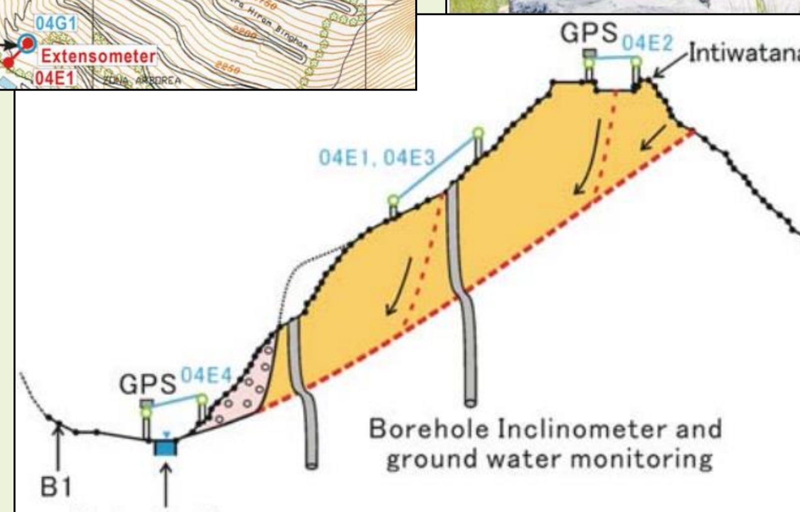


Continuous/Frequent/Intermittent Monitoring

- Mass Movement monitoring
  - ❖ *Electronic Distance Measurement (EDM)*
  - ❖ *Inclinometers, Extensometers, and Strain Meters*
  - ❖ *Ground tiltmeters*

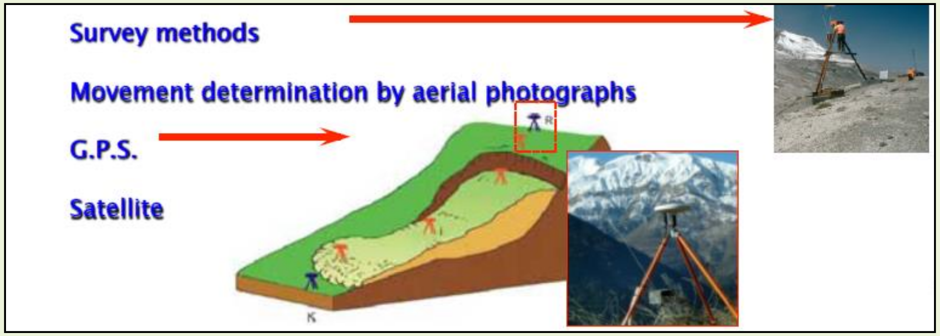


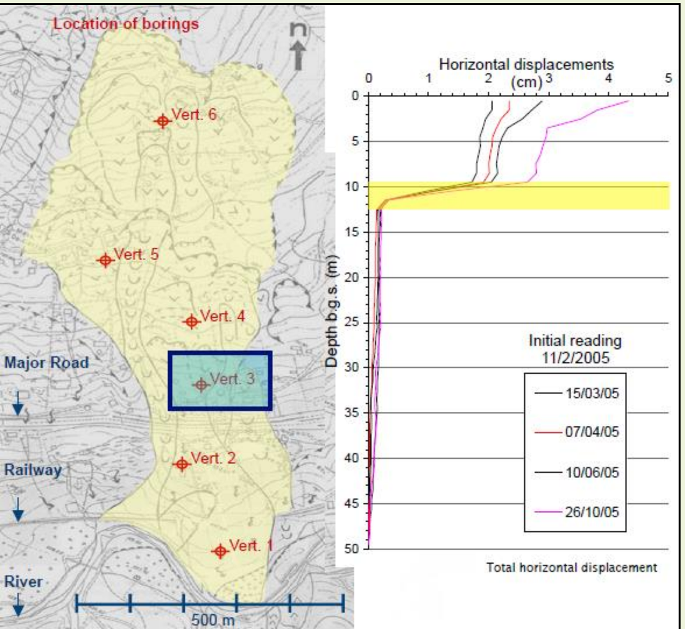


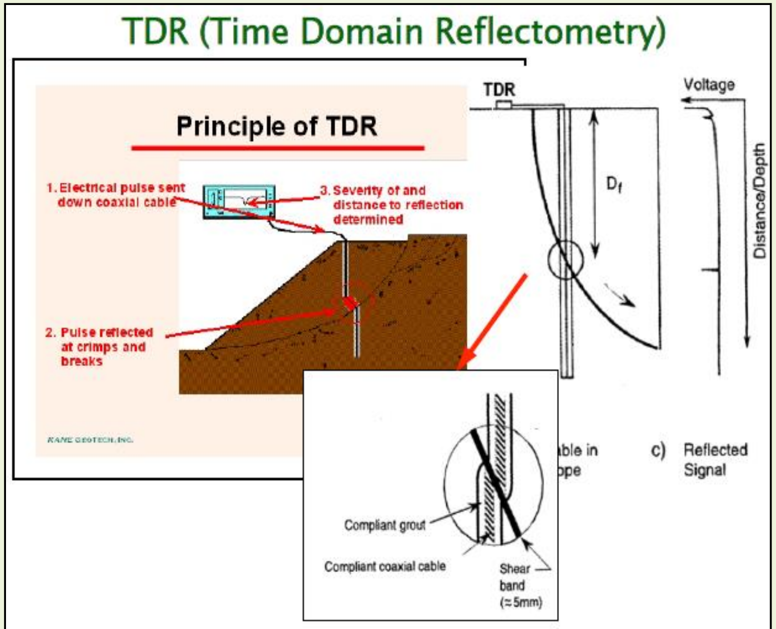


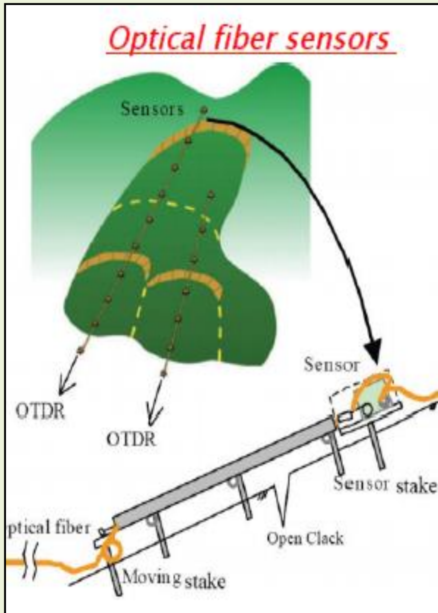
Continuous/Frequent/Intermittent Monitoring

- Mass Movement monitoring
  - ❖ *Ariel photographs and Advanced surveying techniques using GPS and Satellite images*
  - ❖ *Time domain reflectometry*
    - Use of Optical fiber sensors









Final Words

- Myriads of Field Investigations
  - *Which to choose?*
    - Exploratory borings, Geophysical, Geohydrological, Aerie surveys etc…
    - Extent of survey and cost involved
      - Requirement of the project
    - Level of interpretation reqruied
      - Simplified or Robust
    - Time and duration of investigation
      - Seasonal variation
      - One-time, intermittent, frequent or continuous
    - Variability of soil and ambient influence
      - Spatial variation
      - Temporal variation

SCIENTIFIC AND ENGINERING JUDGEMENT

ACCOMPANIED BY PROPER INTERPRETATION

Thank You for Patient Hearing