

21 Ground Investigation Boreholes

BOREHOLE DRILLING METHODS

Holes may be drilled with a great variety of commercially available rigs; methods fall mainly into three groups, dictated by the need for soil or rock penetration and required sample or core recovery.

LIGHT PERCUSSION DRILLING

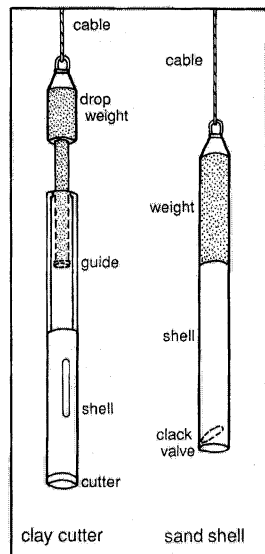
Mobile A-frame, easily erected, with power winch. Steel shell is driven into ground by weight repeatedly dropped 1–2 m and lifted by cable over A-frame (hence 'cable and tool' rig).

Only for shallow exploration of soils and soft clay rocks. In clays, smooth shell is driven by weight dropped onto it and soil adheres inside.

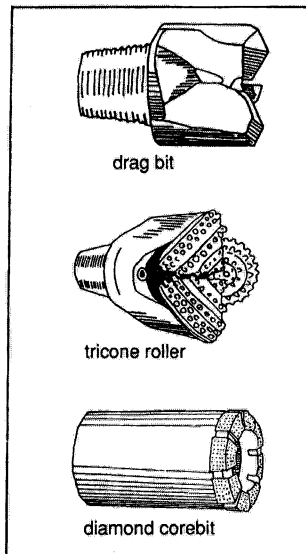
In sands, whole weighted shell may be surged and dropped, and soil is held inside by hinged clack valve. Can add light rotary drive for auger drill in clays (hence 'shell and auger' rig) but less suitable for most site investigations as sample is disturbed.

May use chisel head for limited rock penetration.

Widely used, as all sites need soil investigation; usually with 100 mm sampler inside 150 mm casing, reaching depths of 15–40 m.



Alternative shells for light percussion drills



Alternative drill bits for rock penetration

TRIAL PITS and TRENCHES

Cheapest method of shallow soil exploration.

Dug with any site excavator with backhoe.

Usually 2–5 m deep; may need temporary support or safety cage to allow full inspection of exposed walls.

Especially useful in variable man-made fills.

Valuable in disturbed or slipped material, including soliflucted head, as shear surfaces may be recognized in clean cut walls and not in borehole cores.

Can cut block samples, or drive in U100 sample tubes with backhoe, or test load a plate on pit floor.

Trenches can expose rockhead in search for fractures or outcrops.

Avoid trenches precisely on foundation sites; backfill with compacted soil or lean concrete.

Pits and boreholes may need sealing to prevent groundwater movement through breached aquiclude.



Light percussion rig sampling soils to a depth of 10 m for a construction project in Derbyshire

ROTARY CORING

Truck-mounted rig with full rotary drive which can be applied with downward force.

Air, water or bentonite mud flush, pumped down inside drill string, and washes chippings back up outside.

Tip of cylindrical drill bit is tungsten carbide or with diamond inserts (hence 'diamond drilling'). Normally double tube barrel holds full core in inner non-rotating barrel about 1–3 m long.

Can penetrate any soil or rock to >100 m deep.

Commonly use N size, providing 54 mm diameter core from cased hole of 89 mm diameter. Larger diameter is better in weaker rocks.

Continuous flight hollow-stem auger can be used in clays not common in exploration.

ROCK PROBING

Rotary percussion rig with hammer action capable of rock penetration.

Tricone roller or drag bits with air or water flush to remove chippings (hence 'open hole drilling').

Truck mounted to provide rotation and downward force large rigs can reach >100 m deep.

No core recovery (hence 'destructive drilling') but much cheaper than diamond drilling.

Penetration rate indicates strength of rock, soil or voids flushed chippings can be examined; flush loss also indicates cavities.

Wash boring uses water flushing in driven shell to probe soils (common in USA but rare in Britain).

Hand held pneumatic drill can reach 8 m in uniform rock. Used mainly to locate cavities in rock and rockhead beneath soils.

BOREHOLE RECORDS

All boreholes must be logged as completely as possible to be cost-effective.

Best to use conventional symbols for ease of reading.

Log must record at least the data on this example, on some style of conventional prepared booking sheet, though there is no single all-purpose format.

Description, thickness, depth, and the scale pictorial log provide a basic understanding.

In situ tests quantify ground properties.

Standard Penetration Test is easiest borehole strength test for soils; N value increases with strength (section 26). Or use Cone Penetration Test (section 26).

Point Load Strength is field test on borehole core of rock (section 24). Rock Quality Designation is measure of fracture density in rock (section 25), and core recovery is measure of weak broken zones; both values increase with quality and integrity of rock mass.

Water table and inflow points should be recorded, and permeability may be determined by packer tests (section 18).

Sample points are noted.

Trent Drilling				Summary Log			Number 422		
Client John Smith				Location Derwent Road Nottingham			NGR SK387274		
Equipment Cable Percussion 6.0m Rotary Coring 24.0m				Site co-ordinates 267.1 N 303.0 E			Level 64.1m OD Date 29 - 2 - 93		
S	K m/s	I MPa	100 R %	100 C %	N blows	Depth m	Log	Thick m	Description
D					6	1.4	[Symbol]	1.4	Mixed rubble and fill
U	6x10 ⁻⁵				18	3.2	[Symbol]	3.2	Firm boulder clay with cobbles and pebbles in grey sandy clay matrix
U					22	4.6	[Symbol]	2.3	Dense grey-yellow sands (weathered bedrock)
54mm core		0.7			34	6.9	[Symbol]	3.6	Hard buff sandstone occasional pebbles, thick bedded
	2x10 ⁻⁵	1.2			>50	10.4	[Symbol]	0.6	Weak, poorly sorted pebble bed
		1.9				11.0	[Symbol]	1.4	Hard, massive buff sandstone
	7x10 ⁻⁸	1.1				12.4	[Symbol]	2.9	Strong, dark grey mudstone sandy to 13.8. Ironstone nodules below 14.0.
		0.9				15.3	[Symbol]	1.3	Cross-bedded yellow sandstone
						16.6	[Symbol]	0.6	Void
						17.2	[Symbol]	0.8	Debris with timber traces
						18.0	[Symbol]	0.5	Friable coal with dirt bands
						18.5	[Symbol]	2.2	Very stiff, pale grey clay with coal traces
	8x10 ⁻⁵	0.2				20.6	[Symbol]	0.8	Strong black fissured limestone
						21.4	[Symbol]	1.1	Medium strong, blocky shale
		1.8				22.5	[Symbol]	2.5	Strong buff sandstone
						24.0	end		

S Sampling K Permeability R Rock Quality Designation
 D Disturbed sample I Point Load Strength C Core recovery
 U Undisturbed sample U100 N Standard Penetration Test

HOW MANY BOREHOLES, HOW DEEP?

Spacing: buildings 10–30 m apart;
road lines 30–300 m apart;
landslides at least 5 in line for profile.

Depth: 1.5 × foundation width, below founding depth, plus at least one deeper control hole to 10 m below foundation unless rockhead found; 3 m below rockhead to prove sound rock; probes to 3–10 m to locate rock cavities.

These are only rough guidelines.

Spacing and depth may be varied considerably in light of local conditions and appropriate to size of structure. Cavernous rock may need probes at each column base. Old mine working may need proving to depths of 30 m, and location of old shafts may need probes on 1 m grid.

BOREHOLE COSTS

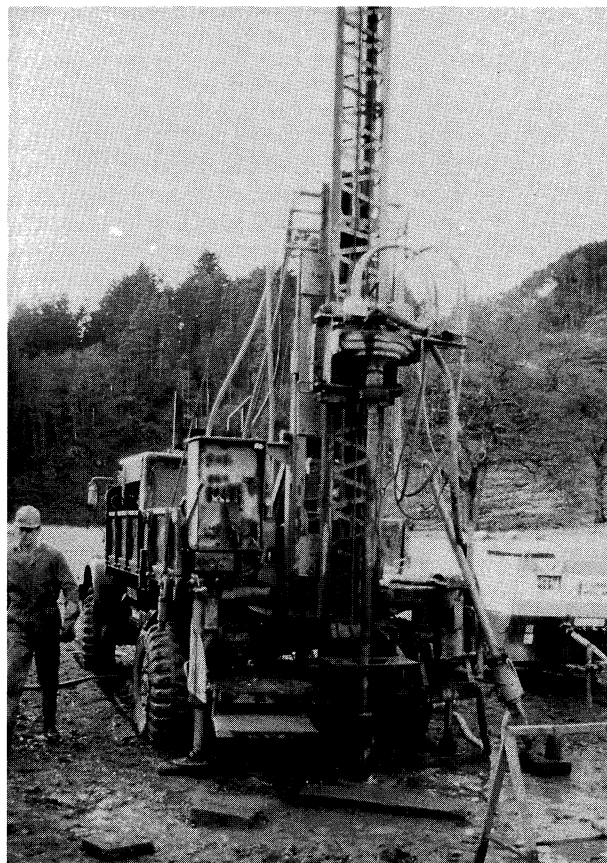
Drilling costs are best estimated as accumulation of:

- Cost to supply rig onto site
- Cost of set-up on each new hole
- Cost per metre of hole drilled

Table shows approximate relative costs (2001 figures in £)

	on site + per hole + perm		
Light percussion, soil <10 m deep	300	30	14
>10 m deep	300	30	16
Probing in rock or soil	350	40	12
Rotary coring in rock	350	40	40
Trial pits, 4 m deep, backfilled	250 for 4 pits		

Costs vary with number of in situ tests required. Probes are cheaper on close-spaced grid and in uniform rocks which do not require casing of hole.



Rotary rig coring drift and rock to a depth of 30 m for a road bridge in North Wales

22 Geophysical Surveys

The techniques of geophysical exploration involve the remote sensing of some physical property of the ground using instruments which in most cases remain on the ground surface.

Passive methods accurately measure earth properties and search for minute anomalies (local distortions within the overall pattern). These include gravity and magnetic surveys (and radioactivity which is inapplicable to site investigation).

Induction methods send a signal into the ground and pick it up again nearby. These include seismic, electrical, electromagnetic and radar surveys.

Interpretation of geophysical surveys invariably requires some borehole data, either to calibrate profiles or to test-drill anomalies.

Geophysical surveys have two main uses in ground investigations:

- Filling in detail between boreholes;
- Searching a large area for anomalies before drilling.

Geophysics is low cost compared to multiple boreholes. It can be cost-effective in site investigation in certain difficult ground conditions where a particular type of geophysical survey may be appropriate; there is no single geophysical system applicable to all problems.

GROUND PROBING RADAR (GPR)

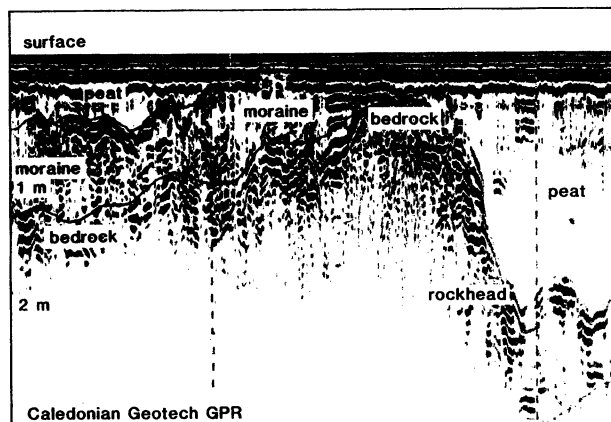
Trolley-mounted transmitter and receiver record microwave electromagnetic radar signals reflected from ground contrasts. High cost equipment, needs trained operator and assistant.

Ground cross-section is produced as computer output; some outputs are complicated by reflection interference, but many are realistic displays. Calibrate depth and materials with borehole.

Limited depth penetration is main restriction: 10–20 m in dry sand, only 1–3 m in wet clay.

Can tow behind car at 5 km/h for continuous profile.

Can use to map shallow drift profiles, filled sinkholes, shallow voids.



Ground radar profile of drift and rockhead for a road project in Scotland. Transverse length is 200 m

ELECTRICAL SURVEYS

Numerous methods applied successfully to mineral exploration.

Resistivity surveys with Wenner arrays of four ground electrodes can be used to map lateral and vertical changes in ground conditions.

Difficult to interpret; limited use in site investigation.

SEISMIC SURVEYS

Shock waves, produced by hammer-blows, explosions, etc., are reflected or refracted on geological boundaries.

Reflection seismic

Seismic waves reflected from deep strata boundaries. Successfully used for all primary oil exploration.

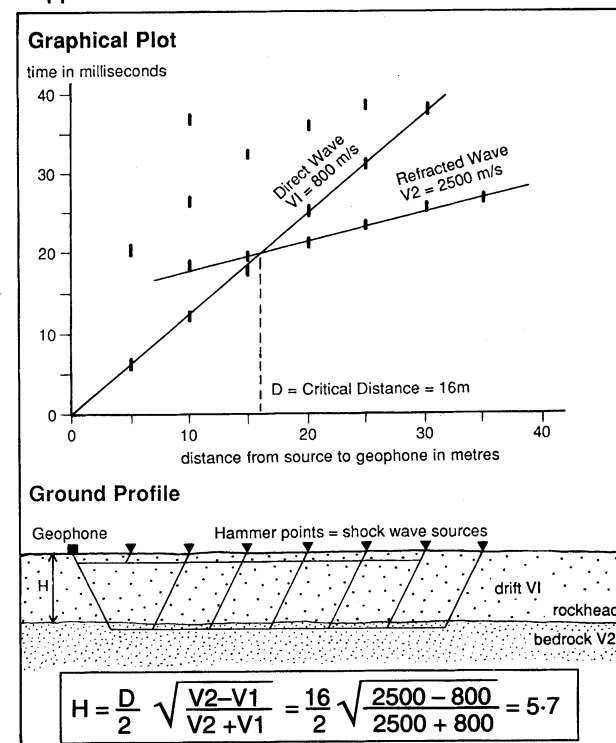
Difficult and little used in shallow ground investigation.

Refraction seismic

Seismic waves refracted at shallow geological boundaries and returned to surface.

Drop-hammer or 3 kg sledge hammer adequate for 20 m penetration; deeper with explosive shock source; small geophones detect wave arrivals; low cost equipment, 2 man operation.

Refraction relies on faster layer at depth: rockhead is ideal boundary to detect, with slow soil over fast rock. Graphical plot of first wave arrivals reveals both velocities and boundary depth. Other simple relationships apply to 3-layer situations and dipping or stepped boundaries.



Seismic profile over alluvium above mudstone

Cross Hole Seismic

Seismic waves transmitted between boreholes have scope for detection of isolated voids and complete tomographic profiling, but require trained operators.

Seismic velocities (speed of shock waves through rock) increase with strength of rock, and decrease with more fracturing (related to RQD, see section 25).

Typical seismic velocities (V_p)

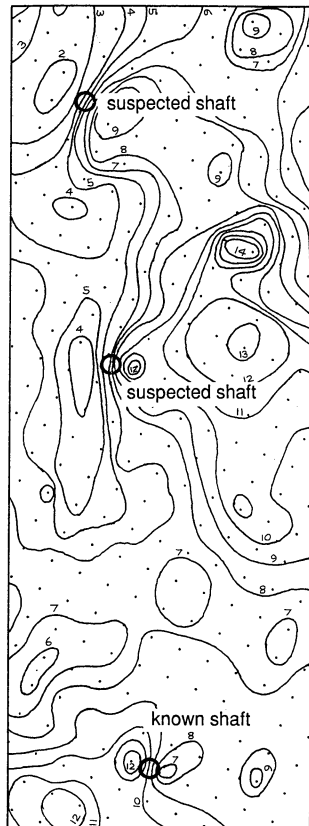
Drift and soil	500–1500 (m/s)
Shale and sandstone	1500–4000
Limestone	3000–5000
Granite	4500–5500
Fractured rock	unfractured $V_p \times \text{RQD}/100$

MAGNETIC SURVEYS

Record distortions of Earth's magnetic field. Proton magnetometer measures total field; low cost, robust equipment. Measures to 1 nanoTesla ($1\text{nT} = 1\gamma = \text{about } 1/50\,000 \text{ Earth's field}$).

Simple to use, 10 seconds per station, 1 man operation.

Dipole anomalies – positive next to negative, so easily recognized – are due to vertical linear features, e.g. buried mine shafts. Unlined shafts with fill which is magnetically similar to wallrock may go undetected. Fences, drains, powerlines, iron-rich fill prohibit use.



Proton magnetometer and map of a magnetic survey on a site in the Derbyshire coalfield. Stations are on 3 m grid; contours are at 100 nT intervals above a base of 48 000 nT. Dipole anomalies lie over one known shaft and indicate the location of two more shafts

USES IN GROUND INVESTIGATION

The new geophysical techniques can be, and have been, applied effectively to certain specific problems in ground investigation:

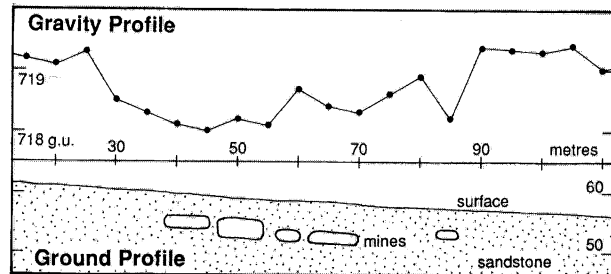
- Search for unknown cavities: GPR if depth < 10 m, or gravity survey if depth < size
- Search for suspected mineshafts: magnetic survey.
- Trace lateral contrasts, notably between sand and clay, in shallow drift: GPR, electromagnetic survey.
- Rockhead profiling between boreholes: refraction seismic survey.
- Estimate rock fracturing ahead of new tunnel drive – seismic survey, reflection or refraction depending on depth of cover.

Magnetic searches for buried mineshafts are simple enough for operation and interpretation by untrained personnel with low-cost rented equipment. All other geophysical surveys are best interpreted by specialists working as part of a ground investigation team.

GRAVITY SURVEYS

Record minute variations in Earth's gravitational force. Gravimeter measures length of internal weighted spring; high cost, delicate instrument. Measures to 0.01 gravitational unit ($1\text{gu} = 10^{-6}\text{m s}^{-2} = 0.1\text{mgal}$). Ten minutes per station, one man operation.

Negative anomalies due to underground voids (cave or mine) or low density soil or rock (in buried valleys or sinkholes); both significant to engineering. The limit is set by background noise, but microgravity surveys with computer analysis of closely spaced data points can recognize voids with diameter much less than their cover depth. Can trace small mines to depths of 20 m, and larger limestone features to much deeper. Depth and size of void may be interpreted from shape of anomaly, but normally drill all negative anomalies.



Gravity surveys over sand mines in Nottingham

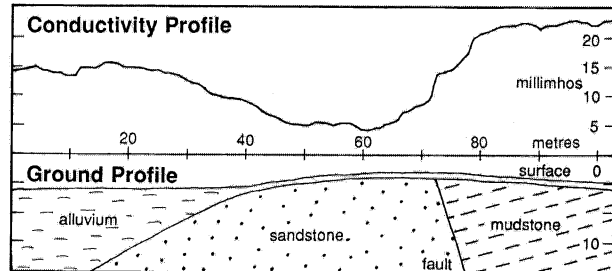
ELECTROMAGNETIC SURVEYS

Non-contacting terrain conductivity meter creates electromagnetic field in ground and measures field intensity 3-7 m away; low cost equipment, simple to use, similar to large metal detector. Measures mean conductivity in hemisphere of ground reaching 6 m deep (deeper on some meters).

Continuous reading, 1 man operation.

High conductivity of clay, basalt and water, contrasts low conductivity of sand and limestone.

Can use to map shallow lateral changes: clay-filled fissure zones, filled sinkholes, rockhead steps, alluvial channel fills, high permeability fracture zones.



Electromagnetic traverse over faulted mudstone and sandstone with variable alluvium cover

GEOPHYSICAL SURVEY COSTS

Comparisons of costs are tenuous because each method is best applied to only certain ground problems. Rough guide is given by approximate coverage which can be achieved for a given fee – in this case £500 at 2001 prices.

Microgravity survey	0.1 ha on 2 m grid
Magnetic survey	0.5 ha on 3 m grid
Electromagnetic survey	0.5 ha on 3 m grid
Ground probing radar	600 m of line profile
Seismic refraction	5 soundings to 20 m deep
Borehole	1 cored hole 10 m deep

26 Soil Strength

Properties of a soil depend on the grain size, mineralogy and water content, all of which are inter-related. Clay minerals can hold high water content; for fine grained soils, critical concept is consistency related to water content.

SOIL CONSISTENCY

With varying water content, a soil may be solid, plastic or liquid. Most natural clays are plastic.

Water content (w) = weight of water as % of dry weight. Consistency limits (Atterberg limits) are defined as:

Plastic limit (PL) = minimum moisture content where a soil can be rolled into a cylinder 3 mm in diameter. Disturbed soil at PL has shear strength around 100 kPa.

Liquid limit (LL) = minimum moisture content at which soil flows under its own weight. Disturbed soil at LL has shear strength around 1 kPa.

Plasticity index (PI) = $LL - PL$. This refers to the soil itself and is the change in water content required to increase strength 100 times; it is the range of water content when the soil is plastic or sticky.

High PI soils are less stable, with large swelling potential.

Liquidity Index (LI) = $(w - PL) / PI$. This is a measure of soil consistency and strength at a given water content.

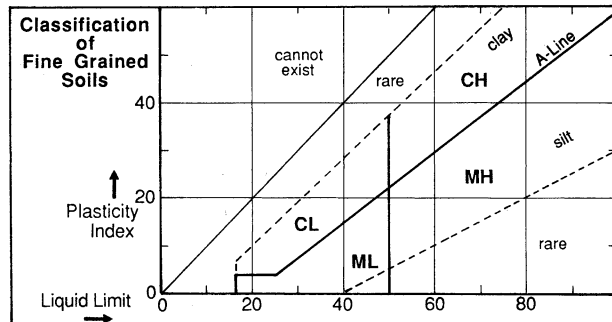
Clay Mineral	Activity	PI	ϕ
Kaolinite	0.4	30	15
Illite	0.9	70	10
Smectite	>2	400	5
PI values are for soil with 75% clay fraction			

SOIL CLASSIFICATION

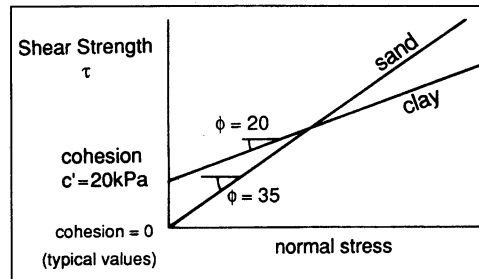
Soils are classified on grain size and consistency limits.

A-line distinguishes visually similar clays and soils.

More subdivisions exist in a full soil classification.



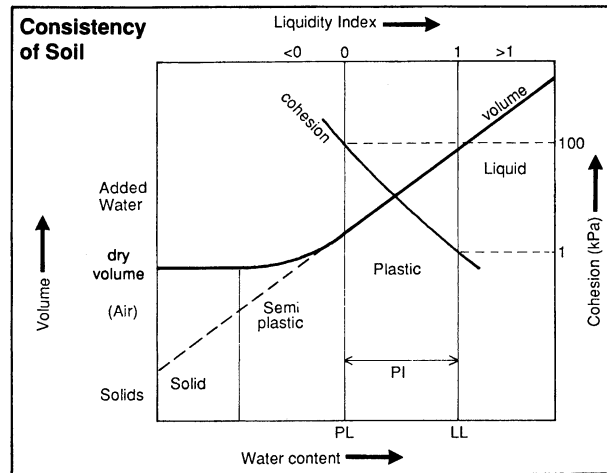
Soil Classification		grainsize mm	typical values		
type	class		LL	PI	ϕ
Gravel	G	2-60			>32
Sand	S	0.06-2			>32
Silt	ML	0.002-0.006	30	5	32
Clayey silt	MH	0.002-0.06	70	30	25
Clay	CL	<0.002	35	20	28
Plastic clay	CH	<0.002	70	45	19
Organic	O	-			<10



Properties of Cohesive Clay Soils

Material	State	LI	SPT, N	CPT, MPa	c, kPa	m_v , m ² /MN	ABP, kPa
Alluvial clays	soft	>0.5	2-4	0.3-0.5	20-40	>1.0	<75
	firm	0.2-0.5	4-8	0.5-1	40-75	0.3-1.0	75-150
Till and Tertiary clays	stiff	-0.1-0.2	8-15	1-2	75-150	0.1-0.3	150-300
	v. stiff	-0.4-0.1	15-30	2-4	150-300	0.05-0.1	300-600
	hard	<-0.4	>30	>4	>300	<0.005	>600

Cohesion (c) is equivalent to short term shear strength



CLAY MINERALS

Plasticity and properties of clay soils depend on amount and type of clay minerals.

Soils with < 25% clay minerals are generally stronger, with low PI and $\phi < 20\%$.

Activity of clay = $PI / \% \text{ fines } (< 0.002 \text{ mm diameter})$.

Soils with high clay fraction and high activity can retain high water content, giving them low strength, and also have low permeability.

Activity is mainly due to clay mineral type; smectite (montmorillonite) clays are the most unstable.

SHEAR STRENGTH

All soils fail in shear.

Shear strength is a combination of cohesion and internal friction; expressed by Coulomb failure envelope.

Cohesion (c) derives from interparticle bonds; significant in clays, zero in pure sands.

Angle of internal friction (ϕ) is due to structural roughness; higher in sand than in clay.

- Shear strength = cohesion + normal stress $\times \tan \phi$

Normal stress is critical to shear strength but pore water pressure (pwp) carries part of overburden load on soil, thereby reducing normal stress.

- Effective stress (σ') = normal stress (σ) - pwp.

Shear strength is correctly defined in terms of effective stress, so that:

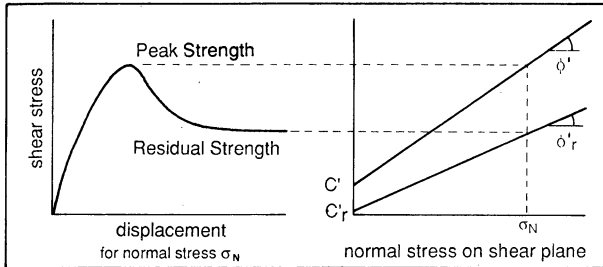
- Shear strength (τ) = $c' + \sigma' \tan \phi'$

STRENGTH DECLINE IN CLAYS

Drainage progress of a loaded clay is critical as any increase of pore water pressure may lead to failure; significant in new excavations and embankments.

Peak strength declines to residual strength due to restructuring, notably alignment of mineral plates, during dislocation along a plane. Change is due to almost total loss of cohesion and also reduction in friction angle. Significant in all clays, notably those with higher PI.

- Brittleness = % decline from peak strength.



Sensitive clays lose great proportion of their strength on restructuring of entire mass; they have high LI and small grain size, so cannot drain rapidly and load is taken by pwp; shear strength approaches zero.

- Sensitivity = ratio of undisturbed:disturbed strengths and relates to undrained brittleness.

CONSOLIDATION

This is decrease of volume, under stress.

Primary consolidation is large and fast; due to expulsion of water until excess pwp is zero.

Secondary consolidation is small and slow; due to restructuring and lateral movement; same as drained creep.

Normally consolidated clays are those compacted by their present overburden of sediments.

Over-consolidated clays are those more compacted in the past by overburden soils since removed by erosion (or by glacier ice); they can bear loading up to their previous overburden stress with only minimal compression and settlement.

Compression coefficient = m_v = reduction of thickness with increase of stress; correlates closely with LL.

Non-cohesive Soils

Sand soils, and gravels have no cohesion, except that derived from any clay matrix and water suction. Sand stands in steep slopes when wet due to negative pore pressure (critical in building sand castles), but will not stand when dry or saturated.

Strength, slope stability and bearing capacity all derive from internal friction; ϕ for granular soils (sands and gravels) range 30–45°; increases due to grading, packing density and grain angularity.

Settlement is small and rapid; not usually considered, except on very loose sands and artificial fills.

Properties are best assessed in situ by SPT; N values are a function of packing density and grading.

Bearing capacity of sandy soils may be improved by dynamic consolidation (with a 20 ton weight repeatedly dropped from a crane) or by vibrocompaction.

Properties of Sands

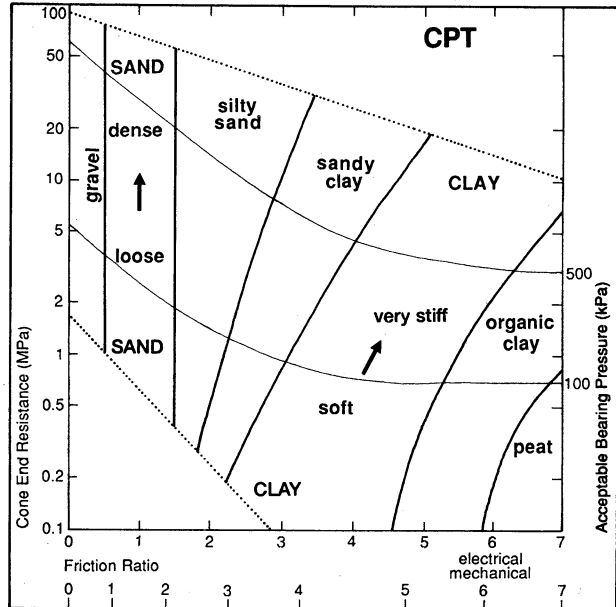
Packing	RD	SPT	CPT	ϕ	SBP
v. loose	<0.2	< 5	<2	<30	<30
loose	0.2–0.4	5–10	2–4	30–32	30–80
m. dense	0.4–0.6	11–30	4–12	32–36	80–300
dense	0.6–0.8	31–50	12–20	36–40	300–500
v. dense	>0.8	>50	≥20	≥40	≥500

CONE PENETRATION TEST (CPT)

In a site investigation borehole, a 60° cone (= 36 mm in diameter) is driven into soil at 15–25 mm/second, followed by a concentric outer sheath.

End resistance and sheath resistance are measured: Friction ratio = (side friction/end friction) | 100; ratios on standard electrical systems differ on less commonly used mechanical systems.

Values relate to soil types and packing state, and give indication of Acceptable Bearing Pressure.



ACCEPTABLE BEARING PRESSURE

Values relate largely to soil water content and consolidation history.

Depend on SBP and acceptable settlement.

- Settlement = $m_v \times$ thickness \times imposed stress.

Rate of settlement depends on permeability; slow in clay soils which cannot drain rapidly.

Settlements on clay may be large: then referred to as subsidence, along with other processes which affect clays (section 28).

STANDARD PENETRATION TEST (SPT)

In a site investigation borehole, a 51 mm split tube sampler is driven for 150 mm.

Using 64 kg hammer dropped 760 mm, number of blows (N) is counted to drive the tube the next 300 mm.

A simple, effective test; N values closely relate to sand properties; should be used with care in clay soils.

(At shallow depth N may be multiplied by empirical correction factor, F, to allow for low stress;

$$F = 350 / (25D + 70), \text{ where } D = \text{depth in m.})$$

Relative Density is a measure of grain packing on a scale from loosest to densest possible states of compaction.

SPT refers to corrected N values.

CPT values are end resistances, in MPa, for fine sand; values are lower in silts and lighter in gravels. Friction angles are for average sand; add 2° for angular grains; subtract 3° for rounded grains; add 5° for gravels.

SBP values, in kPa, are for foundations 3 m wide with settlement < 25 mm; multiply by 1.4 for strip foundations 1 m wide; values are halved for sand stressed below water table.