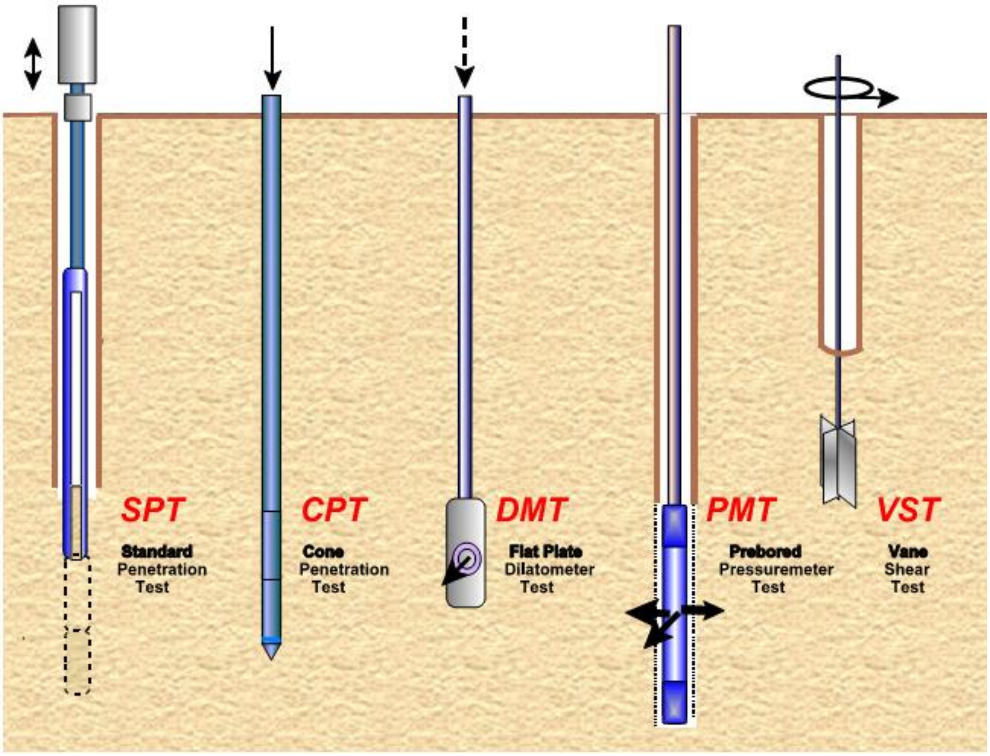
In Situ Testing

- In-situ tests define the geo stratigraphy and obtain direct measurements of soil properties and geotechnical parameters.
- The common tests include: standard penetration test (SPT), cone penetration test (CPT), flat dilatometer test (DMT), pressuremeter test (PMT), vane shear test (VST), plate bearing test, and many others.



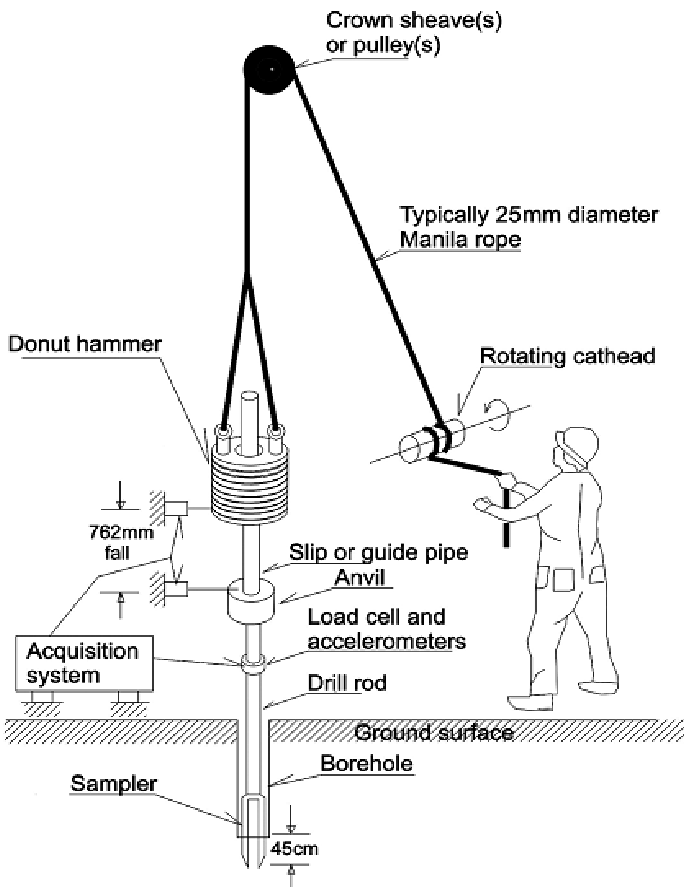
- Laboratory testing is the best method for determining soil parameters under controlled conditions, if good-quality samples can be obtained.
- In some types of ground are either difficult or impossible to get soil samples, so in situ tests should be used:

a) Very soft or sensitive clays;
b) Sands and gravels, sand sampling is possible using freezing techniques, but tends to be expensive;
c) Weak, or fractured rock.

Standard Penetration Test (SPT)

The test was introduced by the Raymond Pile Company in 1902. The earliest reference to a 'SPT' procedure is in a paper by Terzaghi in 1947.

- The International Test Reference are (BS 1377-9: 1990), (ASTM D1586-99: 1999), (AASHTO T-206).
- The SPT is one of the oldest and most widely used in-situ tests worldwide. Its popularity is largely due to its low cost and simplicity, and the fact that testing may be conducted rapidly as a borehole is drilled.
- The standard penetration test is the most commonly used in-situ test, especially for cohesionless soils which cannot be easily sampled. The test is extremely useful for determining the relative density and the angle of shearing resistance of cohesionless soils. It can also be used to determine the unconfined compressive strength of cohesive soils.



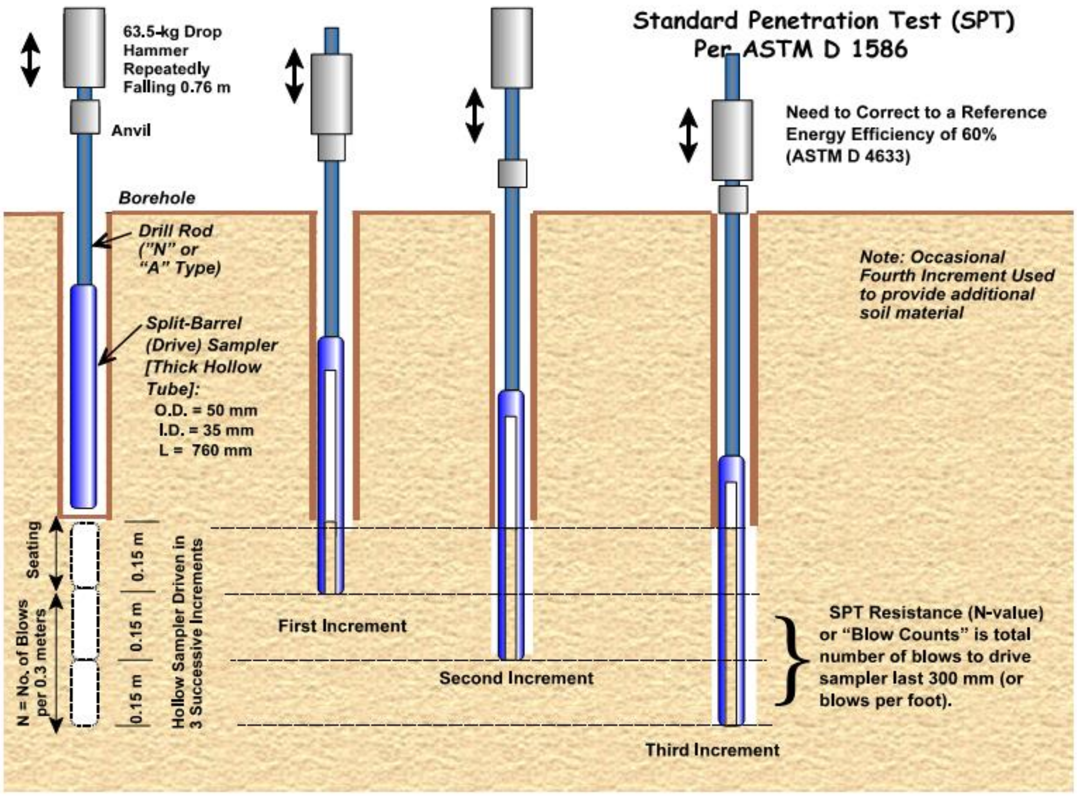
STP Test

Test Procedure

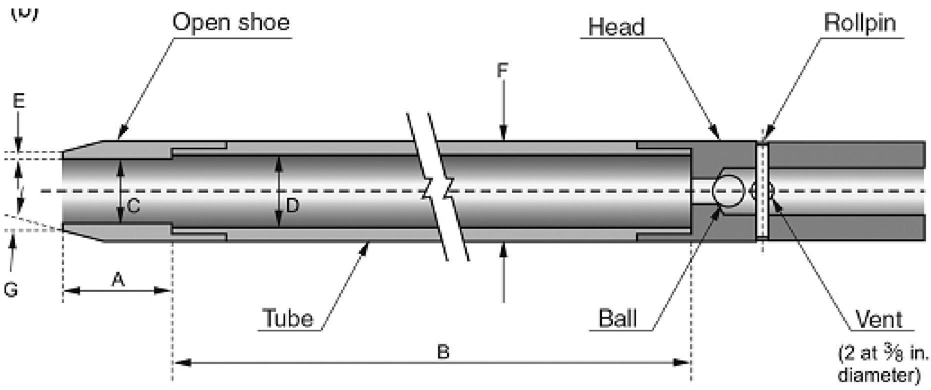
The standard penetration test is conducted in a bore hole using a standard split-spoon sampler, When the bore hole h.as been drilled to the desired depth, the drilling tools are removed and the sampler is lowered to the bottom of the hole. The sampler is driven into the soil by a drop hammer of 63.5 kg mass falling through a height of 750 mm at the rate of 30 blows per minute (IS: 2131- 1963).

The number of hammer blows required to drive 150 mm of the sample is counted. The sampler is further driven by 150 mm and the number of blows recorded. likewise, the sampler is once again further driven by 150 mm and the number of blows recorded. The number of blows recorded for the first 150 mm is disregarded. The number of blows recorded for the last two 150 mm intervals are added to give tbc standard penetration number (N). In other words, the standard penetration number is equal to the number of blows required for 300 mm of penetration beyond a seating drive of 150 mm.

- *The SPT can be stopped when the number of blows exceeds 50 in any given 150-mm increment, or if the sampler fails to advance during 10 consecutive blows.*



Sequence of driven split-barrel sampler during SPT



A = 1.0 to 2.0 in. (25 to 50 mm)
B = 18.0 to 30.0 in. (0.457 to 0.762 m)
C = 1.375 ± 0.005 in. (34.93 ± 0.13 mm)
D = 1.50 ± 0.05 – 0.00 in. (38.1 ± 1.3 – 0.0 mm)
E = 0.10 ± 0.02 in. (2.54 ± 0.25 mm)
F = 2.00 ± 0.05 – 0.00 in. (50.8 ± 1.3 – 0.0 mm)
G = 16.0° to 23.0°

SPT split-spoon sampler: ASTM D 1586 (1999)

Factors Affecting the SPT

The factors that influence the measurement of the SPT N value are:

A. Drilling and borehole technique;
B. SPT equipment;
C. Test procedure.

A. Drilling and Borehole Techniques

The main factors that may influence the SPT N-value are:

i. Method of borehole advancement;
ii. Method of borehole support;
iii. Size of borehole

Drilling methods that add flush fluid have the advantage of keeping the borehole full of fluid and minimize any rapid flow of groundwater into the borehole during drilling and the borehole cleaning process.
The ASTM standard limits the borehole size between 2 to 6 inches.

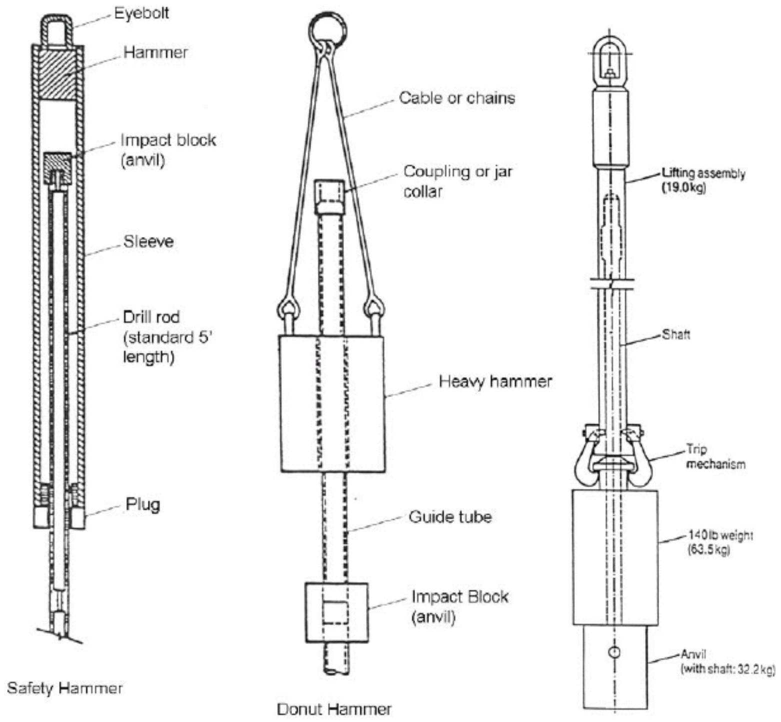
B. SPT Equipment

The factors that may influence the SPT N-value associated with equipment are:

i. Hammer design;
ii. Rod size and type;

The hammer consists of the hammer, anvil and the lift-release mechanism. The standards hammer weight is 63.5kg and must be 'free falling' from a height of 762mm.

➢ There are three types of drop hammers (donut, safety, and automatic) are used in SPT.



The energy delivered to the split spoon varies from 35% to 85% using donut or safety hammers of the free-fall energy. While, the automatic trip-hammers can deliver between 80 to 100% efficiency.

Heavier anvils reduce the energy transmitted from the hammer and increase the measured N-values.

Long strings or lighter rods produce higher N-values, as a result of energy lost in bending and through the many rod couplings.

➢ N-value is inversely proportional to the energy delivered to the split spoon. Thus if two different hammer/rod systems deliver different energies, where

$$\frac{N_1}{N_2} = \frac{E_2}{E_1}$$

Corrections of SPT number:

The recorded N_{field} should be adjusted and corrected for the effects of some factors such as effective overburden pressure (C_N), hammer efficiency (η_h), borehole size (η_b), sampler (η_s) and rod length (η_r). Due to various types of driving hammers with different efficiencies, the hammer energy ratio E_r is referenced to a standard or basic energy ratio, E_{rb}, such that η_h be equal to ratio of the particular hammer energy to the standard E_{rb}, which is equal to either 60 or 70%.

When N_{field} is adjusted to η_h, η_b, η_s and ηr corrections, it is generally referred to as N_{60} or N_{70} according to the E_{rb} value, as follows:

$$N_{60} = \frac{E_r \cdot \eta_b \cdot \eta_s \cdot \eta_r \cdot N_{field}}{60}$$

$$N_{70} = \frac{E_r \cdot \eta_b \cdot \eta_s \cdot \eta_r \cdot N_{field}}{70}$$

Table 1 gives values of Er for different types of SPT hammers. Table 2 gives values for borehole, sampler and rod correction factors.

When N60 and N70 are corrected for the effective overburden pressure, they are written as N60 and N70, where

$$N'_{60} = C_N \, N_{60}$$

$$N'_{70} = C_N \, N_{70}$$

Table 1: SPT hammer efficiencies (adapted from Clayton, 1990).

Country	Hammer type	Hammer release mechanism	Efficiency, E_r
Argentina	Donut	Cathead	45
Brazil	Pin weight	Hand dropped	72
China	Automatic	Trip	60
	Donut	Hand dropped	55
	Donut	Cathead	50
Colombia	Donut	Cathead	50
Japan	Donut	Tombi triggers	78–85
	Donut	Cathead, two turns + special release	65–67
UK	Automatic	Trip	73
US	Safety	Cathead, two turns	55–60
	Donut	Cathead, two turns	45
Venezuela	Donut	Cathead	43

Table 2: Borehole, sampler and rod correction factors (adapted from Skempton, 1986).

Factor	Equipment variables	Value
η_b	65–115 mm (2.5–4.5 in)	1.0
	150 mm (6 in)	1.05
	200 mm (8 in)	1.15
η_s	Standard sampler	1.0
	with liner for dense sand and clay	0.8
	with liner for loose sand	0.9
η_r	<4 m (<13 ft)	0.75
	4–6 m (13–20 ft)	0.85
	6–10 m (20–30 ft)	0.95
	>10 m (>30 ft)	1.0

Overburden Pressure

In granular soils, the overburden pressure affects the penetration resistance. If the two soils having same relative density but different confining pressures are tested, the one with a higher confining pressure gives a higher penetration number. As the confining pressure in cohesionless soils increases with the depth, the penetration number for soils at shallow depths is underestimated and that at greater depths is overestimated. For uniformity, the N-values obtained from field tests under different effective overburden pressures are corrected to a standard effective overburden pressure.

The effective overburden pressure factor C_N, may be determined from different empirical relationships, such as:

Liao and Whitman (1986):

$$C_N = \sqrt{\frac{100}{\sigma'_o}}$$

Skempton (1986):

$$C_N = \frac{200}{100 + \sigma'_o} \qquad for\ normally\ consolidated\ fine\ or\ medium\ sand$$

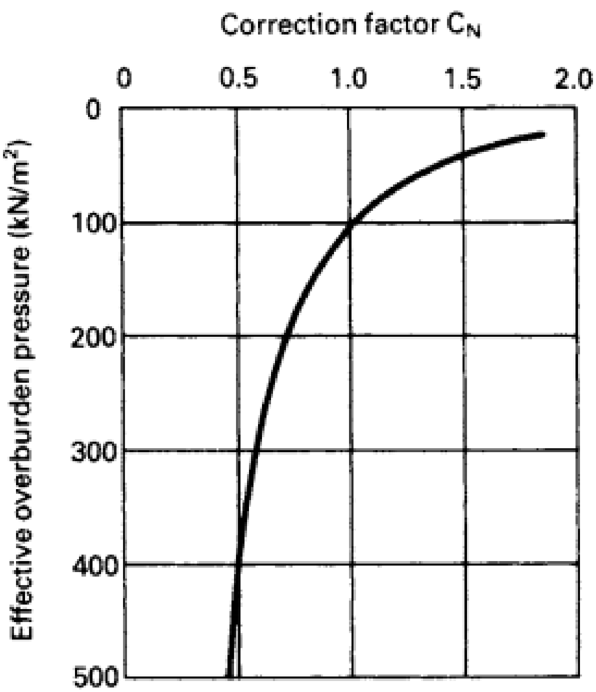
$$C_N = \frac{300}{200 + \sigma'_o} \qquad for\ normally\ consolidated\ coarse\ sand$$

$$C_N = \frac{170}{70 + \sigma'_o} \qquad for\ over\ consolidated\ sand$$

where σ'_o is the effective overburden pressure in kPa.

Seed et al (1975):

$$C_N = 1 - 1.25\ \log\left(\frac{\sigma'_o}{100}\right)$$



Authors	Proposed correction factor
Bazaraa (1967)	$C_N = \dfrac{4}{1+4\left(\dfrac{\sigma'_{vo}}{p_a}\right)}$ for $\dfrac{\sigma'_{vo}}{p_a} \leq 0.75$ $C_N = \dfrac{4}{3.25+\left(\dfrac{\sigma'_{vo}}{p_a}\right)}$ for $\dfrac{\sigma'_{vo}}{p_a} > 0.75$
Peck et al. (1974)	$C_N = 0.77\log\left(\dfrac{20}{\sigma'_{vo}/p_a}\right)$ for $\dfrac{\sigma'_{vo}}{p_a} \geq 0.25$
Seed et al. (1975)	$C_N = 1 - 1.25\log\left(\dfrac{20}{\sigma'_{vo}/p_a}\right)$
Skempton (1986)	$C_N = \dfrac{2}{1+\left(\dfrac{\sigma'_{vo}}{p_a}\right)}$ for normally consolidated fine sand $C_N = \dfrac{3}{2+\left(\dfrac{\sigma'_{vo}}{p_a}\right)}$ for normally consolidated coarse sand $C_N = \dfrac{1.7}{0.7+\left(\dfrac{\sigma'_{vo}}{p_a}\right)}$ for overconsolidated sand
Liao and Whitman (1986)	$C_N = \sqrt{\dfrac{p_a}{\sigma'_{vo}}}$

Overburden Correction Factor C_N

iii. Pore Water Pressure

When testing below the groundwater table, care must be taken to avoid entry of water through the bottom of the borehole as this would tend to loosen the sand due to upward seepage pressure. When the test is carried out in fine sand or silty sand below the water table the measured N value, if greater than 15, should be corrected for the increased resistance due to negative excess pore water pressure set up during driving and unable to dissipate immediately. Terzaghi and Peck (1967) have recommended the following additional correction where the soil is fine sand or silty sand below the water table:

$$N'_{\text{field}} = 15 + \frac{1}{2}(N_{\text{field}} - 15) \qquad \text{for } N_{\text{field}} > 15$$

Note: This correction is applied first and then the overburden and other corrections are applied.

Peck et al. proposed that linear interpolation should be used between a reduction of 50% if the water table is at ground level and zero reduction if the water table is at depth B below the foundation. The correction factor C_w, is:

$$C_w = 0.5 + 0.5\frac{D_w}{D + B}$$

where D_w is the depth of the water table below the surface, D the depth of placement of the foundation and B is the width of the foundation. Hence, the corrected SPT N-value is:

$$(N_1)_{60} = N\, C_E\, C_N\, C_w$$

Where $(N_1)_{60}$ is the penetration resistance, under a vertical stress of 100 kPa, corrected for rod energy, for overburden pressure and pore water pressure.

The design N_{60} is the average of all N_{60} values of SPT conducted at the depth intervals encountered within the influence zone. For example, for a spread footing the zone of interest is from about one-half footing width B above the estimated foundation level to a depth of about 2B below that level. For shallow foundations, weighted average using depth increment × N may be preferable to an ordinary arithmetic average; that is,

$$N_{average} = \sum(N \times z_i)/\sum z_i \text{ and not } \sum N_i/i.$$

For deep foundations, the simple ordinary average may be adequate unless the stratum is very thick. In case of thick stratum, it may be better to subdivide the stratum into several strata and average the N values for each subdivision (Bowles, 2001).

SPT Interpretation

Numerous empirical correlations have been developed to estimate geotechnical parameters from the SPT N-value for a wide range of soil and weak rock.

1- The classification of soil is:

Sand	$(N_1)_{60}$	0–3	Very loose
		3–8	Loose
		8–25	Medium
		25–42	Dense
		42–58	Very dense
Clay	$(N)_{60}$	0–4	Very soft
		4–8	Soft
		8–15	Firm
		15–30	Stiff
		30–60	Very stiff
		>60	Hard
Residual soils*	$(N)_{60}$	0–5	Completely weathered
		5–10	Very weathered (lateritic)
		10–15	Weathered
		>15	Moderately weathered (saprolitic)
Weak rock	$(N)_{60}$	0–80	Very weak
		80–200	Weak
		>200	Moderately weak to very strong

2- The angle of internal friction is:

$$\emptyset' = (15.4(N_1)_{60})^{0.5} + 20°$$

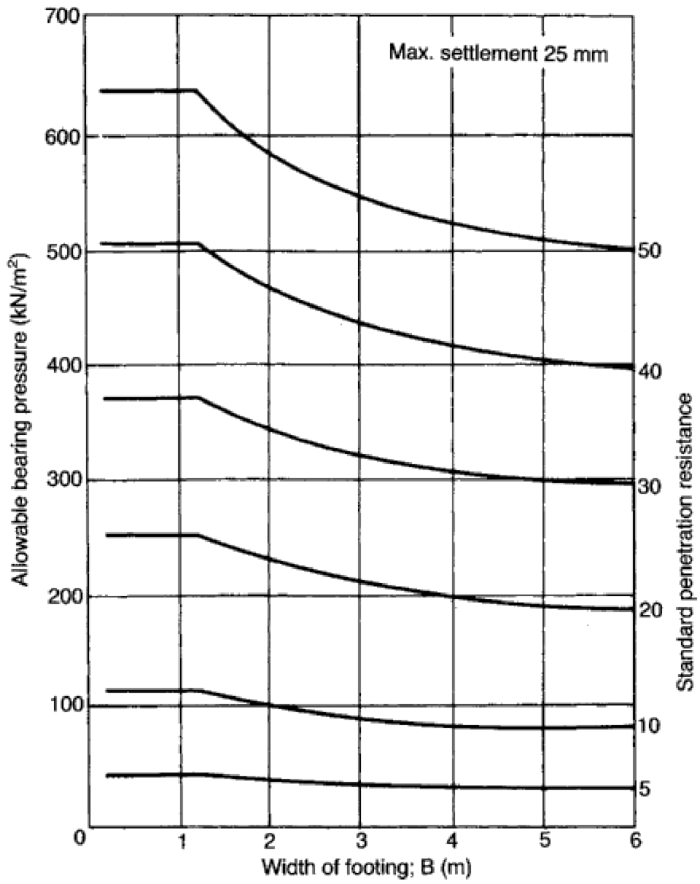
3- The coefficient of volume compressibility (m_v)is:

$$m_v = 400N \quad (m^2/MN)$$

4- The bearing capacity of soil is:

$$q_s = 0.31\, N_{60}\, \rho \left(\frac{B+0.3}{B}\right)^2$$

q_s =allowable bearing capacity, in (kPa);
B = width of foundation, in (m);
N_{60} = corrected SPT value (N-value);
ρ = allowable settlement, in (mm).



For cohesionless soils, the SPT number can be correlated with the relative density Dr and effective angle of shearing resistance Ø . Some of the published empirical relationships are:

Marcuson and Bieganousky (1977):

$$D_r\% = 11.7 + 0.76\left(222N_{60} + 1600 - 53\,\sigma'_o - 50\,C_u^2\right)^{½}$$

Kulhawy and Mayne (1990):

$$D_r\% = 12.2 + 0.75\left(222N_{60} + 2311 - 711OCR - \frac{779\sigma'_o}{P_a} - 50\,C_u^2\right)^{½}$$

Cubrinovisky and Ishihara (1999):

$$D_r\% = \left[\frac{N_{60}\left(0.23+\frac{0.06}{D_{50}}\right)^{1.7}}{9}\left(\frac{1}{\frac{\sigma'_o}{P_a}}\right)\right]^{½}$$

Kulhawy and Mayne (1990):

$$D_r = \sqrt{\frac{N'_{60}}{C_P C_A C_{OCR}}} \times 100$$

Where:

$C_p = 60 + 25 \log D_{50}$ = Grain size correction factor

$C_A = 1.2 + 0.05 \log\left(\frac{t}{100}\right)$ = Aging correction factor

t = age of soil in year (time since deposition)

$C_{OCR} = (OCR)^{0.18}$ = Overconsolidation correction factor

N'_{60} = corrected SPT N – value

σ'_o = effective overburden pressure, kN/m^2

P_a = atmospheric pressure ($\approx 100\ kPa$)

D_{50} = sieve size through which 50 % of the soil will pass (mm)

C_u = uniformity coefficient of the sand

$$OCR = \text{overconsolidation ratio} = \frac{\text{preconsolidation pressure, } \sigma'_C}{\text{effective overburden pressur, } \sigma'_O}$$

Table 3 gives approximate relation between Dr, N $_{60}$, Ø, unit weight γ and denseness description for cohesionless soils.

Table 3: Correlation for Dr, N_{60}, Ø , γ, soil denseness.

N'_{60}	D_r %	Ø′	γ, kN/m³	Denseness
0–5	5–15	25–32°	11–16	Very loose
5–10	15–30	27–35°	14–18	Loose
10–30	30–60	30–40°	17–20	Medium
30–50	60–85	35–45°	17–22	Dense
> 50	> 85	> 45°	20–23	Very dense

Peck et al. (1974) gives a correlation between N60 and Ø in a graphical form which can be approximated (Wolff, 1989) as:

$$Ø' = 27.1 + 0.3N'_{60} - 0.00054\left(N'_{60}\right)^2$$

Kulhawy and *Mayne* (1990):

$$Ø' = \tan^{-1}\left[\frac{N_{60}}{12.2 + 20.3\left(\frac{\sigma'_O}{P_a}\right)}\right]^{0.34}$$

Hatanac and *Ushida* (1996):

$$Ø' = \sqrt{20N'_{60}} + 20$$

The SPT number N60 is correlated to the modulus of elasticity (Es) of sands as follows: Kulhawy and Mayne (1990):

$$\frac{E_s}{P_a} = \alpha N_{60}$$

Where: Pa = atmospheric pressure (same unit as Es) α = 5, 10 and 15 for sands with fines, clean normally consolidated sand, and clean overconsolidated sand, respectively.

The SPT number is also correlated to unconfined compression strength q_u and undrained shear strength s_u of fine-grained soils as given in Table 4 and the following equations. It is important to point out that the obtained values of q_u and s_u should be used as a guide only; local cohesive soil samples should be tested to verify that the given relationships or correlations are valid.

N'_{60}	Consistency	q_u, kN/m^2
0–2	Very soft	0–25
2–5	Soft	25–50
5–10	Medium stiff	50–100
10–20	Stiff	100–200
20–30	Very stiff	200–400
> 30	Hard	> 400

Stroud and Butler (1975):

$s_u = kN_{60}$ for insensitive overconsolidated clay

where k=4.5 kPa for PI >30
k=4– 6 kPa f or PI =30 -15

Hara et al (1971):

$$c_u = 29(N_{60})^{0.72},\ \text{kPa}$$

Mayne and Kemper (1988):

$$OCR = 0.193\left(\frac{N_{60}}{\sigma'_O}\right)^{0.689}$$

where σ'_O = effective overburden pressure in MN/m^2

Szechy and Varga (1978) gave the correlations presented in Table 5.

Table 5: Correlations for N60, CI, q_u and consistency.

N_{60}	Consistency	CI	q_u, MN/m^2
< 2	Very soft	< 0.5	< 25
2–8	Soft to medium	0.5–0.75	25–80
8–15	Stiff	0.75–1.0	80–150
15–30	Very stiff	1.0–1.5	150–400
> 30	Hard	> 1.5	> 400

Where:

$$CI = \text{consistency index} = \frac{LL-\omega}{LL-PI}$$

ω = natural moisture content
LL = liquid limit
PL = plastic limit
N_{60} = SPT N-value corrected for field procedures only

Note: As mentioned earlier, any correlation or relationship between N60, su, cu, OCR, CI and qu for cohesive soils is approximate and should be used as a guide only.

Standard penetration test induces excess pore water pressures in cohesive soils and hence reduces the effective stress near the sampler, which can underestimate the blow count and make the penetration results unreliable when used in estimating the soil parameters. In addition, there is significant reduction in the blow count with increasing sensitivity.

Terzaghi and Peck (1967) suggested the relationship among N_{60}, cu, and the consistency of the clay as shown in Table 6. The correlations suggested in Table 7 are very approximate and should be used with caution. Here, some of the correlations are based on N values at different hammer energies and hence the scatter is large.

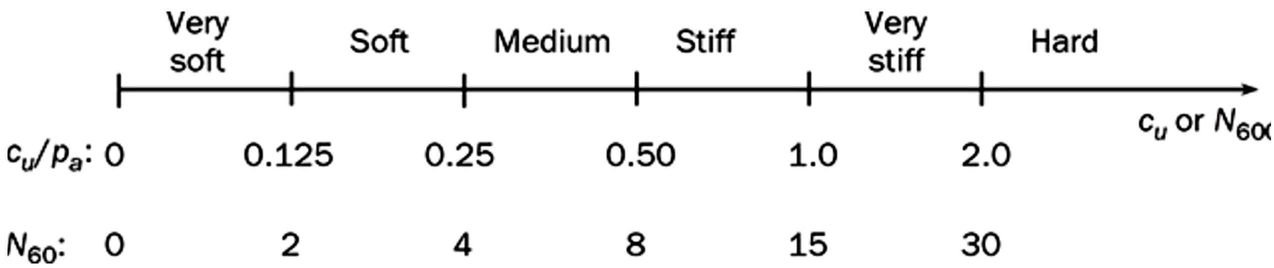


Table 6 Interrelationship among N_{60}, Cu, and consistency of clays.

Parameter	Equation	Comments
c_u	$\frac{c_u}{p_a} = \alpha N_{60}$ $\frac{c_u}{p_a} = 0.29 N_{60}^{0.72}$	Terzaghi and Peck (1967) table approximated by Kulhaway and Mayne (1990) as $\alpha = 0.06$. Values in the range 0.04–0.15 reported in the literature. Low end is more reliable. From Hara et al. (1974) for 25 clay sites in Japan—Overestimates c_u.
σ'_p	$\frac{\sigma'_p}{p_a} = 0.47 N_{60}^{m}$ $\frac{\sigma'_p}{p_a} = 0.15 N_{60}$	Mayne (2007). $m = 0.6$ for clean quartz sand, 0.8 for silty sand to sandy silt, 1.0 for intact clays and clayey silts. Kulhawy and Chen (2007)
OCR	$OCR = 0.58 N \left(\frac{p_a}{\sigma'_o}\right)$	Kulhawy and Mayne (1990). Uncorrected N.
K_0	$K_o = 0.073 N \left(\frac{p_a}{\sigma'_o}\right)$	Kulhawy and Mayne (1990). Uncorrected N.

Table 6 Some Approximate SPT Correlations for Clays

H.W. No. 2

From the following SPT data:

a) Draw the corrected and uncorrected SPT values with depth,

b) Determine the bearing capacity for shallow foundation and pile foundation, using correction values of (N_{60}).

Borehole No: BH1						Coordinate: N=	
Borehole Diameter: 15cm						Date of Drilling:	
Depth of Borehole: 15m						Method of Drilling: Aogar	
Depth (m)		Sample type	S.P.T 15 cm	S.P.T 15cm	S.P.T 15cm	Description of soil and Symbol	Time
1	0-1.5	DS	—	—	—	Clay	
2	1.5-2	SPT	4	6	6	Clay	
3	2-3	DS	—	—	—	Clay	
4	3-3.5	US	—	—	—	Clay	
5	3.5-4	SPT	3	5	6	Sand with Clay	
6	4-5.5	DS	—	—	—	Sand	
7	5.5-6	SPT	5	6	6	Sand	
8	6-7	DS	—	—	—	Sand	
9	7-7.5	SPT	7	9	10	Sand	
10	7.5-8.5	DS	—	—	—	Sand	
11	8.5-9	SPT	6	8	11	Sand	
12	9-9.5	DS	—	—	—	Sand	
13	9.5-10	SPT	9	11	13	Sand	
14	10-11	DS	—	—	—	Sand	
15	11-11.5	SPT	7	14	16	Sand	
16	11.5-13	DS	—	—	—	Sand	
17	13-13.5	SPT	10	13	17	Sand	
18	13.5-14.5	DS	—	—	—	Sand	
19	14.5-15	SPT	13	16	21	Sand	

Initial Water Table level in: 4.5m

Final Water Table level: 3.5m