CE 382

Chapter 4

Plasticity and Structure of Soil

Omitted Topic
Section 4.9

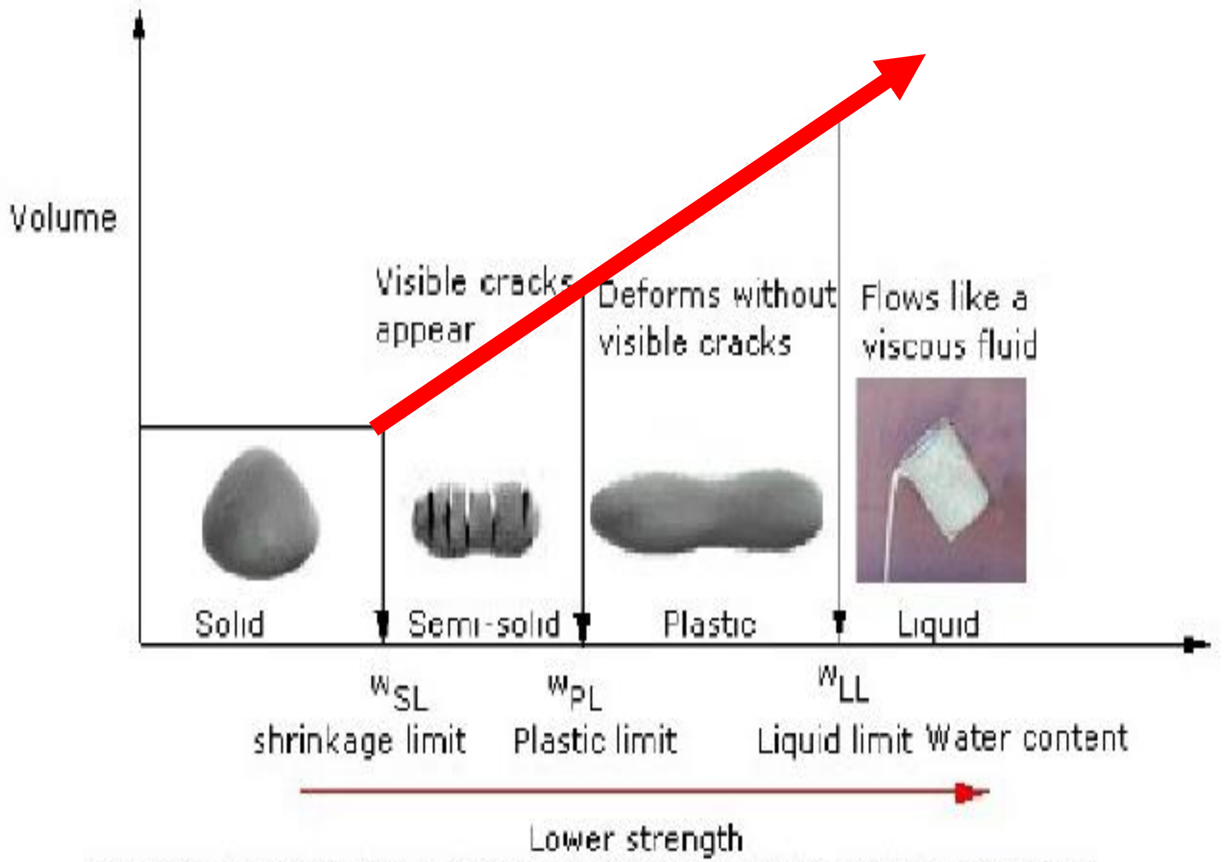
GENERAL

- The consistency of clays and other cohesive soils (fine-grained soils) is greatly influenced by the water content of the soil.

- Depending on the moisture content, the behavior of soil can be divided into four basic states:

  - Solid
  - Semisolid
  - Plastic
  - Liquid

- The water content at which a soil passes from one state to another is different for different soils and can be used in a qualitative way, to distinguish between, or classify different fine-grained soil types.



Changes in soil states as a function of soil volume and water content

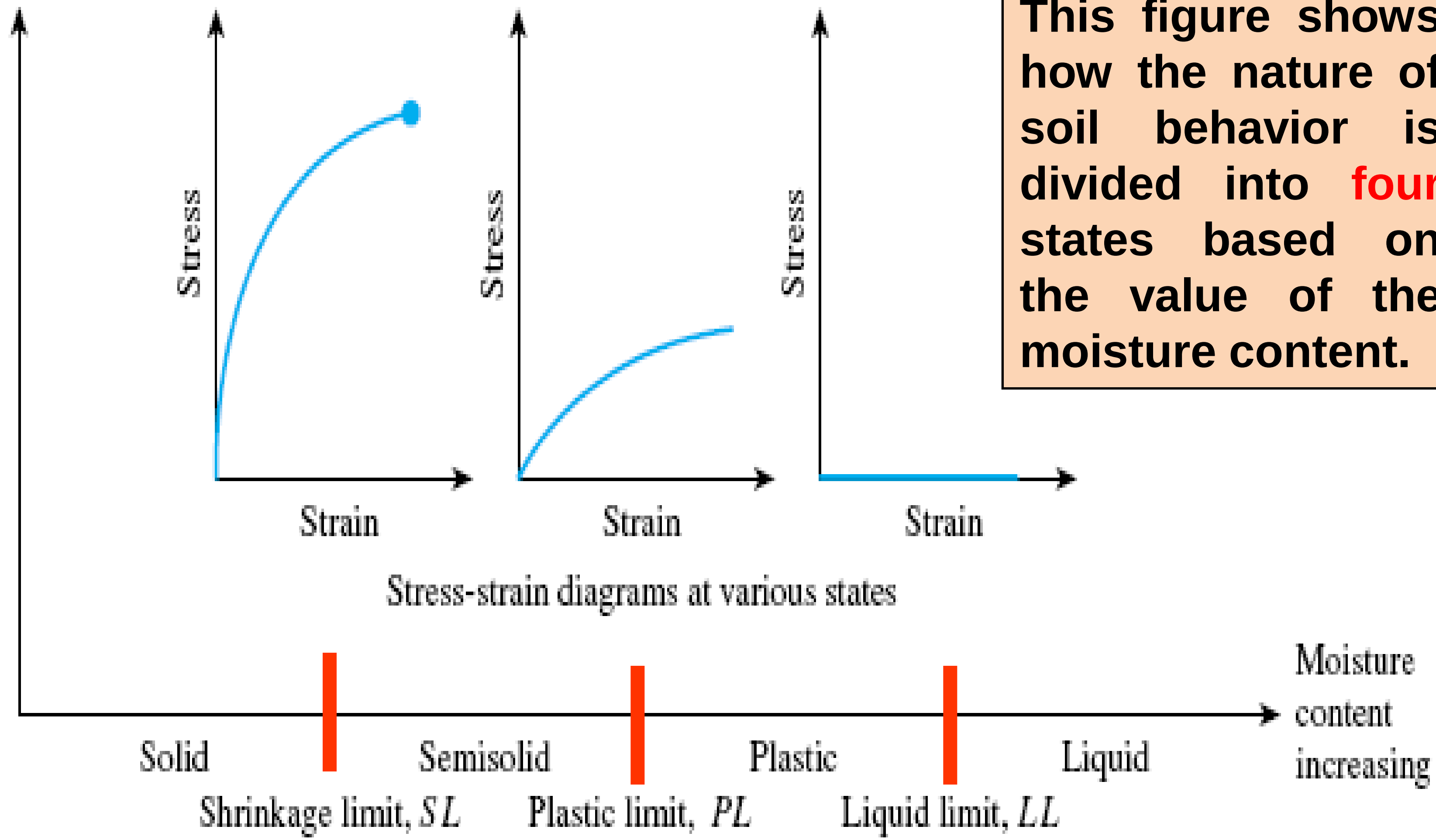


Figure 4.1 Atterberg limits

This figure shows how the nature of soil behavior is divided into **four** states based on the value of the moisture content.

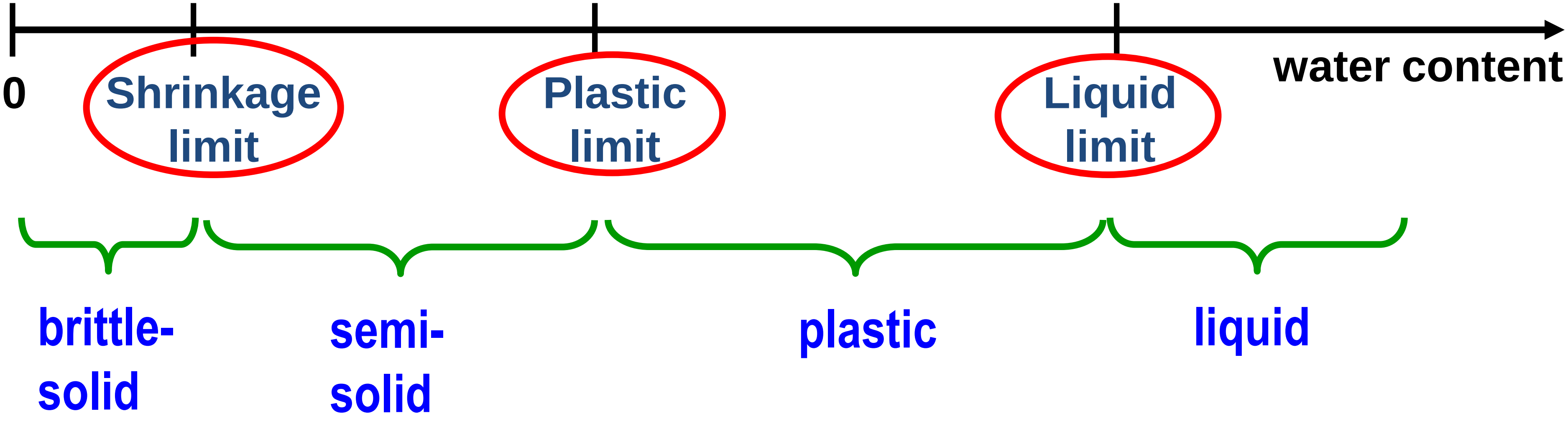
Summary

1. Water influences consistency of fine-grained soils.
2. Soils passes from one state to another state as water content changes.
3. Different soils passes from state to state at different water contents.
4. The water content at which different soils pass from one state to another state can be used to classify or distinguish different fine-grained soils.
5. How we can find the water content at which a given soil passes from a given state to another?.

Atterberg (A Swedish scientist) developed a method to describe the consistency of fine-grained soils with varying degrees of moisture content. He defined several limits of consistency which are called Atterberg limits.

Atterberg Limits

Border line **water contents**, separating the different **states** of a fine grained soil



Atterberg Limits

Liquid Limit (LL): **The moisture content, in percent, at the point of transition from plastic to liquid state**

Plastic Limit (PL): **The moisture content, in percent, at the point of transition from semisolid to plastic state**

Shrinkage Limit (SL): **The moisture content, in percent, at the point of transition from solid to semisolid state**

Atterberg Limits

There are also another two limits, but they have no significance for civil engineers:

Sticky Limit: **The water content at which a soil loses its ADHESION to a metal blade.**

Cohesion Limit: **The water content at which the grains cease to cohere to each other, e.g. at which cultivation of the soil does not result in clods or lumps forming.**

These two limits are important for the agriculturist and to earthwork contractors, and also in ceramic industry.

Importance of Atterberg limits

- If we know how the water content of our sample is relative to the Atterberg limits, then we already know a great deal about the engineering response of our sample.

- The Atterberg limits are water contents at certain limiting or critical stages in soil behavior.

- The Atterberg limits along with the natural water content, are the most important items in the description of fine-grained soils.

Uses of Atterberg Limits

The Atterberg limits are used for four general applications:

1. To obtain general information about a soil and its strength, compressibility, permeability, shrinkage, and swell properties.

2. Used in empirical correlations for some engineering properties.

3. For soil classification

4. In construction specifications

Remark

Atterberg limits are conducted on completely REMOLDED soils. They therefore do not account for the importance of the structure of the soil as related to the soil behavior. So there main usefulness is in classification of soils and only qualitatively they give some ideas about behavior.

Determination of Atterberg Limits

- Atterberg's original consistency limit tests were rather arbitrary and not easily reproducible.

- A. Casagrande subsequently standardized the apparatus and the procedures to make the measurement more repeatable .

Determination of Liquid Limit

I. Percussion cup method (ASTM D-4318)

1. **Multi-Point Method**
2. **One-Point Method**

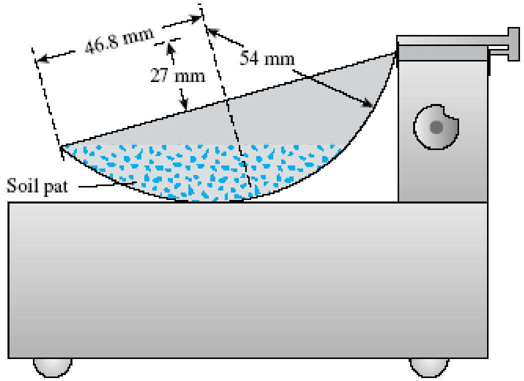
II. Fall-Cone Method (British Standard – BS1377)

Determination of Liquid Limit

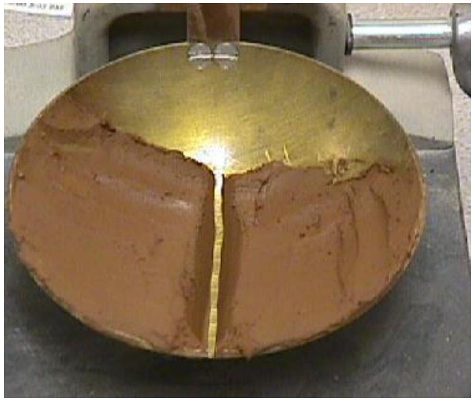
I. Percussion cup method (ASTM D-4318)

1. Multi-Point Method

The water content required to close a distance of ½ inch (12.7 mm) along the bottom of the groove after 25 blows is defined as the Liquid Limit.



(a)



Casagrande Cup

Casagrande cup method
Percussion cup method

Determination of Liquid Limit

I. Percussion cup method (ASTM D-4318)

- **It is difficult to adjust the moisture content in soil to meet the required ½ inch closure of the groove at 25 blows. Hence, at least 4 tests for the same soil are made at varying w%, and then w% values are plotted against the logarithm of the number of blows, N.**

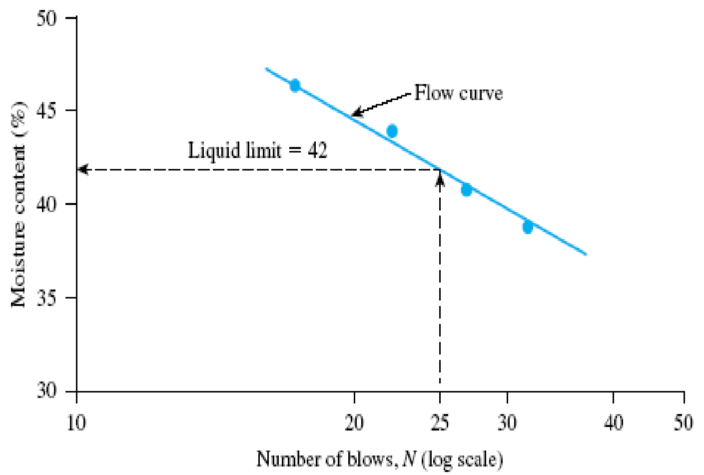


Figure 4.5 Flow curve for liquid limit determination of a clayey silt

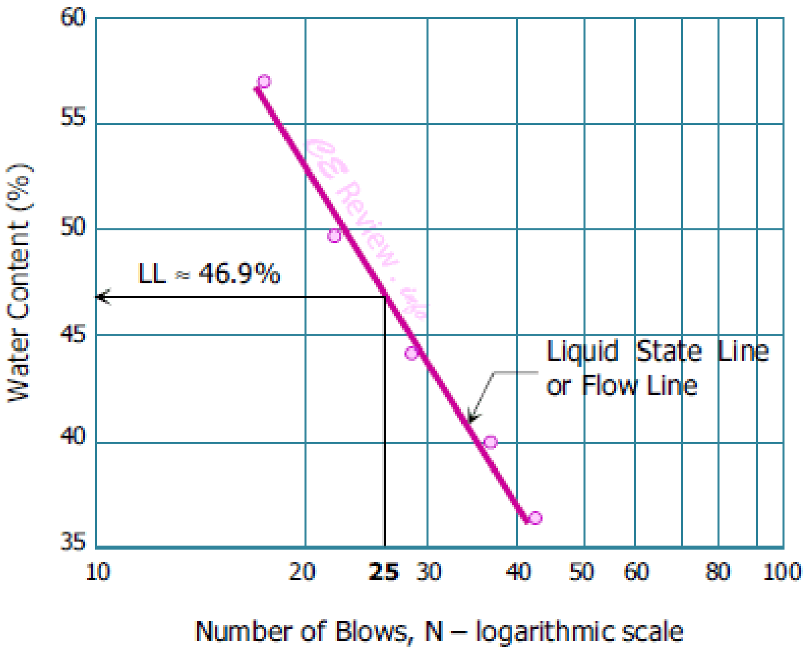


Figure 3 Typical liquid limit results from the Casagrande cup method.

Determination of Liquid Limit

Example 4.1

Following are the results of a test conducted in the laboratory. Determine the liquid limit (LL) and the flow index (I_F).

Number of blows, N	Moisture content (%)
15	42.0
20	40.8
28	39.3

Solution

The plot of w against N (log scale) is shown in Figure 4.6. For $N = 25$, $w = \mathbf{39.5\%} = \boldsymbol{LL}$.

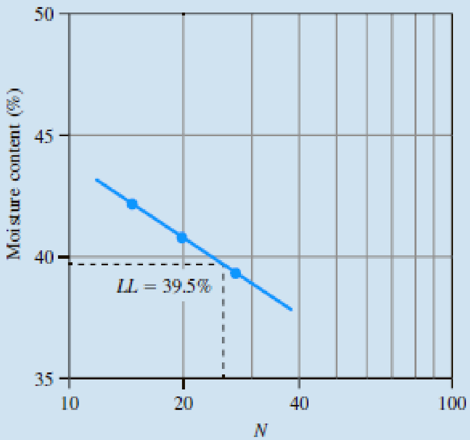


Figure 4.6

From Eq. (4.1),

$$I_F = \frac{w_1 - w_2}{\log\left(\frac{N_2}{N_1}\right)} = \frac{42 - 39.3}{\log\left(\frac{28}{15}\right)} = \mathbf{9.96}$$

Determination of Liquid Limit

2. One-Point Method (ASTM D-4318)

- **Proposed by the USACE in 1949 based on the analysis of hundreds of liquid limit tests.**

$$LL = w_N \left(\frac{N}{25}\right)^{\tan\beta}$$

$$\tan\beta = 0.121$$

w_N = moisture content of the soil which closed in N blows (N should be between 10 and 40).
N = number of blows required to close the standard groove for a distance of ½ inch (12.7mm)

- **This formula generally yields good results for the number of blows between 20 and 30.**

Determination of Liquid Limit

II. Fall-Cone Method (British Standard – BS1377)

- **This method is popular in Europe and Asia.**
- **The cone is released for 5 seconds so that it may penetrate the soil.**
- **The liquid limit is defined as the water content of the soil which allows the cone to penetrate exactly 20 mm during that period of time.**

Figure 4.8 Fall cone apparatus (*Courtesy of N. Sivakugan, James Cook University, Australia*)

Determination of Liquid Limit

II. Fall-Cone Method (British Standard – BS1377)

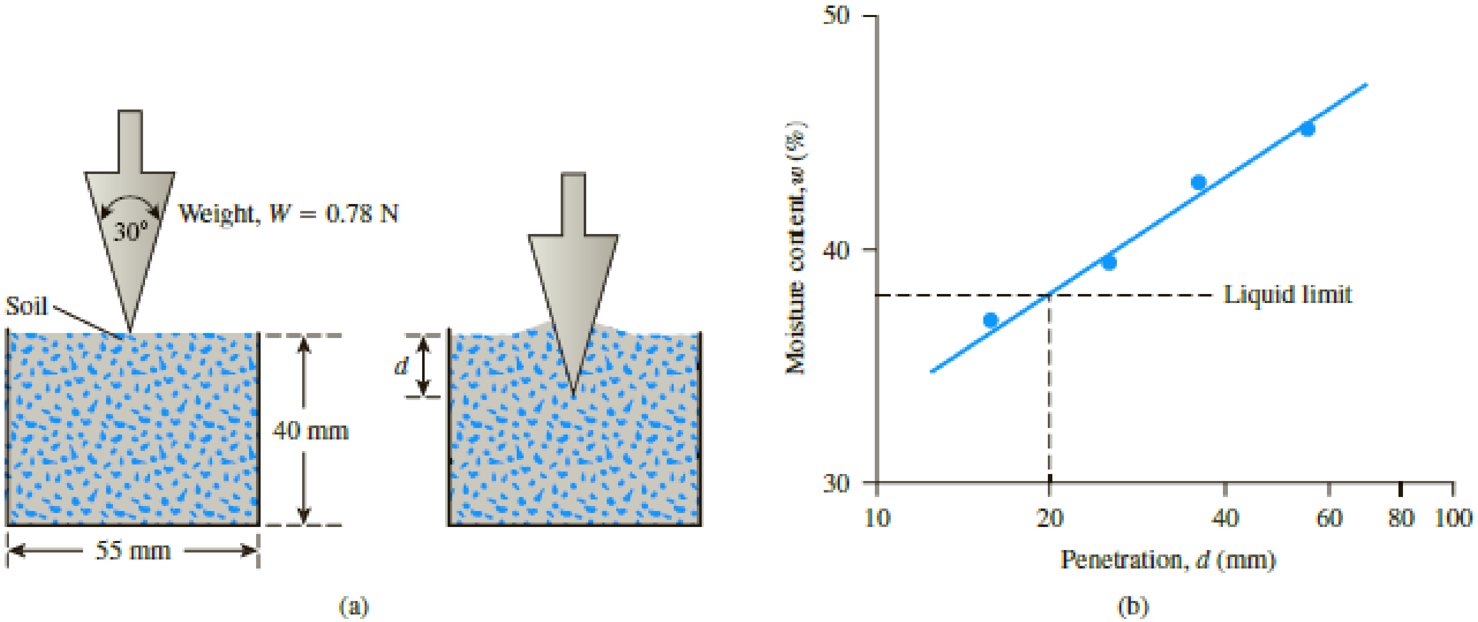


Figure 4.7 (a) Fall cone test (b) plot of moisture content vs. cone penetration for determination of liquid limit

Determination of Liquid Limit

Example 4.3

Following are the results of a liquid limit test using a fall cone. Estimate the liquid limit.

Cone penetration, *d* (mm)	Moisture content (%)
15	29.5
26	35.5
34	38.5
43	41.5

Solution

Figure 4.9 shows the moisture content versus *d* (mm). From this plot, the moisture content can be determined to be **32.5**.

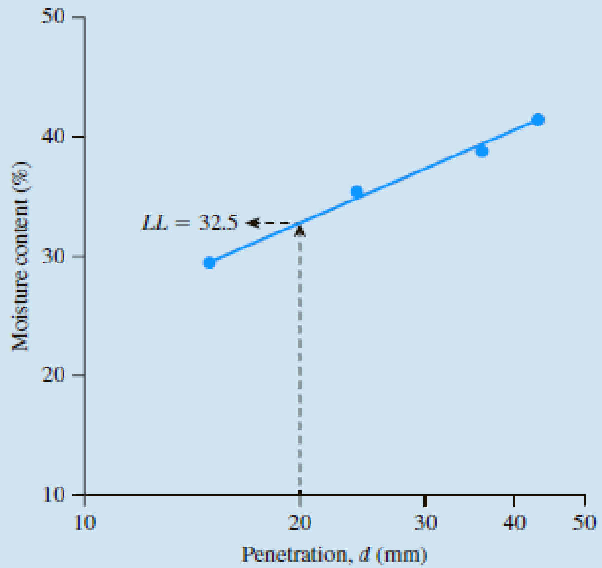


Figure 4.9

Determination of Liquid Limit

II. Fall-Cone Method (British Standard – BS1377)

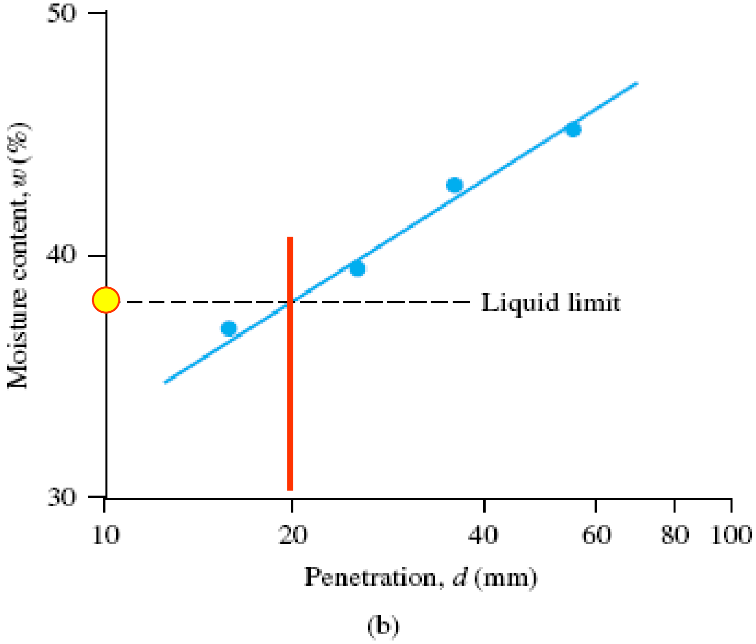
$$LL = \frac{w}{0.77 \log d}$$

$$LL = \frac{w}{0.65 + 0.0175d}$$

$$LL = w\left(\frac{20}{d}\right)^{0.33}$$

Determination of Liquid Limit

Fall-Cone Method (British Standard – BS1377)



Casagrande Cup Method (ASTM D-4318)

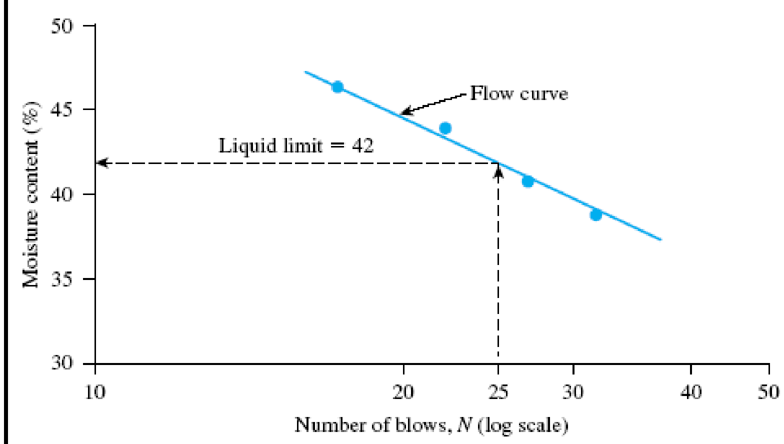


Figure 4.5
Flow curve for liquid limit determination of a clayey silt

REMARKS

Table 4.2 Summary of Main Differences among Fall Cones (Summarized from Budhu, 1985)

Country	Cone details	Penetration for liquid limit (mm)
Russia	Cone angle = 30° Cone mass = 76 g	10
Britian, France	Cone angle = 30° Cone mass = 80 g	20
India	Cone angle = 31° Cone mass = 148 g	20.4
Sweden, Canada (Quebec)	Cone angle = 60° Cone mass = 60 g	10

Note: Duration of penetration is 5 s in all cases.

$$LL_{(BS)} = 2.6 + 0.94[LL_{(ASTM)}]$$

Cone

Cup

REMARKS

- The liquid limit of a soil containing substantial amounts of organic matter decreases dramatically when the soil is oven-dried before testing. Comparison of the liquid limit of a sample before and after oven-drying can therefore be used as a qualitative measure of organic matter content of a soil.

- The multipoint liquid limit method is generally more precise than the one-point method. It is recommended that the multipoint method be used in cases where test results may be subject to dispute, or where greater precision is required .

- The correlation on which the calculations of the one-point method are based may not be valid for certain soils, such as organic soils or soils from a marine environment. It is strongly recommended that the liquid limit of these soils be determined by the multipoint method .

Determination of Plastic Limit

1. Rolling into Thread Method (ASTM D-4318)

The plastic limit is defined as the moisture content in percent, at which the soil crumbles, when rolled into threads of 3.18 mm (1/8 in.) in diameter.

Determination of Plastic Limit

2. Fall-Cone Method

Similar to Liquid Limit test only the weight of the cone is 2.35 N (240 grams) instead of 0.78 N (80 grams). (three times heavier).

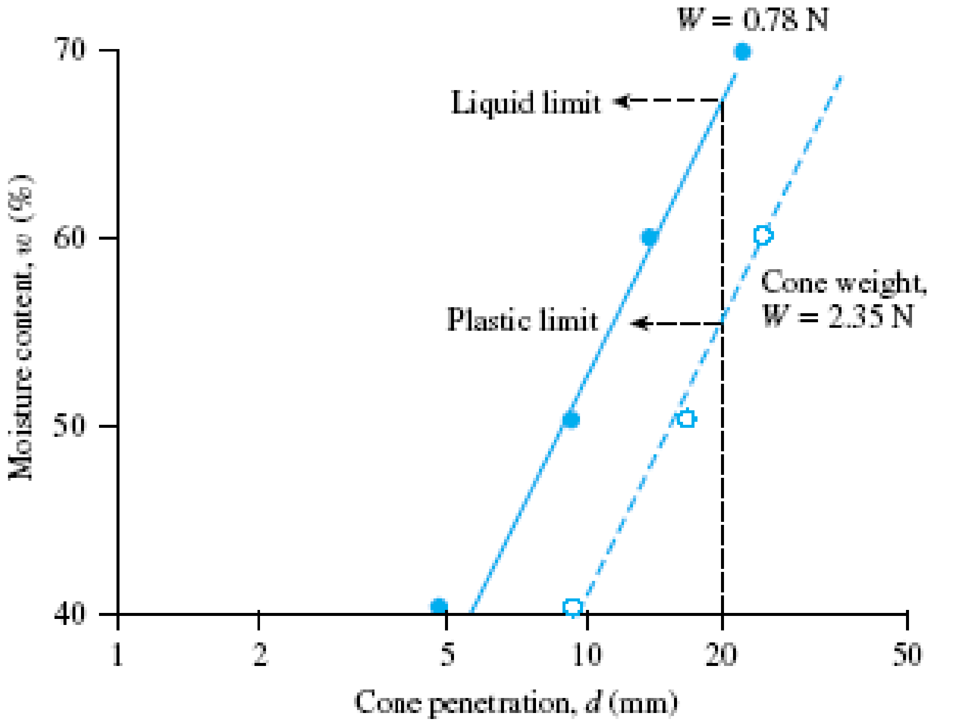


Figure 4.8
Liquid and plastic limits for Cambridge Gault clay determined by fall cone test

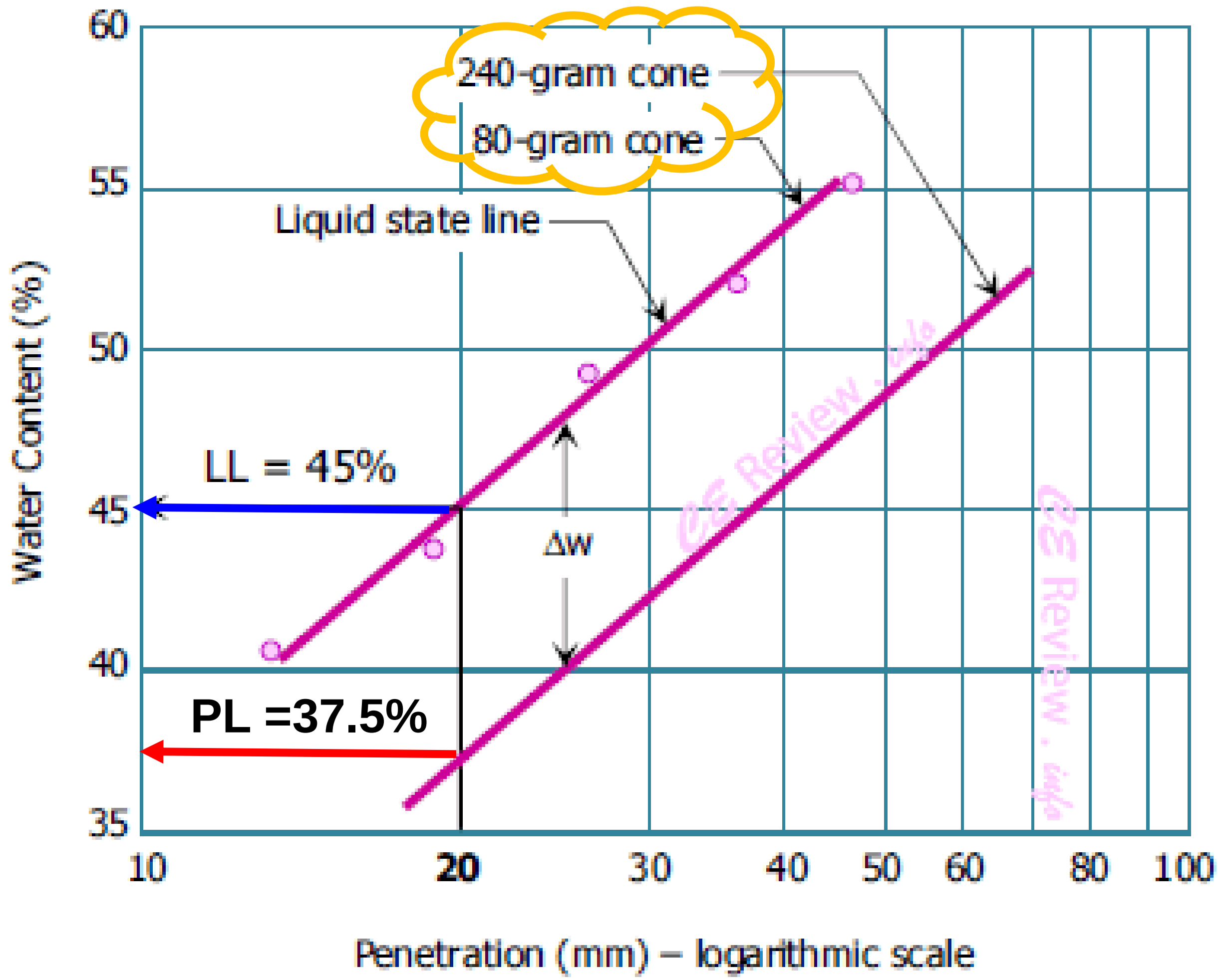


Figure 4 Typical test results from the fall cone apparatus.

Determination of Shrinkage Limit

- Soil shrinks as moisture is gradually lost from it. With continuing loss of moisture, a stage of equilibrium is reached at which more loss of moisture will result in no further volume change.
- The shrinkage limit is defined as the moisture content, in percent, at which the volume of the soil mass ceases to change.

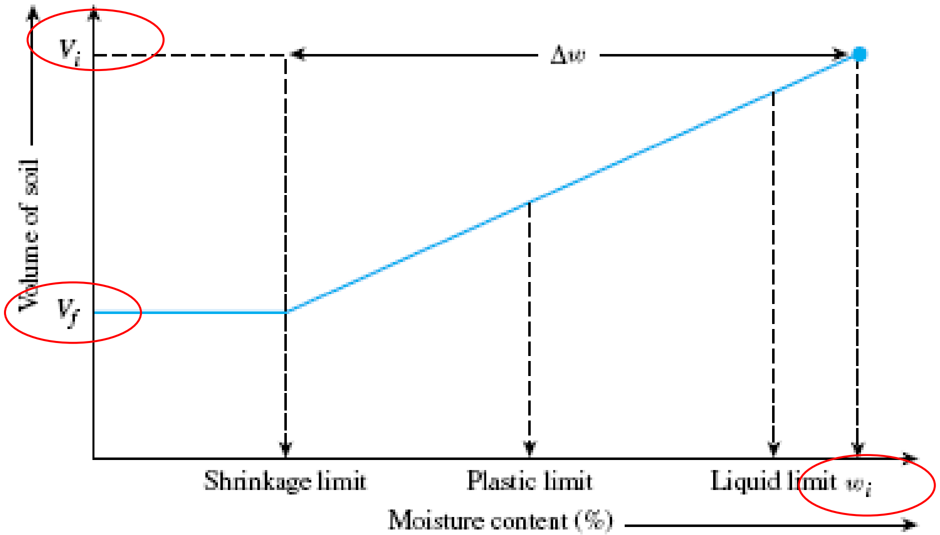


Figure 4.9 Definition of shrinkage limit

$$SL = w_i\,(\%) - \Delta w\,(\%) \tag{4.12}$$

where w_i = initial moisture content when the soil is placed in the shrinkage limit dish
Δw = change in moisture content (that is, between the initial moisture content and the moisture content at the shrinkage limit)

Determination of Shrinkage Limit

$$w_i\,(\%) = \frac{M_1 - M_2}{M_2} \times 100 \qquad (4.13)$$

where M_1 = mass of the wet soil pat in the dish at the beginning of the test (g)
M_2 = mass of the dry soil pat (g) (see Figure 4.14)

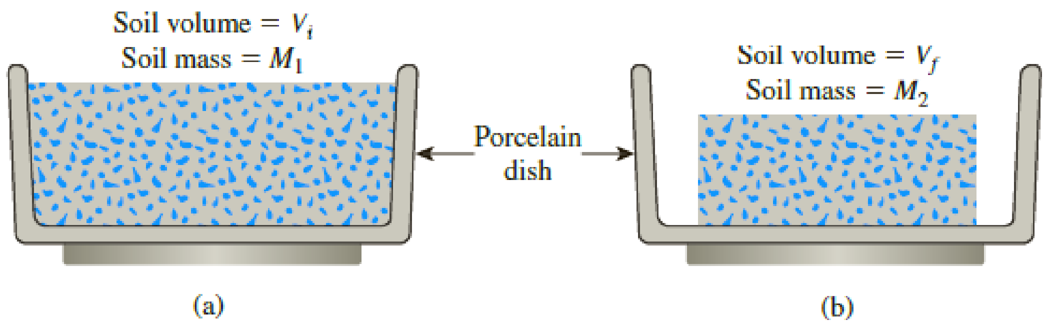


Figure 4.14 Shrinkage limit test: (a) soil pat before drying; (b) soil pat after drying

Determination of Shrinkage Limit

$$\Delta w\,(\%) = \frac{(V_i - V_f)\rho_w}{M_2} \times 100 \qquad (4.14)$$

where V_i = initial volume of the wet soil pat (that is, inside volume of the dish, cm^3)
V_f = volume of the oven-dried soil pat (cm^3)
ρ_w = density of water (g/cm^3)

Finally, combining Eqs. (4.12), (4.13), and (4.14) gives

$$SL = \left(\frac{M_1 - M_2}{M_2}\right)(100) - \left(\frac{V_i - V_f}{M_2}\right)(\rho_w)\,(100) \qquad (4.15)$$

ASTM (2014) Test Designation D-4943 describes a method where volume V_i is determined by filling the shrinkage limit dish with water, or

$$V_i = \frac{\text{Mass of water to fill the dish (g)}}{\rho_w\ (g/cm^3)} \qquad (4.16)$$

In order to determine V_f, the dry soil pat is dipped in a molten pot of wax and cooled. The mass of the dry soil and wax is determined in air and in submerged water. Thus

$$M_5 = M_3 \quad M_4 \qquad (4.17)$$

where M_3 = mass of dry soil pat and wax in air (g)
M_4 = mass of dry soil pat and wax in water (g)
M_5 = mass of water displaced by dry soil pat and wax (g)

The volume of the dry soil pat and wax can be calculated as

$$V_{fwx}\,(cm^3) = \frac{M_5\,(g)}{\rho_w\ (g/cm^3)} \qquad (4.18)$$

The mass of wax (M_6) coating the dry soil pat is then obtained as

$$M_6\,(g) = M_3\,(g) - M_2\,(g) \qquad (4.19)$$

Determination of Shrinkage Limit

Thus the volume of wax coating (V_{wx}) is

$$V_{wx}\,(\text{cm}^3) = \frac{M_6\,(\text{g})}{G_{wx}\,\rho_w\,(\text{g/cm}^3)} \tag{4.20}$$

where G_{wx} = specific gravity of wax

Finally, the volume of the dry soil pat (V_f) can be obtained as

$$V_f\,(\text{cm}^3) = V_{fwx} - V_{wx} \tag{4.21}$$

Equations (4.16) and (4.21) can be substituted into Eq. (4.15) to obtain the shrinkage limit.

Mineral	Shrinkage limit
Montmorillonite	8.5–15
Illite	15–17
Kaolinite	25–29

Shrinkage limit is more relevant to the study of unsaturated soil mechanics.

Shrinkage Limit

Example 4.5

Following are the results of a shrinkage limit test:

- Initial volume of soil in a saturated state = 24.6 cm^3
- Final volume of soil in a dry state = 15.9 cm^3
- Initial mass in a saturated state = 44.0 g
- Final mass in a dry state = 30.1 g

Determine the shrinkage limit of the soil.

Solution

From Eq. (4.15),

$$SL = \left(\frac{M_1 - M_2}{M_2}\right)(100) - \left(\frac{V_i - V_f}{M_2}\right)(\rho_w)(100)$$

$$M_1 = 44.0 \text{ g} \qquad V_i = 24.6 \text{ cm}^3 \qquad \rho_w = 1 \text{ g/cm}^3$$

$$M_2 = 30.1 \text{ g} \qquad V_f = 15.9 \text{ cm}^3$$

$$SL = \left(\frac{44.0 - 30.1}{30.1}\right)(100) - \left(\frac{24.6 - 15.9}{30.1}\right)(1)(100)$$

$$= 46.18 - 28.9 = \mathbf{17.28\%}$$

Shrinkage Limit

Shrinkage Ratio

- Another parameter that can be determined from a shrinkage limit test is the *shrinkage ratio*, which is the ratio of the volume change of soil as a percentage of the dry volume to the corresponding change in moisture content, or

$$SR = \frac{\left(\frac{\Delta V}{V_f}\right)}{\left(\frac{\Delta M}{M_2}\right)} = \frac{\left(\frac{\Delta V}{V_f}\right)}{\left(\frac{\Delta V \rho_w}{M_2}\right)} = \frac{M_2}{V_f \rho_w}$$

Acceleration of gravity

$$\mathrm{SR} = \frac{M_2 g}{V_2 \gamma_w}$$

- It can also be shown that

$$G_s = \frac{1}{\frac{1}{SR} - \left(\frac{SL}{100}\right)}$$

Shrinkage Limit

Volumetric Shrinkage

- The maximum expected volumetric shrinkage, **VS** at given moisture contents (*w*) can be calculated as

$$VS\ (\%) = SR[w(\%) - SL]$$

Linear Shrinkage

- The maximum expected linear shrinkage, ***LS*** at given moisture contents (*w*) can be calculated as

$$LS\ (\%) = 100\left[1 - \left(\frac{100}{VS(\%) + 100}\right)^{\frac{1}{3}}\right]$$

INDICES OF SOIL CONSISTENCY

Various indices have been developed using Atterberg limits.

1. Plasticity Index (PI)

$$PI = LL - PL$$

- **This index provides a measure of a soil plasticity, which is the amount of water that must be added to change a soil from its plastic limit to its liquid limit.**

- **The PI is useful in engineering classification of fine-grained soils, and many engineering properties have been found to correlate with the PI.**

- **The plasticity index, in conjunction with the mechanical analysis, provides the basis for several of the engineering classification of soils.**

INDICES OF SOIL CONSISTENCY

1. Plasticity Index (PI)

Table 4.1 Typical Values of Liquid Limit, Plastic Limit, and Activity of Some Clay Minerals

Mineral	Liquid limit, *LL*	Plastic limit, *PL*	Activity, *A*
Kaolinite	35–100	20–40	0.3–0.5
Illite	60–120	35–60	0.5–1.2
Montmorillonite	100–900	50–100	1.5–7.0

PI	Description
0	Nonplastic
1–5	Slightly plastic
5–10	Low plasticity
10–20	Medium plasticity
20–40	High plasticity
>40	Very high plasticity

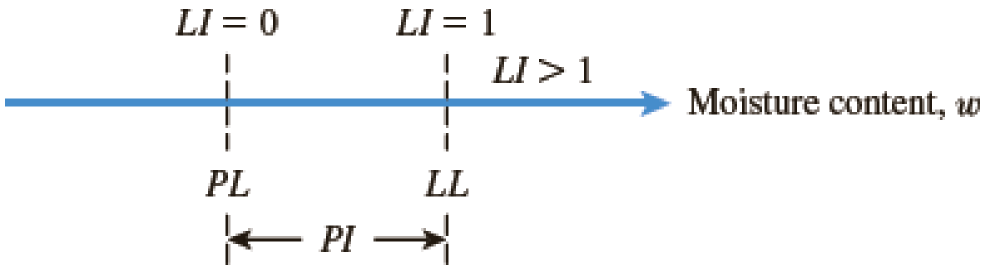
INDICES OF SOIL CONSISTENCY

2. Liquidity Index (LI)

- The relative consistency of a cohesive soil in the natural state can be defined by a ratio called the Liquidity Index, which is given by

$$LI = \frac{w - PL}{LL - PL}$$

- This index provides a clue as the condition of the in situ soil. This index helps us to know if our sample was likely to behave as a plastic, a brittle, or a liquid.



- If LI< 0 Brittle behavior (desiccated (dried) hard soil)
- If 0 <LI <1 The soil behave like a plastic
- If LI>1 The soil is a very viscous liquid.

INDICES OF SOIL CONSISTENCY

3. Consistency Index

Another index that is commonly used for engineering purposes is the consistency index (CI)

$$CI = \frac{LL - w}{LL - PL}$$

4. Flow Index

This index is the slope of the flow curve. A low number (flat slope) indicates that a small change in moisture content is likely to produce a significant change in the soil CONSISTENCY.

From Percussion Cup Method

$$I_F = \frac{w_1 - w_2}{\log\left(\frac{N_2}{N_1}\right)}$$

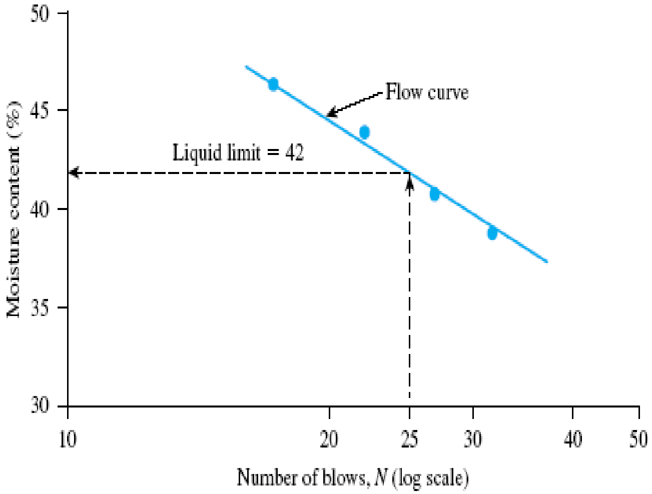


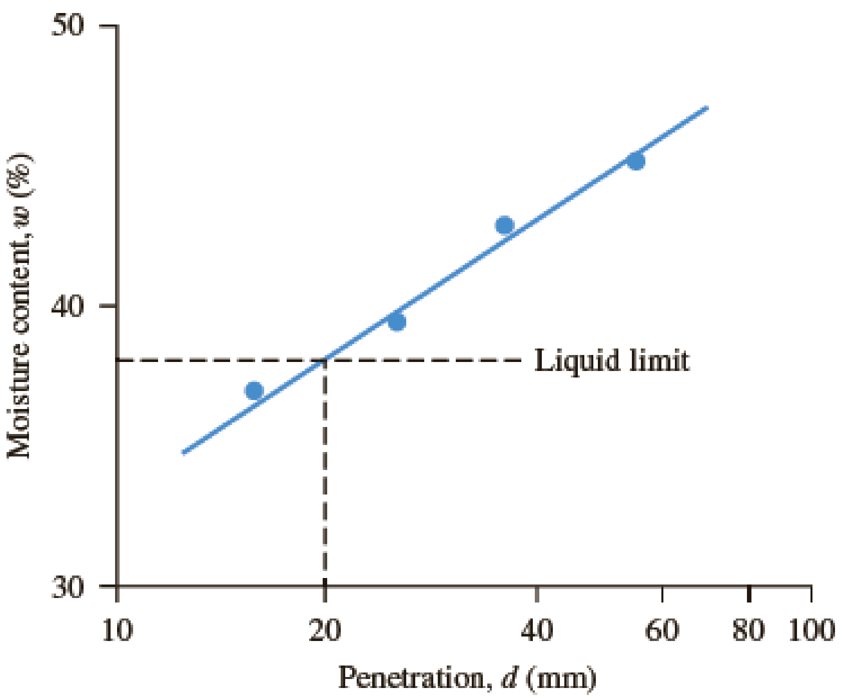
Figure 4.5 Flow curve for liquid limit determination of a clayey silt

INDICES OF SOIL CONSISTENCY

4. Flow Index

From Fall Cone Method

$$I_{FC} = \frac{w_2\,(\%) - w_1\,(\%)}{\log d_2 - \log d_1}$$



INDICES OF SOIL CONSISTENCY

5. Activity

- The presence of even small amounts of certain clay minerals in a soil mass can have a significant effect on the properties of the soil.

- Identifying the type and amount of clay minerals may be necessary in order to predict the soil's behavior or to develop methods for minimizing detrimental effects.

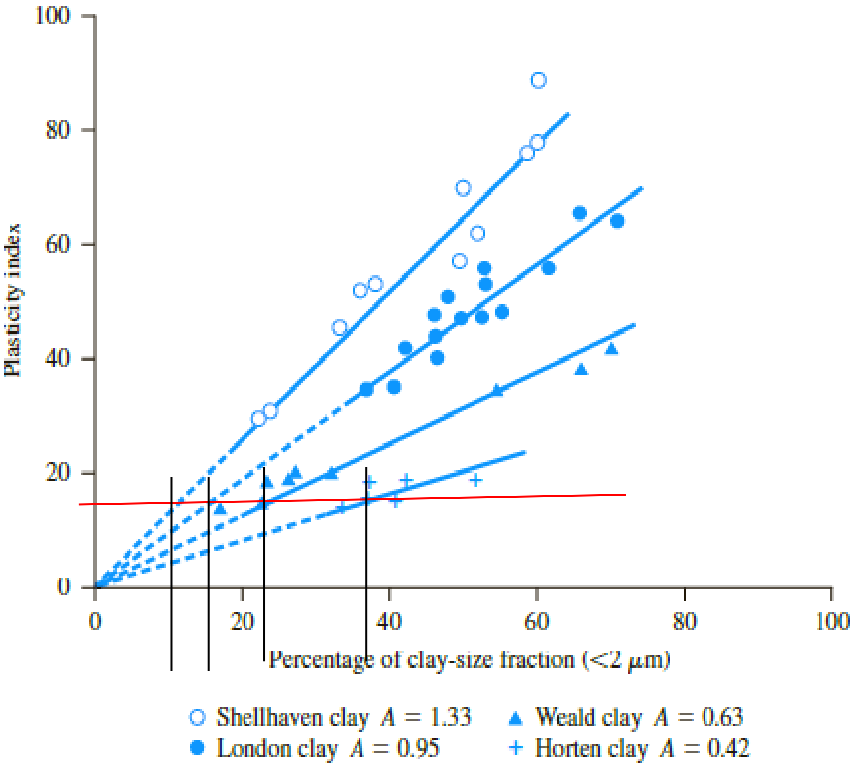
- An indirect method of obtaining information on the type and effect of clay minerals in a soil is to relate plasticity to the quantity of clay–sized particles.

- It is known that for a given amount of clay mineral, the plasticity resulting in a soil will vary for the different types of clays.

INDICES OF SOIL CONSISTENCY

- The plasticity index (PI) of a soil increases linearly with the percentage of clay-size fraction (%finer than 2 micrometer by weight present).
- We can see form the plot below that different clays have different correlation of PI with clay-size fraction. This is because that ***different clay minerals have different plasticity characteristics***.

- PI increases with increasing clay fraction
- Rate of increase of PI with clay fraction is different for different clay



INDICES OF SOIL CONSISTENCY

- **Activity is defined as the slope of the line correlating PI and %finer then 2 micrometer and expressed as:**

$$A = \frac{PI}{(\text{\%of clay-size fraction, by weight})}$$

Note: The line is considered to pass through the origin.

Table 4.1 Typical Values of Liquid Limit, Plastic Limit, and Activity of Some Clay Minerals

Mineral	Liquid limit, *LL*	Plastic limit, *PL*	Activity, *A*
Kaolinite	35–100	20–40	0.3–0.5
Illite	60–120	35–60	0.5–1.2
Montmorillonite	100–900	50–100	1.5–7.0

- **The activity factor gives information on the type and effect of CLAY MINERAL in a soil.**

INDICES OF SOIL CONSISTENCY

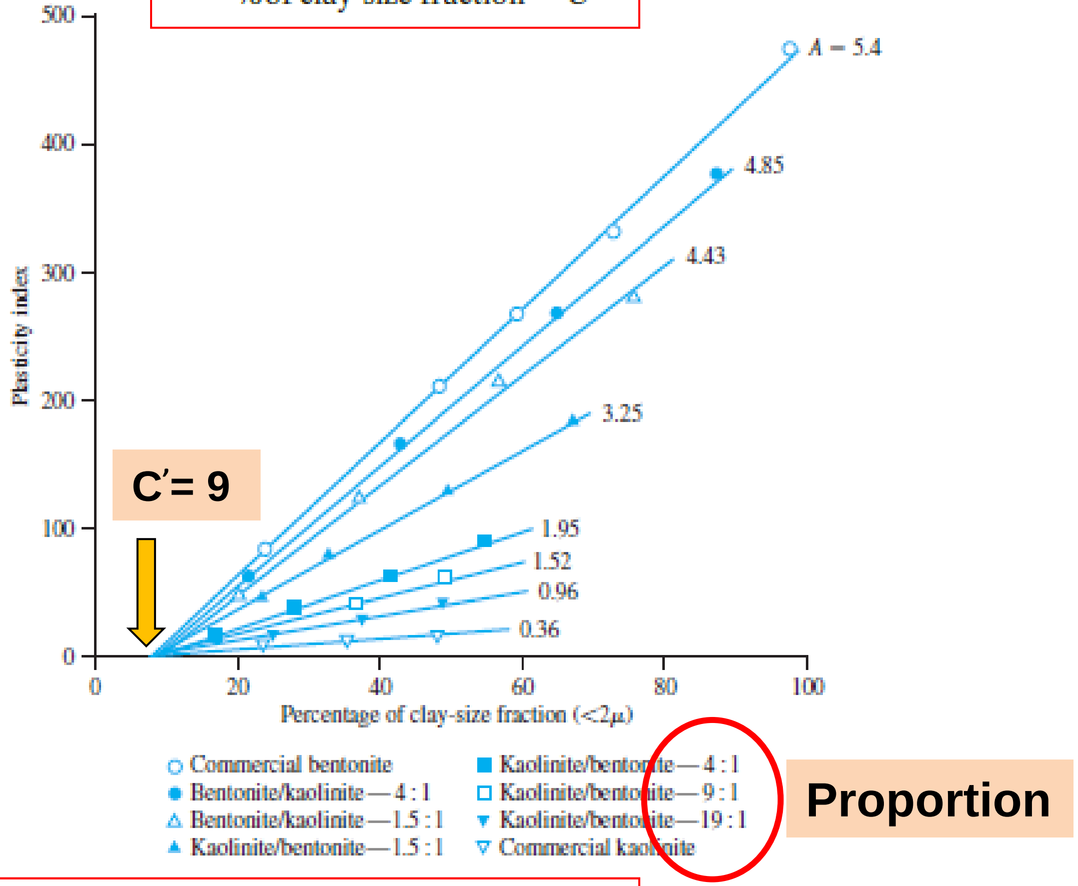
- Clay minerals with KAOLINITE have LOW activity, whereas those soils with MONTMORILLONITE will have a HIGH activity value.

- Activity is used as an index for identifying the swelling potential of clay soils.

Activity	Classification
<0.75	Inactive clays
0.75-1.25	Normal Clays
>1.25	Active Clays

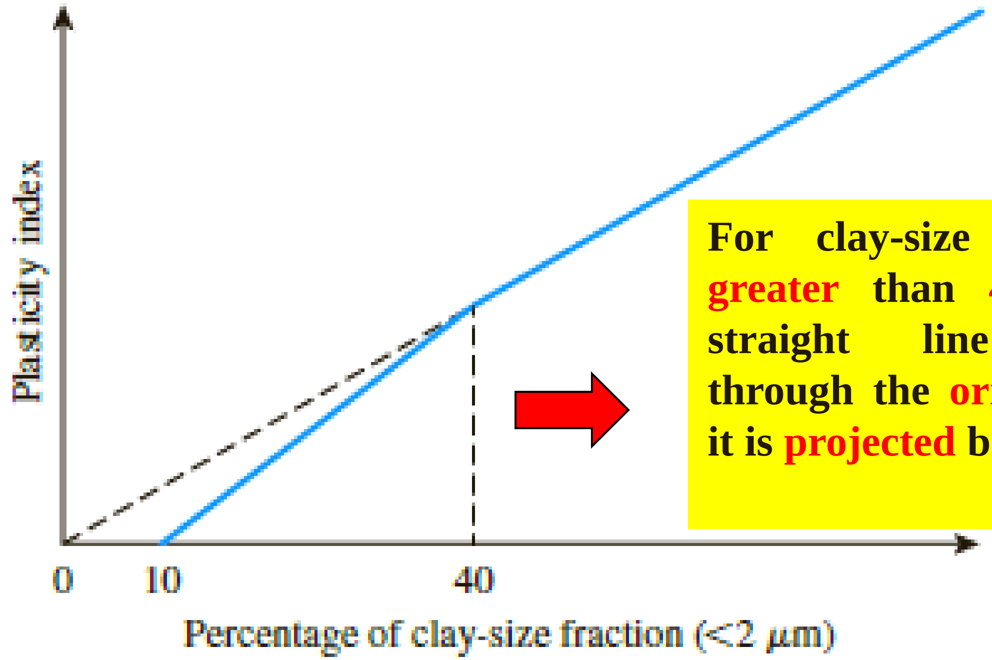
INDICES OF SOIL CONSISTENCY

$$A = \frac{PI}{\%\text{of clay-size fraction} - C'}$$



where C' is a constant for a given soil.

INDICES OF SOIL CONSISTENCY



For clay-size fractions greater than 40%, the straight line passes through the origin when it is projected back.

Figure 4.20 Simplified relationship between plasticity index and percentage of clay-size fraction by weight *(After Seed, Woodward, and Lundgren, 1964b. With permission from ASCE.)*

PLASTICITY CHART

- Casagrande (1932) studied the relationship of the plasticity index to the liquid limit of a wide variety natural soils.

- On the basis of the test results, he proposed a plasticity chart as shown next.

- This chart was developed by plotting the results of several hundred tests.

PLASTICITY CHART

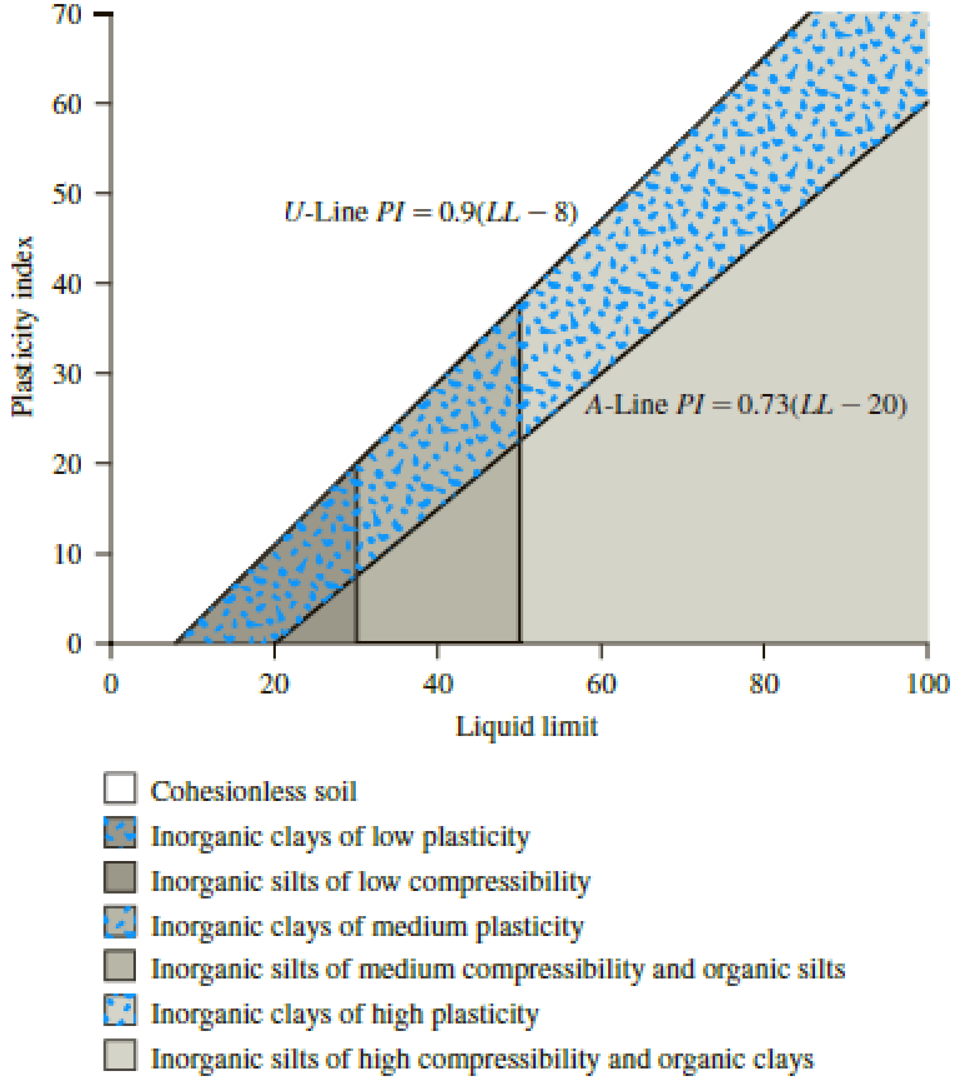
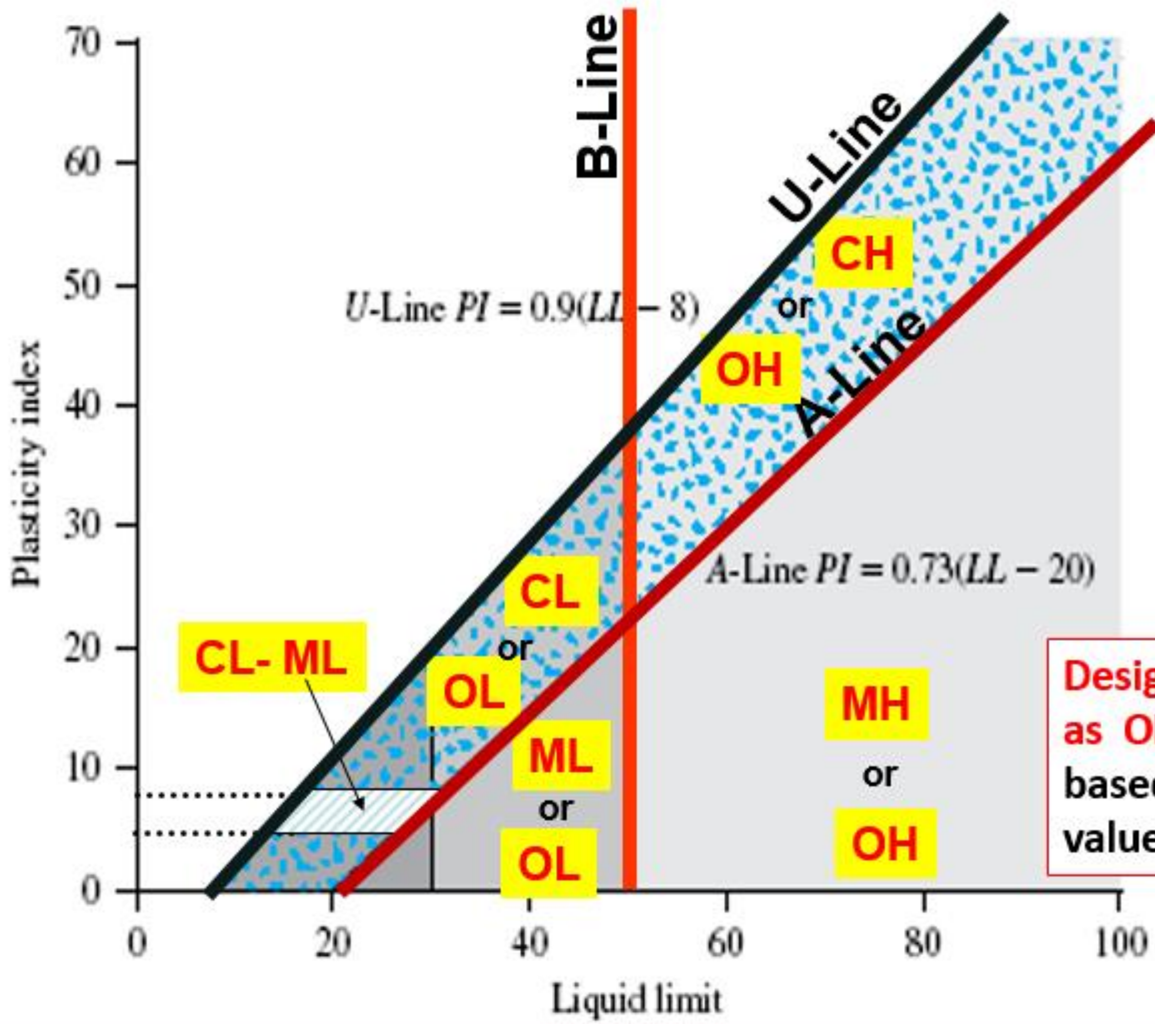


Figure 4.21 Plasticity chart

PLASTICITY CHART



Designating a soil as OL and OH is based on the value of α.

PLASTICITY CHART

- **Above A-line Clays**
  Below A-line Silts

- **Left of B-line --→Low plasticity**
  Right of B-line--→ High plasticity

- **U-line is approximately the upper limit of the relationship of PI and the LL for any soil found so far. The data plotting above or to the left of U-Line should be considered as likely in error and should be rechecked.**

- **All the lines (A, U, and B) are empirical.**

- **The plasticity chart is the basis for the classification of the fine-grained soils according to USCS.**

PLASTICITY CHART

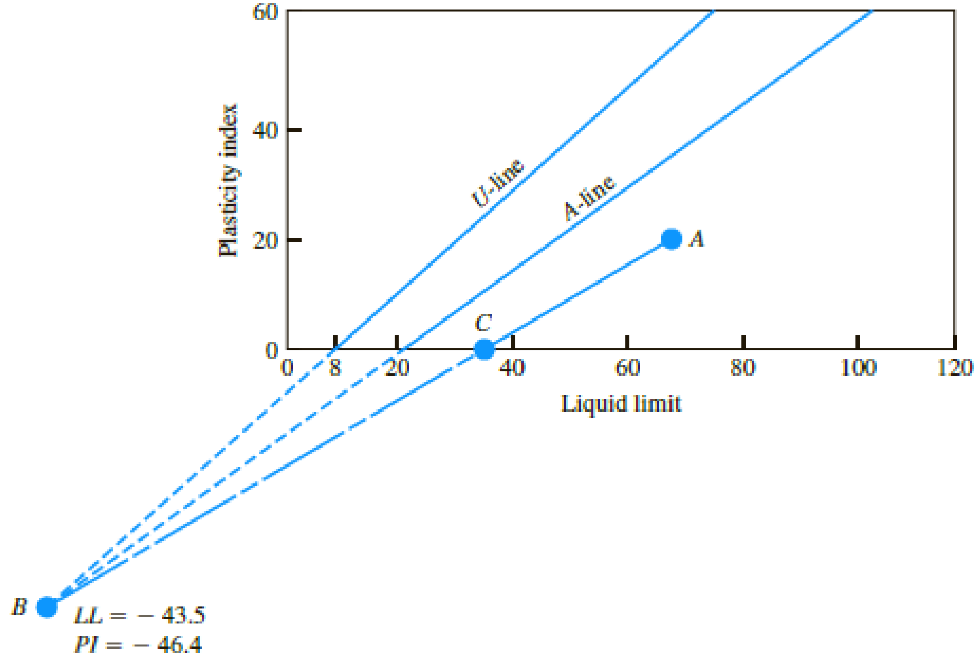


Figure 4.22 Estimation of shrinkage from plasticity chart (*Adapted from Holtz and Kovacs, 1981*)

a. Plot the plasticity index against the liquid limit of a given soil such as point *A* in Figure 4.22.
b. Project the *A*-line and the *U*-line downward to meet at point *B*. Point *B* will have the coordinates of $LL = -43.5$ and $PI = -46.4$.
c. Join points *B* and *A* with a straight line. This will intersect the liquid limit axis at point *C*. The abscissa of point *C* is the estimated shrinkage limit.

THE END