Solutions Manual
to accompany

Physical and Geotechnical Properties of Soils

JOSEPH E. BOWLES

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McGraw-Hill Book Company
New York St. Louis San Francisco Auckland Bogotá Düsseldorf
Johannesburg London Madrid Mexico Montreal New Delhi Panamá
Paris São Paulo Singapore Sydney Tokyo Toronto

SOLUTIONS MANUAL

for

Physical and Geotechnical Properties of Soils

To User: I have assembled a set of solutions for all of the problems which are not "opinion" problems for which a number of answers may be acceptable. I have not included "solutions" for discussion questions since these must be read by the instructor on an individual basis.

I have not included any "solutions" where the student is asked to verify the text example. Most derivations include a solution unless the solution is given in the text and the student is asked to derive the equation already given.

These solutions are in a format suitable for separation and inclusion in the back of the instructors lecture notes (notebook) for ready reference and pull-out for grading.

I have included more steps than is usually given in "solutions manuals" and by typing for appearance some typing errors may have crept in. I have made a reasonable check for correctness and the answers should be correct. Missing parenthesis or misplaced parenthesis, while being nuisances, should not detract from the manual's value as a teaching aid.

Joseph E. Bowles

ERRATA Physical and Geotechnical Properties of Soils (1st printing as of December 1978).

p. 25 Change to read as follows:

.....will investigate at a sample population of N = 1 test which requires interpolation to obtain

$$n = 0.726 + 0.5(1.376 - 0.726) = 1.051 \text{ say, } 1.0$$

In other words one test gives an approximate 75 percent reliability that any single test will be 19.86 ± 2.128 percent for our example.

(rest of page is O.K.)

p. 29 In Eq. (a) $V_w = W_w/G_{\underline{w}}\gamma_w = W_w$

p. 52 In Problem 2-3: Change: Ex. 2-1 to Ex. 2-3. (see solutions manual)

p. 93 5 lines from top: No. 0 to No. 4

p. 212 Delete Eq. (8-9) number from Eq. numbered for k_2.

p. 232 In Prob. 8-10 change Fig. 8-14 to Fig. 8-15.

p. 270 In Prob. 9-3: Change 3.6 to 4.0 m and 10 to 13 m (see solutions manual)

p. 283 Last line: Fig. 6-10b to Fig. 6-10.

p. 284 In Eq. (10-9) change (+) to (-).

p. 297 10 lines from top: $\varepsilon_i = \ldots\ldots(1 - \exp(-1.5t))$

p. 352 Change: $s = P_v/A_o$ and $\sigma_n = P_h/A_o$ to $s = P_h/A_o$ and $\sigma_n = P_v/A_o$.

p. 456 In Example 16-3. Column headed P_p: 4628 2876 1835 1684 are revised values. Replotting results in F = 1.9 instead of 2.1

p. 458 Answers for 16-4 and 16-6 are mixed--see solutions manual for correct values and order for all points.

1-1. Given: A material has a density of 1.76 g/cm^3.

Required: Unit weight in fps and SI.

Solution:

fps: γ = 1.76x62.4 = <u>109.8 pcf</u>

SI: γ = 1.76x9.807 = <u>17.26 kN/m^3</u>

1-2. Given: A soil sample has a diam. = 62.3 mm.

Required: area in fps and SI.

Solution:

diam = 62.3/25.4 = 2.543 in

fps: A = 0.7854(2.453)^2 = <u>4.276 sq in</u>

SI: A = 0.7854(6.23)^2 = 30.48 sq cm

= 4048 sq mm

= 0.003048 sq m

1-3. Given: Compaction test data as follows:

γ = 17.3	17.1	17.7 kN/m^3
18.4	16.9	18.1
17.9	17.2	18.0
18.3	17.0	17.9

Required: mean unit weight, γ.

$\bar{\sigma}$ (standard deviation)

$\bar{C}$ (coefficient of variance)

Estimate of percent chance single test will be within $\pm\ \bar{\sigma}$.

Solution:

$$\gamma_{mean} = \bar{X} = \frac{\Sigma V}{N} = \frac{17.3 + 17.1 \ \ldots\ldots + 17.9}{12} = \frac{211.8}{12} = \underline{17.65 \text{ kN/m}^3}$$

Find $\bar{\sigma}$:

γ	$\Delta = \gamma_i - \bar{X}$	γ	Δ	γ	Δ
17.3	0.35	17.1	0.55	17.7	0.05
18.4	0.75	16.9	0.75	18.1	0.45
17.9	0.25	17.2	0.45	18.0	0.35
18.3	0.65	17.0	0.65	17.9	0.25

$\Sigma V^2 = 3741.32$ $\quad$ $N(17.65)^2 = 3738.27$

$$\bar{\sigma} = ((3741.32 - 3738.27)/12)^{\frac{1}{2}} = \underline{0.504 \text{ kN/m}^3}$$

Find coefficient of variance:

$$\bar{C} = \bar{\sigma}/\bar{X} = 0.504/17.65 = \underline{0.02856}$$

Percent chance any single test will be within standard deviation:

Actual range = 17.65 ± 0.504 = 18.15 say 18.2

= 17.15 say 17.2

In range = 7 tests

Out or range = 5 tests

$$\% \text{ reliability} = \frac{7}{12} \times 100 = \underline{58 \text{ percent}}$$

From Table 1-2 and interpolating for N = 12 tests for n = 1

R = 0.810 + 0.026 = 0.826 = 82.6 percent reliable

Correlation is very poor.

1-4. Given the following series of plastic limit water content values:

Test No.	w_p, %	Test No.	w_p, %
1	24.3	5	19.3
2	26.2	6	24.2
3	18.1	7	23.8
4	24.1	8	25.1
		9	24.9

Required: Mean water content, $\bar{X}$
Standard deviation $\bar{\sigma}$

Coefficient of variance $\bar{C}$
Percent reliability R

Solution:

$$w_{P(mean)} = \bar{X} = \frac{\Sigma V}{9} = \frac{210}{9} = \underline{23.3\ \%} \longleftarrow$$

$$\bar{\sigma}^2 = \frac{\Sigma V^2 - N\bar{X}^2}{N} = \frac{4959.94 - 4900}{9} = 6.66$$

$$\bar{\sigma} = (6.66)^{1/2} = \underline{2.58\ \%} \longleftarrow$$

$$\bar{C} = 2.58/23.3 = \underline{0.11} \longleftarrow$$

Finding percent reliability:

From Table 1-2:	0.90	R	0.80
N = 9:	1.383	(1.00)	0.883

$\Delta R = 1.383 - 0.883 = 0.500 \qquad 1.000 - 0.883 = 0.117$

$R = 0.80 + 0.1(0.117)/0.5 = \underline{0.823 \text{ or } 82.3\ \%} \longleftarrow$

Actual percent reliability:

No. tests inside $\bar{X} \pm 2.58$ = 6

Actual percent = 6/9 x100 = 67 percent. ⟵

Again correlation is not too good.

If the two extreme points are discarded the theoretical and actual reliability converges.......

1-5. Estimate the minimum number of tests to give R = 85 percent (0.85) that a single test

$$V = \bar{X} \pm \bar{\sigma}$$

Solution: This is a case where n = 1.0

It is required to find N

Since 0.85 = (0.90 + 0.80)/2

Find where $R_{0.9} + R_{0.8} = 2.00$

At N = 105: $R_{0.9} = 1.290$

$R_{0.8} = 0.845$

$2.135 > 2.00$

Therefore it will take more than 105 tests ⟵

1-6. What is the best (minimum) value of k to give

$$V = \bar{X} \pm k\bar{\sigma}$$

with 92 percent reliability for not more than 10 tests?

Solution:

At N = 10 $R_{.90} = 1.372$

$R_{.92} = \_\_\_\_$ 1.552 (from below)

$R_{.95} = 1.813$

$$\Delta R = \left(\frac{1.813 - 1.372}{0.05}\right)0.02 = 0.18$$

$k = 1.372 + 0.18 = \underline{1.552}$ ⟵

2-4. Given: Sample of clay V_T = 105.0 cm³; Weight of sample in natural state = 143.0 g; Weight of dry sample = 111.3 g. Assume G_s = 2.70.

Required: What is natural moisture content of clay, w_N?

What is degree of saturation, S?

Solution:

$$w_N = \frac{W_w}{W_s}(100) = \frac{143.0 - 11.3}{111.3}(100) = 31.7(100)/111.3 = \underline{28.5\ \%}$$

Finding degree of saturation, S:

$$V_s = W_s/(G_s\gamma_w) = 111.3/(2.70\text{x}1) = 41.22\ \text{cm}^3$$

$$V_v = V_T - V_s = 105.0 - 41.22 = 63.78\ \text{cm}^3$$

$$V_w = W_w = 31.7\ \text{cm}^3$$

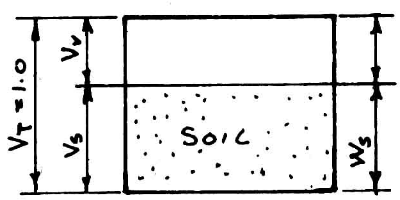
$$S = \frac{V_w}{V_v}(100) = 31.7(100)/63.78 = \underline{49.7\ \%}$$

2-5. Given: ρ_{dry} = 1.73 g/cm ; Void ratio, e = 0.55

Required: γ_{wet} at S = 50 %

γ_{wet} at S = 100 %

γ_{wet} at S = 100 % using oil at G_{oil} = 0.90



$$e = V_v/V_s = 0.55 \qquad V_v = 0.55V_s$$

$$V_T = V_v + V_s = 1.00$$

$$0.55V_s + V_s = 1.00$$

$$V_s = 1/1.55 = 0.645\ \text{cm}^3(\text{or ft}^3 \text{ or m}^3)$$

$$V_v = 1 - V_s = 1 - 0.645 = 0.355\ \text{cm}^3$$

$$\rho_{.50} = 1.73 + 0.5(0.355)(1) = 1.91\ \text{g/cm}^3$$

$$\gamma = 1.91\text{x}9.807 = \underline{18.73\ \text{kN/m}^3}$$

$$\rho_{100} = 1.73 + 1.0(0.355)(1) = 2.09\ \text{g/cm}^3$$

$$\gamma = \underline{20.50\ \text{kN/m}^3}$$

Using oil at G_o = 0.90

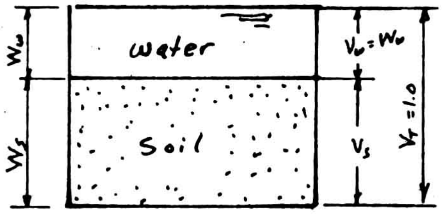
$$\rho_{100} = 1.73 + 1.0(0.355)(0.9) = 2.05\ \text{g/cm}^3$$

$$\gamma_o = 2.05\text{x}9.807 = \underline{20.10\ \text{kN/m}^3}$$

2-6. Given: A saturated clay. Water content w = 160 percent; G_s = 2.40.

Required: γ_{dry} and $\gamma_{saturated}$.

Solution: (refer to sketch)



Assume V_T = 1.00

$V_s + V_v = 1.00$

$V_s = W_s/(G_s\ _w) = W_s/G_s$

$V_w = V_v = W_w/G_w = W_w$

$W_w = wW_s = 1.60W_s = V_w$

Substituting:

$1.60W_s + W_s/G_s = 1.00 \rightarrow \rightarrow 1.60(2.40)W_s + W_s = 1.0(2.40)$

$W_s = 2.40/4.84 = 0.496$ g

$W_w = wW_s = 1.60(0.496) = 0.793$ g

$W_T = W_s + W_w = 0.496 + 0.793 = 1.289$ g

$\rho = 1.289/1 = 1.289$ g/cm³

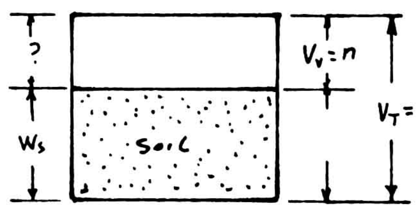
$\gamma_{sat} = 1.289 \times 9.807 = \underline{12.64 \text{ kN/m}^3}$

$\gamma_{dry} = 0.496 \times 9.807/1 = \underline{4.86 \text{ kN/m}^3}$

2-7. Given: G_s, n, γ_w.

Required: Derive an expression for γ_{dry}.

Solution: (refer to sketch)



Assume V_T = 1.00

$n = V_v/V_T = V_v/1.0 = V_v$

$V_s = V_T - V_v = 1 - n$

$W_s = V_s G_s \gamma_w = G_s \gamma_w (1-n)$

$\gamma_{dry} = W_s/V_T = W_s/1 = W_s = \underline{G_s \gamma_w (1 - n)}$

2-8. Required: Derive an expression for $\gamma_{sat} = f(G_s, e, \gamma_w)$

Solution:

$$\text{Let } V_s = 1.0 \; ; \quad e = V_v/V_s = V_v/1.0 = V_v$$

$$V_T = V_s + V_v = 1 + e$$

$$W_w = V_v G_w \gamma_w = eG_w\gamma_w = e\gamma_w$$

$$W_s = G_s V_s \gamma_w = G_s\gamma_w$$

$$W_T = W_w + W_s = e\gamma_w + G_s\gamma_w = (G_s + e)\gamma_w$$

$$\gamma_{sat} = W_T/V_T = \frac{(G_s + e)}{1 + e}\gamma_w \longleftarrow$$

2-9. Required: Derive an expression for $e = f(\gamma_{sat}, \gamma_w, w)$

Solution:

$$e = V_v/V_s \qquad \text{for } S = 100 \text{ percent:} \quad V_v = V_w = W_w/\gamma_w = wW_s/\gamma_w$$

$$V_s = 1 - V_v = 1 - wW_s/\gamma_w$$

Substituting for e:

$$e = \frac{wW_s/\gamma_w}{1 - wW_s/\gamma_w} = \frac{wW_s}{\gamma_w - wW_s}$$

$$\text{Now } W_T/1.0 = \gamma_{sat} = W_s + W_w = W_s + wW_s$$

$$\text{therefore: } W_s = \gamma_{sat}/(1 + w)$$

$$e = \frac{w\gamma_{sat}/(1 + w)}{\gamma_w - w\gamma_{sat}/(1 + w)} = \frac{w\gamma_{sat}}{\gamma_w - (\gamma_{sat} - \gamma_w)w} \longleftarrow$$

Valid for: γ_{sat} = kN/m³, pcf or g/cm³

2-10. Required: Plot a curve of $n = f(e)$.

Solution:

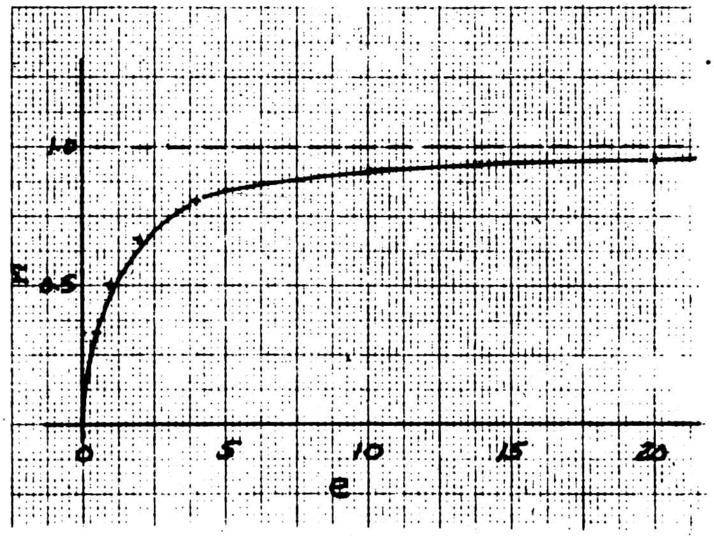
$n = V_v/V_t$ $\qquad$ $e = V_v/V_s$ $\qquad$ $V_v = eV_s$

$V_T = V_v + V_s = eV_s + V_s$

substituting:

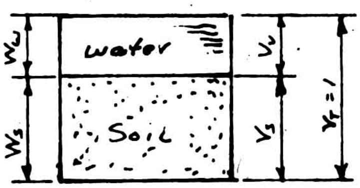
$$n = \frac{eV_s}{V_s + eV_s} = \frac{e}{1 + e}$$

e	e/(1 + e)	n
0	0/1	0
0.5	0.5/1.5	0.33
1.0	1/2	0.5
2.0	2/3	0.67
4.0	4/5	0.80
10.0	10/11	0.91
20.0	20/21	0.952
→ ∞		→ 1.0



2-11. Required: Prove that $e = wG_s$ for $S = 100\ \%$.

Solution: Refer to sketch.



$e = V_v/V_s$ $\qquad$ but $V_s = W_s/G_s\gamma_w$

$S = V_w/V_v$

$V_v = 1.0 - V_s = V_w/S$

$V_w/S = wW_s/(SxG_wx\gamma_w)$

From which $e = wW_s/(SxG_w\gamma_wxV_s) = wG_sW_s\gamma_w/(SxG_w\gamma_wxW_s) = wG_s/(SG_w)$

Noting $G_w = 1.0$

$e = wG_s/S$ but if $S = 1.0$

$\underline{e = wG_s}$ ←

2-12. Given: Data from a w_L test.

N	20	28	34
w%	68.0	60.1	54.3

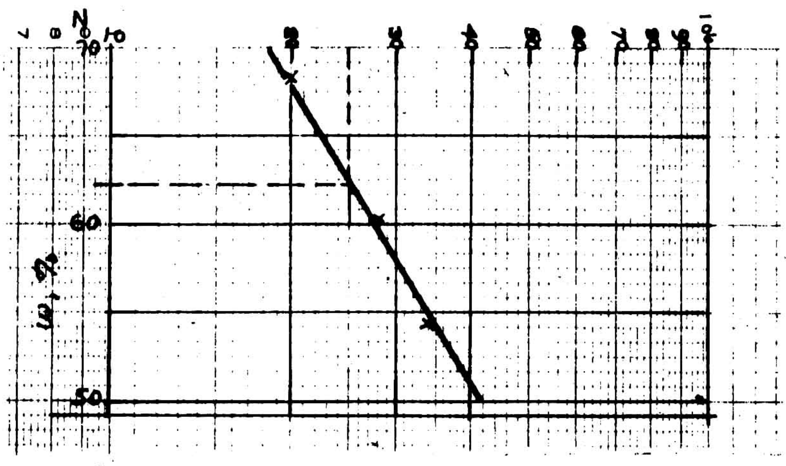
w_P = 28.6 and 29.1 percent (2 tests); w_N = 78.0 percent.

Required: Liquid and plastic limits for soil

Liquidity index and Consistency index

Make appropriate comments on soil in natural state

Solution: Plot water content data for liquid limit tests as shown and obtain w_L.



from plot above w_L = 62.8 percent From plastic limit data w_P = (29.1 + 28.6)/2 = 28.9 percent.

$$I_P = 62.8 - 28.9 = 33.9$$

$$I_L = \frac{w_N - w_P}{I_P} = \frac{78.0 - 28.9}{33.9} = 1.448$$

$$I_C = (w_L - w_N)/I_P = (62.8 - 78.0)/33.9 = -0.448$$

The in situ soil is in a potentially unstable state since any remolding will convert it into a viscous fluid. ....

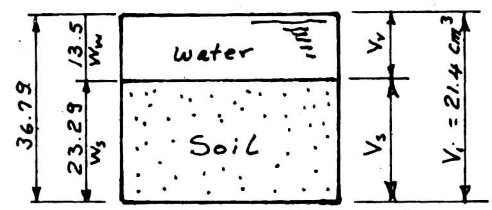
2-13. Given: Sample of saturated clay: $V_i = 21.4\ cm^3$ $V_{dry} = 13.7\ cm^3$

$W_i = 36.7\ g$ $W_{dry} = 23.2\ g$

Required: In <u>natural</u> state find: (a) w_N; (b) G_s; (c) Void ratio, e;

(d) γ_{sat}; (e) γ_{dry}; (f) Shrinkage limit w_S

Solution: Refer to sketch



(a) Natural water content w_N:

$$w_N = \frac{36.7 - 23.2}{23.2} = \frac{13.5}{23.2}(100) = \underline{58.2\ \%}$$

(b) Find specific gravity G_s:

Since $W_w = V_w = 13.5\ g = 13.5\ cm^3$

$V_s = V_t - V_w = 21.4 - 13.5 = 7.9\ cm^3$

$G_s = W_s/(V_s\gamma_w) = 23.2/(7.9x1.0) = \underline{2.94}$

(c) Find void ratio e:

$e = V_v/V_s = 13.5/7.9 = \underline{1.709}$

(d) Find saturated unit weight

$\gamma_{sat} = W_t/V_t = 36.7(9.807)/21.4 = \underline{16.82\ kN/m^3}$

(e) Find dry unit weight

$\gamma_{dry} = W_s/V_t = 23.2(9.807)/21.4 = \underline{10.63\ kN/m^3}$ (based on natural state)

(f) Shrinkage limit w_S

ΔV to $w_S = 21.4 - 13.7 = 7.7\ cm^3 = \Delta W_w = 7.7\ g$

V_s at $w_S = 13.7 - H_2O$ in soil $\rightarrow \rightarrow$ H_2O in soil $= 13.5 - 7.7 = 5.8\ g$

$V_s = 13.7 - 5.8 = 7.9\ cm^3$ (as before and checks)

$w_S = W_w/W_s = 5.8(100)/23.2 = \underline{25\ \%}$

2-14. Given: Soil specimen with $V = 60.0\ cm^3$

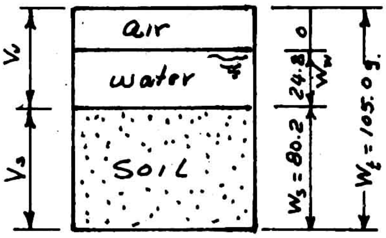
$W_t = 105.0$ g

$W_s = 80.2$ g (after drying); $G_s = 2.65$

Required: (a) water content w; (b) void ratio e; (c) porosity n;

(d) G_{mass}; (e) degree of Saturation S.

Solution: Refer to sketch



(a) Water content

$$w = \frac{105.0 - 80.2}{80.2}(100) = 24.8(100)/80.2$$

$w = \underline{30.9\ \%}$

(b) Void ratio

$V_s = W_s/(G_s\gamma_w) = 80.2/2.65 = 30.26\ cm^3$

$V_v = V_t - V_s = 60.0 - 30.26 = 29.74\ cm^3$

$$e = V_v/V_s = 29.74/30.26 = \underline{0.983}$$

(c) Porosity n

$$n = V_v/V_t = 29.74/60.0 = \underline{0.496}$$

(d) Specific gravity of mass (not grains)

$$G_m = W/(V \times \gamma_w) = 105/(60.0 \times 1.0) = \underline{1.75}$$

(e) degree of Saturation S

$$V_w = W_w/(G_w\gamma_w) = 24.8/(1 \times 1) = 24.8\ cm$$

$$S = V_w(100)/V_v = 24.8(100)/29.74 = \underline{83.4\ \%}$$

2-15. Given: Medium graded damp sand ρ = 1.77 g/cm . The water content

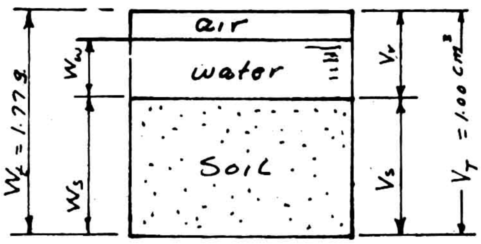
w = 15.1 %.

Required: (a) void ratio e; (b) dry unit weight γ_{dry};

(c) degree of Saturation S.

Solution: (refer to sketch)

It is necessary to assume G_s = 2.65



(a) Void ratio

$W_t = W_s + W_w = 1.77$

$w = W_w/W_s = 0.151$

$W_s + 0.151W_s = 1.77$

$W_s = 1.77/1.151 = 1.538$ g

$V_s = W_s/(G_s\gamma_w) = 1.538/(2.65x1) = 0.580$ cm^3

$V_v = 1.0 - 0.580 = 0.420$ cm^3

$e = V_v/V_s = 0.420/0.580 = \underline{0.724}$

(b) Dry unit weight

Since the volume = 1.00

$\gamma_{dry} = W_s(9.807/1 = 1.538(9.807) = 15.08$ kN/m^3

(c) Degree of Saturation

$S = V_w(100)/V_v$

$V_w = W_w = W_t - W_s = 1.770 - 1.538 = 0.232$ g (or cm^3)

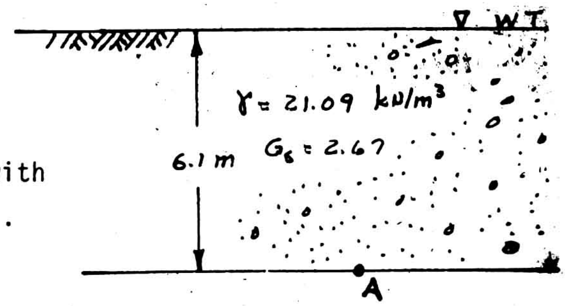
$S = 0.232(100)/0.420 = \underline{55.2\ \%}$

2-16. Given: Soil profile shown

Required: (a) σ' at point A

(b) σ' and σ_{tot} if water table falls to a and with w = 10 percent in soil.

(c) Redo "b" in fps units.



(a) σ' at A:

Obviously the unit weight shown is the saturated weight since it is below water table with no qualifying remarks.

$$\sigma' = h(\gamma_{sat} - \gamma_w) = 6.1(21.09 - 9.807) = \underline{68.83 \text{ kPa}}$$

(b) σ' and γ_{tot} if water table falls and water content in soil = 10 %.

γ_{wet}: $V_s + V_w = 1 \text{ cm}^3$

$W_s + W_w = 21.09/9.807 \rightarrow \quad \rightarrow W_w = 2.15 - W_s$

but $W_w = V_w$ in cgs units

Substituting:

$$W_s/G_s + 2.15 - W_s = 1.0$$

$$W_s - W_s/2.67 = 2.15 - 1.0$$

$$0.6255W_s = 1.15$$

$$W_s = 1.839 \text{ g}$$

Check: $V_s = W_s/G_s = 1.839/2.67 = 0.689 \text{ cm}^3$

$V_v = 1 - V_s = 0.311 \text{ cm}^3$

$W_t = (1.839 + 0.311)9.807 = 21.09 \text{ kN/m}^3$ O.K.

The weight of wet soil: $\gamma_{wet} = \gamma_{dry} + w\gamma_{dry} = 1.839(1.10)9.807 = 19.81 \text{ kN/m}^3$

$$\sigma' = \sigma_{tot} = 19.81(6.1) = \underline{120.8 \text{ kPa}}$$

(c) Part "b" in fps units:

$$\sigma' = \sigma_{tot} = \frac{19.81}{9.807}(62.4)\left(\frac{6.1\text{x}3.2808}{1000}\right) = \underline{2.52 \text{ k/sq ft}}$$