SOLUTIONS MANUAL

PAVEMENT ANALYSIS AND DESIGN

SECOND EDITION

YANG H. HUANG

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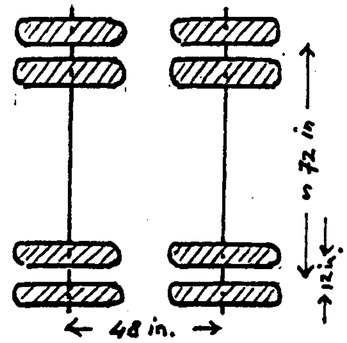
Contents

Chapter 1
Introduction

1-1. The wheel configuration for a dual-tandem axle is as follows :



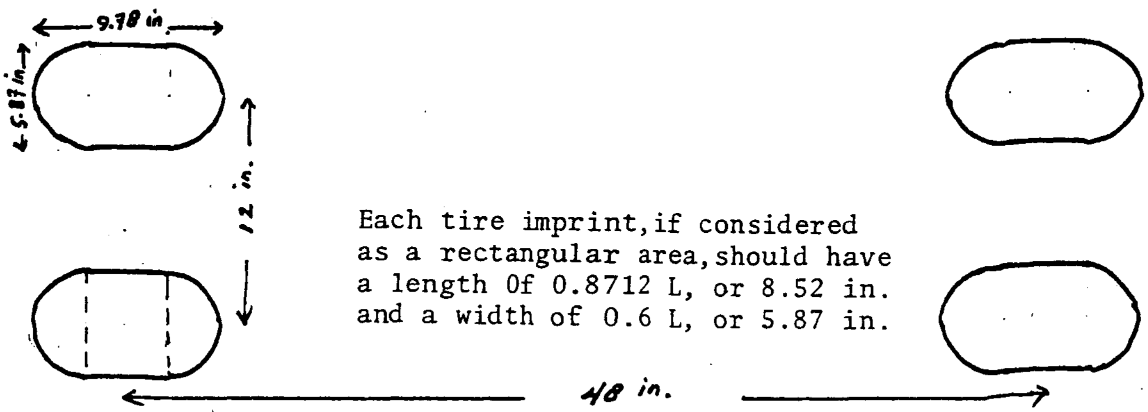
The 40 Kip load is applied over 8 tires. Thus, each tire bears 5000 Lbs (22.2 kN) load with 100 Psi (690 kPa) tire pressure. The contact area of each tire, Ac= Load of each tire/tire pressure = 5000/100 = 50 in.^{2} (8.2 x 10^4 mm^2). The dimension of the contact area is :

From Eq.1.7. (Lecture Text) :

$$L = \sqrt{Ac/0.5227} = \sqrt{50/0.5227}$$
$$= 9.78 \text{ in. } (248 \text{ mm}).$$

$$\text{width} = 0.6\ L = 5.87 \text{ in } (149 \text{ mm.})$$

The most realistic contact area consisting a rectangle and two semi-circles as shown in following figure :



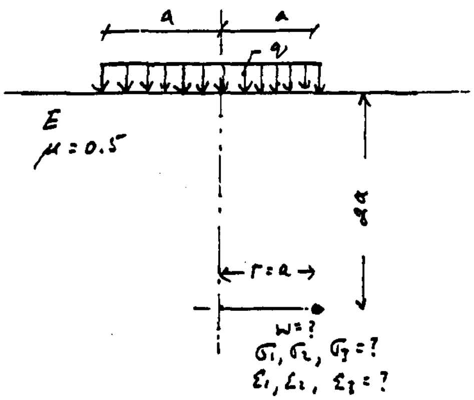
Each tire imprint,if considered as a rectangular area,should have a length Of 0.8712 L, or 8.52 in. and a width of 0.6 L, or 5.87 in.

1-2. Freezing Index = (32 - 24) x 30 +(32 + 3) x 31 + (32 - 14) x 31 + (32 - 16) x 28 + (32 - 22) x 31 + (32 -25) x 30 = <u>2851</u> degree days.

Yes, this value is likely to be different because the last few days in October and the first few days in May may have mean daily temperatures lower than 32°F, so the degree days for these two months may not be zero.

Chapter 2
Stresses and Strains in Flexible Pavements

2-1.



Solution:

$r/a = 1$; $z/a = 2$

From Fig. 2.2:

$(\sigma_z/q)100\% = 18$

$\sigma_z = 0.18\,q$

From Fig 2.3:

$(\sigma_r/q) \times 100\% = 4.05$

$\sigma_r = 0.0405\,q$

From Fig 2.4:

$(\sigma_t/q)\,100\% = 1.1$

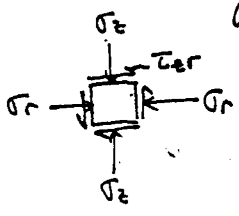
$\sigma_t = 0.011\,q$

From Fig. 2.5: $\left(\frac{\tau_{rz}}{q}\right)100\% = 8.0$

$\therefore\ \tau_{rz} = 0.08\,q.$

The principal stresses can be calculated by following formula:

General form: $\sigma_1, \sigma_2 = \frac{\sigma_x+\sigma_y}{2} \pm \sqrt{\tau_{xy}^2 + \left(\frac{\sigma_x-\sigma_y}{2}\right)^2}$



$$\sigma_1, \sigma_3 = \frac{\sigma_z+\sigma_r}{2} \pm \sqrt{\tau_{rz}^2 + \left(\frac{\sigma_z-\sigma_r}{2}\right)^2}$$

$$= \frac{0.18q + 0.0405q}{2} \pm \sqrt{0.08q^2 + \left(\frac{0.18q - 0.0405q}{2}\right)^2}$$

$\underline{\sigma_1 = 0.22\,q}$ & $\underline{\sigma_3 = 0.0041\,q}.$

(z - r plane).

There is no shear stress in z - t plane, therefore

$\underline{\sigma_t = \sigma_2 = 0.011\,q}$ is principal stress.

Vertical displacement:

From Fig. 2.6, for $\frac{r}{a} = 1$ & $z/a = 2 \rightarrow F = 0.57$

$\therefore\ w = \frac{qa}{E} \times F = \underline{0.57\,\frac{qa}{E}}$

Strains:

$\varepsilon_1 = \frac{1}{E}(\sigma_1 - \mu(\sigma_2 + \sigma_3))$

$= \frac{q}{E}[0.22 - 0.5(0.0041 + 0.011)]$

$\underline{\varepsilon_1 = 0.212\,q/E}$

$$\varepsilon_2 = \frac{1}{E}\left[(\sigma_2 - \mu(\sigma_1 + \sigma_3)\right]$$
$$= \frac{q}{E}\left[(0.011 - 0.5(0.22 + 0.0041)\right]$$
$$\underline{\varepsilon_2 = -0.101\ q/E} \checkmark$$

$$\varepsilon_3 = \frac{1}{E}\left[(\sigma_3 - \mu(\sigma_1 + \sigma_2)\right]$$
$$= q/E\left[0.0041 - 0.5(0.22 + 0.011)\right]$$
$$\underline{\varepsilon_3 = -0.1114\ q/E} \checkmark$$

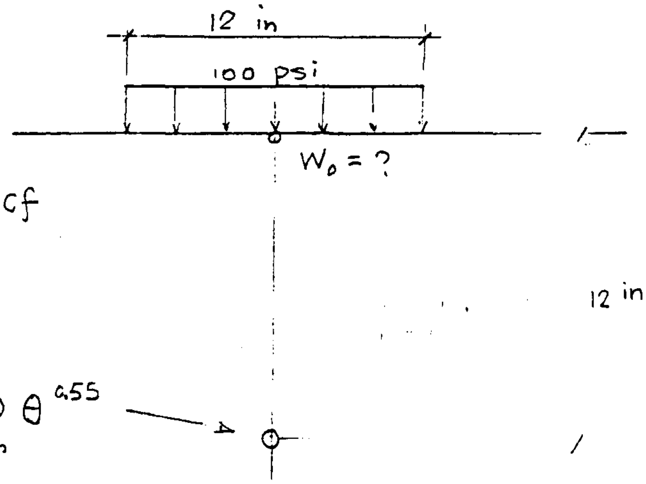
$\therefore\ \sigma_1 = 0.22\,q,\quad \sigma_2 = 0.011\,q,\quad \sigma_3 = 0.0041\,q$

$\varepsilon_1 = 0.212\ q/E;\ \varepsilon_2 = -0.101\ q/E;\ \varepsilon_3 = -0.1114\ q/E$

$w = 0.57\ \frac{qa}{E}$ ✓

2-2.

Given:



$\gamma = 100$ pcf

$K_0 = 0.6$

$\nu = 0.35$

$a = 6$ in

$E = 3000\ \theta^{0.55}$

$z = 12$ in

Boussinesq's stress distribution is valid

$$\theta = \sigma_z + \sigma_r + \sigma_t + \gamma \cdot z \cdot (1 + 2K_0)$$

$$\sigma_z = q\left[1 - \frac{z^3}{(a^2+z^2)^{3/2}}\right]$$
$$= 100\left[1 - \frac{12^3}{(6^2+12^2)^{3/2}}\right]$$
$$= 28.446 \text{ psi}$$

$$\sigma_r = \sigma_t = \frac{q}{2}\left[1 + 2\nu - \frac{2(1+\nu)z}{(a^2+z^2)^{1/2}} + \frac{z^3}{(a^2+z^2)^{3/2}}\right]$$
$$= \frac{100}{2}\left[1 + 2*0.35 - \frac{2(1+0.35)*12}{(6^2+12^2)^{1/2}} + \frac{12^3}{(6^2+12^2)^{3/2}}\right]$$
$$= 0.0294 \text{ psi}$$

$$\theta = 28.446 + 2 * 0.0294 + \frac{100}{12^3} * 12 * (1 + 2 * 0.6)$$

$$= 30.03 \text{ psi}$$

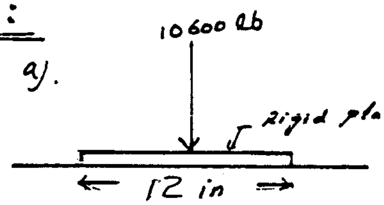
$$E = 3000\, \theta^{0.55} = 19489.34 \text{ psi}$$

$$W_o = \frac{(1+\nu) q a}{E} 2(1-\nu) = \frac{2(1-\nu^2) q a}{E}$$

$$= \frac{2(1-0.35^2)\, 100 * 6}{19489.34} = \underline{0.054} \text{ in} \quad \#$$

2-3 :

a).



Rigid plate deflects 0.2 in.

The average pressure on the plate :

$$q = \frac{P}{A} = \frac{10600}{\frac{1}{4}\pi\, 12^2} = 93.7 \text{ psi}.$$

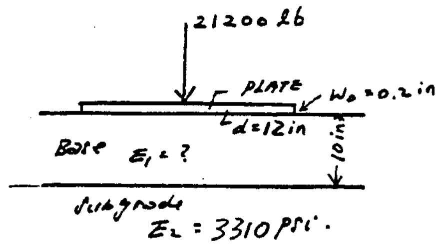
deflection of plate can be calculated by :

$$W_o = \frac{\pi(1-\mu^2) q a}{2 E_2} \qquad W_o = 0.2 \text{ in};\ a = 6 \text{ in};\ \mu = 0.5.$$

$$E_2 = \frac{\pi(1-\mu^2) q a}{2 W_o} = \frac{\pi(1-0.5^2) \times 93.7 \times 6}{2 \times 0.2}$$

$$E_2 = \underline{3310 \text{ psi}}.$$

b).



$$q = \frac{P}{\frac{1}{4}\pi d^2} = \frac{21200}{\frac{1}{4}\pi\, 12^2} = \underline{187.5 \text{ psi}}.$$

$h_1 = 10$ in. $\quad W_o = 0.2$ in.
$a = 6$ in

Two-layer system → Burmister :

$$h_1/a = \frac{10}{6} = 1.67$$

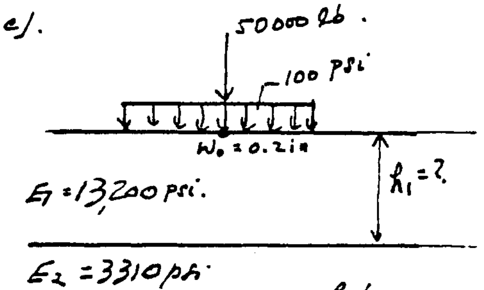
for Rigid plate : $W_o = \frac{1.178\, q \cdot a}{E_2} F_2$

$$F_2 = \frac{W_o E_2}{1.178\, q \cdot a} = \frac{0.2 \times 3310}{1.178 \times 187.5 \times 6} = 0.5$$

for $h_1/a = 1.67$; $F_2 = 0.5$, from Fig. 2.17, E_1/E_2 can be determined

$$E_1/E_2 = 4 \rightarrow E_1 = 13{,}200 \text{ psi}$$

e/.



$h_1/a = ?$

$$A_c = \frac{P}{\sigma} = \frac{50000}{100} = 500 \text{ in}^2.$$

$$a = 12.6 \text{ in}$$

surface deflection

$$W_o = \frac{1.5\, q a}{E_2} F_2$$

$$F_2 = \frac{W_o E_2}{1.5\, q\, a} = \frac{0.2 \times 3310}{1.5 \times 100 \times 12.6}$$

$$F_2 = 0.35$$

from Fig. 2.17, for $F_2 = 0.35$ and $E_1/E_2 = 4$

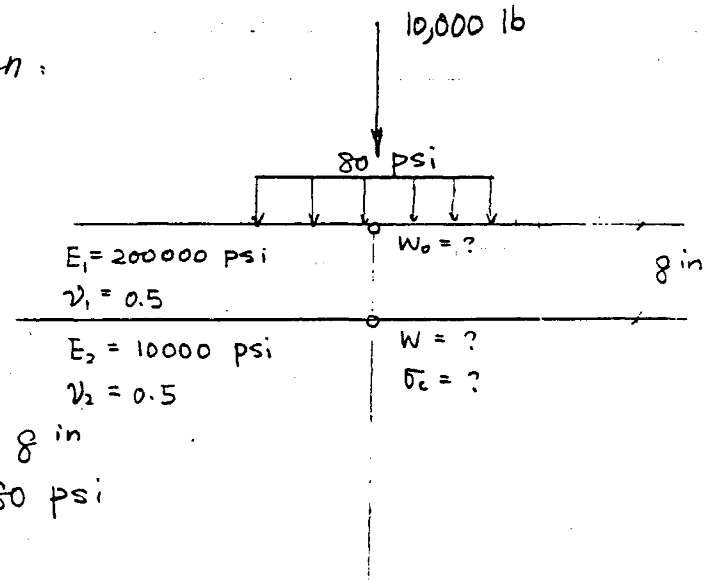
$$\frac{h_1}{a} = 5.5$$

$$h_1 = 5.5\, a = 5.5 \times 12.6 = \underline{70 \text{ in.}}$$

$\therefore$ $E_2 = 3310$ psi ; $E_1 = 13{,}200$ psi ; $h_1 = 70$ in. ✓

2-4.

Given :



$h_1 = 8$ in

$q = 80$ psi

$$\frac{10000}{\pi a^2} = 80$$

$$a = \sqrt{\frac{10000}{\pi * 80}} = 6.31 \text{ in}$$

$$W_o = \frac{1.5\, q\, a}{E_2} F_2$$

($E_1/E_2 = 20$, $h_1/a = 1.268$)

$F_2 = 0.33$ (Fig 2.17)

$$= \frac{1.5 * 80 * 6.31}{10000} * 0.33$$

$$= \underline{0.025} \text{ in} \checkmark$$

$$W = \frac{q\,a}{E} \cdot F = \frac{80 * 6.31}{10000} * 0.483 = \underline{0.0244} \text{ in } \checkmark$$

($E_1/E_2 = 20$, $h_1/a = 1.268$, $r/a = 0$

Interpolate (Fig 2.19) $\begin{cases} E_1/E_2 = 10 & F = 0.595 \\ E_1/E_2 = 25 & F = 0.425 \end{cases}$

$E_1/E_2 = 20 \quad F = 0.483$

$$\sigma_c/q = 0.153$$

$$\sigma_c = 0.153\, q = \underline{12.24} \text{ psi} \; * \checkmark$$

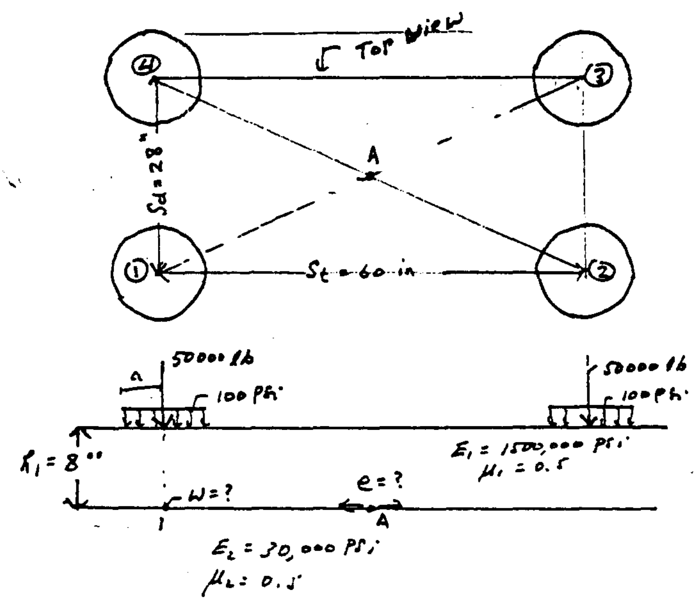
Interpolate (Fig 2.15) $\begin{cases} E_1/E_2 = 10 & \sigma_c/q = 0.21 \\ E_1/E_2 = 25 & \sigma_c/q = 0.125 \end{cases}$

$E_1/E_2 = 20 \quad \sigma_c/q = 0.153$

$a/h = 0.789$

Note. The linear interpolation is used to get the coefficient value between 2 chart given values. The nolinear interpolation has been also tried and no big differecen was shown say linear interpolation $\sigma_c/q = 0.153$ use 2 points.
Nolinear interpolation $\sigma_c/q = 0.15$ use 3 points

d-v:



Contact area $A = \frac{P}{q} = \frac{50000}{100}$

$A = 500 \text{ in}^2$.

$a = 12.6$ in.

$Sd = 28$ in

$St = 60$ in.

$E_1/E_2 = 50$

Here design charts are based on $Sd = 24$ in. thus, for $Sd = 28$ in a, h, St' must be modified:

$$St' = St \, \frac{24}{28} = 60 \times \frac{24}{28} = 51.4 \text{ in.}$$

$$a' = \frac{24}{28} a = 10.8 \text{ in}" \; ; \; h' = \frac{24}{28} h = 6.86 \text{ in.}$$

Determination Conversion factor C, using Figs. 2.26 and 2.27

- For $S_t = 48$ in ; $E_1/E_2 = 50$; $h' = 6.86$

$C_2 = 1.135$ & $C_1 = 1.08$

$$C = C_1 + 0.2\,(h'-3) \times (C_2 - C_1) = 1.166$$

- For $S_t = 72$ in ; $E_1/E_2 = 50$; $h' = 6.86$

$C_2 = 1.3$; $C_1 = 1.12$

$$C = 1.12 + 0.2\,(10.8-3)(1.3-1.12) = 1.4.$$

$S_t = 72$ in $\rightarrow C = 1.4$

$S_t' = 57.4$ in $\rightarrow C = ?$ $\rightarrow$ Linear interpolation

$S_t = 48$ in $\rightarrow C = 1.166$

$$C \text{ for } S_t' = 57.4 \text{ in} = 1.4 - \left(\frac{1.4-1.166}{72-48}\right)(72-51.4)$$

$$= \underline{\underline{1.2}}.$$

Strain Factor (F_e):

From Fig. 2.21 for $\frac{h'}{a}$ or $\frac{h}{a} = 0.64$ and

$E_1/E_2 = 50$, $F_e = 2.5$

Modified $F_e = F_e' = C \times F_e = 1.2 \times 2.5 = 3.0$.

Critical tensile strain : $e = \frac{q}{E_1} F_e'$

$$= \frac{100}{150\,000} \times 3$$

$$\underline{\underline{e = 2.0 \times 10^{-4}}} \quad \text{(below point A).}$$

b). Vertical deflection on surface of subgrade under the center of one wheel (say, point 1).

using Fig. 2.17

deflection factor F can be determined.

	LOADING ① (x)	LOADING ②	LOADING ③	LOADING ④
E_1/E_2	50	50	50	50
h_1/a	0.635	0.635	0.635	0.635
a (in)	12.6	12.6	12.6	12.6
r (in)	0 (x)	60	66.2	28
r/a	0	4.76	5.25	2.22
F	0.62	0.20	0.15	0.37

(x). See: wheel configuration.

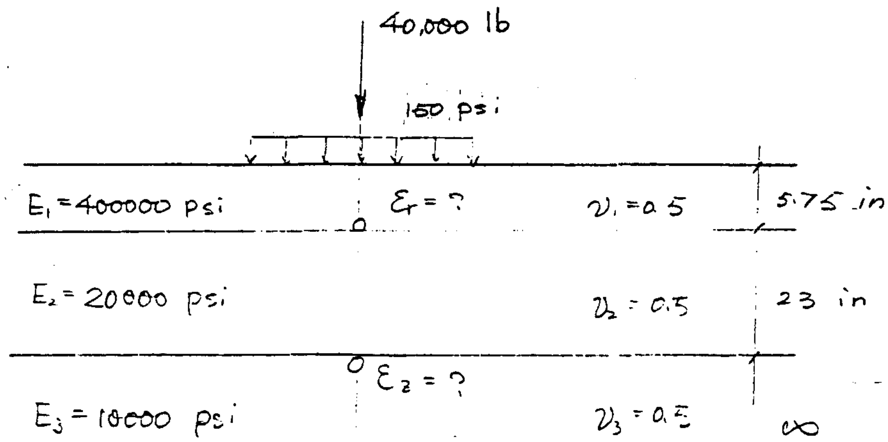
$$F_{total} = 1.34$$

$$w = \frac{q \cdot a}{E_2} F = \frac{100 \times 12.6}{30000} \times 1.34 = \underline{\underline{0.0563 \text{ in.}}}$$

Answer: $e = 2.0 \times 10^{-4}$; $w = 0.0563$ in.

2-6

Given



$$a = \sqrt{\frac{40000}{\pi \cdot 150}} = 5.21 \text{ in}$$

$$K_1 = \frac{E_1}{E_2} = 20$$

$$K_2 = \frac{E_2}{E_3} = 2$$

$$A = \frac{a}{h_2} = \frac{9.21}{23} = 0.4$$

$$H = \frac{h_1}{h_2} = \frac{5.75}{23} = 0.25$$

$$\frac{RR1 - ZZ1}{2} = 2 \quad \text{(Fig 2.31c)}$$

$$\varepsilon_r = \frac{-q}{E}\left(\frac{RR1 - ZZ1}{2}\right)$$

$$= \frac{-150}{400000} \times 2$$

$$= \underline{-0.00075} \quad \text{(tension)}$$

If use Table 2.3

$221 - RR1 = 2.86779$

$$\varepsilon_r = \frac{q}{E_1}\,\frac{(RR1 - ZZ1)}{2}$$

$$= -\frac{150}{400000}\cdot\frac{2.86779}{2}$$

$$= -0.000725 \quad \text{(tension)}$$

No big difference between using Table from using Figures.

when $\nu = 0.5$.

Table 2.3

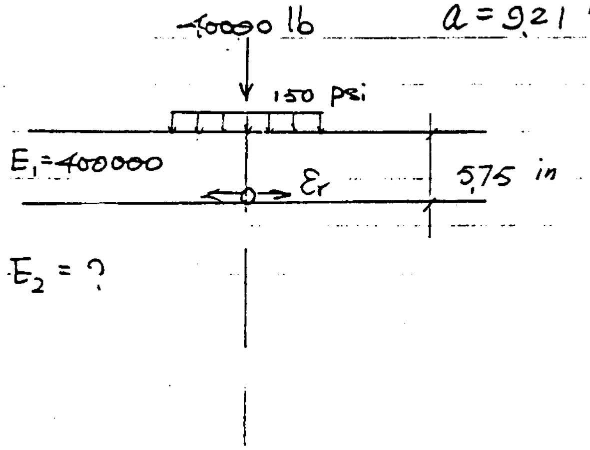
$(ZZ2 - RR2) = 0.14159$

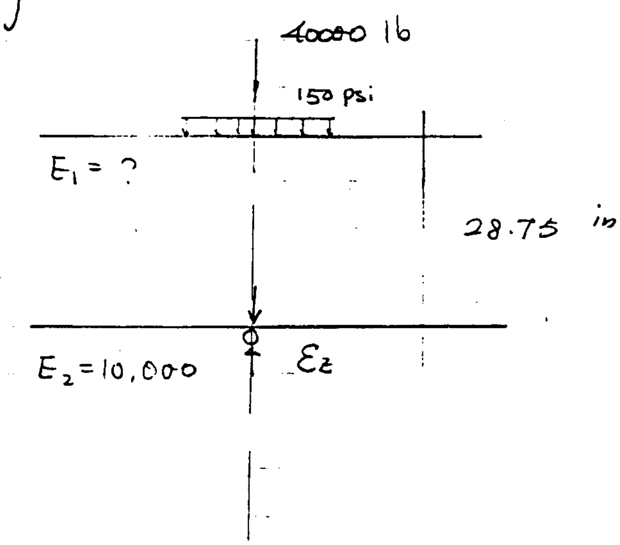
$$\sigma_{z2} - \sigma_{r2} = q\,(ZZ2 - RR2)$$
$$= 150 * 0.14159 = 21.23$$
$$\sigma_{z2} - \sigma_{r2}' = (\sigma_{z2} - \sigma_{r2})/k_2$$
$$= 21.23/2 = 10.61 \text{ psi}$$
$$\varepsilon_z = \frac{\sigma_{z2} - \sigma_{r2}'}{E_2} = \frac{10.61}{10000} = \underline{0.001062}$$
✓ #

2-7.

Given, $\varepsilon_r = -0.000725$, $\varepsilon_z = 0.001062$ } from 2-6

$a = 9.21$ in ✓





$$\varepsilon_r = \frac{q}{E_1}\,F_e$$

$$F_e = \frac{\varepsilon_r \cdot E_1}{q} = \frac{0.000725 \times 400000}{150} = 1.933 \;✓$$

$h_1/a = 0.624$ ✓

$E_1/E_2 \doteq 20$ from Fig. 2.17

$E_2 = E_1/20 = 400000/20 = \underline{20000}$ psi. ✓

$\varepsilon_z = 0.00106$, from Eq. 2.21, $\varepsilon_r = 0.5\,\varepsilon_z = 0.00053$

By trial and error, it was found $E_1 = 35{,}000$ psi

because when $E_1 = 35000$ psi $\quad F_e = \dfrac{0.00053 \times 35000}{150} = 0.124$

and with $\dfrac{h_1}{a} = \dfrac{28.75}{9.21} = 3.12$, from Fig. 2.21

$\dfrac{E_1}{E_2} = 3.5$ or $E_1 = 3.5 \times 10{,}000 = \underline{35{,}000 \text{ psi}}$

2-8. For the Maxwell model $D(t) = \dfrac{1}{E_0}\left(1 + \dfrac{t}{T_0}\right)$

$$w_0 = \frac{2(1-\nu^2)\,q\,a}{E} = \frac{2 \times 0.91 \times 80 \times 6}{10{,}000}\left(1 + \frac{t}{10}\right)$$

$$= 0.0874\,(1 + 0.1t)$$

(a) For triangular loading

$$L(t) = \frac{2t}{d} + 1 \qquad \text{for } -\frac{d}{2} < t \le 0$$

$\dfrac{dL}{dt} = \dfrac{2}{d}$ Since the first term of w_0 is constant independent of t, so Boltzmann's superposition principle need only be applied to the second term

$$w_0 = 0.0874 + 0.0874 \times \frac{2}{10}\int_{-5}^{0} 0.1\,t\,dt$$

$$= 0.0874 + 0.00175\,\frac{t^2}{2}\Big|_{-5}^{0} = \underline{0.109} \text{ in.}$$

(b) For haversine loading, from Eqs 2.57 and 2.58

$$w_0 = 0.0874 + 0.0874\left(-\frac{\pi}{10}\right) \times 0.1 \int_{-5}^{0} \sin\left(\frac{2\pi t}{10}\right) t\,dt$$

$$= 0.0874 - 0.00275\left[\frac{1}{(0.2\pi)^2}\sin(0.2\pi t) - \frac{t}{0.2\pi}\cos(0.2\pi t)\right]_{-5}^{0}$$

$$= 0.0874 + 0.00275\left(\frac{5}{0.2\pi}\right) = \underline{0.109} \text{ in.}$$

Chapter 3
KENLAYER Computer Program

```
1   (1) NPROB
Problem 3.1
2  0  1  1  (3) MATL NDAMA NPY NLG
0.001  (4) DEL
2  1  80  1  0  (5) NL NZ ICL NSTD NUNIT
12    (6) TH
0.35   0.35   (7) PR
0    (8) ZC
1   (9) NBOND
3000    3000    (11) E
0    (13) LOAD
6    100    (14) CR CP
1    (16) NR
0    (17) RC
2   2   (25) NOLAY ITENOL
1    0    2    0    (26) LAYNO NCLAY
12    12    (27) ZCNOL
0  0  0  0  0.01  (28) RCNOL XCNOL YCNOL SLD DELNOL
1    (29) RELAX
145    0    (30) GAM
0.55  0.6   (31) K2 K0
0.55  0.6   (31) K2 K0
0    3000    (33) PHI K1
0    3000    (33) PHI K1
```

answer: 0.05339 in.

```
1  (1) NPROB
PROBLEM 3.2
1  0  1  1  (3) MATL NDAMA NPY NLG
0.001  (4) DEL
2  2  80  5  0  (5) NL NZ ICL NSTD NUNIT
8   (6) TH
0.5    0.5    (7) PR
0    8    (8) ZC
1  (9) NBOND
200000   10000    (11) E
0    (13) LOAD
6.308    80    (14) CR CP
1    (16) NR
0    (17) R
```

answer: 0.02512 in.
0.02347 in.
11.394 psi

```
1  (1) NPROB
PROBLEM 3.3
1  0  1  1  (3) MATL NDAMA NPY NLG
0.001  (4) DEL
2  1  80  9  0  (5) NL NZ ICL NSTD NUNIT
8    (6) TH
0.5    0.5    (7) PR
8    (8) ZC
1   (9) NBOND
1500000    30000    (11) E
2    (13) LOAD
12.616    100    (14) CR CP
1    (19) NPT
60    28    0    0    (20) XW YW XPT
```

answer: -2.065E-04
0.05709 in.

```
1   (1) NPROB
PROBLEM 3.4
1  0  1  1   (3) MATL NDAMA NPY NLG
0.001   (4) DEL
3  2  80  9  0   (5) NL NZ ICL NSTD NUNIT
5.75    23    (6) TH
0.5    0.5    0.5    (7) PR
5.75    28.7501    (8) ZC
1   (9) NBOND
400000    20000    10000    (11) E
0    (13) LOAD
9.213    150    (14) CR CP
1    (16) NR
0    (17) RC
```

Answer:
-7.259 E-04
1.065 E-03

```
2   (1) NPROB
PROBLEM 3.5(a)
2  0  1  1   (3) MATL NDAMA NPY NLG
0.001   (4) DEL
4  2  80  9  0   (5) NL NZ ICL NSTD NUNIT
8    2    2    (6) TH
0.45    0.3    0.3    0.4    (7) PR
8    12.0001    (8) ZC
1   (9) NBOND
500000    30000    15000    5000    (11) E
0    (13) LOAD
4.5    75    (14) CR CP
1    (16) NR
0    (17) RC
3   15   (25) NOLAY ITENOL
2    0    3    0    4    1    (26) LAYNO NCLAY
9    11    13    (27) ZCNOL
0  0  0  0  0.01   (28) RCNOL XCNOL YCNOL SLD DELNOL
0.5    (29) RELAX
145    135    135    130    (30) GAM
0.5   0.6   (31) K2 K0
0.5   0.6   (31) K2 K0
6.2   1110   178   0.8   (31) K2 K3 K4 K0
0    10000    (33) PHI K1
0    10000    (33) PHI K1
1827    7682    3020    (33) EMIN EMAX K1
```

answer:
-1.019 E-04
2.845 E-04

```
PROBLEM 3.5(b)
2  0  1  1   (3) MATL NDAMA NPY NLG
0.001   (4) DEL
3  2  80  9  0   (5) NL NZ ICL NSTD NUNIT
8    4    (6) TH
0.45    0.3    0.4    (7) PR
8    12.0001    (8) ZC
1   (9) NBOND
500000    20000    5000    (11) E
0    (13) LOAD
4.5    75    (14) CR CP
1    (16) NR
0    (17) RC
2   15   (25) NOLAY ITENOL
2    0    3    1    (26) LAYNO NCLAY
9    13    (27) ZCNOL
0  0  0  0  0.01   (28) RCNOL XCNOL YCNOL SLD DELNOL
0.5    (29) RELAX
145    135    130    (30) GAM
0.5   0.6   (31) K2 K0
6.2   1110   178   0.8   (31) K2 K3 K4 K0
10000    10000    (33) PHI K1
1827    7682    3020    (33) EMIN EMAX K1
```

answer:
-1.040 E-04
2.853 E-04

```
1   (1) NPROB
PROBLEM 3.6
2  1  1  1  (3) MATL NDAMA NPY NLG
0.001  (4) DEL
3  0  80  9  0  (5) NL NZ ICL NSTD NUNIT
4   8   (6) TH
0.4   0.3   0.45   (7) PR
1  (9) NBOND
400000   10000   10000   (11) E
1   (13) LOAD
4.5   75   (14) CR CP
3   (19) NPT
0   13.5   0   0   0   4.5   0   6.75   (20) XW YW XPT
1  15  (25) NOLAY ITENOL
2   0   (26) LAYNO NCLAY
6   (27) ZCNOL
0  0  0  0  0.01  (28) RCNOL XCNOL YCNOL SLD DELNOL
0.5   (29) RELAX
145 135   0   (30) GAM
0.5  0.6  (31) K2 KO
8000 8000  (33) PHI K1
1  1  (46) NLBT NLTC
1   (47) LNBT
3   (48) LNTC
36500   (49) TNLR
0.0796   3.291   0.854   (50) FT1 FT2 FT3
1.365E-09   4.477   (51) FT4 FT5
```

answer: 5.49 years

```
1  (1) NPROB
PROBLEM 3.7
2  1  1  1  (3) MATL NDAMA NPY NLG
0.001  (4) DEL
6  0  80  9  0  (5) NL NZ ICL NSTD NUNIT
4   2   2   2   2   (6) TH
0.4   0.3   0.3   0.3   0.3   0.45   (7) PR
1  (9) NBOND
400000   50000   40000   30000   20000   10000   (11) E
1   (13) LOAD
4.5   75   (14) CR CP
3   (19) NPT
0   13.5   0   0   0   4.5   0   6.75   (20) XW YW XPT
4  15  (25) NOLAY ITENOL
2   0   3   0   4   0   5   0   (26) LAYNO NCLAY
5   7   9   11   (27) ZCNOL
0  0  0  0  0.01  (28) RCNOL XCNOL YCNOL SLD DELNOL
0.5   (29) RELAX
145   135   135   135   135   130   (30) GAM
0.5  0.6  (31) K2 KO
0.5  0.6  (31) K2 KO
0.5  0.6  (31) K2 KO
0.5  0.6  (31) K2 KO
0   8000  (33) PHI K1
0   8000  (33) PHI K1
0   8000  (33) PHI K1
0   8000  (33) PHI K1
1  1  (46) NLBT NLTC
1  (47) LNBT
6   (48) LNTC
36500   (49) TNLR
.0796  3.291  .854  (50) FT1 FT2 FT3
1.365E-09   4.477   (51) FT4 FT5
```

answer: 5.08 years

```
1   (1) NPROB
PROBLEM 3.8
2  0  1  1  (3) MATL NDAMA NPY NLG
0.001  (4) DEL
3  1  80  9  0  (5) NL NZ ICL NSTD NUNIT
4   8   (6) TH
0.4   0.3   0.45   (7) PR
6   (8) ZC
1  (9) NBOND
400000 8000  10000  (11) E
1   (13) LOAD
4.5   75   (14) CR CP
1   (19) NPT
0   13.5   0   6.75   (20) XW YW XPT
1  15  (25) NOLAY ITENOL
2   0   (26) LAYNO NCLAY
6   (27) ZCNOL
0  0  0  0  0.01  (28) RCNOL XCNOL YCNOL SLD DELNOL
0.5   (29) RELAX
145   135   0   (30) GAM
0.5  0.6  (31) K2 KO
8000   8000   (33) PHI K1
```

answer: 2.956E+04 psi
14.003 psi
1.113 psi
-3.083 psi

```
1  (1) NPROB
PROBLEM 3.9
3  0  1  1  (3) MATL NDAMA NPY NLG
0.001  (4) DEL
2  1  80  1  0  (5) NL NZ ICL NSTD NUNIT
8   (6) TH
0.5   0.5   (7) PR
0   (8) ZC
1  (9) NBOND
0   10000   (11) E
0   (13) LOAD
6   75   (14) CR CP
1   (16) NR
0   (17) RC
0  (36) DUR
1  1   (37) NVL LNV
6  (38) NTYME
0   0.01   0.1   1   10   100   (39) TYME
0.113   70   (41) BETA TEMPREF
0.000002  2.37E-06   3.81E-06   4.38E-06   4.57E-06   0.0000046   (42) CREEP
70   (44) TEMP
```

answer: 0.01561 in., 0.01657 in.,
0.01957 in., 0.02056 in.,
0.02087 in., 0.02092 in.

```
1  (1) NPROB
PROBLEM 3.10
3  1  1  1  (3) MATL NDAMA NPY NLG
0.001  (4) DEL
2  0  80  9  0  (5) NL NZ ICL NSTD NUNIT
8   (6) TH
0.5   0.5   (7) PR
1  (9) NBOND
0   10000   (11) E
0   (13) LOAD
6   75   (14) CR CP
1   (16) NR
0   (17) RC
0.1   (36) DUR
1  1   (37) NVL LNV
11  (38) NTYME
0.001   0.003   0.01   0.03   0.1   0.3   1   3   10   30   100   (39) TYME
```

answer: 21.09 years

```
0.113   70   (41) BETA TEMPREF
2.04E-06   2.12E-06   2.37E-06   2.92E-06   3.81E-06   4.19E-06   4.38E-06
4.49E-06   4.57E-06   0.0000046   0.0000046   (42) CREEP
70   (44) TEMP
1  1  (46) NLBT NLTC
1   (47) LNBT
2   (48) LNTC
100000   (49) TNLR
0.0796   3.291   0.854   (50) FT1 FT2 FT3
1.365E-09   4.477   (51) FT4 FT5
```

NDAMA should be 2 to get the following: Damage ratio due to max. tensile strain = 0.04357 and that due to differential strain = 0.008804

```
1  (1) NPROB
PROBLEM 3.11
1  1  1  1  (3) MATL NDAMA NPY NLG
0.001  (4) DEL
3  0  80  9  0  (5) NL NZ ICL NSTD NUNIT
6   8   (6) TH
0.4   0.35   0.45   (7) PR
1  (9) NBOND
740000   23000   11000   (11) E
2   (13) LOAD
4.52   70   (14) CR CP
3   (19) NPT
48   13.5   0  0  0  3.375  0  6.75   (20) XW YW XPT
1  1  (46) NLBT NLTC
1   (47) LNBT
3   (48) LNTC
200000   (49) TNLR
0.0796   3.291   0.854   (50) FT1 FT2 FT3
1.365E-09   4.477   (51) FT4 FT5
```

answer: 19.09 years

```
3  (1) NPROB
Problem 3-12(a)
2  1  1  1  (3) MATL NDAMA NPY NLG
0.001  (4) DEL
7  2  80  9  0  (5) NL NZ ICL NSTD NUNIT
2   2   2   2   2   2   (6) TH
0.35   0.35   0.35   0.35   0.35   0.35   0.45   (7) PR
1  (9) NBOND
120000   100000   80000   68000   40000   20000   5000   (11) E
0   (13) LOAD
6   100   (14) CR CP
1   (16) NR
0   (17) RC
7  15  (25) NOLAY ITENOL
1   0   2   0   3   0   4   0   5   0   6   0   7   1   (26) LAYNO NCLAY
1   3   5   7   9   11   13   (27) ZCNOL
0  0  0  0  0.01  (28) RCNOL XCNOL YCNOL SLD DELNOL
0.5   (29) RELAX
135   135   135   135   135   135   115   (30) GAM
0.5  0.6  (31) K2 K0
0.5  0.6  (31) K2 K0
0.5  0.6  (31) K2 K0
0.5  0.6  (31) K2 K0
0.5  0.6  (31) K2 K0
0.5  0.6  (31) K2 K0
6.2  1110  178  0.8  (31) K2 K3 K4 K0
0   10000   (33) PHI K1
0   10000   (33) PHI K1
0   10000   (33) PHI K1
0   10000   (33) PHI K1
0   10000   (33) PHI K1
```

```
0   10000   (33) PHI K1
1827   7682   3020   (33) EMIN EMAX K1
0  1  (46) NLBT NLTC
7   (48) LNTC
1000   (49) TNLR
1.365E-09   4.477   (51) FT4 FT5
```

answer: 1.89 years

```
Problem 3-12(b)
2  2  1  1  (3) MATL NDAMA NPY NLG
0.001  (4) DEL
2  2  80  9  0  (5) NL NZ ICL NSTD NUNIT
12   (6) TH
0.35   0.45   (7) PR
1  (9) NBOND
10000   3020   (11) E
0   (13) LOAD
6   100   (14) CR CP
1   (16) NR
0   (17) RC
2  15  (25) NOLAY ITENOL
1   0   2   1   (26) LAYNO NCLAY
4   13   (27) ZCNOL
0  0  0  0  0.01  (28) RCNOL XCNOL YCNOL SLD DELNOL
0.5   (29) RELAX
135   115   (30) GAM
0.5  0.6  (31) K2 K0
6.2  1110  178  0.8  (31) K2 K3 K4 K0
10000   10000   (33) PHI K1
1827   7682   3020   (33) EMIN EMAX K1
0  1  (46) NLBT NLTC
2   (48) LNTC
1000   (49) TNLR
1.365E-09   4.477   (51) FT4 FT5
```

answer: 24.22 years

```
Problem 3-12(c)
2  2  1  1  (3) MATL NDAMA NPY NLG
0.001  (4) DEL
2  2  80  9  0  (5) NL NZ ICL NSTD NUNIT
12   (6) TH
0.35   0.45   (7) PR
1  (9) NBOND
10000   3020   (11) E
0   (13) LOAD
6   100   (14) CR CP
1   (16) NR
0   (17) RC
2  15  (25) NOLAY ITENOL
1   0   2   1   (26) LAYNO NCLAY
6   13   (27) ZCNOL
0  0  0  0  0.01  (28) RCNOL XCNOL YCNOL SLD DELNOL
0.5   (29) RELAX
135   115   (30) GAM
0.5  0.6  (31) K2 K0
6.2  1110  178  0.8  (31) K2 K3 K4 K0
40   10000   (33) PHI K1
1827   7682   3020   (33) EMIN EMAX K1
0  1  (46) NLBT NLTC
2   (48) LNTC
1000   (49) TNLR
1.365E-09   4.477   (51) FT4 FT5
```

answer: 7.75 years

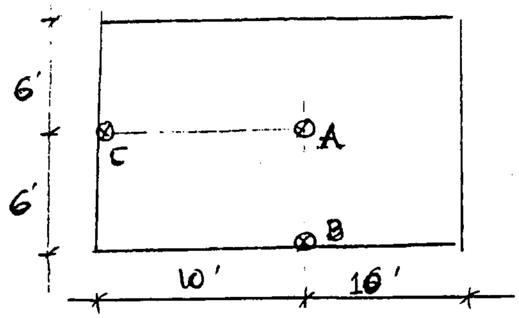
```
2  (1) NPROB
PROBLEM 3-13(a)
3  1  1  1  (3) MATL NDAMA NPY NLG
0.001  (4) DEL
2  2  80  9  0  (5) NL NZ ICL NSTD NUNIT
10   (6) TH
0.5   0.5   (7) PR
1  (9) NBOND
0   0   (11) E
0   (13) LOAD
10   100   (14) CR CP
1   (16) NR
0   (17) RC
0.1  (36) DUR
2  1   2   (37) NVL LNV
7  (38) NTYME
0.01   0.03   0.1   0.3   1   3   10   (39) TYME
0   0   (41) BETA TEMPREF
1.02E-06  1.06E-06  1.21E-06  1.59E-06  2.68E-06  4.84E-06  9.27E-06   (42) CREEP
0   0   (41) BETA TEMPREF
0.000105   0.000289   0.000732   0.00125   0.00195   0.00359   0.00732   (42) CREEP
0   0   (44) TEMP
1  1  (46) NLBT NLTC
1   (47) LNBT                          answer:   11.62 years
2   (48) LNTC
60000   (49) TNLR
0.0796   3.291   0.854   (50) FT1 FT2 FT3
1.365E-09   4.477   (51) FT4 FT5
PROBLEM 3-13(b)
3  1  1  1  (3) MATL NDAMA NPY NLG
0.001  (4) DEL
2  2  80  9  0  (5) NL NZ ICL NSTD NUNIT
10   (6) TH
0.5   0.5   (7) PR
1  (9) NBOND
0   0   (11) E
0   (13) LOAD
10   100   (14) CR CP
1   (16) NR
0   (17) RC
0.2  (36) DUR
2  1   2   (37) NVL LNV
7  (38) NTYME
0.01   0.03   0.1   0.3   1   3   10   (39) TYME
0   0   (41) BETA TEMPREF
1.02E-06  1.06E-06  1.21E-06  1.59E-06  2.68E-06  4.84E-06  9.27E-06   (42) CREEP
0   0   (41) BETA TEMPREF
0.000105   0.000289   0.000732   0.00125   0.00195   0.00359   0.00732   (42) CREEP
0   0   (44) TEMP
1  0  (46) NLBT NLTC
2   (47) LNBT                          answer:   7.54 years
60000   (49) TNLR
0.0796   3.291   0.854   (50) FT1 FT2 FT3
```

```
 1  (1) NPROB
 PROBLEM 3-14
 4  1  2  2   (3) MATL NDAMA NPY NLG
 0.001   (4) DEL
 6  0  80  9  0   (5) NL NZ ICL NSTD NUNIT
 6   2   2   2   2    (6) TH
 0.4   0.35   0.35   0.35   0.35   0.45   (7) PR
 1  (9) NBOND
 0   7500   7500   7500   7500   3020   (11) E
 0   10000   10000   10000   10000   12340   (11) E
 0   (13) LOAD
 5.35   100   (14) CR CP
 1   (16) NR
 0   (17) RC
 1   (13) LOAD
 4.52   70   (14) CR CP
 3   (19) NPT
 0   13.5   0   0   0   3.375   0   6.75   (20) XW YW XPT
 5  15  (25) NOLAY ITENOL
 2   0   3   0   4   0   5   0   6   1   (26) LAYNO NCLAY
 7   9   11   13   15   (27) ZCNOL
 0  0  6.75  0  0.01  (28) RCNOL XCNOL YCNOL SLD DELNOL
 0.5   0.5   (29) RELAX
 145   135   135   135   135   125   (30) GAM
 0.5  0.6  (31) K2 K0
 0.5  0.6  (31) K2 K0
 0.5  0.6  (31) K2 K0
 0.5  0.6  (31) K2 K0
 6.2  1110  178  0.8  (31) K2 K3 K4 K0
 0   7500   (33) PHI K1
 0   7500   (33) PHI K1
 0   7500   (33) PHI K1
 0   7500   (33) PHI K1
 1827   7682   3020   (33) EMIN EMAX K1
 0   10000   (33) PHI K1
 0   10000   (33) PHI K1
 0   10000   (33) PHI K1
 0   10000   (33) PHI K1
 7605   17002   12340   (33) EMIN EMAX K1
 0.1  (36) DUR
 1  1   (37) NVL LNV
 11  (38) NTYME
 0.001   0.003   0.01   0.03   0.1   0.3   1   3   10   30   100   (39) TYME
 0.113   70   (41) BETA TEMPREF
 3.7E-07   5.2E-07   8.6E-07   1.45E-06   0.0000025   0.000004   0.0000062   0.0000086
0.000012   0.000016   0.000019   (42) CREEP
 60   (44) TEMP
 80   (44) TEMP
 1  1  (46) NLBT NLTC
 1   (47) LNBT
 3   (48) LNTC
 9125   18250   (49) TNLR
 9125   18250   (49) TNLR
 0.0796   3.291   0.854   (50) FT1 FT2 FT3
 1.365E-09   4.477   (51) FT4 FT5
```

answer: 25.15 years

4-1

(a)



$h = 8''$

$k = 50$ pci

$\Delta t = -24\,°F$

$E = 4\times10^{6}$ psi

$\nu = 0.15$

$\alpha_t = 5\times10^{-6}/°F$

at interior

$$\sigma_x = \overset{\text{// x-dir}}{\frac{E\,\alpha_t\,\Delta t}{2(1-\nu^2)}} + \overset{\text{// y-dir}}{\frac{\nu\,E\,\alpha_t\,\Delta t}{2(1-\nu^2)}}$$

$$= \frac{E\,\alpha_t\,\Delta t}{2(1-\nu^2)}(1+\nu) = \frac{E\,\alpha_t\,\Delta t}{2(1-\nu)}$$

$$= \frac{4\times10^{6}\times5\times10^{-6}/°F\times(+24°F)}{2(1-0.15)} = \underline{282.353} \text{ psi}$$

at edge ; $\sigma_x = \overset{\text{x-dir //}}{\frac{E\,\alpha_t\,\Delta t}{2}}$

$$= \frac{4\times10^{6}\times5\times10^{-6}\times24}{2} = \underline{240} \text{ psi}$$

(b) $l = \sqrt[4]{\frac{E h^3}{12(1-\nu^2)k}} = \sqrt[4]{\frac{4\times10^{6}\times512}{12(1-0.15^2)\times50}} = 43.228''$

$L_x/l = \frac{20'\times12''}{43.228''} = 5.552 \longrightarrow C_x = 0.825$ from Chart (4.4)

$L_y/l = \frac{12'\times12''}{43.228''} = 3.33 \longrightarrow C_y = 0.23$

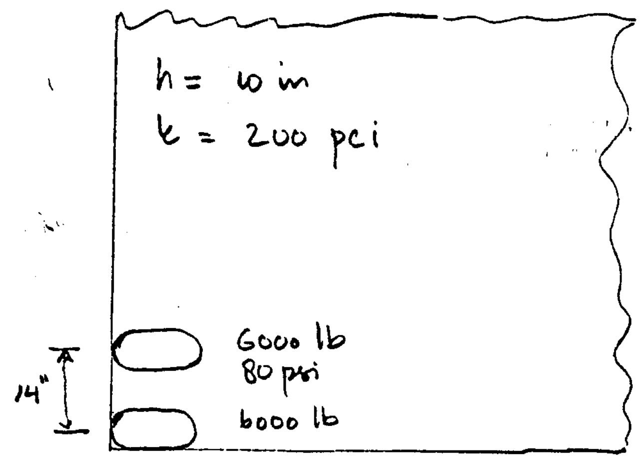
$$\sigma_{xA} = \frac{E \times \alpha_t \cdot \Delta t}{2(1-\nu^2)} (C_x + \nu C_y) = \frac{4\times10^6 \times 5\times10^{-6} \times 24}{2(1-0.15^2)} (0.825 + 0.23 \times 0.15)$$

$$= \underline{211.03} \text{ psi} \checkmark$$

$$\sigma_{xB} = \frac{E \times \alpha_t \Delta t\, C_x}{2} = \frac{4\times10^6 \times 5\times10^{-6} \times 24 \times 0.825}{2} = \underline{198} \text{ psi} \checkmark$$

$$\sigma_{yC} = \frac{E \times \alpha_t \Delta t \times C_y}{2} = \frac{4\times10^6 \times 5\times10^{-6} \times 24 \times 0.23}{2} = \underline{55.2} \text{ psi} \checkmark$$

4-2.



$\nu = 0.15$

$q = 80$ psi

$P_d = 6{,}000$ lb

$P = 12{,}000$ lb.

$S_d = 14$ in. $\qquad E = 4 \times 10^6$ psi (concrete)

Maximum stress in concrete by Westergaard's equation with equivalent contact area

$$l = \sqrt[4]{\frac{E h^3}{12(1-\nu^2)k}}$$

$$= \sqrt[4]{\frac{4\times10^6 (10)^3}{12[1-(0.15)^2]\, 200}} = 36.135''$$

$$a = \sqrt{\frac{0.8521\ P_d}{q\,\pi} + \frac{S_d}{\pi}\sqrt{\frac{P_d}{0.5227\ q}}}$$

$$= \sqrt{\frac{0.8521\,(6000)}{80\ \pi} + \frac{14}{\pi}\sqrt{\frac{6000}{0.5227\,(80)}}}$$

$$= 8.586''$$

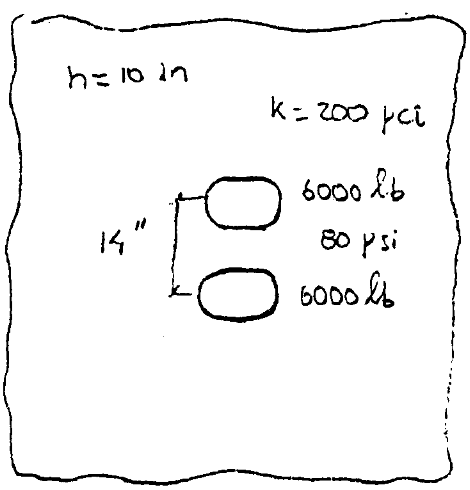
Maximum Stress in concrete (σ_c)

$$\sigma_c = \frac{3P}{h^2}\left[1 - \left(\frac{a\sqrt{2}}{\ell}\right)^{0.6}\right]$$

$$= \frac{3 \times 12{,}000}{10^2}\left[1 - \left(\frac{8.586\sqrt{2}}{36.135}\right)^{0.6}\right]$$

$$\underline{\underline{\sigma_c = 172.8 \text{ psi}}}$$

4.3 a) Westergaard's Eqn.



$S_d = 14''$

$q_h = 80$ psi

$P_d = 6000$ lb

$$a = \sqrt{\frac{0.8521\ P_d}{q_h\,\pi} + \frac{S_d}{\pi}\sqrt{\frac{P_d}{0.5227\ q_h}}}$$

$$= \sqrt{\frac{0.8521\,(6000)}{80\ \pi} + \frac{14}{\pi}\sqrt{\frac{6000}{0.5227\,(80)}}}$$

$$= 8.59 \text{ in}$$

$$\sigma_i = \frac{0.316\, P}{h^2}\left[4 \log\left(\frac{l}{b}\right) + 1.069\right]$$

$$l = \sqrt[4]{\frac{E h^3}{12(1-\nu^2)k}} = \sqrt[4]{\frac{(4\times10^6)(10)^3}{12(1-0.15^2)\,200}} = 36.14 \text{ in}$$

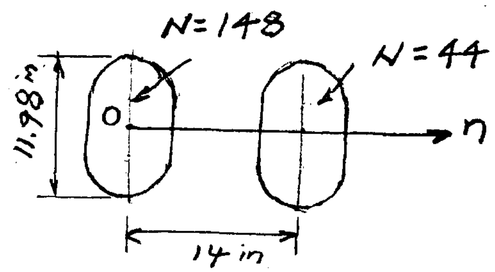
$$(1.724\, h = 17.24 \text{ in}) > (8.59 \text{ in} = a)$$

$$b = \sqrt{1.6a^2 + h^2} - 0.675\, h = 8.02 \text{ in}$$

$$\sigma_i = \frac{0.316\,(12000)}{100}\left[4 \log\left(\frac{36.14}{8.02}\right) + 1.069\right] = \underline{139.71} \text{ psi}$$

(b) Influence Chart

From Eq. 4.30 $\quad L = \sqrt{\frac{6000}{0.5227 \times 80}} = 11.98$ in



use $l = 36.14$ in on the top of Figure 4.14 as a scale, draw the configuration of the dual tires on a tracing paper. Center point o at the center of the chart and count the number of blocks. $N = 192$

From Eq. 4.32a $\quad M = \frac{80 \times (36.14)^2 \times 192}{10{,}000} = 2006$ lb-in./in.

From 4.32b $\quad \sigma = \frac{6 \times 2006}{(10)^2} = \underline{120.36}$ psi

4-4.

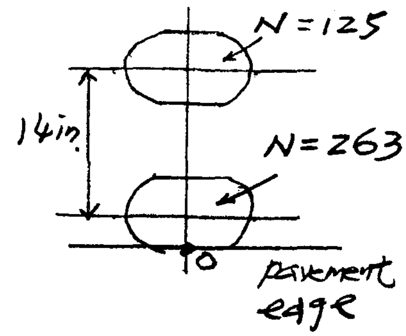
From problem 4-3 $a = 8.59$ in. $\ell = 36.14$ in.

(a) Westergaard's Equation (Eq. 4.26)

$$\sigma_e = \frac{0.803 \times 12{,}000}{(10)^2}\left[4 \log\left(\frac{36.14}{8.59}\right) + 0.666\left(\frac{8.59}{36.14}\right) - 0.034\right]$$

$$= \underline{252.49} \text{ psi}$$

(b) Influence Chart (Fig 4.15)



place point O at pavement edge and count the number of blocks

$N = 263 + 125 = 388$

$$M = \frac{q \ell^2 N}{10{,}000} = \frac{80 \times (36.14)^2 \times 388}{10{,}000} = 4054 \text{ in-lb/in.}$$

$$\sigma_e = \frac{6M}{h^2} = \frac{6 \times 4054}{(10)^2} = \underline{243.3} \text{ psi}$$

4-5. Using a scale, measure the length of the tire corresponding 22.6 in., say 2.05 units. Measure the length ℓ at the top, say 5.27 units

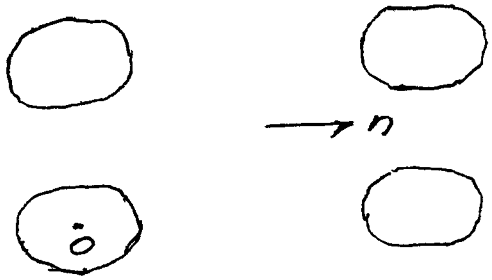
$$\ell : 22.5 = 5.27 : 2.05$$

$$\ell = \frac{5.27}{2.05} \times 22.6 = \underline{58.1} \text{ in.}$$

The number of blocks covered by the foure tires

$N = 280$ $M = \dfrac{100 \times (58.1)^2 \times 280}{10{,}000} = 9452$ in-lb/in.

$$\sigma_i = \frac{6 \times 9452}{(11)^2} = \underline{469} \text{ psi}$$



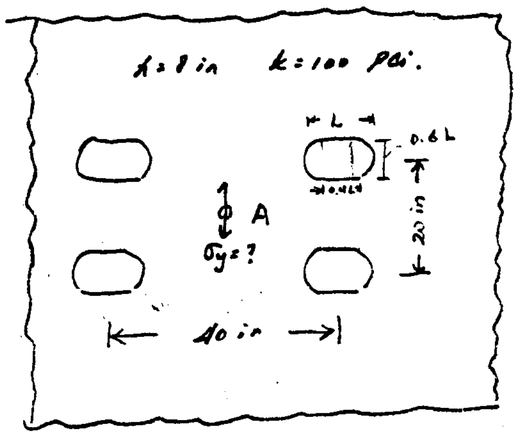
To determine the moment in the longitudinal direction, the orientation of the tires must be ~~rotated~~ 90°, as shown in the left figure. Note that the right two tires straddles between positive and negative blocks and have very little effect on the block count $N = 250$

$$M = \frac{100 \times (58.1)^2 \times 250}{10{,}000} = 8439 \text{ in.-lb/in.} \qquad \sigma_i = \frac{6 \times 8939}{(11)^2} = \underline{418} \text{ psi}$$

4-6:

Total weight = 40,000 lb or = 10000 lb / wheel

q = 100 psi



$L: \sqrt{10000/(0.5227 q)} = 13.775$ in

$B = 0.6L = 8.265$ in.

$E_c = 4 \times 10^6$ psi ; $\mu_c = 0.15$

$h = 8$ in $k = 100$ pci.

Radius of Relative Stiffness (ℓ):

$$\ell = \sqrt[4]{\frac{4 \times 10^6 \times 8^3}{12(1-0.15^2)100}} = 36.35 \text{ in.}$$

Place point A on the center of influence chart. Due to symmetry only 1 tire imprint area is needed.

x direction : number of blocks for 1 tire = 36.1 (X direction).

$$N = 4 \times 36.1 = 144.4$$

$$M_x = \frac{q\ell^2 N}{10000} = \frac{100 \times 36.35^2 \times 144.1}{10000} = 1904$$

$$\sigma_x = \frac{6M}{h^2} = 178.5 \text{ psi}$$

y direction:

Number of blocks for 1 tire = 56.3

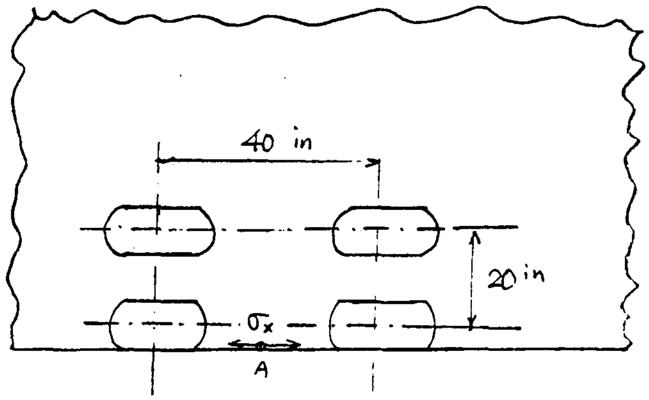
$$N = 4 \times 56.3 = 225.2$$

$$M_x = \frac{q\ell^2 N}{10000} = 2975.6$$

$$\sigma_y = \frac{6 \times 2975.6}{8^2} = \underline{\underline{279}} \text{ psi}$$

4-7. Given:

$h = 8$ in
$K = 100$ pci
$P_d = 10{,}000$ lb
$q = 100$ psi



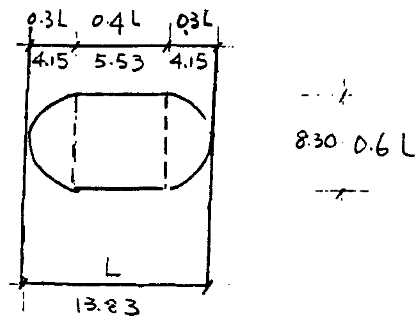
Asked:
σ_x at point A

1). Converting duals into a semicircular area

$$L = \sqrt{P_d / (0.5227 q)}$$

$$= \sqrt{10000 / (0.5227 * 100)}$$

$$= 13.83 \text{ in}$$



2). Radius of relative stiffness ℓ

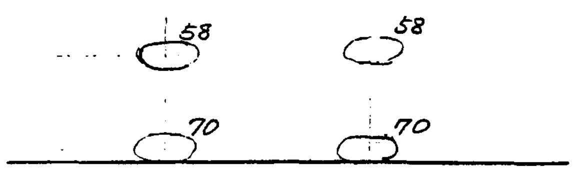
$$\ell = \sqrt[4]{\frac{E h^3}{12(1-\nu^2) K}}$$

For concrete
$E = 4 * 10^6$ psi
$\nu = 0.15$

$$= \sqrt[4]{\frac{4 * 10^6 * 8^3}{12(1-0.15^2) * 100}} = 36.35 \text{ in.}$$

$$M = \frac{q \ell^2 N}{10000}$$

N =

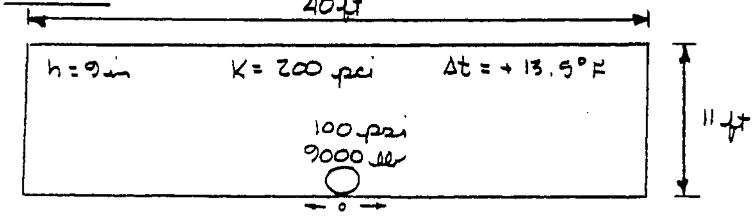


$\ell = 36.35$ in
$N = 58 + 58 + 70 + 70 = 256$
$q = 100$ psi

$$M = \frac{100 * 36.35^2 * 256}{10{,}000} = 3382.6 \text{ lb-in/in}$$

$$\sigma = \frac{6M}{h^2} = \frac{6 * 3382.6}{8^2} = \underline{317} \text{ psi}$$

PA-8



σ_e due to combined curling and loading?

(a) Curling stress Temp. diff. = 1.5°F per in. of slab

$$l = \left[\frac{Eh^3}{12(1-\nu^2)K}\right]^{0.25} = \left[\frac{(4\times10^6)(9)^3}{12(1-0.15^2)(200)}\right]^{0.25} = 33.39 \text{ in} \quad ✓$$

$L_x/l = (40 \times 12)/33.39 = 14.38$

$L_y/l = (11 \times 12)/33.39 = 3.95$

From fig. 4.4,

$C_x = 1.04$ (max)

$C_y = 0.4$

$$\sigma = \frac{CE\alpha_t \Delta t}{2} = \frac{(1.04)(4\times10^6)(5\times10^{-6})(13.5)}{2} = \underline{140.4 \text{ psi}} \quad ✓$$

(b) $a = \sqrt{\dfrac{9000}{100\pi}} = 5.35$ in

$$\sigma_e = \frac{0.803P}{h^2}\left[4\log\left(\frac{l}{a}\right) + 0.666\left(\frac{a}{l}\right) - 0.034\right]$$

$$\sigma_e = \frac{0.803(9000)}{(9)^2}\left[4\log\left(\frac{33.39}{5.35}\right) + 0.666\left(\frac{5.35}{33.39}\right) - 0.034\right]$$

$\sigma_e = \underline{290.3 \text{ psi}}$ ✓

(c) Combined stress

$290.3 - 140.4 = \underline{149.9 \text{ psi}}$ ✓

4-9. $A_s = \dfrac{\gamma_c h L f_a}{2 f_s}$

longitudinal $A_s = \dfrac{0.0868(9)(40\times12)(1.5)}{2\times43{,}000} = 0.00654 \text{ in}^2/\text{in}$

$= \underline{0.0785} \text{ in}^2/\text{ft}$

Transverse $A_s = \dfrac{0.0868(9)(11 \times 12)(1.5)}{43{,}000}$

$= 0.003597\ in^2/in. = \underline{0.0432}\ in^2/ft$

use $\underline{6 \times 12 - W4.5 \times W4.5}$ wire mesh.

Because the allowable stress for tiebar is 27,000 psi

Area required $= \dfrac{43{,}000}{27{,}000} \times 0.0432 = 0.0688\ in^2/ft$

use 1/2 in. bar Area 0.2 in. Spacing $= \dfrac{0.2}{0.0688} = 2.9$ ft

use $\underline{\frac{1}{2}}$ in. deformed bars at $\underline{3}$ ft spacing.

Length of bar $t = \frac{1}{2}\left(\frac{f_s d}{\mu}\right) + 3$

$t = \frac{1}{2}\left(\frac{27{,}000 \times 0.5}{350}\right) + 3 = 19.3 + 3 = 22.3$ in. use $\underline{2\ ft}$

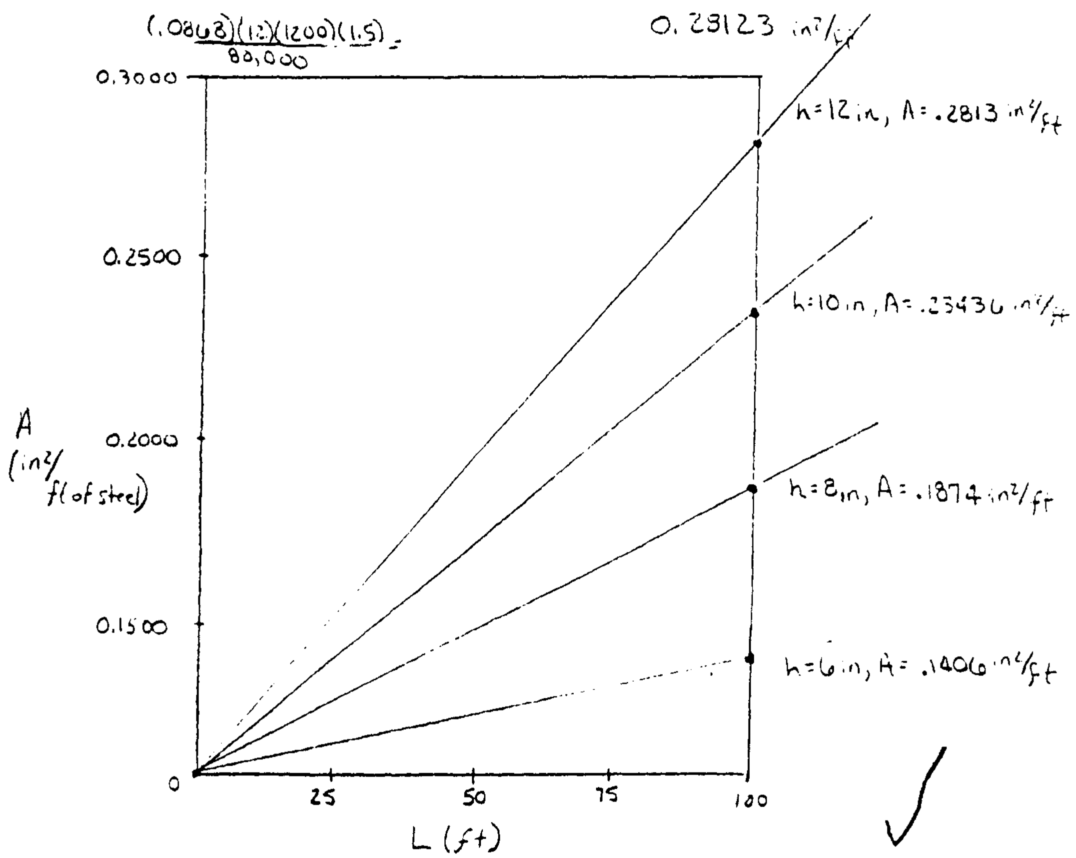
4.10 Develop a design chart for required area of temp. steel in terms of the thickness and length of slab, assuming allowable $\sigma_T = 40{,}000$ psi

(4.37) $A_s = \dfrac{\gamma_c h L F_a}{2 f_s} = \dfrac{(.0868)(6)(100 \times 12)(1.5)}{2(40{,}000)} = 0.011718\ in \times \dfrac{12\ in}{ft\ of\ steel} = 0.1406\ in^2/ft$ of steel

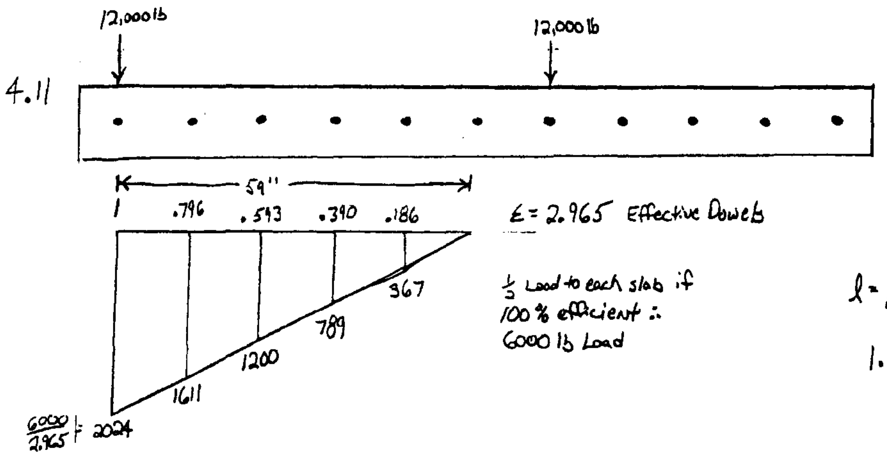
$\dfrac{(.0868)(8)(1200)(1.5)}{2(40{,}000)}$ 0.1874 in^2/ft

$\dfrac{(.0868)(10{,}000)(1.5)}{80{,}000} =$ 0.23436 in^2/ft

$\dfrac{(.0868)(12)(1200)(1.5)}{80{,}000} =$ 0.28123 in^2/ft



4.11



$\Sigma = 2.965$ Effective Dowels

$\frac{1}{2}$ Load to each slab if 100% efficient ∴ 6000 lb Load

Width = 12' = 144"

Thickness = 10"

K = 300 pci

Joint = 0.25 in

Dowels = 1 in @ 12 in on centers

$$l = \left[\frac{Eh^3}{12(1-\nu^2)k}\right]^{.25} = \left[\frac{(4\times10^6)\,10^3}{12(1-\nu^2)\,300}\right]^{.25} = 32.65''$$

$$1.8\,l = 1.8(32.65) = 58.77'' \simeq 59''$$

$$I_d = \frac{1}{64}\pi d^4$$

$$= \frac{1}{64}\pi(1)^4 = 0.0491\ in^4 \qquad \underline{Eq\ 4.43}$$

$$\beta = \sqrt[4]{\frac{Kd}{4E_d I_d}} \qquad \underline{Eq\ 4.44}$$

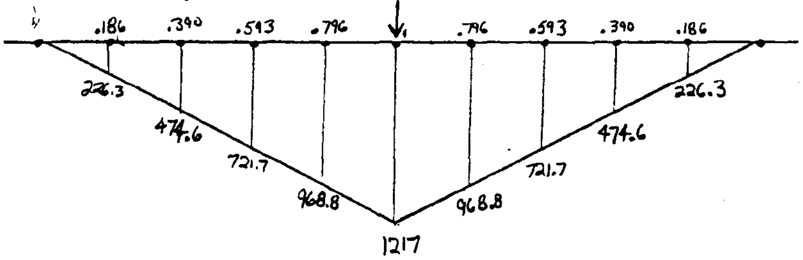
$$= \left[\frac{(1.5\times10^6)(1)}{4(29\times10^6)\,0.0491}\right]^{.25} = 0.71637$$

$$\sigma_b = \frac{K P_t (2+\beta z)}{4\beta^3 E_d I_d} \qquad z = \text{Joint width}$$

$$= \frac{(1.5\times10^6)\,2024\,(2+0.71637*(.25))}{4(.71637)^3\,(29\times10^6)\,.0491} \qquad \underline{Eq.\ 4.45}$$

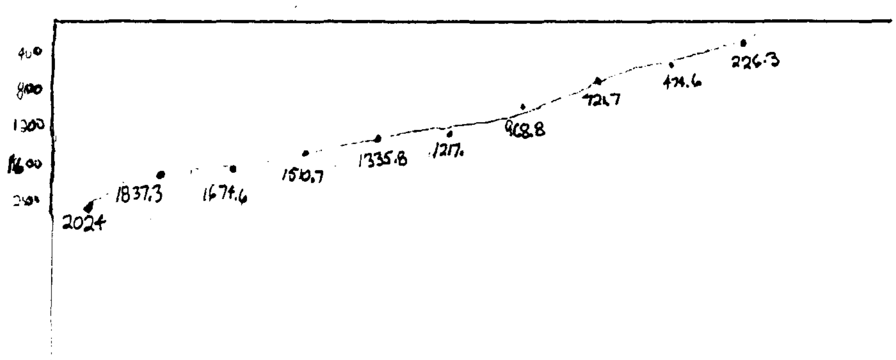
$$= \underline{3159.5\ psi}$$ Max Bearing stress between concrete and Dowel

The maximum stress is at the dowel near to the edge so you don't have to consider the interior load.



$\Sigma = 4.93$ Effective Dowels

$$\frac{6000}{4.93} = 1217$$



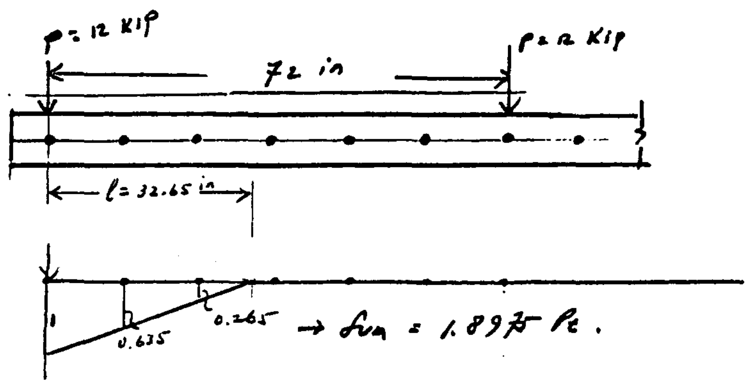
4-12:

Slab width = 12 ft = 144 in.

h : 10 in , k = 300 pci , Axle load = 24000 lb.

$$\ell = \sqrt[4]{\frac{E h^3}{12(1-\mu^2)k}} = \sqrt[4]{\frac{4\times10^6 \times 10^3}{12(1-0.15^2)300}} = 32.65 \text{ in.}$$

Max. ⊖ moment ⊖ occurs at a distance of ℓ = 1.0 ℓ = 32.65 in



→ Sum = 1.8975 Pt.

Since loading spacing = 72 in > ℓ = 32.65 in, only load near the pavement edge to be considered. The right wheel has no effect on the maximum force (P_t) on the dowel near the pavement edge.

If Joint 100% efficiency → $P_t = \frac{12000 \times 0.5}{1.8975} = 3162$ lb.

$I_d = \frac{1}{64}\pi d^4 = 0.0491 \text{ in}^4$ (d = 1 in).

$$\beta = \sqrt[4]{\frac{k\, d}{4 E_d I_d}} = \sqrt[4]{\frac{1.5\times10^6 \cdot 1}{4\times 29\times10^6 \times 0.0491}} = 0.7164$$

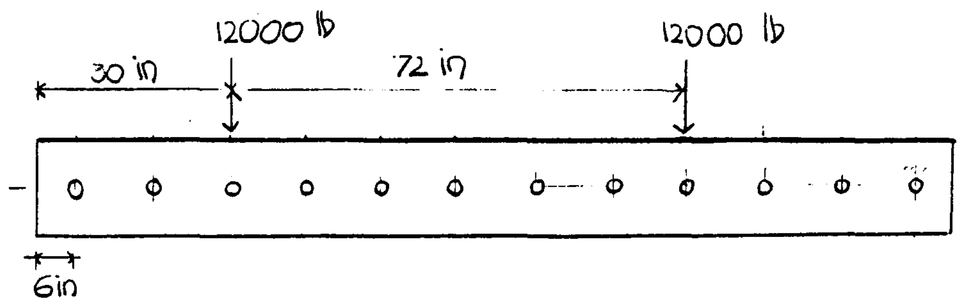
$$\sigma_b = \frac{k\ P_t}{4\beta^3 E_d\, I_d}(2+\beta z)$$

for z = 0.25

$$\sigma_b = \frac{1.5\times10^6 \times 3162}{4\times 0.7164^3 \times 29\times10^6 \times 0.0491}(2 + 0.7164\times 0.25)$$

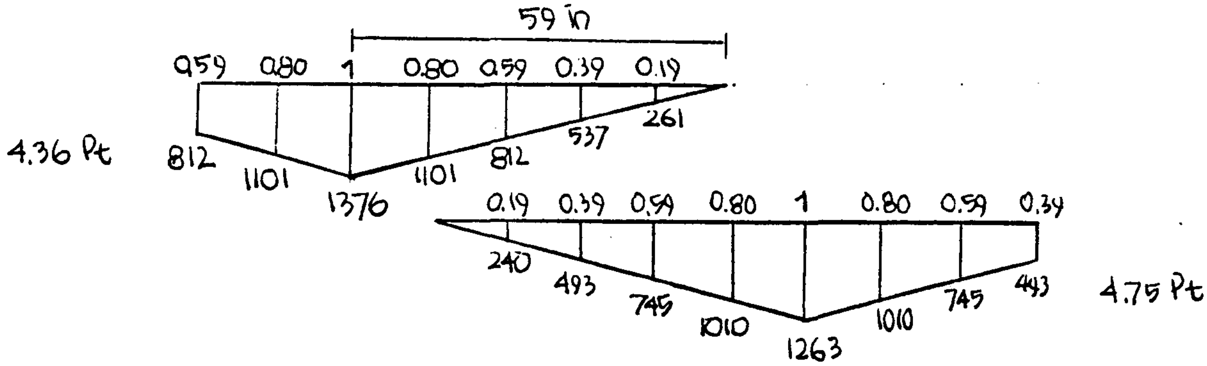
$= \underline{4935}$ psi ✓

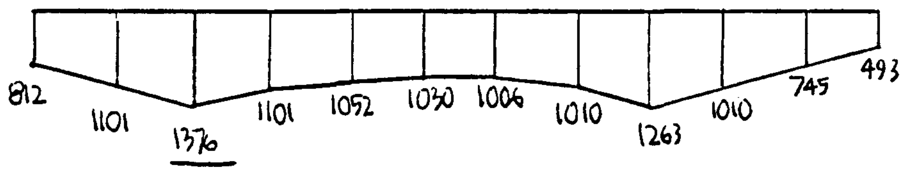
4.13.



$$\ell = \sqrt[4]{\frac{Eh^3}{12(1-\nu^2)k}} = \sqrt[4]{\frac{4\times10^6 \times 10^3}{12(1-0.15^2)\,300}} = 32.65 \text{ in}$$

$\rightarrow \; 1.8\,\ell \approx 59$ in.





$$I_d = \frac{1}{64}\pi (d)^4 = \frac{1}{64}\pi\, 1^4 = 0.049$$

$$\beta = \sqrt[4]{\frac{K_d}{4E_d I_d}} = \sqrt[4]{\frac{(1.5\times10^6)\,1}{4(29\times10^6)\,0.049}} = 0.717 \text{ in}^{-1}$$

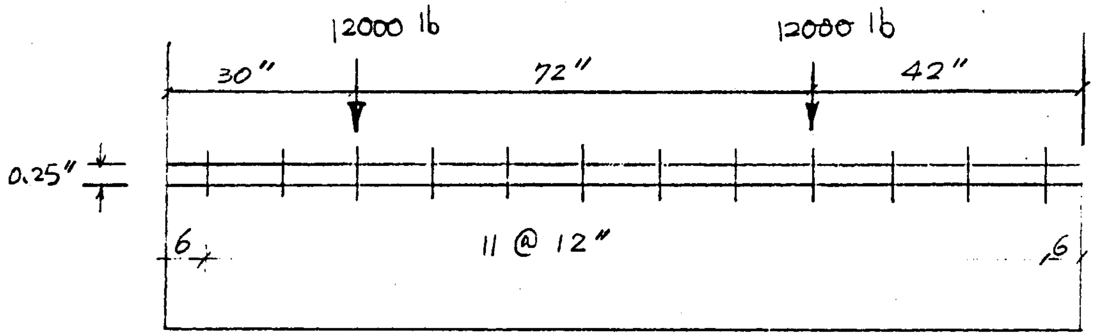
$$\sigma_b = \frac{K P_t}{4\beta^3 E_d I_d}(2+\beta z) = \frac{(1.5\times10^6)\,1376}{4(0.717)^3(29\times10^6)(0.049)}(2+0.717\times0.25)$$

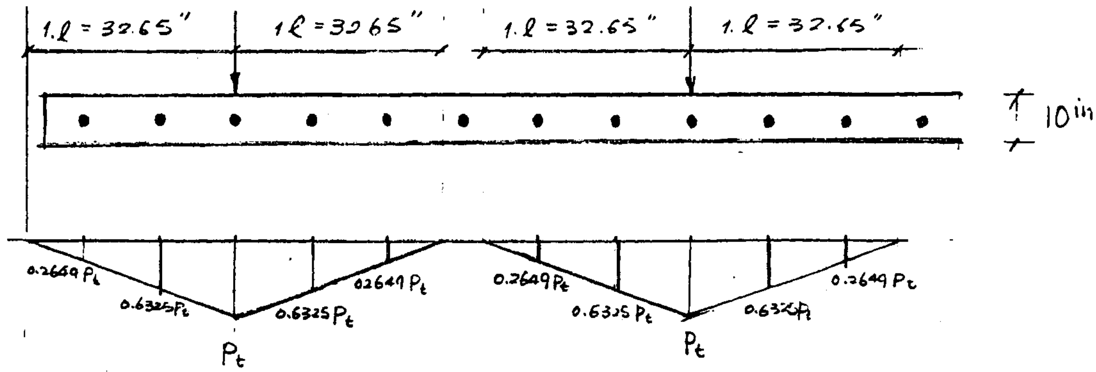
$\sigma_b = \underline{2147}$ psi.

4-14. Given:

$B = 12$ ft $= 144$ in
$h = 10$ in
$K = 300$ pci
$E_c = 4\times10^6$ psi
$\nu_c = 0.15$
$E_s = 29\times10^6$ psi
$\nu_s = 0.3$

100% transfer.
$z = 0.12$ in
$1.0\,\ell$
$d = 1$ in
$K_d = 1.5\times10^6$ psi
$E_d = 29\times10^6$ psi





SUM: $2.7948\ P_t = 12000\ \text{lb}/2$, $P_t = 2146\ \text{lb}$ $\qquad$ $2.7948\ P_t = 12000\ \text{lb}/2$, $P_t = 2146\ \text{lb}$

$$\ell = \sqrt[4]{\frac{Eh^3}{12(1-\nu^2)K}} = \sqrt[4]{\frac{4*10^6*10^3}{12*(1-0.15^2)*300}} = 32.65 \text{ in}$$

$$I_d = \frac{1}{64}\pi d^4 = \frac{1}{64}*\pi*1^4 = 0.0491 \text{ in}^4$$

$$\beta = \sqrt[4]{\frac{K_t d}{4E_d I_d}} = \sqrt[4]{\frac{1.5*10^6*1}{4*29*10^6*0.0491}} = 0.7164 \text{ in}^{-1}$$

$$\sigma_b = \frac{K_d P_t}{4\beta^3 E_d \cdot I_d}(2+\beta z) = \frac{1.5*10^6*2146*(2+0.7164*0.\ )}{4*0.7164^3*29*10^6*0.0491}$$

$$= \underline{3206.4} \text{ psi}$$

Chapter 5
KENSLABS Computer Program

5-1.

(a) Given $\sigma = 400$ psi and h = 7 in, find bending moment per in. width of slab

$\sigma = 6M/h^2$, so $M = \sigma h^2/6 = (400 \times 49)/6 = \underline{3267}$ lb-in./in. of slab.

(b) Given: $E_1 = 7 \times 10^5$ psi, $E_2 = 4 \times 10^6$ psi and two bonded layer with h_1 = 3 in. and h_2 = 5 in. Find bending stress at top and bottom. With $E_1/E_2 = 0.175$, from Eq. 5.8,

$$d = \frac{0.175x3(0.5x3 + 7) + 0.5(7)^2}{0.175x3 + 7} = 3.849 \text{ in.} \quad \text{From Eq.5.9,}$$

$$I_c = 0.175\left[\frac{1}{12}(3)^3 + 3(0.5x3 + 7 - 3.849)^2\right] + \frac{1}{12}(7)^3 + 7(3.849 - 0.5x7)^2$$

$$= 11.750 + 28.583 + 0.853 = 41.186 \text{ in}^3$$

Bending stress at bottom of PCC

$$f_2 = \frac{3267x3.849}{41.186} = \underline{305.3} \text{ psi}$$

Bending stress at top of HMA

$$f_1 = \frac{3267x(10 - 3.849)}{41.186} x0.175 = \underline{85.4} \text{ psi}$$

5-2. Same as 5-1, but the two layers are unbonded.

From Eqs. 5.12, the modulus of rigidity of each layer

$$R_1 = \frac{7x10^5 x(3)^3}{12[1 - (0.4)^2]} = 1.875x10^6 \text{ lb} - \text{in.}^2$$

$$R_2 = \frac{4x10^6 x(7)^3}{12[1 - (0.15)^2]} = 1.1696x10^8 \text{ lb} - \text{in.}^2$$

$R_1 + R_2 = 1.1884 \times 10^8$ The moment carried by each layer is proportional to R,

$M_1 = (1.875 \times 10^6/1.1884 \times 10^8) \times 3267 = 51.545$ in.-lb/in.

$M_2 = 3267 - 51.545 = 3215.455$ in.-lb/in.

$f_1 = (51.545 \times 6)/(3)^2 = \underline{34.4}$ psi

$f_2 = (3215.455 \times 6)/(7)^2 = \underline{393.7}$ psi

```
1   (1) NPROB
Problem 5-3
0  0  1  1  (3) NFOUND NDAMA NPY NLG
1  0  (4) NSLAB NJOINT
9   6   0   0   0   0   (5) NX NY JONO1 JONO2 JONO3 JONO4
1  1  0  0  0  0  0  1  0  1  0  0  9  6  0  0  2  1  2 (6) NLAYER NNCK NOTCON NGAP
NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL
-24 150 0 500 0 0.000005 0.001  1   (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX
17.61   0   17.61   0   (8) F1(1) F1(2) F2(1) F2(2)
0  12  28  44  60  76  92  108  120  0 12  28  44  60  72   (9) X's and then Y's
8   0.15   4000000   (10) T PR YM
0   (12) NUDL
0   (13) NCNF
0   0   (14) NNMX NNMY
6   12   18   24   30   36   42   48   54   (19) NODSX
49   50   51   52   53   54   (20) NODSY
1   (22) FSAF
0   50   (24) NAS SUBMOD
```

Answer: at Node 54   -214.269 psi

49   -207.423 psi

6   -57.865 psi

```
1  (1) NPROB
Problem 5.4
0  0  1  1  (3) NFOUND NDAMA NPY NLG
1  0  (4) NSLAB NJOINT
7   6   0   0   0   0   (5) NX NY JONO1 JONO2 JONO3 JONO4
1  1  0  0  0  0  0  0  0  1  0  0  0  0  0  0  1  2  2 (6) NLAYER NNCK NOTCON NGAP
NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL
0 150  0 500 0  0.000005  0.001  1   (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX
17.61  0   17.61   0   (8) F1(1) F1(2) F2(1) F2(2)
0   12   24   36   54   78   120   0  17.6  36   54   78   120   (9) X's and then Y's
10   0.15   4000000   (10) T PR YM
2   (12) NUDL
0   (13) NCNF
0   0   (14) NNMX NNMY
1   0   10.44   0   7.19   79.932   (15) LS XL1 XL2 YL1 YL2 QQ
1   0   10.44   14.005   21.195   79.932   (15) LS XL1 XL2 YL1 YL2 QQ
1   (22) FSAF
0   200   (24) NAS SUBMOD
```

answer: at node 20   174.576 psi

```
1  (1) NPROB
Problem 5.5
0  0  1  1  (3) NFOUND NDAMA NPY NLG
1  0  (4) NSLAB NJOINT
7   7   0   0   0   0   (5) NX NY JONO1 JONO2 JONO3 JONO4
1  1  0  0  0  0  0  0  0  1  0  0  7  7  0  0  1  2  2 (6) NLAYER NNCK NOTCON NGAP
NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL
0 150 0 500 0  0.000005  0.001  1   (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX
17.61   0   17.61   0   (8) F1(1) F1(2) F2(1) F2(2)
0   7   14   26   48   83   118  0   7   14   26   48   83   118   (9) X's and then Y's
10   0.15   4000000   (10) T PR YM
1   (12) NUDL
0   (13) NCNF
0   0   (14) NNMX NNMY
1  0  5.22  3.405  10.595  79.932  (15) LS XL1 XL2 YL1 YL2 QQ
1   8   15   22   29   36   43   (19) NODSX
1   2   3   4   5   6   7   (20) NODSY
1   (22) FSAF
0   200   (24) NAS SUBMOD
```

answer: at Node 2   -128.407

```
1  (1) NPROB
Problem 5.6
0  0  1  1  (3) NFOUND NDAMA NPY NLG
1  0  (4) NSLAB NJOINT
7  7  0  0  0  0  (5) NX NY JONO1 JONO2 JONO3 JONO4
1 1 0 0 0 0 0 0 0 1 0 0 0 7 0 0 1 2 2 (6) NLAYER NNCK NOTCON NGAP
NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL
0 150 0 500 0  0.000005  0.001  1  (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX
17.61  0  17.61  0  (8) F1(1) F1(2) F2(1) F2(2)
0  8  18  30  54  84  120  0  8  17.6  30  54  84  120  (9) X's and then Y's
10  0.15  4000000  (10) T PR YM
2  (12) NUDL
0  (13) NCNF
0  0  (14) NNMX NNMY
1  0  5.22  0  7.19  79.932  (15) LS XL1 XL2 YL1 YL2 QQ
1  0  5.22  14.005  21.195  79.932  (15) LS XL1 XL2 YL1 YL2 QQ
1  2  3  4  5  6  7  (20) NODSY
1  (22) FSAF
0  200  (24) NAS SUBMOD
```

answer: at Node 1 -251.392 psi

```
1  (1) NPROB
Problem 5.7
0  0  1  1  (3) NFOUND NDAMA NPY NLG
1  0  (4) NSLAB NJOINT
7  7  0  0  0  0  (5) NX NY JONO1 JONO2 JONO3 JONO4
1 1 0 0 0 0 0 0 0 1 0 0 7 7 0 0 1 2 2 (6) NLAYER NNCK NOTCON NGAP
NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL
0 150 0 500 0  0.000005  0.001  1  (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX
17.61  0  17.61  0  (8) F1(1) F1(2) F2(1) F2(2)
0  10  20  40  60  90  120  0  10  20  40  60  90  120  (9) X's and then Y's
8  0.15  4000000  (10) T PR YM
1  (12) NUDL
0  (13) NCNF
0  0  (14) NNMX NNMY
1  13.975  26.025  5.85  14.15  99.985  (15) LS XL1 XL2 YL1 YL2 QQ
1  8  15  22  29  36  43  (19) NODSX
1  2  3  4  5  6  7  (20) NODSY
1  (22) FSAF
0  100  (24) NAS SUBMOD
```

answer: at Node 1 -299.320 psi

```
1  (1) NPROB
Problem 5.8
0  0  1  1  (3) NFOUND NDAMA NPY NLG
1  0  (4) NSLAB NJOINT
7  7  0  0  0  0  (5) NX NY JONO1 JONO2 JONO3 JONO4
1 1 0 0 0 0 0 0 0 1 0 0 0 7 0 0 1 2 2 (6) NLAYER NNCK NOTCON NGAP
NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL
0 150 0 500 0  0.000005  0.001  1  (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX
17.61  0  17.61  0  (8) F1(1) F1(2) F2(1) F2(2)
0  10  20  40  60  90  120  0  12  24.15  36  60  90  120  (9) X's and then Y's
8  0.15  4000000  (10) T PR YM
2  (12) NUDL
0  (13) NCNF
0  0  (14) NNMX NNMY
1  13.975  26.025  0  8.3  99.985  (15) LS XL1 XL2 YL1 YL2 QQ
1  13.975  26.025  20  28.3  99.985  (15) LS XL1 XL2 YL1 YL2 QQ
1  2  3  4  5  6  7  (20) NODSY
1  (22) FSAF
0  100  (24) NAS SUBMOD
```

answer: at Node 1 -314.844 psi

```
1  (1) NPROB
Problem 5.9
0  0  1  1  (3) NFOUND NDAMA NPY NLG
1  0  (4) NSLAB NJOINT
8   6   0   0   0   0   (5) NX NY JONO1 JONO2 JONO3 JONO4
1  1  0  0  0  0  0  1  0  1  0  0  0  6  0  0  1  1  2 (6) NLAYER NNCK NOTCON NGAP
NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL
13.5 150 0 500 0 0.000005  0.001 1 (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX
17.61   0   17.61   0   (8) F1(1) F1(2) F2(1) F2(2)
0   12   30   54   90  138  186  240  0  12   24   48  84  132   (9) X's and then Y's
9   0.15   4000000   (10) T PR YM
1   (12) NUDL
0   (13) NCNF
0   0   (14) NNMX NNMY
1   0   4.744   0   9.487   99.997   (15) LS XL1 XL2 YL1 YL2 QQ
1   2   3   4   5   6   (20) NODSY
1   (22) FSAF
0   200   (24) NAS SUBMOD
```

answer: at Node 1 -158.257 psi

```
1  (1) NPROB
Problem 5.10
0  0  1  1  (3) NFOUND NDAMA NPY NLG
2  1  (4) NSLAB NJOINT
6   9   0   1   0   0   (5) NX NY JONO1 JONO2 JONO3 JONO4
6   9   1   0   0   0   (5) NX NY JONO1 JONO2 JONO3 JONO4
1  46  0  0  0  0  0  0  0  1  0  0  0  0  0  0  1  2  2 (6) NLAYER NNCK NOTCON NGAP
NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL
0 150 0 500 0  0.000005  0.001  1  (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX
17.61   0   17.61   0   (8) F1(1) F1(2) F2(1) F2(2)
0   30   60   90  108 120  0  12  24  42  66  78  90  117  144   (9) X's and then Y's
0   12   30   60  90  120  0  12  24  42  66  78  90  117  144   (9) X's and then Y's
10   0.15   4000000   (10) T PR YM
2   (12) NUDL
0   (13) NCNF
0   0   (14) NNMX NNMY
1   108   120   0   12   83.333   (15) LS XL1 XL2 YL1 YL2 QQ
1   108   120   72   84   83.333   (15) LS XL1 XL2 YL1 YL2 QQ
1   (22) FSAF
0   300   (24) NAS SUBMOD
29000000  0.3  (34) YMSB PRSB
0   0   1500000   1   12   0.25   0   0   (35) SPCON1 SPCON2 SCKV BD BS WJ GDC NNAJ
```

answer: at node 46 -4529.8 psi

```
1  (1) NPROB
Problem 5.11
0  0  1  1  (3) NFOUND NDAMA NPY NLG
2  1  (4) NSLAB NJOINT
6   14   0   1   0   0   (5) NX NY JONO1 JONO2 JONO3 JONO4
6   14   1   0   0   0   (5) NX NY JONO1 JONO2 JONO3 JONO4
1  46  0  0  0  0  0  0  0  1  0  0  0  0  0  0  1  2  2 (6) NLAYER NNCK NOTCON NGAP
NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL
0 150 0 500 0  0.000005  0.001  1  (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX
17.61   0   17.61   0   (8) F1(1) F1(2) F2(1) F2(2)
0   30   60   90   108   120   0   6   18   30   42   54   66   78   90   102   114
126   138   144   (9) X's and then Y's
0   12   30   60   90   120   0   6   18   30   42   54   66   78   90   102   114
126   138   144   (9) X's and then Y's
10   0.15   4000000   (10) T PR YM
2   (12) NUDL
0   (13) NCNF
0   0   (14) NNMX NNMY
1   108   120   0   12   83.333   (15) LS XL1 XL2 YL1 YL2 QQ
```

answer: at Node 72 -4042.9 psi
78 -170.826 psi
71 0.02277 in.

```
1   108   120   72   84   83.333   (15) LS XL1 XL2 YL1 YL2 QQ
1   (22) FSAF
0   300   (24) NAS SUBMOD
29000000  0.3  (34) YMSB PRSB
0   0   1500000   1   12   0.25   0   14   (35) SPCON1 SPCON2 SCKV BD BS WJ GDC NNAJ
0   1   1   1   1   1   1   1   1   1   1   1   1   0   (36) BARNO
```

```
1  (1) NPROB
Problem 5.12
0  0  1  1  (3) NFOUND NDAMA NPY NLG
2  1  (4) NSLAB NJOINT
6   9   0   1   0   0   (5) NX NY JONO1 JONO2 JONO3 JONO4
6   9   1   0   0   0   (5) NX NY JONO1 JONO2 JONO3 JONO4
1  46  0  0  0  0  0  0  1  0  0  0  0  0  0  1  2  2 (6) NLAYER NNCK NOTCON NGAP
NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL
0 150 0 500 0  0.000005  0.001  1   (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX
17.61   0   17.61   0   (8) F1(1) F1(2) F2(1) F2(2)
0  30  60  90  108  120  0  12  24  42  66  78  90   117   144   (9) X's and then Y's
0  12  30  60  90   120  0  12  24  42  66  78  90   117   144   (9) X's and then Y's
10   0.15   4000000   (10) T PR YM
2   (12) NUDL
0   (13) NCNF                answer: at Node 46    -3829.1 psi
0   0   (14) NNMX NNMY
1   108   120   0   12   83.333   (15) LS XL1 XL2 YL1 YL2 QQ
1   108   120   72   84   83.333   (15) LS XL1 XL2 YL1 YL2 QQ
1   (22) FSAF
0   300   (24) NAS SUBMOD
29000000  0.3  (34) YMSB PRSB
0   0  1500000   1   12   0.25   0.01   0   (35) SPCON1 SPCON2 SCKV BD BS WJ GDC NNAJ
```

```
1  (1) NPROB
Problem 5.13
0  0  1  1  (3) NFOUND NDAMA NPY NLG
2  1  (4) NSLAB NJOINT
6  6   0   1   0   0   (5) NX NY JONO1 JONO2 JONO3 JONO4
6   6   1   0   0   0   (5) NX NY JONO1 JONO2 JONO3 JONO4
1  34  0  0  0  0  0  0  0  1  0  0  12  0  0  0  2  2  1 (6) NLAYER NNCK NOTCON NGAP
NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL
0 150 0 500 0  0.000005  0.001 10   (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX
17.61   0   17.61   0   (8) F1(1) F1(2) F2(1) F2(2)
0   30   60   90   108   120   0   15   30   42   54   72   (9) X's and then Y's
0   12   30   60   90    120   0   15   30   42   54   72   (9) X's and then Y's
10   0.15   4000000   (10) T PR YM
0   (12) NUDL
1   (13) NCNF                answer: at Node 34    -2267.0 psi
0   0   (14) NNMX NNMY
34   12000   (16) NN FF
1   7   13   19   25   31   37   43   49   55   61   67   (19) NODSX
1   (22) FSAF
0   300   (24) NAS SUBMOD
29000000  0.3  (34) YMSB PRSB
0   0   1500000   1   12   0.25   0   0   (35) SPCON1 SPCON2 SCKV BD BS WJ GDC NNAJ
```

```
1  (1) NPROB
Problem 5.14
0  0  1  1  (3) NFOUND NDAMA NPY NLG
2  1  (4) NSLAB NJOINT
6   8   0   1   0   0   (5) NX NY JONO1 JONO2 JONO3 JONO4
6   8   1   0   0   0   (5) NX NY JONO1 JONO2 JONO3 JONO4
1  45  0  0  0  0  0  0  0  1  0  0  12  0  0  0  2  2  1 (6) NLAYER NNCK NOTCON NGAP
```

```
NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL
0 150 0 500 0  0.000005  0.001 10  (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX
17.61   0   17.61   0   (8) F1(1) F1(2) F2(1) F2(2)
0   30   60   90   108   120   0   6   18   30   42   54   66   72   (9) X's and then Y's
0   12   30   60   90   120   0   6   18   30   42   54   66   72   (9) X's and then Y's
10   0.15   4000000   (10) T PR YM
0   (12) NUDL
1   (13) NCNF
0   0   (14) NNMX NNMY
45   12000   (16) NN FF
1   9   17   25   33   41   49   57   65   73   81   89   (19) NODSX
1   (22) FSAF
0   300   (24) NAS SUBMOD
29000000   0.3   (34) YMSB PRSB
0   0   1500000   1   12   0.25   0   8   (35) SPCON1 SPCON2 SCKV BD BS WJ GDC NNAJ
0   1   1   1   1   1   1   0   (36) BARNO
```

answer: at Node 45 -2284.2 psi

```
1  (1) NPROB
Problem 5.15
0  0  1  1  (3) NFOUND NDAMA NPY NLG
2  1  (4) NSLAB NJOINT
6   6   0   1   0   0   (5) NX NY JONO1 JONO2 JONO3 JONO4
6   6   1   0   0   0   (5) NX NY JONO1 JONO2 JONO3 JONO4
1  34  0  0  1  0  0  0  0  1  0  0  12  0  0  0  2  2  1 (6) NLAYER NNCK NOTCON NGAP
NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL
0 150 0 500 0  0.000005  0.001  1  (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX
17.61   0   17.61   0   (8) F1(1) F1(2) F2(1) F2(2)
0   30   60   90   108   120   0   15   30   42   54   72   (9) X's and then Y's
0   12   30   60   90   120   0   15   30   42   54   72   (9) X's and then Y's
10   0.15   4000000   (10) T PR YM
0   (12) NUDL
1   (13) NCNF
0   0   (14) NNMX NNMY
34   12000   (16) NN FF
34   (18) NP
1   7   13   19   25   31   37   43   49   55   61   67   (19) NODSX
1   (22) FSAF
0   300   (24) NAS SUBMOD
29000000   0.3   (34) YMSB PRSB
0   0  1500000   1   12   0.25   0.01   0   (35) SPCON1 SPCON2 SCKV BD BS WJ GDC NNAJ
```

Answer: at Node 34 -1655.9 psi

```
1  (1) NPROB
Problem 5.16
0  0  1  1  (3) NFOUND NDAMA NPY NLG
1  0  (4) NSLAB NJOINT
9   6   0   0   0   0   (5) NX NY JONO1 JONO2 JONO3 JONO4
1  22  0  0  0  0  0  0  0  1  0  0  9  6  0  0  1  2  2 (6) NLAYER NNCK NOTCON NGAP
NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL
0 150 0 500 0  0.000005  0.001  1  (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX
17.61   0   17.61   0   (8) F1(1) F1(2) F2(1) F2(2)
0  14  28  41  54  72  96  132  168  0  10  20  29.5  38.75  48  (9) X's and then Y's
8   0.15   4000000   (10) T PR YM
1   (12) NUDL
0   (13) NCNF
0   0   (14) NNMX NNMY
1   37.5   44.5   23.5   35.5   150   (15) LS XL1 XL2 YL1 YL2 QQ
1   7   13   19   25   31   37   43   49   (19) NODSX
1   2   3   4   5   6   (20) NODSY
1   (22) FSAF
0   150   (24) NAS SUBMOD
```

Answer: at Node 22 -283.756 psi

```
1  (1) NPROB
Problem 5.17
1  0  1  1  (3) NFOUND NDAMA NPY NLG
2  1  (4) NSLAB NJOINT
6   14   0   1   0   0    (5) NX NY JONO1 JONO2 JONO3 JONO4
6   14   1   0   0   0    (5) NX NY JONO1 JONO2 JONO3 JONO4
1  46  0  0  42  0  0  0  0  1  0  0  0  0  0  1  2  2 (6) NLAYER NNCK NOTCON NGAP
NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL
0 150 0 500 0  0.000005  0.001  1  (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX
17.61   0   17.61   0    (8) F1(1) F1(2) F2(1) F2(2)
0   30   60   90   108   120   0   6   18   30   42   54   66   78   90   102   114
126   138   144   (9) X's and then Y's
0   12   30   60    90   120   0   6   18   30   42   54   66   78   90   102   114
126   138   144   (9) X's and then Y's
```

Answer: at Node 72 -3087.4 psi
78 -185.269 psi
71 0.02249 in.

```
10   0.15   4000000   (10) T PR YM
2   (12) NUDL
0   (13) NCNF
0   0   (14) NNMX NNMY
1   108   120   0   12   83.333   (15) LS XL1 XL2 YL1 YL2 QQ
1   108   120   72   84   83.333   (15) LS XL1 XL2 YL1 YL2 QQ
43   44   45   46   47   48   49   50   51   52   53   54   55   56   57   58   59
60   61   62   63   64   65   66   67   68   69   70   71   72   73   74   75   76
77   78   79   80   81   82   83   84   (18) NP
1   (22) FSAF
16000   0.4   (28) YMS PRS
29000000  0.3  (34) YMSB PRSB
0   0   1500000   1   12   0.25   0   14   (35) SPCON1 SPCON2 SCKV BD BS WJ GDC NNAJ
0   1   1   1   1   1   1   1   1   1   1   1   1   0   (36) BARNO


2  (1) NPROB
PROBLEM 5.18 (1st step)
1  0  1  1  (3) NFOUND NDAMA NPY NLG
2  1  (4) NSLAB NJOINT
7   8   0   1   0   0    (5) NX NY JONO1 JONO2 JONO3 JONO4
6   8   1   0   0   0    (5) NX NY JONO1 JONO2 JONO3 JONO4
1  49  0  0  11  0  0  0  1  10  0  0  0  0  0  0  2  1  2 (6) NLAYER NNCK NOTCON
NGAP NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL
0 150 0  0  0  0.000005  0.001  1  (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX
0   0   0   0   (8) F1(1) F1(2) F2(1) F2(2)
0  60  110  128  146  164  180  0  16  41  66  82  98  121  144   (9) X's and then Y's
0  16   40   80  120  180   0  16  41  66  82   98   121   144   (9) X's and then Y's
7   0.15   4000000   (10) T PR YM
0   (12) NUDL
0   (13) NCNF
0   0   (14) NNMX NNMY
17   25   29   33   41   49   50   51   52   53   54   (18) NP
1   (22) FSAF
5000   0.45   (28) YMS PRS
29000000  0.3  (34) YMSB PRSB
0   0   1500000   1   12   0.25   0   0   (35) SPCON1 SPCON2 SCKV BD BS WJ GDC NNAJ
PROBLEM 5.18 (2nd step)
1  0  1  1  (3) NFOUND NDAMA NPY NLG
2  1  (4) NSLAB NJOINT
7   8   0   1   0   0    (5) NX NY JONO1 JONO2 JONO3 JONO4
6   8   1   0   0   0    (5) NX NY JONO1 JONO2 JONO3 JONO4
1  49  0  0  11  1  0  0  0  10  0  0  0  0  0  0  1  1  2 (6) NLAYER NNCK NOTCON
NGAP NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL
0 150  0  0  0  0.000005 0.001  1  (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX
0   0   0   0   (8) F1(1) F1(2) F2(1) F2(2)
0  60  110  128  146  164  180  0  16  41  66  82  98  121  144   (9) X's and then Y's
0  16   40   80  120  180   0  16  41   66  82   98  121   144   (9) X's and then Y's
7   0.15   4000000   (10) T PR YM
8   (12) NUDL
0   (13) NCNF
```

```
0    0    (14)  NNMX NNMY
1    123.983    132.017    0    5.532    90.007    (15) LS XL1 XL2 YL1 YL2 QQ
1    123.983    132.017    13.234    18.766    90.007    (15) LS XL1 XL2 YL1 YL2 QQ
1    123.983    132.017    72.484    78.016    90.007    (15) LS XL1 XL2 YL1 YL2 QQ
1    123.983    132.017    85.984    91.516    90.007    (15) LS XL1 XL2 YL1 YL2 QQ
1    171.967    180    0    5.532    90.007    (15) LS XL1 XL2 YL1 YL2 QQ
1    171.967    180    13.234    18.766    90.007    (15) LS XL1 XL2 YL1 YL2 QQ
1    171.967    180    72.484    78.016    90.007    (15) LS XL1 XL2 YL1 YL2 QQ
1    171.967    180    85.984    91.516    90.007    (15) LS XL1 XL2 YL1 YL2 QQ
17   25    29    33    41    49    50    51    52    53    54    (18) NP
1    (22) FSAF
5000    0.45    (28) YMS PRS
29000000    0.3    (34) YMSB PRSB
0    0    1500000    1    12    0.25    0    0    (35) SPCON1 SPCON2 SCKV BD BS WJ GDC NNAJ
```

Answer: at Node 25   -226.331 psi
49   0.05384 in.

```
1  (1) NPROB
PROBLEM 5.19
1  2  2  3  (3) NFOUND NDAMA NPY NLG
1  0  (4) NSLAB NJOINT
9   9   0   0   0   0   (5) NX NY JONO1 JONO2 JONO3 JONO4
1  1  0  0  3  0  0  0  0  1  0  0  0  9  0  0  1  2  2 (6) NLAYER NNCK NOTCON NGAP
NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL
0  0  0  600 0 0.000005  0.001  1  (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX
14.75   0   17.61   0   (8) F1(1) F1(2) F2(1) F2(2)
0 12 24 36 48 72 96 132 168 0  10  20  39  58  77  97  120  144  (9) X's and then Y's
8    0.15    4000000    (10) T PR YM
4    4    8    (12) NUDL
0    (13) NCNF
0    0    (14) NNMX NNMY
1    0    4.042    0    5.567    100    (15) LS XL1 XL2 YL1 YL2 QQ
1    0    4.042    14.433    20    100    (15) LS XL1 XL2 YL1 YL2 QQ
1    0    4.042    77    82.567    100    (15) LS XL1 XL2 YL1 YL2 QQ
1    0    4.042    91.433    97    100    (15) LS XL1 XL2 YL1 YL2 QQ
1    19.958    28.042    0    5.567    100    (15) LS XL1 XL2 YL1 YL2 QQ
1    19.958    28.042    14.433    20    100    (15) LS XL1 XL2 YL1 YL2 QQ
1    19.958    28.042    77    82.567    100    (15) LS XL1 XL2 YL1 YL2 QQ
1    19.958    28.042    91.433    97    100    (15) LS XL1 XL2 YL1 YL2 QQ
1    0    4.042    0    5.567    100    (15) LS XL1 XL2 YL1 YL2 QQ
1    0    4.042    14.433    20    100    (15) LS XL1 XL2 YL1 YL2 QQ
1    0    4.042    77    82.567    100    (15) LS XL1 XL2 YL1 YL2 QQ
1    0    4.042    91.433    97    100    (15) LS XL1 XL2 YL1 YL2 QQ
1    43.958    52.042    0    5.567    100    (15) LS XL1 XL2 YL1 YL2 QQ
1    43.958    52.042    14.433    20    100    (15) LS XL1 XL2 YL1 YL2 QQ
1    43.958    52.042    77    82.567    100    (15) LS XL1 XL2 YL1 YL2 QQ
1    43.958    52.042    91.433    97    100    (15) LS XL1 XL2 YL1 YL2 QQ
1    19    37    (18) NP
1    2    3    4    5    6    7    8    9    (20) NODSY
1    0.8    (22) FSAF
5000    0.4    (28) YMS PRS
3650    3650    3650    (37) TNLR
3650    3650    3650    (37) TNLR
```

Answer: Design life for Example 4 is 17.44 years.

If F1 = 14.75, the design life is 17.41 years. The Secondary Cracking Index = 0.00000307 + 0.00001733 + 0.00000253 + 0.00002067 = 0.0000436, which is 0.076 % of a total of 0.057433.

```
2  (1) NPROB
PROBLEM 5.20 (first step)
2  0  1  1  (3) NFOUND NDAMA NPY NLG
2  1  (4) NSLAB NJOINT
8   9   0   1   0   0   (5) NX NY JONO1 JONO2 JONO3 JONO4
8   9   1   0   0   0   (5) NX NY JONO1 JONO2 JONO3 JONO4
1  68  0  32  0  0  0  1  1  10  0  0  1  0  1  0  2  1  2 (6) NLAYER NNCK NOTCON
NGAP NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL
-20 150 135 0  0  0.000005 0.001 1 (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX
0   0   0   0   (8) F1(1) F1(2) F2(1) F2(2)
0  40  80 120 140 160 170 180 0  26  52  62  72  82  92 118 144  (9) X's and then Y's
0  10  20  40  60 100 140 180 0  26  52  62  72  82  92 118 144  (9) X's and then Y's
10   0.15   4000000   (10) T PR YM
0   (12) NUDL
0   (13) NCNF
0   0   (14) NNMX NNMY
1   (19) NODSX
9   0.05   18   0.05   27   0.05   36   0.05   45   0.05   54   0.05   63   0.05   72
0.05   81   0.05   90   0.05   99   0.05   108   0.05   117   0.05   126   0.05   135
0.05   144   0.05   64   0.05   65   0.05   66   0.05   67   0.05   68   0.05   69
0.05   70   0.05   71   0.05   73   0.05   74   0.05   75   0.05   76   0.05   77
0.05   78   0.05   79   0.05   80   0.05   (21) NG CURL
1   (22) FSAF
2   30   (30) NL MAXIC
8   (31) TH
20000   5000   (32) E
0.3   0.4   (33) PRBF
29000000  0.3  (34) YMSB PRSB
0   0   1000000   1   12   0.125   0   0   (35) SPCON1 SPCON2 SCKV BD BS WJ GDC NNAJ
PROBLEM 5.20 (second step)
2  0  1  1  (3) NFOUND NDAMA NPY NLG
2  1  (4) NSLAB NJOINT
8   9   0   1   0   0   (5) NX NY JONO1 JONO2 JONO3 JONO4
8   9   1   0   0   0   (5) NX NY JONO1 JONO2 JONO3 JONO4
1  68  0  0  0  1  0  0  0  10  0  0  1  0  0  0  1  1  2 (6) NLAYER NNCK NOTCON NGAP
NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL
0 150 135 0  0  0.000005 0.001  1  (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX
0   0   0   0   (8) F1(1) F1(2) F2(1) F2(2)
0  40  80 120 140 160 170 180 0  26  52  62  72  82  92 118 144  (9) X's and then Y's
0  10  20  40  60 100 140 180 0  26  52  62  72  82  92 118 144  (9) X's and then Y's
10   0.15   4000000   (10) T PR YM
1   (12) NUDL
0   (13) NCNF
0   0   (14) NNMX NNMY
1   170   180   67   77   200   (15) LS XL1 XL2 YL1 YL2 QQ
1   (19) NODSX
1   (22) FSAF
2   30   (30) NL MAXIC
8   (31) TH
20000   5000   (32) E
0.3   0.4   (33) PRBF
29000000  0.3  (34) YMSB PRSB
0   0   1000000   1   12   0.125   0   0   (35) SPCON1 SPCON2 SCKV BD BS WJ GDC NNAJ
```

Answer: at Node 68   -459.416 psi
at Node 68   -2407.9 psi

```
1   (1) NPROB
Problem 5.21
1  0  1  1  (3) NFOUND NDAMA NPY NLG
2  1  (4) NSLAB NJOINT
6   6   0   1   0   0   (5) NX NY JONO1 JONO2 JONO3 JONO4
6   6   1   0   0   0   (5) NX NY JONO1 JONO2 JONO3 JONO4
1  34  0  0  1  0  0  0  0  1  0  0  12  0  0  0  2  2  1 (6) NLAYER NNCK NOTCON NGAP
NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL
0  150  0 500  0 0.000005 0.001  1 (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX
17.61   0   17.61   0   (8) F1(1) F1(2) F2(1) F2(2)
0   30   60   90   108   120   0   15   30   42   54   72   (9) X's and then Y's
0   12   30   60   90   120   0   15   30   42   54   72   (9) X's and then Y's
10   0.15   4000000   (10) T PR YM
0   (12) NUDL
1   (13) NCNF
0   0   (14) NNMX NNMY
34   12000   (16) NN FF
34   (18) NP
1   7   13   19   25   31   37   43   49   55   61   67   (19) NODSX
1   (22) FSAF
15000   0.4   (28) YMS PRS
29000000  0.3  (34) YMSB PRSB
0   0   1500000   1   12   0.25   0   0   (35) SPCON1 SPCON2 SCKV BD BS WJ GDC NNAJ
```

Answer: at Node 34 -2050.2 psi

```
1  (1) NPROB
Problem 5.22
1  0  1  1  (3) NFOUND NDAMA NPY NLG
2  1  (4) NSLAB NJOINT
6   8   0   1   0   0   (5) NX NY JONO1 JONO2 JONO3 JONO4
6   8   1   0   0   0   (5) NX NY JONO1 JONO2 JONO3 JONO4
1  45  0  0  1  0  0  0  0  1  0  0  12  0  0  0  2  2  1 (6) NLAYER NNCK NOTCON NGAP
NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL
0 150 0 500 0  0.000005  0.001 10 (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX
17.61   0   17.61   0   (8) F1(1) F1(2) F2(1) F2(2)
0   30   60   90  108  120  0  6   18   30   42   54   66   72   (9) X's and then Y's
0   12   30   60   90  120  0  6   18   30   42   54   66   72   (9) X's and then Y's
10   0.15   4000000   (10) T PR YM
0   (12) NUDL
1   (13) NCNF
0   0   (14) NNMX NNMY
45   12000   (16) NN FF
45   (18) NP
1   9   17   25   33   41   49   57   65   73   81   89   (19) NODSX
1   (22) FSAF
15000   0.4   (28) YMS PRS
29000000  0.3  (34) YMSB PRSB
0   0   1500000   1   12   0.25   0   8   (35) SPCON1 SPCON2 SCKV BD BS WJ GDC NNAJ
0   1   1   1   1   1   1   0   (36) BARNO
```

Answer: at Node 45 -2063.2 psi

Chapter 6
Traffic Loading and Volume

6-1 $S_d = 34$ in

$P_d = 45{,}000/2 = 22500$ lb. $p = 100$ psi

$z = 25$ in

$$a = \sqrt{\frac{P_d}{\pi \cdot p}} = \sqrt{\frac{45000/2}{\pi \cdot 100}} = 8.46284$$

$$d = S_d - 2a = 34 - 2 \cdot 8.46284 = 17.0743 \text{ in}$$

1). Boyd and Foster Method.

$$\log(ESWL) = \log P_d + \frac{0.301 \log\left(\frac{2 \cdot z}{d}\right)}{\log\left(\frac{4 S_d}{d}\right)}$$

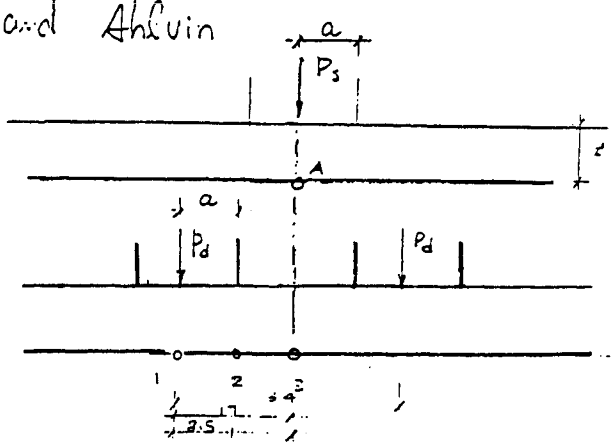
$$= \log 22500 + \frac{0.301 \log\left(\frac{2 \cdot 25}{17.0743}\right)}{\log\left(\frac{4 \cdot 34}{17.0743}\right)}$$

$$= 4.35218 + 0.301 \cdot 0.466671 / 0.901196$$

$$= 4.5080337$$

$$ESWL = \underline{32213.2} \text{ lb}$$

2). Foster and Ahlvin



Point No.	Left Wheel r/a	F	right wheel r/a	F	Sum F_d
1	0	0.48	4	0.22	0.60
2	1	0.42	3	0.27	0.69
3	2	0.35	2	0.35	0.70

$z/a = 2.954$

$$ESWL = \frac{0.70}{0.48} \times 22500 = \underline{32812.5} \text{ lb.}$$

c, Huang's Method.

$S_d = 34. \quad a = 8.46284$

$$a' = \frac{48}{S_d} * a = \frac{48}{34} * 8.46284 = \overset{11.948}{11.665}''$$

$h_1 = 25$

$$h_1' = \frac{48}{S_d} \times h_1 = \frac{48}{34} \times 25 = 35.294$$

$E_1/E_2 = 1$

$L_1 = 1.395$
$L_2 = 1.345$ } from Fig. 6.4

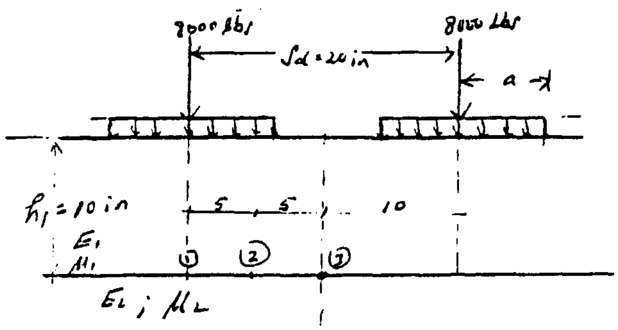
$$L = L_1 - (L_1 - L_2)\frac{a'-6}{10}$$

$$= 1.395 - (1.395 - 1.345) \times \frac{\overset{11.948}{11.665} - 6}{10}$$

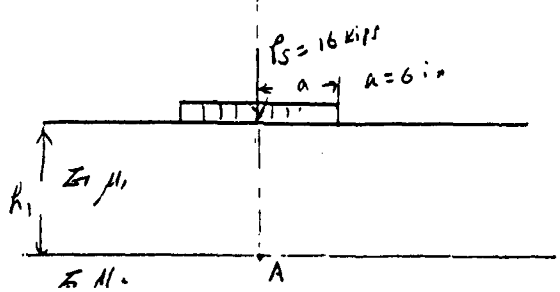
$$= 1.3666$$

$$ESWL = \frac{2P_d}{L} = \frac{2 * 22500}{1.3666} = \underline{32928.4} \text{ lb.}$$

6-2



$P_d = 8000$ lb.
$a = 6$ in
$E_1 = 250{,}000$ psi
$E_2 = 10{,}000$ psi
$\mu_1 = \mu_2 = 0.5$



a. Based on Equal interface deflection

single load :
$h_1/a = \frac{10}{6} = 1.667$
$r/a = 0$

using interface vertical deflection (Huang) fig. 2.19.
for $E_1/E_2 = 25 \rightarrow F = 0.35$

Dual loads : (for $E_1/E_2 = 25$ & $h_1/a = 1.667$) :
Using Interface def. (After Huang) :

POINT	Left Wheel r/a	Left Wheel F	Right Wheel r/a	Right Wheel F	SUM OF F
1	0	0.35	3.333	0.23	0.58
2	0.833	0.32	2.5	0.285	0.605
3	1.667	0.3	1.667	0.3	0.60

$F_d = 0.612$; $F_s = 0.35$

$$\frac{F_d}{F_s} = \frac{0.605}{0.35} = 1.73$$

$\therefore$ ESWL = 1.73 P_d = 1.73 x 8000 = 13840 lbs. ✓

b/ Based on tensile strain at the bottom of asphalt layer.
$S_d = 20$ in ; $a = 6$ in.

Using Fig. 2.23. Conversion factor for dual wheel (after Huang 1990)

$a' = \frac{24}{20} \cdot 6 = 7.2$ in

$h' = \frac{24}{20} \times 10 = 12$ in $\} \longrightarrow C_1 = 1.27$ ✓ $C_2 = 1.58$ ✓

$E_1/E_2 = 25$

$C = C_1 + 0.2\,(a' - 3) \times (C_2 - C_1)$

$= 1.3624$ ✓

ESWL = $C \times P_d$ = 1.3624 x 8000 = 10,899 lbs ✓

6-3. Given : 20 years = 20 * 365 days

1). TAI : table 6.4 2) $EALF = \left(\frac{L_x}{18}\right)^4$

L_x Axle Load (Kip)	F_i EALF	n_i Number per day	EALF
12	0.189	200	0.198
14	0.360	117.4	0.366
16	0.623	84.5	0.624
18	1.000	61.4	1.000
20	1.51	47.2	1.524
22	2.18	21.4	2.232
24	3.03	12.9	3.160
26	4.09	6.1	4.353
28	5.39	2.9	5.855
30	6.97	1.2	7.716
32	8.88	0.7	9.988
34	11.18	0.3	12.729

1) $$EAL = \sum_{i=1}^{12} F_i\, n_i * 365 * 20 = 2.99 * 10^6$$ ✓

2) $$EAL = \sum_{i=1}^{12} F_i\, n_i * 365 * 20 = 3.07 * 10^6$$

6-5

$$GY = \int_0^Y (1+r)^n \, dn = \left. \frac{(1+r)^n}{\ln(1+r)} \right|_0^Y$$

$$\ln(1+r) = r - \frac{1}{2}r^2 + \cdots\cdots\cdots$$

When r is much smaller than 1, the second and all the higher order terms can be neglected or

$\ln(1+r) = r$, so

$$GY = \frac{(1+r)^Y}{r} - \frac{1}{r} = \frac{(1+r)^Y - 1}{r}$$

The assumption is $r \lll 1$

6-6.

From Eq. 6.30 $ESAL = (ADT)_0 (T)(T_f)(G)(D)(L)(365)(Y)$

$(ADT)_0 (T) = 1{,}000$, From Table 6.10, $T_f = 0.52$

From Eq. 6.33 $(G)(Y) = \dfrac{(1+0.05)^{20} - 1}{0.05} = 33.06$

From Table 6.15 $(DL) = 0.45$

$ESAL = 1{,}000 \times 0.52 \times 0.45 \times 365 \times 33.06$

$= \underline{2{,}823{,}654}$

6-7

SINGLE AXLE

LOAD	EALF (TABLE 6.4)	NUMBER	ESAL
1.5	.0001	0	0
5	.005	3188	15.94
7.5	.02695	2843	76.61885
10	.0877	9942	871.9134
14	.36	3111	1119.96
17	.796	1899	1511.604
18.5	1.12	1078	1207.36
19.5	1.375	423	581.625
21	1.83	598	1094.34
23	2.58	144	371.52
25	3.53	6	21.18
28	5.39	6	32.34

TANDEM AXLE

LOAD	EALF (TABLE 6.4)	NUMBER	ESAL
3	0	7	0
9	0	2631	0
15	.036	2541	91.476
21	.148	2362	349.576
27	.426	3103	1321.878
30.75	.72925	703	512.66275
31.75	.831	141	117.171
33	.971	503	488.413
35	1.23	388	477.24
37	1.53	280	428.4
39	1.89	247	466.83
41	2.29	183	419.07
43	2.76	160	441.6
45	3.27	51	166.77
48	4.17	64	266.88
52	5.63	7	39.41

COMBINED ESAL FOR 24 DAY PERIOD	12491.778
ESAL DURING FIRST YEAR (365.25 DAYS)	190109

6-8.

Load kips	EALF Table 6.7	Number Table P6.7	ESAL col C x col D
Single Axle			
5	0.006	3188	19.128
7.5	0.0265	2843	75.3395
10	0.082	9942	815.244
14	0.341	3111	1060.851
17	0.802	1899	1522.998
18.5	1.1425	1078	1231.615
19.5	1.4275	423	603.8325
21	1.955	598	1169.09
23	2.85	144	410.4
25	4.015	6	24.09
28	6.29	6	37.74
			6970.328
Tandem Axle			
3	0.0003	7	0.0021
9	0.009	2631	23.679
15	0.065	2541	165.165
21	0.257	2362	607.034
27	0.736	3103	2283.808
30.75	1.271	703	893.513
31.75	1.446	141	203.886
33	1.705	503	857.615
35	2.175	388	843.9
37	2.73	280	764.4
39	3.385	247	836.095
41	4.145	183	758.535
43	5.015	160	802.4
45	6.005	51	306.255
48	7.73	64	494.72
52	10.6	7	74.2
		Sum	9915.2071
		Total Sum	16885.5351

$$\text{ESAL (for 1st year)} = \frac{16885.535}{24} \times 365.25$$

$$= \underline{256,977}$$

6-9

Total Vehicles Counted for 24 days

$= 12197$

Equivalent Total Vehicle Counted for One Year

$= 12197 * \frac{365}{24}$

$= 185496.0417$

Total EAL for One year

$= 191992.4$

Truck factor

$\frac{191992.4}{185496.0417} = \underline{1.035}$ ✓

6-10.

Total vehicle counted for 24 days $= 12{,}197$

Total vehicle counted for one year $= 12{,}197 \times \frac{365}{24}$

$= 185{,}500$

Total ESAL from problem 6-8 $= 257{,}000$

Truck factor $= \frac{257{,}000}{185{,}500} = \underline{1.38}$

Chapter 7
Material Characterization

7-1 . The result of repeated load tests on granular material :

Confining Press. (Psi)	Deviator Stress σ_d (Psi)	Recoverable Strain ε_r (10^{-4})	M_R (10^3) (Psi)	Stress Invariant θ (Psi)
2	6	5.8	10.345	12
5	15	7.4	20.270	30
10	30	9.5	31.579	60
20	60	11.4	52.632	120
2	6	6.0	10.000	12

Note:

$M_R = \frac{\sigma_d}{\varepsilon_r}$

$\theta = \sigma_1 + 2\sigma_3 = \sigma_d + 3\sigma_3$

The values of M_R vs. θ are plotted on log-log plot as shown in Fig. below.

Based on Regression analysis :

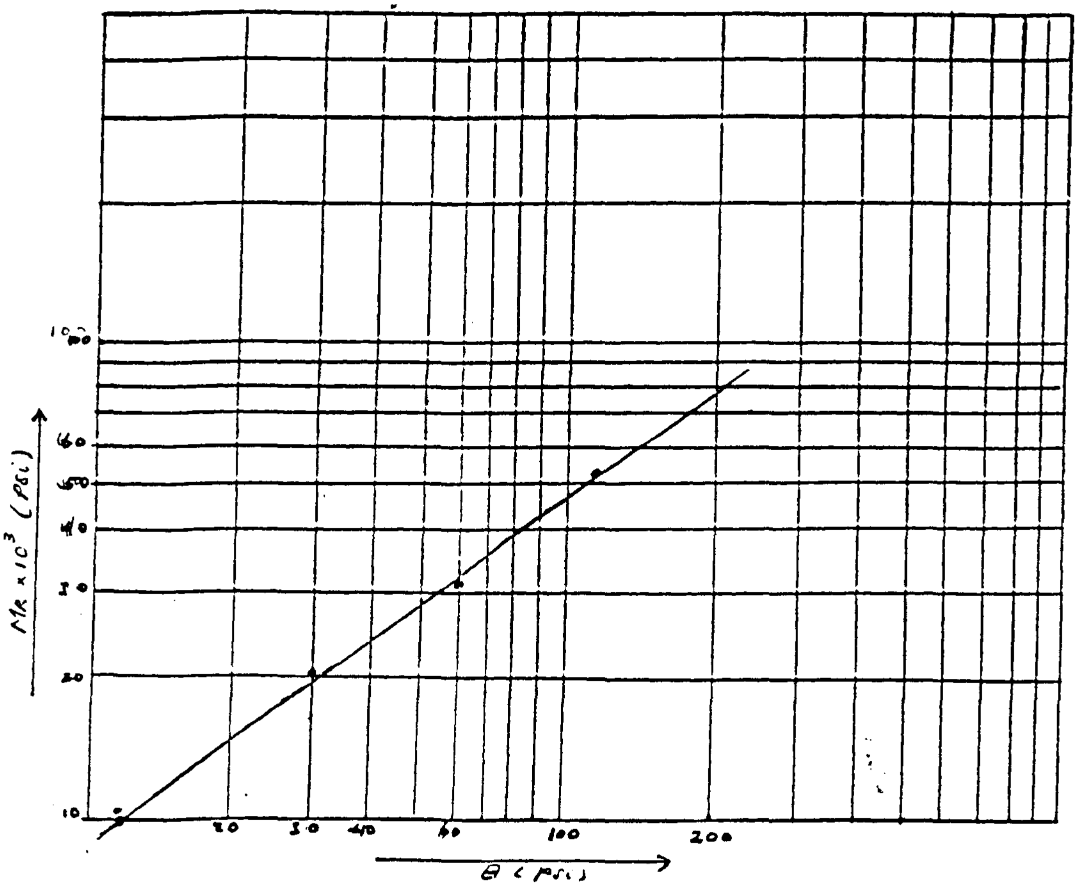
$\log M_R = 3.24308 + \overbrace{0.7109}^{s} \log \theta$.

For $\theta = 1$. psi . $\log M_R = 3.24308$

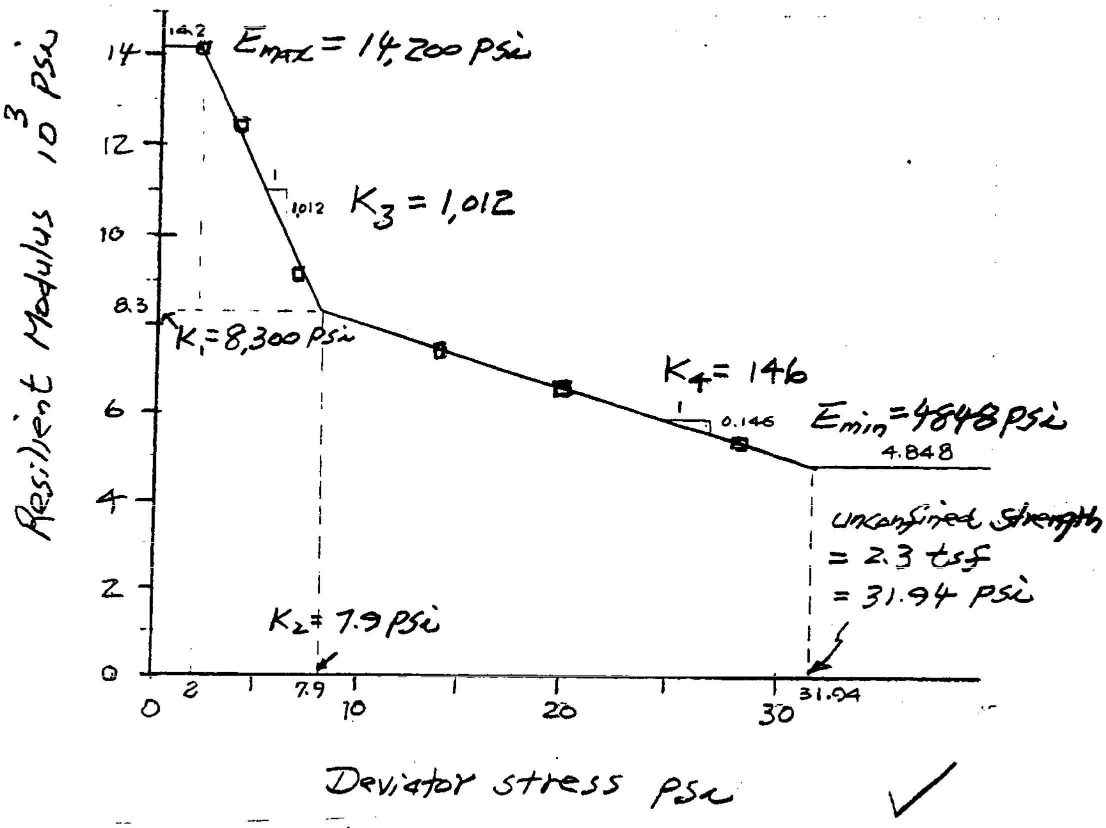
$M_R = 1750$ psi

Slope of the Regression line $= S = 0.7109$

Thus: $\boxed{M_R = 1750\ \theta^{0.7109}}$ ✓ See Page 52



7-2



7-3. The Results of a series of fatigue tests on HMA are as follows:

Test	Stress (psi)	E_s (psi)
1	278	1×10^5
2	254	1.14×10^5
3	228	1.15×10^5
4	197	1.34×10^5
5	180	1.60×10^5
6	165	2.07×10^5
7	137	2.12×10^5
8	115	2.78×10^5
9	91	3.15×10^5

The values of Log E_s & stress are plotted as shown

Based on Regression analysis:

$$\log E_s = 5.7664 - 2.861 \times 10^{-3}\, \sigma$$

for $\sigma = 0 \rightarrow \log E_s = 5.7664$

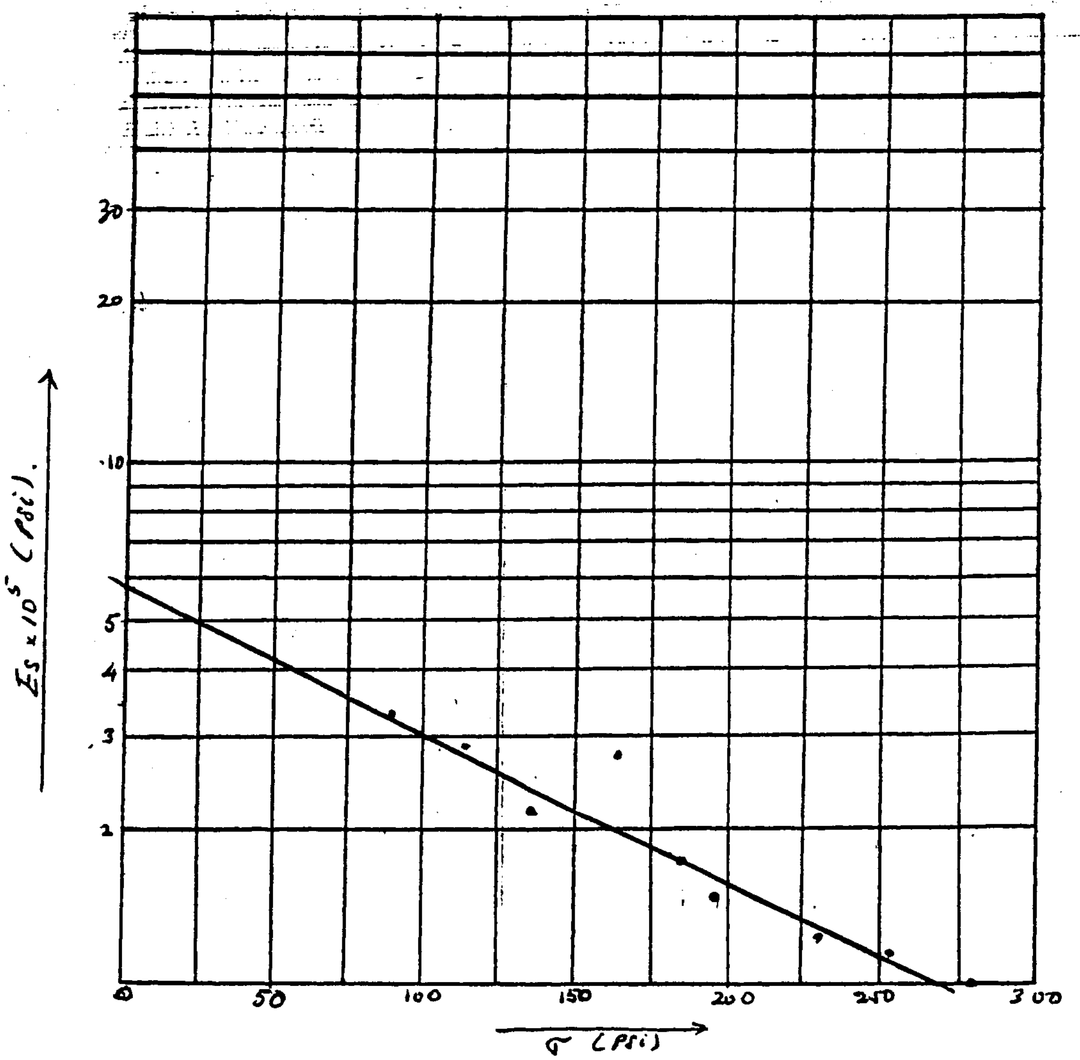
$E_s = E_0 = 583983$ psi

From Eq. 7.15:

Dynamic Modulus (Complex Modulus) for $f = 8$ Hz is

$$|E^*| = 0.18089\, f^{2.1456}\, E_o^{\left(\frac{14.6918}{f^{0.01}} - 13.5739\right)}.$$

$$= \underline{7.9 \times 10^5}\ psi$$ ✓



Based on Regression Analysis:

$$\log E_s = 5.7664 - 2.861 \times 10^{-3}\, \sigma$$

$$\sigma = 0 \rightarrow \log E_s = 5.7664 \rightarrow E_s = E_o = 583983\ psi.$$

Eq. 7.15: $f = 8$ Hz.

$$|E^*| = 0.18089\, f^{2.1456}\, E_o^{\left(\frac{14.6918}{f^{0.01}} - 13.5739\right)}$$

$$= \underline{7.9 \times 10^5\ psi.}$$ ✓

See also P. 52

7-4 See page 52

p7.1

log x	log y
1.079181	4.014730
1.477121	4.306854
1.778151	4.499398
2.079181	4.721250
1.079181	4

Regression Output: $\log K_1$

Constant		3.243085
Std Err of Y Est		.0111520
R Squared(Adj,Raw)	.9987188	.9990391
No. of Observations		5
Degrees of Freedom		3
Coefficient(s)	.7109222 (K_2)	
Std Err of Coef.	.0127294	

$$M_R = K_1 \theta^{K_2}$$

$$\log M_R = \log K_1 + K_2 \log \theta$$

$$M_R = 1750\, \theta^{0.711}$$

p7.3

x	log y
278	5
254	5.056905
228	5.060698
197	5.127105
185	5.204120
165	5.457882
137	5.346353
115	5.444045
91	5.498311

Regression Output: $\log E_o$

Constant		5.773954
Std Err of Y Est		.0740420
R Squared(Adj,Raw)	.8558775	.8738928
No. of Observations		9
Degrees of Freedom		7
Coefficient(s)	-.002891	
Std Err of Coef.	.0004151	

$$E_s = E_o A_1^{\sigma}$$

$$\log E_s = \log E_o + \sigma \log A_1$$

$$E_o = 594{,}229$$

$$|E^*| = 0.18089\,(8)^{2.1456} \times (5.942\times10^5)^{\frac{14.6918}{8^{0.01}} - 13.5739}$$

$$= 8.0\times10^5 \text{ psi}$$

p7.4

log x	log y
-2.50169	1.544068
-2.58336	1.875061
-2.60380	2
-2.71670	2.468347
-2.79860	2.531479
-2.89620	2.986772
-2.96257	3.212188
6	3.553033

Regression Output: $\log f_1$

Constant		-7.17659
Std Err of Y Est		.0708248
R Squared(Adj,Raw)	.9896900	.9911629
No. of Observations		8
Degrees of Freedom		6
Coefficient(s)	-3.50710 (f_2)	
Std Err of Coef.	.1351934	

$$N_f = f_1 (\varepsilon_t)^{f_2}$$

$$\log N_f = \log f_1 + f_2 \log \varepsilon_o$$

$$N_f = 6.66\times10^{-8} (\varepsilon_t)^{-3.507}$$

p7.9

log x	log y
-1	-4.93629
0	-4.45917
1	-3.93806
2	-3.50624
3	-3.20424

Regression Output: $\log I_1$

Constant		-4.45050
Std Err of Y Est		.0751524
R Squared(Adj,Raw)	.9885204	.9913903
No. of Observations		5
Degrees of Freedom		3
Coefficient(s)	.4417041 (S)	
Std Err of Coef.	.0237653	

$$\log \varepsilon_p = \log I_1 + S \log t$$

$$S = 0.4417 \quad \alpha = 1 - 0.4417 = 0.5583$$

$$\log I = -4.4505 + 0.4417 \log 0.1$$

$$= -4.8922 \quad I = 1.28\times10^{-5}$$

$$\mu = \frac{1.28\times10^{-5} \times 0.442}{3.045\times10^{-5}} = 0.186$$

p7.10

log x	log y
0	-4.62709
1	-4.23426
2	-3.89371
2.301030	-3.85605
3	-3.70520
4	-3.44032
5	-3.13368

Regression Output: $\log I$

Constant		-4.54931
Std Err of Y Est		.0578542
R Squared(Adj,Raw)	.9861963	.9884969
No. of Observations		7
Degrees of Freedom		5
Coefficient(s)	.2863923 (S)	
Std Err of Coef.	.0138164	

$$\log \varepsilon_p = \log I + S \log N$$

$$S = 0.2864 \quad \alpha = 1 - 0.2864 = 0.7136$$

$$\log I = -4.54931$$

$$I = 2.823\times10^{-5}$$

$$\mu = \frac{2.823\times10^{-5} \times 0.2864}{4.128\times10^{-5}} = 0.196$$

7-5.

Asphalt Mixture : Asphalt Content = 7% ; Bulk S.G. = 2.24

Asphalt : S.G. = 1.02 ; Penetration at 77°F = 50 ; $T_{R\&B}$ = 120°F.

Aggregate : S.G. = 2.61.

Determine $|E^*|$ at T = 74°F and loading time of 0.02 sec.

Note: 120°F = 49°C ; 77°F = 25°C ; 74 F = 23.3°C ; $C = (F-32)\frac{5}{9}$.

Eq. 7.17: $A = \dfrac{\log Pen\ at\ T - \log 800}{T - T_{R\&B}} = \dfrac{\log 50 - \log 800}{T - T_{R\&B}}$

$= \dfrac{\log 50 - \log 800}{25 - 49} = 0.0502$

Eq. 7.16: $PI = \dfrac{20 - 500A}{1 + 50A} = -1.453$.

① Determination of Stiffness Modulus of asphalt Binder

Fig. 7.19 for $t = 0.02$, $T_{diff} = 49 - 23.33 = 25.67$, $PI = -1.453$ } Stiff. Mod. $= 2 \times 10^7$ N/m².

②. Determination of Stiff. Modulus of asphalt Mixture:

P_b = asphalt Content = 7% = 0.07

G_m = S.G. of Mixture = 2.24

G_g = S.G. of aggregate = 2.61.

% Volume of aggregate $V_g = \dfrac{100\ (1 - P_b)\, G_m}{G_g} = \dfrac{100(1 - 0.07)\, 2.24}{2.61}$

$= 79.816$ %

% Volume of Binder $V_b = \dfrac{100\, P_b\, G_m}{G_a} = \dfrac{100\,(0.07)\, 2.24}{1.02} = 15.37$ %

% Volume of Void/air $V_a = 100 - V_g - V_b = 100 - 79.8 - 15.4 = 4.8$%

Fig. 7.20:

for: Stiff. Mod. of Binder = 2×10^7, $V_b = 15.4$, $V_g = 79.8$ } $|E^*|$ of Mixture = 2×10^9 N/m².

using Eq - 7.24

for: $S_b = 7 \times 10^6$ N/m².

$\beta_1 = 10.82 - \dfrac{1.342\,(100 - V_g)}{V_g + V_b} = 10.82 - \dfrac{1.342\,(100 - 79.8)}{79.8 + 15.4} = 10.534$

$\beta_2 = 8.0 + 0.00568\, V_g + 0.0002135\, V_g^2 = 9.813$

$\beta_3 = 0.6 \log \left[\dfrac{1.37\, V_b^2 - 1}{1.33\, V_b - 1} \right] = 0.7325$ ($V_b = 15.4$).

$\beta_4 = 0.7582\, (\beta_1 - \beta_2) = 0.547$

for $5\times10^6\ N/m^2 < S_b < 10^9\ N/m^2$. $\quad (S_b = 7.0\times10^6\ N/m^2)$.

$$\log S_m = \frac{\beta_4+\beta_3}{2}(\log S_b - 8) + \frac{\beta_4-\beta_3}{2}\left|\log S_b - 8\right| + \beta_2$$

$$= \frac{0.547+0.734}{2}(\log 2\times10^7 - 8) + \frac{0.547-0.734}{2}\left|\log 2\times10^7 - 8\right| + 9.813$$

$$= 9.301.$$

$$S_m = 10^{9.301} = 2\times10^9\ N/m^2.$$

7-6 | Given:

$f = 8$ Hz $\qquad P_{77} = 75$

$T = 74$ °F

$P_{200} = 5$ %

assume: $V_v = 4.8\%$ $\qquad = 100 - V_g - V_b$

$$V_g = \frac{100*(1-0.07)*2.24}{2.61} = 79.81 \qquad = \frac{100(1-P_b)G_m}{G_g}$$

$$V_b = \frac{100*0.07*2.24}{1.02} = 15.37\ \% \qquad = \frac{100\,P_b\,G_m}{G_b}$$

$$\lambda = 29508.2 * (P_{77F})^{-2.1939}$$
$$= 2.27 * 10^6 \text{ poise}$$

$$\beta_5 = 1.3 + 0.49825 \log 5$$
$$= 1.3 + 0.49825 \log 8$$
$$= 1.75$$

$$\beta_4 = 0.483\,V_b = 0.483 * 15.37 =$$
$$= 7.42$$

$$\beta_3 = 0.553833 + 0.028829\,(P_{200} f^{-0.1703})$$
$$- 0.03476\,V_v + 0.070377\,\lambda + 0.931757 f^{-0.02774}$$
$$= 0.553833 + 0.028829 * 5 * 8^{-0.1703}$$
$$- 0.03476 * 5 + 0.070377 * 2.27 + .931757 f^{-0.02774}$$
$$= 1.53$$

$$\beta_2 = \beta_4^{0.5}\,(T^{\beta_5})$$
$$= 7.42^{0.5} * (74)^{1.75} = 5085.8$$

$$\beta_1 = \beta_3 + 0.000005\,\beta_2 - 0.00189\,\beta_2\,(f)^{-1.1}$$
$$= 53 + 0.000005 * 5085.8 - 0.00189 * 50858 * (8)^{-1.1}$$
$$= 0.579$$

$$|E^*| = 100000 * 10^{0.579} = \underline{3.793\times10^5} \text{ psi}$$

7-7

$PI = -1.453$; $V_b = 15.4\%$ $S_m = 2 \times 10^9$ N/m² = 2.9×10^5 psi $\varepsilon_t = 0.00015$

from Fig. 7.26

$N_f = 8.7 \times 10^5$ N/m² for Constant stress test ✓
$N_f = 9 \times 10^7$ N/m² for Constant strain test ✓

using Eq. 7.25:

$N_f = (0.0252\, PI - 0.00126 \times PI \times V_b + 0.00673\, V_b - 0.0167)^5 \times \varepsilon_t^{-5} \times S_m^{-1.4}$

$= (0.0252 \times (-1.453) - 0.00126 \times (-1.453) \times 15.4 + 0.00673 \times 15.4 - 0.0167)^5 \times 0.00015^{-5} \times (2.9 \times 10^5)^{-1.4}$

$N_f = \underline{8.85 \times 10^5}$ (for Constant stress test) ✓

$N_f = (0.17 \times PI - 0.0085\, PI \times V_b + 0.0454 \times V_b - 0.112)^5 \times \varepsilon_t^{-5} \times S_m^{-1.8}$

$= (0.17 \times (-1.453) - 0.0085 \times (-1.453) \times 15.4 + 0.0454 \times 15.4 - 0.112)^5 \times 0.00015^{-5} \times (2.9 \times 10^5)^{-1.8}$

$= \underline{8.13 \times 10^7}$ (for Constant strain test) ✓

7-8 Given:

$|E^*| = 3.793 \times 10^5$ psi $\varepsilon_t = 0.00015$
$V_a = 4.8\%$
$V_b = 15.37\%$

$$M = 4.84 \left(\frac{V_b}{V_a + V_b} - 0.69 \right)$$

$$= 4.84 \times \left(\frac{15.37}{15.37 + 4.8} - 0.69 \right)$$

$= 0.3486$

$C = 10^M = 2.23$

$N_f = 0.00432 \times C \times (\varepsilon_t)^{-3.291} \times |E^*|^{-0.854}$

$= \underline{636533}$ ✓

7-9

The Results of incremental static test on a HMA specimen are plotted in Fig. below for 0.1, 1, 10, 100, and 1000 sec. duration. with permanent strain 1.418×10^{-5}, 3.474×10^{-5}, 11.573×10^{-5}, 31.175×10^{-5} & $62.483\ 10^{-5}$ Respectively.
based on Regression analysis the Relationship of strain and duration are will Represented by:

Log strain = 0.4417 (Log Duration) + 0.5495

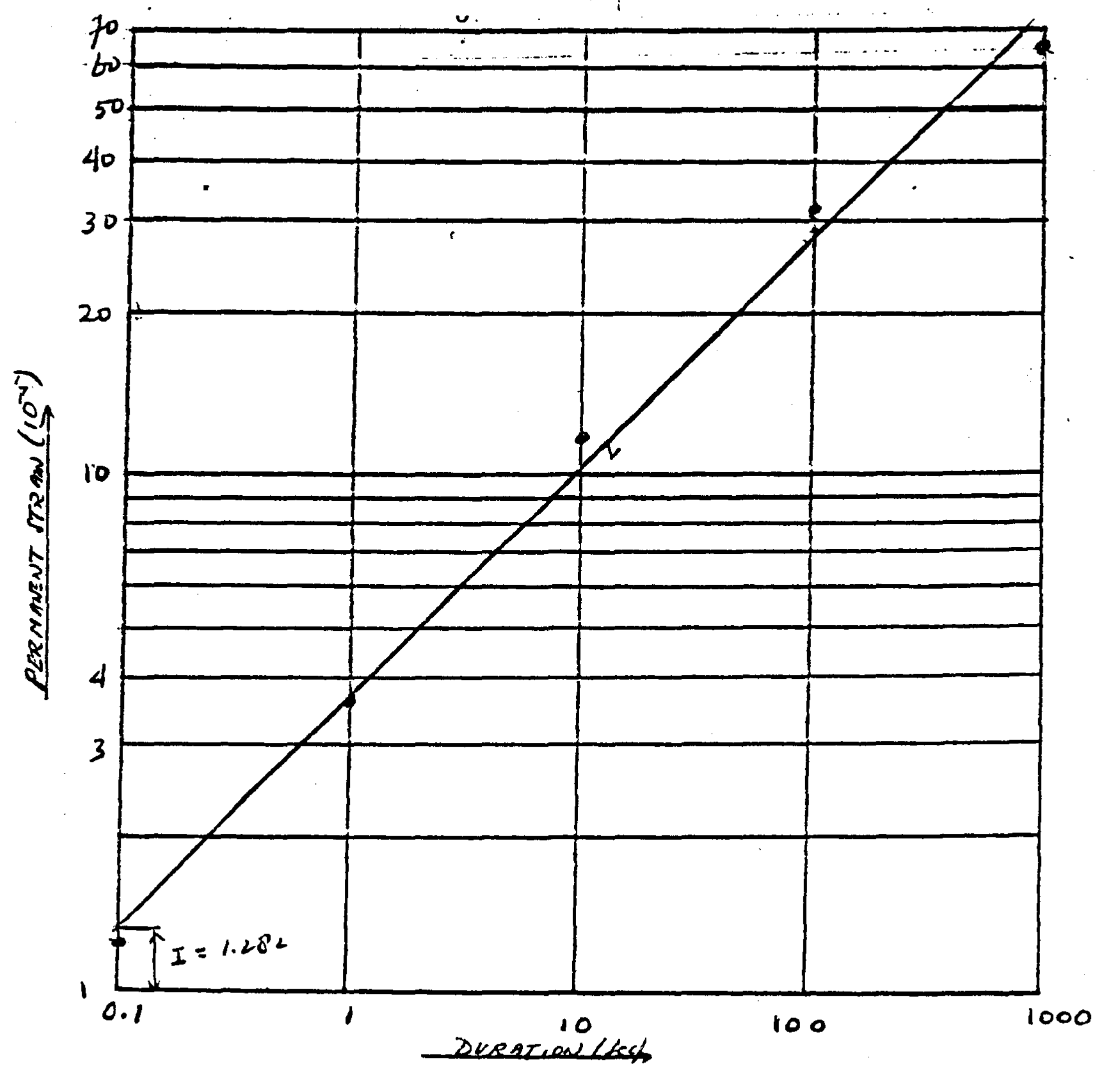
for $d = 0.1$ ksec → strain $= 1.282 \times 10^{-5}$
= I = Intercept

slope of Regression line = 0.4417 (10^{-5}).

from: Eq. 7.43 $\alpha = 1 - s = 1 - 0.4417 = \underline{\underline{0.5583}}$ ✓

Eq. 7.44 $\mu = \frac{I \cdot S}{\varepsilon} = \frac{1.282 \times 0.4417 \times 10^{-5}}{3.045 \times 10^{-5}} = \underline{\underline{0.186}}$ ✓

Note: ε = strain at a time duration of 0.03 = 3.045×10^{-5}

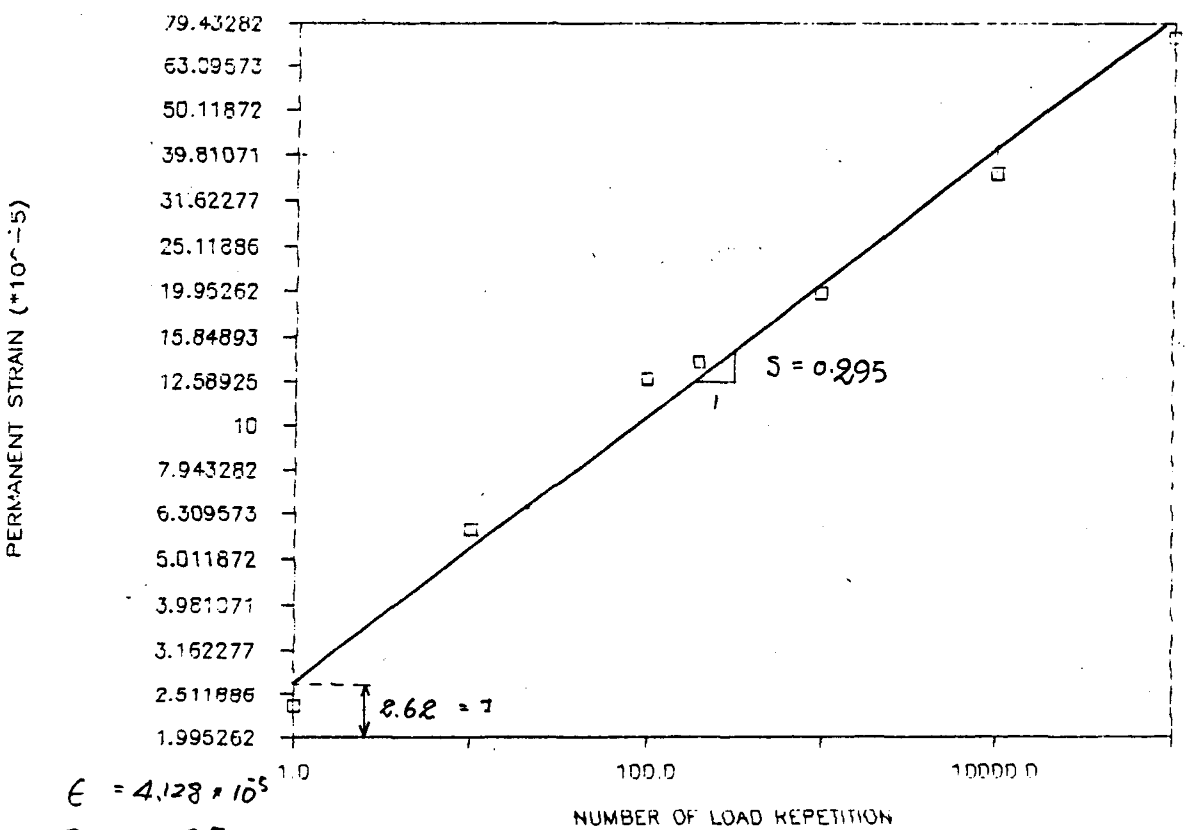


See page 52

7-10.

No. OF REPETITION	PERMANENT STRAIN (10^-5)
1	2.36
10	5.813
100	12.773
200	13.93
1000	19.715
10000	36.281
100000	73.506

PROBLEM 7-10



$\epsilon = 4.128 \times 10^{5}$

$S = 0.295$

$I = 2.62$

$\alpha = 1 - S = 1 - 0.295 = \underline{0.705}$ ✓

$\mu = \frac{I\,S}{\epsilon} = \frac{2.62 \times 0.295}{4.128} = \underline{0.187}$ ✓

See also P. 52

P.8.1

water is sprayed over a 400 ft^2 soil surface – Soil's permeability = 0.001 ft/min.
2.99 gpm what is max. spray rate in gal/min. so that all water will be absorbed by the soil & there is no overland flow

$$(400\ ft^2)(0.001\ ft/min) = (0.4\ ft^3/min)\left(7.48\ \frac{gal}{ft^3}\right)$$

$Q = VA$

$V = ki \quad i = 1$

spray rate $= \boxed{2.99\ g/min}$ ✓

8.2

$$\log D_x = \log D_a + \frac{x-a}{b-a} \log \frac{D_b}{D_a}$$

a) $x = 15$ $\quad D_{15} = ?$
$a = 5.8$ $\quad D_a = .094'' \leftarrow \#8$
$b = 32$ $\quad D_b = .19'' \leftarrow \#4$

$$\log D_{15} = \log .094 + \frac{15-5.8}{32-5.8} \log \frac{.19}{.094} = -0.92$$

3.1

$D_{15} = .120\,in \; \frac{2.54\,cm}{1\,in} \; \frac{100\,mm}{1\,cm} = \boxed{D_{15} = 3.0\ mm}$ ✓

b) $x = 85$ $\quad D_{85} = ?$
$a = 75$ $\quad D_a = .5$
$b = 100$ $\quad D_b = .75$

$$\log D_{85} = \log .5 + \frac{85-75}{100-75} \log \frac{.75}{.5}$$

$D_{85} = .588\,in \; \frac{2.54\,cm}{1\,in} \; \frac{10\,mm}{1\,cm}$ $\quad \boxed{D_{85} = 15\ mm}$ ✓

Problem 8-3

Soil A (filter)
Soil C (soil)

Clogging Criterion (D_{15} filter / D_{85} soil ≤ 5)

0.375 / 0.0125 = 30 Not satisfied

Permeability Criterion (D_{15} filter / D_{15} soil ≥ 5)

0.375 / 0.000225 = 1667 Satisfied

Additional Criteria (D_{50} filter / D_{50} soil ≤ 25)

0.7 / 0.00175 = 400 Not satisfied

Soil A should not be used as a filter for soil C

Soil A (filter)
Soil B (soil)

Clogging Criterion

0.375 / 0.25 = 1.5 Satisfied

Permeability Criterion

0.375 / 0.007 = 54 Satisfied

Additional Criteria

0.7 / 0.0375 = 19 Satisfied

D_{60} filter / D_{10} filter ≤ 25

0.9 / 0.3 = 3 Satisfied

D_5 filter $\ge$ 0.074 mm

0.225 $\ge$ 0.074 Satisfied

Soil B (filter)
Soil C (soil)

Clogging Criterion

0.007 / 0.0125 = 0.56 Satisfied

Permeability Criterion

0.007 / 0.000225 = 31 Satisfied

Additional Criteria

0.0375 / 0.00175 = 21 Satisfied

0.06 / 0.005 = 12 Satisfied

0.0035 < 0.074 Not satisfied

This is important only when drainage layer is used

8-4. (a) Can geotextiles be used as a filter for soil C in Figure P8.3? Why?

Soil C is a clayed soil with 100% passing #200 sieve. Geotextiles cannot be used as a filter because the soil is too fine and will cause clogging.

(b) If geotextiles are used for soil B, what AOS do you recommend?

Soil B has 65% passing #200 sieve with D_{85} = 0.25 mm or #60.

If woven fabric is used, AOS $\leq D_{85}$ or AOS $\geq$ #60

(c) If geotextiles are used for soil A, what AOS do you recommend?

Soil C has less than 50% passing #200, so AOS $\leq$ B x D_{85}

$C_u = D_{60}/D_{10}$ = 0.9/0.3 = 3, which is between 2 and 4, so B = $0.5C_u$ = 1.5

D_{85} = 2 mm, AOS $\leq$ 1.5 x 2 =3 mm or AOS $\geq$ #8

8-5. (a) Estimate the permeability of soil B in Figure P8.3 by Eq. 8.3

From Figure P8.3, D_{10} = 0.0052 mm From Table 8.4, C_k = 5 to 8

From Eq. 8.3, k = $C_k D_{10}$ so

$$k = 5\,(0.0052)^2 = 1.352 \times 10^{-4}\ \text{mm/s}\left(\frac{1\text{ft}}{304.8\text{mm}}\right)\left(\frac{60\text{x}60\text{x}24\,\text{sec}}{1\text{day}}\right)$$

= 0.0383 ft/day (lower limit)

$k = 8\,(0.0052)^2 = 2.163 \times 10^{-4}$ mm/s = 0.0613 ft/day (upper limit)

(b) Given γ_{dry}= 110 lb/ft^3, estimate the permeability of soil B by Eq. 8.5a

Assume G_s = 2.7, from Eq. 8.5b, $n = 1 - \dfrac{110}{62.4\text{x}2.7} = 0.3471$

From Figure P8.3, percent passing #200 (0.075 mm) is P_{200} = 65%

From Eq. 8.5a, $k = \dfrac{6.214\text{x}10^5(0.0052)^{1.478}(0.3471)^{6.654}}{(65)^{0.597}}$ = = 0.0189 ft/day

8-6. Given $N = 2$, $W_p = 22$ ft, $C_s = 40$ ft, from Eq. 8.18

$$q = 0.1\left(2+1+\frac{22}{40}\right) = 0.355 \text{ ft}^3/\text{h/linear ft of pavement}$$

$$= 0.355/22 = \underline{0.016} \text{ ft}^3/\text{h/ft}^2 \text{ (by Eq. 8.18)}$$

From Figure 8.13, the 1-h duration/1-yr. frequency precipitation rate for Kentucky is 1.2 in./hr. Cedergren recommended that the design infiltration rate be obtained by applying a coefficient varying from 0.33 to 0.50, so

$$q = \begin{cases} 0.33 \times 1.2 = 0.396 \text{ in./hr} = \underline{0.033} \text{ ft}^3/\text{hr/ft}^2 \\ 0.50 \times 1.2 = 0.6 \text{ in/hr} = \underline{0.050} \text{ ft}^3/\text{hr/ft}^2 \end{cases}$$

8-7. Given $K = 0.5$ ft/day, $H = 23$ ft, $H_o = 15$ ft, $W = 40$ ft. From Eq. 8.20, $L_i = 3.8(23-15) = 30.4$ ft

So $\frac{L_i + 0.5W}{H_o} = \frac{30.4 + 0.5 \times 40}{15} = 3.36$ and $\frac{W}{H_o} = \frac{40}{15}$

$= 2.67$. From Fig. 8.14, $\frac{K(H-H_o)}{2q_2} = 1.2$ so

$$q_2 = \frac{0.5 \times (23-15)}{2 \times 1.2} = 1.67 \text{ ft}^2/\text{day or}$$

$$q_d = \frac{2 \times 1.67}{40} = \underline{0.084} \text{ ft}^3/\text{day/ft}^2$$

From Eq. 8.19 $q_1 = \frac{0.5(23-15)^2}{2 \times 30.4} = 0.53$ ft^2/day

So $q_L = q_1 + q_2 = 0.53 + 1.67 = \underline{2.2}$ ft^3/day/ft

8-8 For GW-GC with 4 % passing 0.02 mm, from Table 8.5, Heave rate = 2.5 mm/day

$\sigma_p = (145 \times 4 + 120 \times 10)/12 = 148$ psf. From Fig. 8.15,

$$\frac{q_m}{\sqrt{K}} = 0.3 \quad q_m = 0.3\sqrt{0.05} = \underline{0.067} \text{ ft}^3/\text{day/ft}^2$$

8-9. Given $K = 10{,}000$ ft/day, $H = 8$ in., $S = 0.04$

$L = 18$ ft, from Eq. 8.27, the steady-state capacity

$$q = KH\left(S + \frac{H}{2L}\right) = 10{,}000 \times \frac{8}{12}\left(0.04 + \frac{8}{2 \times 18 \times 12}\right)$$

$$= \underline{390} \text{ ft}^3/\text{day}/\text{ft}$$

Given $n_e = 0.25$, from Eq. 8.28

$$t_{50} = \frac{n_e L^2}{2K(H + SL)} = \frac{0.25 \times (18)^2}{2 \times 10{,}000\,(8/12 + 0.04 \times 18)}$$

$$= 0.00292 \text{ day} = \underline{0.07} \text{ hr}$$

From Eq. 8.30 $S_f = \dfrac{18 \times 0.04}{8/12} = 1.08$

From Fig. 8.18 $T_f = 1.5$ or

$$t_{95} = \frac{T_f \cdot n_e L^2}{KH} = \frac{1.5 \times 0.25 \times (18)^2}{10{,}000\left(\frac{8}{12}\right)}$$

$$= 0.0182 \text{ day} = \underline{0.44} \text{ hr}$$

8-10. Given $n = 0.01$, $L_o = 300$ ft, $S = 0.025$,

$D = 4$ in., from Eq. 8.33

$$q_L = \frac{53\, S^{0.5} D^{2.667}}{n L_o}$$

$$= \frac{53\,(0.025)^{0.5}(4)^{2.667}}{0.01 \times 300} = \underline{112.7} \text{ ft}^3/\text{day}/\text{ft}$$

Chapter 9
Pavement Performance

9-1. Given $PSI = A_0 + A_1 \log(RI)$ and Table P9.1
Derive equations and find A_0 and A_1

$$E = \Sigma(PSR - PSI)^2 = \Sigma[PSR - A_0 - A_1 \log(RI)]^2$$

$$\frac{\partial E}{\partial A_0} = -2\,\Sigma[PSR - A_0 - A_1 \log(RI)] = 0$$

$$\overline{PSR} = A_0 + A_1 \overline{\log(RI)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$\frac{\partial E}{\partial A_1} = -2\,\Sigma\{[PSR - A_0 - A_1 \log(RI)] \log(RI)\} = 0$$

$$\Sigma(PSR) \log(RI) = A_0 \Sigma \log(RI) + A_1\, \Sigma[\log(RI)]^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Eqs. 1 and 2 can be used to solve A_0 and A_1

$\overline{PSR} = (1 + 2 + 3 + 4 + 5)/5 = 2.5$

$\overline{\log(RI)} = (\log 800 + \log 300 + \log 200 + \log 150 + \log 80)/5 =$

$(2.903 + 2.477 + 2.301 + 2.176 + 1.903)/5 = 11.76/5 = 2.352$

From Eq. 1 $\quad 2.5 = A_0 + 2.352\, A_1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$

From Eq. 2 $\quad 1 \times 2.903 + 2 \times 2.477 + 2.5 \times 2.301 + 3 \times 2.176 + 4 \times 1.903$

$= 11.76\, A_0 + [(2.903)^2 + (2.477)^2 + (2.301)^2 + (2.176)^2 + (1.903)^2]\, A_1$

$27{,}75 = 11.76\, A_0 + 28.214\, A_1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$

Solve Eqs. 3 and 4 $\quad 27.75 - 2.5 \times 11.76 = (28.214 - 2.352 \times 11.76)\, A_1$

$-1.65 = 0.554\, A_1 \quad$ or $\quad A_1 = -2.98$

$A_0 = 2.5 - 2.352 \times (-2.98) = 9.5$

$\underline{PSI = 9.5 - 2.98 \log(RI)}$

9-2. Given Table P9.2
Develop equation for PSI

Section No.	$\log(1+\overline{SV})$ R_1	$\overline{RD}^2$ R_2	$\sqrt{C+P}$ D_1	PSR	$R_1-\overline{R_1}$	$R_2-\overline{R_2}$	$D_1-\overline{D_1}$	$PSR-\overline{PSR}$
1	0.580	0.0036	0	4.3	-0.519	-0.0139	-2.994	1.34
2	0.833	0.0100	1	3.8	-0.266	-0.0075	-1.994	0.84
3	1.076	0.0121	3.606	3.2	-0.023	-0.0054	0.612	0.24
4	1.250	0.0256	4.796	2.4	0.151	0.0081	1.802	-0.56
5	1.756	0.0361	5.568	1.1	0.657	0.0186	2.574	-1.86
Average	1.099	0.0175	2.994	2.96				

From Eq. 9.9

$$2.96 = A_0 + 1.099\,A_1 + 0.0175\,A_2 + 2.994\,B_1 \quad \ldots\ldots\ldots\ldots\ldots(1)$$

From Eq. 9.11

$$[(-0.519)^2 + (-0.266)^2 + (-0.023)^2 + (0.151)^2 + (0.657)^2]\,A_1 + [(-0.519)(-0.0139) + (-0.266)(-0.0075) + (-0.023)(-0.0054) + (0.151)(0.0081) + (0.657)(0.0186)]\,A_2 + [(-0.519)(-2.994) + (-0.266)(-1.994) + (-0.023)(0.612) + (0.151)(1.802) + (0.657)(2.574)]B_1 = (-0.519)(1.34) + (-0.266)(0.84) + (-0.023)(0.24) + (0.151)(-0.56) + (0.657)(-1.86) \quad \text{or}$$

$$0.7951\,A_1 + 0.0228\,A_2 + 4.033\,B_1 = -2.231 \quad \ldots\ldots\ldots\ldots\ldots(2)$$

From Eq. 9.12

$$0.0228\,A_1 + [(-0.0139)^2 + (-0.0075)^2 + (-0.0054)^2 + (0.0081)^2 + (0.0186)^2]\,A_2 + [(-0.0139)(-2.994) + (-0.0075)(-1.994) + (-0.0054)(0.612) + (0.0081)(1.802) + (0.0186)(2.547)]\,B_1 = (-0.0139)(1.34) + (-.0075)(0.84) + (-0.0054)(0.24) + (0.0081)(-0.56) + (0.0186)(-1.86) \quad \text{or}$$

$$0.0228\,A_1 + 0.00069\,A_2 + 0.1152\,B_1 = -0.0654 \quad \ldots\ldots\ldots\ldots\ldots(3)$$

From Eq. 9.13

$4.033\ A_1 + 0.1152\ A_2 + [(-2.994)^2 + (-1.994)^2 + (0.612)^2 + (1.802)^2 +$

$(2.574)^2\ ]\ B_1 = [(-2.994)(1.34) + (-1.994)(0.84) + (0.612)(0.24) + (1.802)$

$(-0.56) + (2.574)(-1.86)]$ or

$4.033\ A_1 + 0.1152\ A_2 + 23.187\ B_1 = -11.337$ ....(3)

From Eqs. 2, 3, and 4

$A_1 = -1.70$, $A_2 = -38.09$, and $B_1 = -0.004$

From Eq. 1 $A_0 = 2.96 - 1.099\ (-1.7) + 0.0175\ (-38.09) - 2.994\ (-0.004)$

$A_0 = 5.51$ $\underline{PSI = 5.51 - 1.70 \log(1+\bar{SV}) - 38.09\ \bar{RD}^2 - 0.004\sqrt{C+P}}$

9-3. Derive Eq. 9.29

$F = ma$ Average speed $= \frac{V}{2}$ Time to stop $= \frac{2S}{V}$

$$a = \frac{V}{\frac{2S}{V}} = \frac{V^2}{2S} \qquad \mu W = \frac{W}{g} \bullet \frac{V^2}{2S} \qquad \underline{\mu = \frac{V^2}{2gS}} \text{..........(9.29)}$$

9-4. Given volume of beads = 2 in.^{3}, diameter of patch = 10 in., and $SN_{40} = 40$

Determine SN_{20} and SN_{60}

$$\text{MTD} = \frac{2}{\frac{1}{4}\pi(10)^2} = 0.0255 \text{ in.}$$

From Eq. 9.33 $PNG = 0.157\ (0.0255)^{-0.47} = 0.881$

From Eq. 9.31 $40 = SN_0 \exp\left(-\frac{0.881}{100} x 40\right)$ $SN_0 = 56.9$

When V = 20 mph $SN_{20} = 56.9 \times \exp(-0.881 \times 0.2) = \underline{47.7}$

When V = 60 mph $SN_{60} = 56.9 \times \exp(-0.881 \times 0.6) = \underline{33.5}$

```
1   (1) NPROB
PROBLEM 9.5
1  0  1  1   (3) MATL NDAMA NPY NLG
0.001   (4) DEL
3  1  80  1  0   (5) NL NZ ICL NSTD NUNIT
4   12    (6) TH
0.35   0.35   0.45   (7) PR
0   (8) ZC
1  (9) NBOND
500000   35000   9000   (11) E
0   (13) LOAD
6   79.5775   (14) CR CP
7   (16) NR
0   8   12   24   48   72   96   (17) RC
```

← These are E_1, E_2, and E_3 obtained by trial & error.

```
1  (1) NPROB
PROBLEM 9.6
2  0  1  1   (3) MATL NDAMA NPY NLG
0.001  (4) DEL
3  1  80  1  0   (5) NL NZ ICL NSTD NUNIT
4   12    (6) TH
0.35   0.35   0.45   (7) PR
0   (8) ZC
1  (9) NBOND
500000   35000   9000   (11) E
0   (13) LOAD
6   79.5775   (14) CR CP
7   (16) NR
0   8   12   24   48   72   96   (17) RC
1  15   (25) NOLAY ITENOL
2   0   (26) LAYNO NCLAY
7   (27) ZCNOL
0  0  0  0  0.01   (28) RCNOL XCNOL YCNOL SLD DELNOL
0.5   (29) RELAX
145   135   0   (30) GAM
0.5  0.6  (31) K2 K0
8000   8000   (33) PHI K1
```

E_3

E_1

K_1

E_1 = 500,000 psi

E_3 = 9,000 psi

K_1 = 8000

```
1   (1) NPROB
PROBLEM 9.7
2  0  1  1  (3) MATL NDAMA NPY NLG
0.001  (4) DEL
8  1  80  1  0  (5) NL NZ ICL NSTD NUNIT
4   2   2   2   2   2   2    (6) TH
0.35   0.35   0.35   0.35   0.35   0.35   0.35   0.45   (7) PR
0   (8) ZC
1  (9) NBOND
500000   35000   35000   35000   35000   35000   35000   9000   (11) E
0   (13) LOAD
6   79.5775   (14) CR CP
7   (16) NR
0   8   12   24   48   72   96   (17) RC
6  15  (25) NOLAY ITENOL
2   0   3   0   4   0   5   0   6   0   7   0   (26) LAYNO NCLAY
5   7   9   11   13   15   (27) ZCNOL
3  0  0  0.25  0.01  (28) RCNOL XCNOL YCNOL SLD DELNOL
0.5   (29) RELAX
145   135   135   135   135   135   135   0   (30) GAM
0.5  0.6  (31) K2 K0
0.5  0.6  (31) K2 K0
0.5  0.6  (31) K2 K0
0.5  0.6  (31) K2 K0
0.5  0.6  (31) K2 K0
0.5  0.6  (31) K2 K0
0   8000   (33) PHI K1
0   8000   (33) PHI K1
0   8000   (33) PHI K1
0   8000   (33) PHI K1
0   8000   (33) PHI K1
0   8000   (33) PHI K1
```

$E_1 = 500{,}000$ psi

$E_3 = 9{,}000$ psi

$K_1 = 8{,}000$

```
1  (1) NPROB
PROBLEM 9.8
1  0  1  1  (3) MATL NDAMA NPY NLG
0.001  (4) DEL
3  1  80  1  0  (5) NL NZ ICL NSTD NUNIT
8   12   (6) TH
0.35   0.35   0.45   (7) PR
0   (8) ZC
1  (9) NBOND
240000   19200   4800   (11) E
0   (13) LOAD
6   80   (14) CR CP
5   (16) NR
0   12   24   36   48   (17) RC
```

use a realistic E_3 of 4800 psi

$q = 100$ psi, $a = 6$ in., $E_3 = 4800$ psi, $E_2 = 19{,}200$ psi, $E_1 = 240{,}000$ psi, $w_i^c = \dfrac{80 \times 6}{4800} f_i = 0.1 f_i$, so $f_i = 10\, w_i^c$ w_i^c are the surface deflections of 0.02971, 0.02427, 0.01907, 0.01530, and 0.01125 in., as computed by KENLAYER.

9-9. Given $W_0 = 0.0047$ in., $W_1 = 0.004$ in., $W_2 = 0.0035$ in and $W_3 = 0.0026$ in., from Eq. 9.45

$$AREA = 6\left[1 + 2\left(\frac{0.004}{0.0047}\right) + 2\left(\frac{0.0035}{0.0047}\right) + \frac{0.0026}{0.0047}\right]$$

$$= 28.468$$

From Figure 9.39, $\ell = 29$ in.

From Figure 9.40, $d_0 = 0.123$, $d_1 = 0.111$, $d_2 = 0.091$, $d_3 = 0.068$

From Eq. 9.42 $\quad k = \frac{p\, d_i}{W_i\, \ell^2} = \frac{9{,}000}{(29)^2}\left(\frac{d_i}{W_i}\right) = 10.7\left(\frac{d_i}{W_i}\right)$

Based on d_0 and W_0, $\quad k = 10.7\left(\frac{0.123}{0.0047}\right) = 280.0$ pci

" $\quad d_1$ and W_1, $\quad k = 10.7\left(\frac{0.111}{0.004}\right) = 296.9$ pci

" $\quad d_2$ and W_2, $\quad k = 10.7\left(\frac{0.091}{0.0035}\right) = 278.2$ pci

" $\quad d_3$ and W_3, $\quad k = 10.7\left(\frac{0.068}{0.0026}\right) = 279.8$ pci

Average k = <u>283.7</u> pci, say <u>285</u> pci

Given $E_c = 4.7 \times 10^6$ psi, from Eq. 9.48

$$h^3 = \frac{12[1-(0.15)^2] \times 283.7 \times (29)^4}{4.7 \times 10^6} = 500.8 \text{ in}^3$$

h = <u>7.94</u> in., say <u>8 in.</u>

9-10.

From Fig. 9.39, $\ell = 14$ in.

From Fig. 9.41, $d_0 = 0.182$, $d_1 = 0.152$, $d_2 = 0.108$, $d_3 = 0.078$

From Eq. 9.47, $\quad E_f = \frac{2[1-(0.4)^2] \times 9{,}000\, d_i}{14\, W_i} = 1080\left(\frac{d_i}{W_i}\right)$

Based on d_0 and W_0, $\quad E_f = 1080\left(\frac{0.182}{0.0047}\right) = 41{,}821$ psi

" $\quad d_1$ and W_1 $\quad E_f = 1080\left(\frac{0.152}{0.004}\right) = 41{,}040$ psi

Based on d_2 and W_2, $E_f = 1080\left(\frac{0.108}{0.0035}\right) = 33,326$ psi

" d_3 and W_3, $E_f = 1080\left(\frac{0.078}{0.0026}\right) = 32,400$ psi

Average $E_f = \underline{37,147}$ psi

From Eq. 9.49 $$h^3 = \frac{6[1-(0.15)^2]\times 37,147 \times (14)^3}{[1-(0.4)^2]\times 4.7\times 10^6} = 151.4 \text{ in}^3$$

$h = \underline{5.4}$ in.

9-11 Given: $h = 4$ in., $a = 6$ years, $S_{bit} = 200$ kg/cm², $d = 3$ (loam), $m = 20°$c

Required: Cracking index I for low temperature cracking

Solution: From Eq. 9.52b

$$I = 30.3974 + (6.7966 - 0.8741\times 4 + 1.3388\times 6)\log(0.1\times 200) - 2.1516\times 3 - 1.2496\times 20 + 0.06026\times 200 \log 3$$
$$= 19.5 \text{ ft}/500 \text{ ft} \quad \text{or} \quad 39 \text{ ft}/1000 \text{ ft}$$

9-12. From Eq. 9.54a

$$FAULT = (20)^{0.528}[0.1204 + 0.04048(3)^{0.3388} - 0.1492(1)^{0.05911}] = 0.089 \text{ in.}$$

9-13 From Eq. 9.56a

$$JTSPALL = (15)^{2.178}\left[0.0221 - 0.0135\times\begin{Bmatrix}0\\1\end{Bmatrix} - 0.0419\begin{Bmatrix}1\\0\end{Bmatrix} + 0.0000362\times 1,000\right]$$
$$= \begin{cases}6.0 \text{ joints per mile for preformed seal}\\ 16.3 \text{ joints per mile for liquid seal}\end{cases}$$

Chapter 10
Reliability

10-1. Given: $f(x) = \begin{cases} 1/3 & x = 0 \\ 1/2 & x = 1 \\ 1/6 & x = 2 \end{cases}$ Find: expectation and variance of x

From Eq. 10.2a, $E[x] = 0x\frac{1}{3} + 1x\frac{1}{2} + 2x\frac{1}{6} = \frac{5}{6} = \underline{0.833}$

From Eq. 10.7b,

$$V[x] = \left(0 - \frac{5}{6}\right)^2 x\frac{1}{3} + \left(1 - \frac{5}{6}\right)^2 x\frac{1}{2} + \left(2 - \frac{5}{6}\right)^2 x\frac{1}{6} = \underline{0.472}$$

10-2. Given: $f(t) = te^{-\frac{t^2}{2}}$ when $t \geq 0$

$= 0$ when $t<0$

Find: Mean and variance of x

$$E[t] = \int_{-\infty}^{\infty} t\, f(t)dt = \int_0^{\infty} t^2 e^{-\frac{t^2}{2}} dt$$

From mathematical handbook, we can find the following definite integral

$\int_0^{\infty} x^2 e^{-x^2} dx = \frac{\sqrt{\pi}}{4}$ so E[t] must be transformed to the same form, or

$$E[t] = 2\sqrt{2}\int_0^{\infty}\left(\frac{t}{\sqrt{2}}\right)^2 e^{-\left(\frac{t}{\sqrt{2}}\right)^2} d\left(\frac{t}{\sqrt{2}}\right) = 2\sqrt{2}\left(\frac{\sqrt{\pi}}{4}\right)$$

$$= \sqrt{\frac{\pi}{2}} = \underline{1.253}$$

From Eq. 10.8

$$V[t] = E[t^2] - (E[t])^2$$

$$E[t^2] = \int_0^{\infty} t^3 e^{-\frac{t^2}{2}} dt = \frac{1}{2}\int_0^{\infty} t^2 e^{-\frac{t^2}{2}} d(t^2)$$

From mathematical handbook, we can find the following integral

$$\int xe^{ax}dx = \frac{e^{ax}}{a^2}(ax-1)$$

With $x = t^2$ and $a = -\frac{1}{2}$

$$E[t^2] = \frac{1}{2}\left[\frac{e^{-\frac{t^2}{2}}}{\left(-\frac{1}{2}\right)^2}\left(-\frac{t^2}{2}-1\right)\right]_0^\infty = 2\left[e^{-\frac{t^2}{2}}\left(-\frac{t^2}{2}-1\right)\right]_0^\infty$$

When t = ∞, the value is 0 because the exponential term predominates.

When t = 0, the value is –2. so $E[t^2] = 0 - (-2) = 2$. $V[x] = 2 - (1.253)^2 = \underline{0.429}$

10-3. Given: $f(x, y) = \begin{cases} ¼ & x=1 \quad y=2 \\ ¼ & x=2 \quad y=3 \\ 1/2 & x=3 \quad y=4 \end{cases}$ Find: Cov(x, y), ρ(x, y), V[x + y]

From Eq. 10.2a

$$E[x] = 1x\frac{1}{4} + 2x\frac{1}{4} + 3x\frac{1}{2} = 2.25 \qquad E[Y] = 2x\frac{1}{4} + 3x\frac{1}{4} + 4x\frac{1}{2} = 3.25$$

From Eq. 10.15b

$$Cov[x,y] = (1-2.25)(2-3.25)x\frac{1}{4} + (2-2.25)(3-3.25)x\frac{1}{4} +$$

$$(3-2.25)(42-3.25)x\frac{1}{2} = \underline{0.6875}$$

From Eq. 10.7b

$V[x] = (1 - 2.25)^2 \text{ x } 0.25 + (2 - 2.25)^2 \text{ x } 0.25 + (3 - 2.25)^2 \text{ x } 0.5 = 0.6875$

$V[y] = (2 - 3.25)^2 \text{ x } 0.25 + (3 - 3.25)^2 \text{ x } 0.25 + (4 - 3.25)^2 \text{ x } 0.5 = 0.6875$

From Eq. 10.18 $\rho(x,y) = \frac{0.6875}{\sqrt{0.6875x0.6875}} = \underline{1}$

From Eq. 10.21 V[x, y] = 0.6875 + 0.6875 + 2 x 0.6875 = $\underline{2.75}$

10-4. Given: f(x, y) = 6xy(2-x-y) $\quad x \le x \le 1, \quad 0 \le y \le 1$

= 0 $\quad$ otherwise

Find: Cov[x, y] and ρ[x,y]

Note Cov[x, y] = E[x, y] –E[x] E[y], so it is necessary to compute E[x, y], E[x], and E[y].

$$E[x,y] = \int_0^1\int_0^1 xy(12xy - 6x^2y - 6xy^2)dxdy$$

$$= \int_0^1\int_0^1 (12x^2y^2 - 6x^3y^2 - 6x^2y^3)dxdy$$

$$= \int_0^1 \left[4x^3y^2 - \frac{6}{4}x^4y^2 - 2x^3y^3\right]_0^1 dy$$

$$= \left[\frac{4}{3}y^3 - \frac{2}{4}y^3 - \frac{2}{4}y^4\right]_0^1 = \frac{4}{3} - \frac{1}{2} - \frac{1}{2} = \frac{1}{3}$$

$$E[x] = \int_0^1\int_0^1 x(12xy - 6x^2y - 6xy^2)dxdy$$

$$= \int_0^1\int_0^1 (12x^2y - 6x^3y - 6x^2y^2)dxdy$$

$$= \int_0^1 \left[4x^3y - \frac{6}{4}x^4y - 2x^3y^2\right]_0^1 dy$$

$$= \left[2y^2 - \frac{3}{4}y^2 - \frac{2}{3}y^3\right]_0^1 = 2 - \frac{3}{4} - \frac{2}{3} = \frac{7}{12}$$

Because of symmetry of x and y, E[y] = E[x] = 7/12

$$Cov[x,y] = \frac{1}{3} - \frac{7}{12} x \frac{7}{12} = \underline{-\frac{1}{144}}$$

Since $\rho[x,y] = \frac{Cov[x,y]}{\sqrt{V[x]V[y]}}$, it is necessary to determine V[x] and V[y].

Because V[x] = V[y] = E[x^2] –(E[x])^2, E[x^2] must be determined first.

$$E\left[x^2\right]=\int_0^1\int_0^1 x^2(12xy-6x^2y-6xy^2)dxdy$$

$$=\int_0^1\int_0^1(12x^3y-6x^4y-6x^3y^2)dxdy$$

$$=\int_0^1\left[3x^4y-\frac{6}{5}x^5y-\frac{6}{4}x^4y^2\right]_0^1 dy$$

$$=\left[\frac{3}{2}y^2-\frac{3}{5}y^2-\frac{2}{4}y^3\right]_0^1=\frac{3}{2}-\frac{3}{5}-\frac{1}{2}=\frac{2}{5}$$

Because of symmetry of x and y, E[y] = E[x] = 2/5

$$V[x]=V[y]=\frac{2}{5}-\left(\frac{7}{12}\right)^2=\frac{2}{5}-\frac{49}{144}=\frac{43}{720}$$

$$\rho[x,y]=\frac{Cov[x,y]}{\sqrt{V[x]V[y]}}=\frac{-\frac{1}{144}}{\sqrt{\frac{43}{720}\times\frac{43}{720}}}=\underline{-\frac{5}{43}}$$

10-5. Given $t=(0.25+0.125\log n)\left[\sqrt{\left(\frac{75P}{\pi E}\right)^2-a^2}\right]\sqrt[3]{\frac{E}{E_p}}$

t = 6.5 in., n = 100,000, P = 9000 lb, E = 10,000 psi, a = 6 in., and E_p =400,000 psi.

The coefficients of variation of all the above variables are 10 %

Find: Reliability of t based on Taylorseries expansion.

(a) Variance of t due to n

After substituting the values of all variables, except n, the following equation is obtained.

$$t = 6.03266(0.25 + 0.125\log n)$$

$$\frac{\partial t}{\partial n} = 6.03266x0.125x\frac{\log e}{n}$$

$$= 7.5408x10^{-6}x0.4343 = 3.275x10^{-6}$$

$$V[t]_n = \left(\frac{\partial t}{\partial n}\right)^2 V[n]$$

$$= \left(3.275x10^{-6}\right)^2 (100{,}000x0.1)^2 = 1.0726x10^{-3}$$

(b) Variance of t due to P

$$t = 0.25585\sqrt{5.6993x10^{-6}P^2 - 36}$$

$$\frac{\partial t}{\partial P} = \frac{0.25585}{2}\left(5.6993x10^{-6}P^2 - 36\right)^{-0.5} x11.3986P$$

$$= 6.36x10^{-4}$$

$$V[t]_P = \left(6.36x10^{-4}\right)^2 (9000x0.1)^2 = 0.328$$

(c) Variance of t due to E

$$t = 0.0119\sqrt[3]{E}\sqrt{4.616x10^{10}E^{-2} - 36}$$

$$\frac{\partial t}{\partial E} = 0.0119\left(4.616x10^{10}E^{-2} - 36\right)^{0.5} x\frac{1}{3}(E)^{-\frac{2}{3}}$$

$$+ 0.0119\sqrt[3]{E}\left(\frac{1}{2}\right)\left(4.616x10^{10}E^{-2} - 36\right)^{-0.5}\left(-9.232x10^{10}E^{-3}\right)$$

$$= 1.76314x10^{-4}\_6.21x10^{-3}\left(-9.232x10^{-2}\right) = -3.9699x10^{-4}$$

$$V[t]_E = \left(-3.9699x10^{-4}\right)^2 (10{,}000x0.1)^2 = 0.1576$$

(d) Variance of t due to a

$$t = 0.2559\sqrt{461.64 - a^2}$$

$$\frac{\partial t}{\partial a} = 0.2559x0.5\left(461.64 - a^2\right)^{-0.5}(-2a) = -7.442x10^{-2}$$

$$V[t]_a = \left(-7.442x10^{-2}\right)^2 (6x0.1)^2 = 0.1994x10^{-3}$$

(e) Variance of t due to E_P

$$t = 388.917(E_p)^{-\frac{1}{3}}$$

$$\frac{\partial t}{\partial a} = -\frac{388.917}{3}(E_p)^{-\frac{4}{3}} = -4.399x10^{-6}$$

$$V[t]_{E_p} = (-4.399x10^{-6})^2(400000x0.1)^2 = 0.031$$

Variance of t

$$V[t] = V[t]_n + V[t]_P + V[t]_E + V[t]_a + V[t]_{E_p}$$

$$= 0.0011 + 0.328 + 0.1576 + 0.002 + 0.031 = 0.5197$$

Standard deviation of t

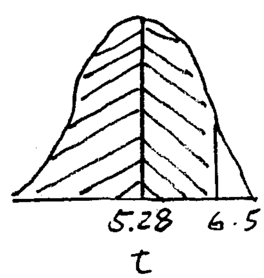
$$S_t = \sqrt{V[t]} = \sqrt{0.5297} = 0.721$$

$$E[t] = (0.25 + 0.125\log n)\left[\sqrt{\left(\frac{75P}{\pi E}\right)^2 - a^2}\right]\sqrt[3]{\frac{E}{E_p}}$$

$$= [0.25 + 0.125\log(100000)]\left[\sqrt{\left(\frac{75x9000}{\pi x10,000}\right)^2 - 36}\right]\sqrt[3]{\frac{10,000}{400000}}$$

$$= 0.875x20.631x0.2924 = 5.28\text{ in.}$$

$$Z = \frac{6.5 - 5.28}{0.721} = 1.692$$



From Tabble 10.1

Area under normal curve = 0.5 + 0.455 = 0.955

Reliability = 95.5%

10-6 Given $t = (0.25 + 0.125 \log n)\left[\sqrt{\left(\frac{75P}{\pi E}\right)^2 - a^2}\right]\sqrt[3]{\frac{E}{E_p}}$

$n = 100{,}000 \pm 10{,}000 = 110000$ and 90000

$P = 9{,}000 \pm 900 = 9{,}900$ and $8{,}100$ lb

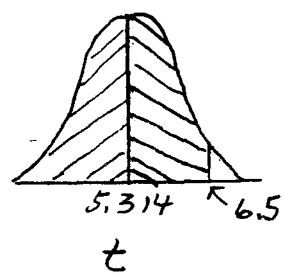
$E = 10{,}000 \pm 1{,}000 = 11{,}000$ and $9{,}000$ psi

$a = 6 \pm 0.6 = 6.6$ and 5.4 in

$E_p = 400{,}000 \pm 40{,}000 = 440{,}000$ and $360{,}000$ psi

By using Excel Spreadsheet and arranging variables in groups of 16, 8, 4, 2, 1, the following results were obtained:

n	P (lb)	E (psi)	a (in.)	Ep (PSI)	t (in.)	(t)^2 (sq. in.)
110000	9900	11000	6.6	440000	5.262368	27.69251
110000	9900	11000	6.6	360000	5.626408	31.65647
110000	9900	11000	5.4	440000	5.352226	28.64632
110000	9900	11000	5.4	360000	5.722482	32.7468
110000	9900	9000	6.6	440000	6.118354	37.43425
110000	9900	9000	6.6	360000	6.541609	42.79265
110000	9900	9000	5.4	440000	6.186164	38.26863
110000	9900	9000	5.4	360000	6.614111	43.74646
110000	8100	11000	6.6	440000	4.193347	17.58416
110000	8100	11000	6.6	360000	4.483434	20.10118
110000	8100	11000	5.4	440000	4.305574	18.53796
110000	8100	11000	5.4	360000	4.603425	21.19152
110000	8100	9000	6.6	440000	4.921882	24.22492
110000	8100	9000	6.6	360000	5.262368	27.69251
110000	8100	9000	5.4	440000	5.005926	25.05929
110000	8100	9000	5.4	360000	5.352226	28.64632
90000	9900	11000	6.6	440000	5.197236	27.01126
90000	9900	11000	6.6	360000	5.556771	30.8777
90000	9900	11000	5.4	440000	5.285982	27.94161
90000	9900	11000	5.4	360000	5.651656	31.94122
90000	9900	9000	6.6	440000	6.042628	36.51335
90000	9900	9000	6.6	360000	6.460645	41.73993
90000	9900	9000	5.4	440000	6.109599	37.3272
90000	9900	9000	5.4	360000	6.532249	42.67028
90000	8100	11000	6.6	440000	4.141446	17.15158
90000	8100	11000	6.6	360000	4.427943	19.60668
90000	8100	11000	5.4	440000	4.252284	18.08192
90000	8100	11000	5.4	360000	4.546449	20.6702
90000	8100	9000	6.6	440000	4.860964	23.62897
90000	8100	9000	6.6	360000	5.197236	27.01126
90000	8100	9000	5.4	440000	4.943968	24.44282
90000	8100	9000	5.4	360000	5.285982	27.94161
				Sum	170.0449	920.5796



$E[t] = 170.0449/32 = 5.314$, $E[t^2] = 920.5796/32 = 28.768$

From Eq. 10.61, $V[t] = 28.768 - (5.314)^2 = 0.529$, $S_t = 0.727$

Given $t = 6.5$, $z = \frac{6.5 - 5.314}{0.727} = 1.631$ From Table 10.1

Area under normal curve $= 0.448 + 0.5 = 0.948$

Reliability $= \underline{94.8\ \%}$

10-7. Find reliability based on n by Taylor's series expansion

$$t = (0.25 + 0.125\log n)\left[\sqrt{\left(\frac{75P}{\pi E}\right)^2 - a^2}\right]\sqrt[3]{\frac{E}{E_p}}$$

$$\log n = \frac{8t}{\left[\left(\frac{75P}{\pi E}\right)^2 - a^2\right]\sqrt[3]{\frac{E}{E_p}}} - 2$$

$$\frac{\partial \log n}{\partial t} = \frac{8}{\left[\sqrt{\left(\frac{75P}{\pi E}\right)^2 - a^2}\right]^2\sqrt[3]{\frac{E}{E_p}}} = \frac{8}{\left[\sqrt{\left(\frac{75\text{x}9000}{\pi\text{x}10{,}000}\right)^2 - 6^2}\right]^2\sqrt[3]{\frac{10{,}000}{400{,}000}}} = 1.326$$

$$\frac{\partial \log n}{\partial p} = \left(-\frac{1}{2}\right)\frac{8t\left(\frac{75}{\pi E}\right)^2(2p)}{\left[\sqrt{\left(\frac{75P}{\pi E}\right)^2 - a^2}\right]^3\sqrt[3]{\frac{E}{E_p}}} = -\frac{8\text{x}6.5\left(\frac{75}{\pi\text{x}10{,}000}\right)^2(9000)}{\left[\sqrt{\left(\frac{75\text{x}9000}{\pi\text{x}10{,}000}\right)^2 - 6^2}\right]^3\sqrt[3]{\frac{10{,}000}{400{,}000}}} = -1.0388\text{ x}10^{-3}$$

$$\frac{\partial \log n}{\partial E} = \frac{-\frac{8t}{3}\sqrt[3]{\frac{E_p}{E^4}}}{\sqrt{\left(\frac{75P}{\pi E}\right)^2 - a^2}} + \frac{8t\left(\frac{75P}{\pi}\right)^2\sqrt[3]{\frac{E_p}{E^{10}}}}{\left[\sqrt{\left(\frac{75P}{\pi E}\right)^2 - a^2}\right]^3}$$

$$= \frac{-\frac{8\text{x}6.5}{3}\sqrt[3]{\frac{400{,}000}{10{,}000^4}}}{\sqrt{\left(\frac{75\text{x}9000}{\pi\text{x}10{,}000}\right)^2 - 6^2}} + \frac{8\text{x}6.5\left(\frac{75\text{x}9000}{\pi}\right)^2\sqrt[3]{\frac{400{,}000}{10{,}000^{10}}}}{\left[\sqrt{\left(\frac{75\text{x}9000}{\pi\text{x}10{,}000}\right)^2 - 6^2}\right]^3}$$

$$= -2.873\text{x}10^{-4} + 9.349\text{x}10^{-4} = 6.476\text{ x}10^{-4}$$

$$\frac{\partial \log n}{\partial a} = \frac{8ta}{\left[\sqrt{\left(\frac{75P}{\pi E}\right)^2 - a^2}\right]^3\sqrt[3]{\frac{E}{E_p}}} = \frac{8\text{x}6.5\text{x}6}{\left[\sqrt{\left(\frac{75\text{x}9000}{\pi\text{x}10{,}000}\right)^2 - 6^2}\right]^3\sqrt[3]{\frac{10{,}000}{400{,}000}}} = 0.1215$$

$$\frac{\partial \log n}{\partial E_p} = \frac{\frac{8}{3}t}{\left[\sqrt{\left(\frac{75P}{\pi E}\right)^2 - a^2}\right]\sqrt[3]{E E_p^{\,2}}} = \frac{\frac{8}{3}x6.5}{\sqrt{\left[\left(\frac{75x9000}{\pi x10{,}000}\right)^2 - 6^2\right]}\sqrt[3]{10{,}000x400{,}000^2}} = 7.183 \text{ x } 10^{-6}$$

$$V[\log n]_t = \left(\frac{\partial \log n}{\partial t}\right)^2 (t\,C[t])^2$$

$$V[\log n]_t = (1.326)^2 + (6.5x0.1)^2 = 0.7429$$

$$V[\log n]_p = (-1.0388x10^{-3})^2 + (9000x0.1)^2 = 0.8741$$

$$V[\log n]_E = (6.476x10^{-4})^2 + (10{,}000x0.1)^2 = 0.4194$$

$$V[\log n]_a = (0.1215)^2 + (6x0.1)^2 = 0.005314$$

$$V[\log n]_{E_p} = (7.183x10^{-6})^2 + (400{,}000x0.1)^2 = 0.08255$$

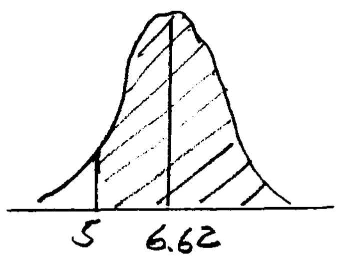
$$V[\log n] = 0.7429 + 0.8741 + 0.4194 + 0.005314 + 0.08255 = 2.1242$$

$$S[\log n] = \sqrt{V[\log n]} = 1.4574$$

$$E[\log n] = \frac{8x6.5}{\left[\sqrt{\left(\frac{75x9000}{\pi x10{,}000}\right)^2 - 6^2}\right]\sqrt[3]{\frac{10{,}000}{400{,}000}}} - 2 = 6.62$$

$$\log n_T = \log 100{,}000 = 5$$

$$z = \frac{\log n_T - E[\log n]}{S[\log n]} = \frac{5 - 6.62}{1.4572} = -1.1116$$

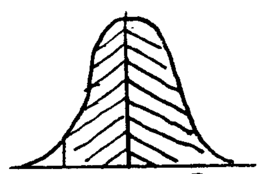


Reliability =86.75%

10-8. Given $\log n = \dfrac{8t}{\left[\sqrt{\left(\frac{75P}{\pi E}\right)^2 - a^2}\right]\sqrt[3]{\frac{E}{E_p}}} - 2$

$t = 6.5 \pm 0.65 = 7.15$ and 5.85, by Excel spreadsheet, the following results were obtained.

t	P (lb)	E (psi)	a (in.)	Ep (PSI)	log n	(log n)^2
7.15	9900	11000	6.6	440000	7.567168	57.26204
7.15	9900	11000	6.6	360000	6.948153	48.27683
7.15	9900	11000	5.4	440000	7.406546	54.85692
7.15	9900	11000	5.4	360000	6.797923	46.21175
7.15	9900	9000	6.6	440000	6.228677	38.79642
7.15	9900	9000	6.6	360000	5.696265	32.44743
7.15	9900	9000	5.4	440000	6.138478	37.68091
7.15	9900	9000	5.4	360000	5.611901	31.49344
7.15	8100	11000	6.6	440000	10.00615	100.1231
7.15	8100	11000	6.6	360000	9.229329	85.18051
7.15	8100	11000	5.4	440000	9.693206	93.95824
7.15	8100	11000	5.4	360000	8.936631	79.86337
7.15	8100	9000	6.6	440000	8.229006	67.71654
7.15	8100	9000	6.6	360000	7.567168	57.26204
7.15	8100	9000	5.4	440000	8.057272	64.91964
7.15	8100	9000	5.4	360000	7.406546	54.85692
5.85	9900	11000	6.6	440000	5.827683	33.96189
5.85	9900	11000	6.6	360000	5.321216	28.31534
5.85	9900	11000	5.4	440000	5.696265	32.44743
5.85	9900	11000	5.4	360000	5.1983	27.02233
5.85	9900	9000	6.6	440000	4.732554	22.39707
5.85	9900	9000	6.6	360000	4.296944	18.46373
5.85	9900	9000	5.4	440000	4.658754	21.70399
5.85	9900	9000	5.4	360000	4.227919	17.8753
5.85	8100	11000	6.6	440000	7.823215	61.2027
5.85	8100	11000	6.6	360000	7.187633	51.66207
5.85	8100	11000	5.4	440000	7.567168	57.26204
5.85	8100	11000	5.4	360000	6.948153	48.27683
5.85	8100	9000	6.6	440000	6.369187	40.56654
5.85	8100	9000	6.6	360000	5.827683	33.96189
5.85	8100	9000	5.4	440000	6.228677	38.79642
5.85	8100	9000	5.4	360000	5.696265	32.44743
				Sum	215.128	1517.269



$E[\log n] = \dfrac{215.128}{32} = 6.723 \quad E[(\log n)^2] = \dfrac{1517.269}{32} = 47.415$

From Eq. 10.61, $V[\log n] = 47.415 - (6.723)^2 = 2.216$

$S_{\log n} = \sqrt{2.216} = 1.489$. Given $n = 100000$ or $\log n = 5$

$z = \dfrac{5 - 6.723}{1.489} = -1.157$ From Table 10.1, Area under normal curve $= 0.376 + 0.5 = 0.876$ so Reliability $= \underline{87.6\%}$

10-9. Given

$$N_f = f_1(\varepsilon_t)^{-f_2}$$

$f_1 = 0.00462$, $C[f_1] = 30\%$

$f_2 = 2.69$, $C[f_2] = 5\%$

$\varepsilon_t = 0.0021$, $C[\varepsilon_t] = 10\%$

$\rho(f_1, f_2) = -0.867$

Find Expectation and variance of N_f based on the first order Taylor series expansion.

First order approximation of expectation or mean is $E[g] = E[\mu]$

$E[N_f] = 0.00462\ (0.0021)^{-2.69} = \underline{73{,}769}$

$$V[N_f] = V[N_f]_{\varepsilon_t} + V[N_f]_{f_1} + V[N_f]_{f_2} + 2\left(\frac{\partial N_f}{\partial f_1}\right)\left(\frac{\partial N_f}{\partial f_2}\right)\mathrm{Cov}[f_1, f_2]$$

(a) $V[N_f]_{\varepsilon_t}$

$$\frac{\partial N_f}{\partial \varepsilon_t} = f_1(-f_2)(\varepsilon_t)^{-f_2-1} = -0.00462\mathrm{x}2.69\mathrm{x}(0.0021)^{-3.69} = -94{,}494{,}180$$

$$V[N_f]_{\varepsilon_t} = \left(\frac{\partial N_f}{\partial \varepsilon_t}\right)^2 V[\varepsilon_t] = (-94{,}494{,}180)^2(0.0021\mathrm{x}0.1)^2 = 3.94\mathrm{x}10^8$$

(b) $V[N_f]_{f_1}$

$$\left(\frac{\partial N_f}{\partial f_1}\right) = (\varepsilon_t)^{-f_2} = (0.0021)^{-2.69} = 0.1597\mathrm{x}10^8$$

$$V[N_f]_{f_1} = \left(\frac{\partial N_f}{\partial f_1}\right)^2 V[f_1] = (0.1597\mathrm{x}10^8)^2(0.00462\mathrm{x}0.3)^2$$

$$= 4.899\mathrm{x}10^8$$

(c) $V[N_f]_{f_2}$

$$\frac{\partial N_f}{\partial f_2} = -f_1[\ln(\varepsilon_t)](\varepsilon_t)^{-f2} = -0.00462[\ln(0.0021)](0.0021)^{-2.69}$$
$$= 4.55 x 10^5$$

$$V[N_f]_{f_2} = \left(\frac{\partial N_f}{\partial f_2}\right)^2 V[f_2] = (4.55 x 10^5)^2 (2.69 x 0.05)^2$$
$$= 37.45 x 10^8$$

(d) Cross – Product

$$Cov[f_1, f_2] = \rho(f_1, f_2)\sqrt{V[f_1]V[f_2]}$$

$$\sqrt{V[f_1]} = 0.00462 x 0.3 = 0.001386$$

$$\sqrt{V[f_2]} = 2.69 x 0.05 = 0.1345$$

$$Cov[f_1, f_2] = -0.867 x 0.001386 x 0.1345 = -1.616 x 10^{-4}$$

$$\left(\frac{\partial N_f}{\partial N_{f_1}}\right)\left(\frac{\partial N_f}{\partial N_{f_2}}\right) Cov[f_1, f_2] = 0.1597 x 10^8 x 4.55 x 10^5 x (-1.616 x 10^{-4})$$
$$= -11.75 x 10^8$$

$$V[N_f] = 3.94 x 10^8 + 4.899 x 10^8 + 37.45 x 10^8 - 2x(11.75 x 10^8)$$
$$= \underline{2.28 x 10^9}$$

10-10. Serviceability index

$$PSI = p_1 - 1.91\ \log(1 + SV) - 1.38\ RD^2 - 0.01\sqrt{C}$$

(a) The expected value of PSI using second order Taylor series

$$E[g] = g(\mu) + \frac{1}{2}\sum_{i=1}^{n}\frac{\partial^2 g}{\partial x_i^2}V[x_i] \qquad g(x_1, x_2, x_3, x_4) = PSI(p_1, SV, RD, C)$$

$$\frac{\partial PSI}{\partial p_1} = 1 \qquad \frac{\partial^2 PSI}{\partial p_1^2} = 0$$

$$\frac{\partial PSI}{\partial SV} = -\frac{1.91}{1+SV}\left(\frac{1}{\ln 10}\right) = -\frac{1.91}{1+1.572}\left(\frac{1}{\ln 10}\right) = -0.323$$

$$\frac{\partial^2 PSI}{\partial SV^2} = \frac{1.91}{(1+SV)^2}\left(\frac{1}{\ln 10}\right) = \frac{1.91}{(1+1.572)^2}\left(\frac{1}{\ln 10}\right) = 0.125$$

$$\frac{\partial PSI}{\partial RD} = -1.38 \times 2 \times RD = 1.38 \times 2 \times 0.284 = -0.784 \qquad \frac{\partial^2 PSI}{\partial RD^2} = -1.38 \times 2 = -2.76$$

$$\frac{\partial PSI}{\partial C} = -0.01\left(\frac{1}{2}\right)\frac{1}{\sqrt{C}} = -0.01\left(\frac{1}{2}\right)\frac{1}{\sqrt{120}} = 0.000456$$

$$\frac{\partial^2 PSI}{\partial C^2} = -0.01\left(\frac{1}{2}\right)\left(-\frac{1}{2}\right)\frac{1}{\sqrt{C^3}} = 0.01\left(\frac{1}{4}\right)\frac{1}{\sqrt{120^3}} = 0.0000019$$

$$E[PSI] = 4.2 - 1.91\ \log(1+1.572) - 1.38 \times (0.284)^2 - 0.01\sqrt{120}$$
$$+ 0.5(0 \times 0.06 + 0.125 \times 0.32 - 2.76 \times 0.003 + 0.0000019 \times 0) = \underline{3.211}$$

(b) Variance

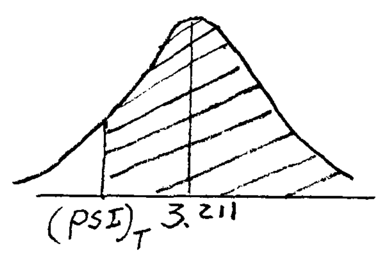
$$V(g) = \sum_{i=1}^{n}\left(\frac{\partial g}{\partial x_i}\right)^2 V[x_i]$$

$$V[PSI] = 1 \times 0.06 + (-0.323)^2 \times 0.32 + (-0.784)^2 \times 0.003 + (0.000456)^2 \times 0 = \underline{0.09522}$$

(c) Terminal serviceability index for 95 % reliability

From Table 8.1, u = 1.645 for 95% reliability

$$\frac{(PSI)_T - E[PSI]}{\sqrt{V[PSI]}} = -1.645$$



$$\frac{(PSI)_T - 3.211}{\sqrt{0.04522}} = -1.645 \quad \text{or} \quad (PSI)_T = \underline{2.703}$$

10-11. Given $g = \frac{1-2r}{1+r} + \frac{2+r}{3+6r+r^2} + \frac{r}{(4+r^2)(6+r)}$ Find V[g] when r=1, C[r]=0.2

$V[r] = (0.2 \times 1)^2 = 0.04$

$$\frac{\partial g}{\partial r} = \frac{(1+r)(-2)-(1-2r)(1)}{(1+r)^2} + \frac{(3+6r+r^2)(1)-(2+r)(6+2r)}{(3+6r+r^2)^2} + \frac{(4+r^2)(6+r)(1)-r(4+12r+3r^2)}{[(4+r^2)(6+r)]^2}$$

For r = 1, $\frac{\partial g}{\partial r} = -\frac{3}{4} + 0.14 + 0.0131 = -0.5969$

$$V[g] = \left(\frac{\partial g}{\partial r}\right)^2 V[r] = (-0.5969)^2(0.04) = \underline{0.01425}$$

10-12. Given $g = \frac{1-2r-s}{1+rs} + \frac{r+s}{3+6s+r^2} + \frac{rs}{(r+s)^2}$, Find V[g] when r = v[r] =10, s = V[s] =20

$$\frac{\partial g}{\partial r} = \frac{(1+rs)(-2)-(1-2r-s)(s)}{(1+rs)^2} + \frac{(3+6s+r^2)(1)-(r+s)(2r)}{(3+6s+r^2)^2} + \frac{(r+s)^2(s)-rs(2r+2s)}{(r+s)^2(r+s)^2} =$$

$$\frac{(1+200)(-2)-(1-20-20)(20)}{(1+20x10)^2} + \frac{(3+6x20+10^2)-(30)x2x10}{3+120+100)^2} + \frac{(10+20)^2x20-20x10(2x10+2x20)}{(30)^2(30)^2}$$

= 0.00936 – 0.00758 + 0.00741 = 0.00919

$$\frac{\partial g}{\partial s} = \frac{(1+rs)(-1)-(1-2r-s)(r)}{(1+rs)^2} + \frac{(3+6s+r^2)(1)-(r+s)x6}{(3+6s+r^2)^2} + \frac{(r+s)^2 r - rs(2s+2r)}{(r+s)^2(r+s)^2}$$

$$= \frac{-201-(-39)(10)}{(201)^2} + \frac{223-180}{(223)^2} + \frac{900x10-200(40+20)}{900x900}$$

$= 0.004678 + 0.000865 - 0.003704$ = 0.001839

$$V(g) = \left(\frac{\partial g}{\partial r}\right)^2 V[r] + \left(\frac{\partial g}{\partial s}\right)^2 V[s]$$

$$V[g] = (0.00919)^2 x10 + (0.001839)^2 x20 = \underline{0.00139}$$

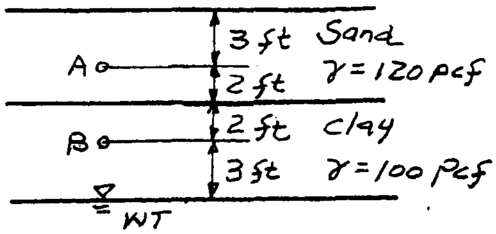
Chapter 11
Flexible Pavement Design

11-1 Find moisture content at Points A and B.

From Eq. 11.2 $\quad u = S + \alpha p$

$u = -z\,\gamma_w$

$S = -z\,\gamma_w - \alpha p$



At Point A with sand, $\alpha = 0$,

$S = -z\,\gamma_w = -7 \times 62.4 = -463.8$ psf = - 3.033 psi

From Fig. P11.1 $\quad w = \underline{10\ \%}$

At Point B with clay, $\alpha = 0.5$,

$P = 5 \times 120 + 2 \times 100 = 800$ psf

$S = -3 \times 62.4 - 0.5 \times 800 = -587.2$ psf = -4.08 psi

From Fig. 11.1 $\quad w = \underline{21\ \%}$

11-2. Estimate the coefficients of permanent deformation (a, b, and m) in the Ohio State Model in Eq. 11.16 based on the test results in Figs. 11.4 and 11.5.

$$\varepsilon_p = a(\varepsilon)^b (N)^{1-m} = a\left(\frac{M_R}{\sigma_d}\right)^b (N)^{1-m}$$

Let $A = a\left(\frac{M_R}{\sigma_d}\right)^b$ or $\log A = \log a - b \log\left(\frac{M_R}{\sigma_d}\right)$

From Fig. 11.5, when A = 0.0002, $M_R/\sigma_d = 10^4$, when A = 0.0006, $M_R/\sigma_d = 3000$

Log(0.0002) = log a – b log(10^4) or $\quad$ -3.69897 = log a – 4 b

Log(0.0006) = log a – b log(3000) or $\quad$ -3.22185 = log a - 3.47712 b

Solving a and b $\quad$ a = $\underline{0.89324}$, b = $\underline{0.9125}$

Fig. 11.4 shows a straight line relationship between $\log(\varepsilon_p/N)$, thus m is a constant, which is equal to the slope of the straight line

From Fig. 11.4

$$m = \frac{\log(2x10^{-5}) - \log(2x10^{-7})}{\log 10{,}000 - \log 70} = \underline{0.79}$$

$$\varepsilon_p = 0.8932(\varepsilon)^{0.9125}(N)^{0.21}$$

11-3. Given: $N_f = 5 \times 10^{-6}(\varepsilon_t)^{-3}$, $\varepsilon_t = 0.0005$, and $C[N_f] = 0.8$.

Find: Percent area cracked if the pavement is subjected to 5000 thermal cycles.

$N_f = 5 \times 10^{-6}(0.0005)^{-3} = 40{,}000$

$V[N_f] = (0.8 \times 40{,}000)^2 = 1.024 \times 10^9$

Cracking Index $c = n/N_f = 5000/40{,}000 = 0.125$

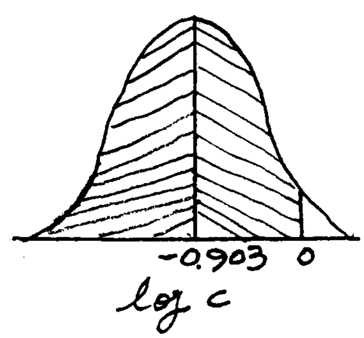
$$V[c] = \left[-\frac{n}{(N_f)^2}\right]^2 V[N_f] = \left[-\frac{5000}{(40{,}000)^2}\right]^2 x1.024x10^9 = 0.01$$

$$V[\log c] = \frac{0.1886}{c^2} V[c] = \frac{0.1886}{(0.125)^2} x0.01 = 0.1207$$

$$S_{\log c} = \sqrt{0.1207} = 0.3474$$

$$\log c = \log(0.125) = -0.903$$

$$Z = \frac{0 + 0.903}{0.3474} = 2.6$$



From Table 10.1, Area under normal curve = 0.5 + 0.495 or

Reliability = 99.5 % Or Area cracked = 100 – 99.5 = 0.5 %

11-4.

(a) $M_p = 68\left(1+\dfrac{1}{0.67+4}\right) - \dfrac{34}{0.67+4} + 6 = \underline{81.3^\circ F}$ ... surface

$M_p = 68\left(1+\dfrac{1}{4+4}\right) - \dfrac{34}{4+4} + 6 = \underline{78.3^\circ F}$ --- binder

(b) $\beta_5 = 1.3 + 0.49825 \log 8 = 1.74996$ ✓✓

$\beta_4 = 0.483 \times 11 = 5.313$ ✓✓

$\beta_3 = 0.553833 + 0.028829 \times 5 \times (8)^{-0.1703} + 0.070377 \times 2.5$ surface ↓

$+ 0.931757\,(8)^{-0.02774} - 0.03476\,V_a = 1.71046 - \square = 1.571425$
1.46714
binder

$\beta_2 = (5.313)^{0.5} \left(\begin{matrix}81.3\\78.3\end{matrix}\right)^{1.74996} = \begin{matrix}5072.8\\4749.8\end{matrix}$

$\beta_1 = \begin{matrix}1.571425\\1.46714\end{matrix} + 0.000005 \times \left(\begin{matrix}5072.8\\4749.8\end{matrix}\right) - 0.00189 \times \left(\begin{matrix}5072.8\\4749.8\end{matrix}\right)(8)^{-1.1}$

$= \begin{matrix}0.623346\\0.57943\end{matrix}$

$|E|^* = 100{,}000 \times 10^{\left(\begin{matrix}0.623346\\0.57943\end{matrix}\right)} = \underline{\begin{matrix}4.2\times 10^5\ \text{psi surface}\\3.8\times 10^5\ \text{psi binder}\end{matrix}}$

$E_1 = \left\{\dfrac{2\times(4.2)^{\frac{1}{3}} + 6\,(3.8)^{\frac{1}{3}}}{8}\right\}^3 = 3.9\times 10^5$ psi

$E_2 = 10.447\,(8)^{-0.471}\,(8)^{-0.041}\,(3.9\times 10^5)^{-0.139}\,(10000)^{0.287}\,(\cancel{\ldots})^{0.868} = \underline{29{,}700}$ psi

11-5.

(a) From Eq 6.30 $ESAL = (ADT)_0(T)(T_f)(G)(D)(L)(365)(Y)$

Given: $(ADT)_0(T) = 1885$, $T_f = 0.52$ (see Table 6.10)
$(D)(L) = 0.4$ (see Table 6.15), and from Eq. 6.33

$(G)(Y) = \dfrac{(1+0.04)^{20}-1}{0.04} = 29.78$

$ESAL = 1885 \times 0.52 \times 29.78 \times 0.4 \times 365 = \underline{4.26\times 10^6}$

(b) With 8" of untreated aggregate base, $M_R = 10^4$ psi, $ESAL = 4.26 \times 10^6$, from Fig 11.17 $h = \underline{10}$ in.

(c) First, use Figures 11.11 and 11.12 to determine the substitution ratio of 1" HMA to 1" of Type I emulsified asphalt mix.

From Fig 11.11, the thickness of full-depth HMA is 11.5 in.

From Fig 11.12, the combined thickness of HMA and emulsified asphalt mix is 12 in.

Assume a minimum HMA of 2 in.

$$\text{Substitution Ratio} = \frac{12-2}{11.5-2} = 1.053$$

If use $\underline{2 \text{ in}}$ of HMA, thickness of emulsified asphalt base $= (10-2) \times 1.053 \doteq \underline{8.5}$ in.

If use $\underline{3.5 \text{ in}}$ of HMA, thickness of emulsified asphalt base $= (10-3.5) \times 1.053 \doteq 7$ in.

11-6. Stage Construction:

$$\left.\begin{array}{l} 1^{st} \text{ stage} = 5 \text{ YRS} \\ 2^{nd} \text{ stage} = 10 \text{ YRS} \\ 3^{rd} \text{ stage} = 15 \text{ YRS} \end{array}\right\} 30 \text{ YRS}$$

Design traffic = 30 000 ESAL

$r = 3\frac{1}{2}\%$

$Dr = \underline{0.5 ; 0.75 ; 1}$

$\therefore$ 1^{st} stage (5 YRS) $GY = \dfrac{(1+0.035)^5 - 1}{0.035} = 5.36$

2^{nd} stage (15 YRS) $GY = \dfrac{(1+0.035)^{15} - 1}{0.035} = 19.296$

3^{rd} stage (30 YRS) $GY = 51.623$

* The first stage:

$n_1 = 30000 \times 5.36 = 160800$ ✓

Eq. 11.45: $N_1 = \frac{n_1}{D_r} = \frac{160800}{0.5} = 321600 = 0.322 \times 10^6$ ✓

fig 11.10 $\longrightarrow$ $h_1 \approx \underline{8.25}$ in. use 8.5 in.

* the second stage:

$n_2 = 30000\,(19.296 - 5.36) = 418080 = 0.418 \times 10^6$

$N_2 = \frac{418080}{(0.75 - 0.5)} = 1.67 \times 10^6$ ✓

$h_2 \approx \underline{10.6}$ in. use 11 in.
or overlay of 2.5 in.

* The third stage:

$n_3 = 30000\,(57.623 - 19.269) = 970620$

$N_3 = \frac{970620}{1 - 0.75} = 3.88 \times 10^6$ ✓

$h_3 \approx \underline{12.5}$ in. or overlay of $\underline{1.5}$ in. ✓

11-7 $\beta_2 = (5.313)^{0.5}(70)^{1.74996} = 3904.07$

$$\beta_1 = \begin{pmatrix} 1.571425 \\ 1.46714 \end{pmatrix} + \left(0.000005 - 0.00189 \times 8^{-1.1}\right) \times 3904.07 = \begin{matrix} 0.84178 \\ 0.73749 \end{matrix}$$

surface

binder

$$E^* = 100{,}000\,(10)^{\substack{0.84178 \\ 0.73749}} = \begin{matrix} 6.9467 \times 10^5 \\ 5.4637 \times 10^5 \end{matrix}$$

$$E_1 = \left\{\frac{2 \times (6.95)^{\frac{1}{3}} + 6\,(5.46)^{\frac{1}{3}}}{8}\right\}^3 = 58 \times 10^5$$

$$E_2 = 10.447\,(8)^{-0.471}(8)^{-0.041}(5.8 \times 10^5)^{-0.139}(10{,}000)^{0.287}(8{,}000)^{0.868} = 19{,}560 \text{ psi}$$

$$a_2 = 0.249 \log 19{,}560 - 0.977 = 0.0916$$

$$SN = 8 \times 0.48 + 8 \times 0.0916 = \underline{4.6} \text{ in.}$$

11-8. MAAT = 45 °F ; Normal Modulus = 22500 psi.
determine the effective roadbed soil resilient modulus based on the monthly moduli (Table 11.10).

Month	M_R (psi)	U_f
JAN	29400	0.00507
FEB	36300	0.00311
MAR	43100	0.00209
APR	50000	0.00148
MAY	15800	0.02143
JUNE	17100	0.01784
JULY	18500	0.01486
AUG.	19800	0.01269
SEPT.	21200	0.01083
OCT.	22500	0.00944
NOV.	22500	0.00944
DEC.	22500	0.00944
	Σ	0.11772

$U_f = 1.18 \times 10^8 \, M_R^{-2.32}$

$\Sigma U_f = 0.11772$

$\bar{U}_f = \frac{0.11772}{12} = 0.00981$

Effective M_R: $M_R^{-2.32} = \frac{\bar{U}_f}{1.18 \times 10^8}$

$M_R^{-2.32} = 8.3136 \times 10^{-11}$

$M_R = \underline{22167}$ psi ✓

11-9. 12 in full depth asphalt pavement on subgrade with
Effective M_R = 10,000 psi

$a = a_1 = 0.44$ (for HMA).

$\Delta PSI = 4.20 - 2.5 = 1.7$; $S_o = 0.5$; $W_{18} = 3 \times 10^7$

For full depth asphalt $SN = a_1 D_1 = 0.44 \times 12 = 5.28$

Eqn. 11.34

$$\log W_{t18} = 9.36 \log \overset{6.28}{(SN+1)} - 0.20 + \frac{\log\left[\frac{\overset{1.7}{4.2-p_t}}{4.2-1.5}\right]}{0.4 + \frac{1094}{(SN+1)^{5.19}}} + 2.32 \log M_R - 8.07$$

$\log W_{t18} = 7.4689 - 0.20 - 0.41942 + 9.28 - 8.07 = 8.05948$ ✓

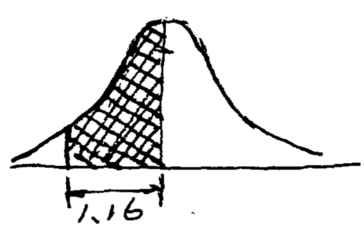
$W_{t18} = \underline{1.147 \times 10^8}$ ✓

$$Z_R = \frac{\log W_{18} - \log W_{t18}}{S_o} = \frac{\log(3 \times 10^7) - \log(1.147 \times 10^8)}{0.5}$$

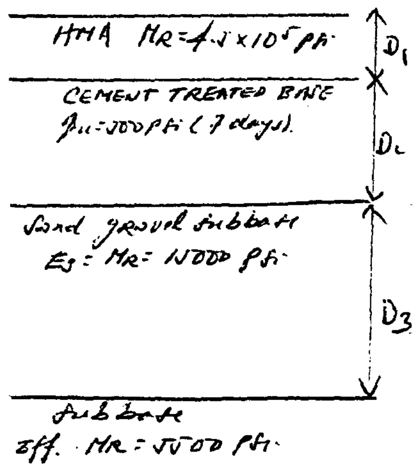
$= -1.16473$ ✓

From Table 10.1, with Z = 1.16, the area under the normal curve, as shown by the cross hatched area, is 0.377 so

R = 0.5 + 0.377 = 0.877 or <u>88</u> %



11-10: Design ESAL = 1.2×10^6 ; $\Delta PSI = 2$



Drainage: fair, 25% of the time of the pavement will be exposed to moisture levels approaching saturation.

HMA: $M_R = 4.5 \times 10^5$ psi → Fig. 11.26
$a_1 = 0.44$.

CTB: Fig 7.12c → $M_R = 6.5 \times 10^5$ psi
$a_2 = 0.17$

Granular subbase:
$a_3 = 0.227(\log M_R) - 0.839$ (Eq. 11.40).
$a_3 = 0.109$.

Drainage coeff = 0.80 (Table 11.20)

- Thickness of HMA:
  AASHTO Method unaplicable because $M_R = 6.5 \times 10^5 >> 40000$

  Let take $D_1 = \underline{3\ in}$ (minimum Thickness required).

- Thickness of CTB

$$\left.\begin{aligned} &ESAL = 1.2 \times 10^6 \\ \text{subbase} \rightarrow\ &M_R = 15000\ psi \\ &\Delta PSI = 2 \end{aligned}\right\}\ \text{From Fig 11.24} \quad SN_2 = 2.3$$

$$SN_2 = a_1 D_1 + a_2 D_2 m_2$$

Assume that CTB is unsusceptible to moisture change → $m_2 = 1$

$$2.3 = 3 \times 0.44 + 0.17\, D_2 \times 1$$

$$D_2 = 5.8 \simeq \underline{6\ in} \quad ✓$$

- Thickness of subbase:

$$\left.\begin{aligned} &ESAL = 1.2 \times 10^6 \\ &M_R = 5500\ psi \\ &\Delta PSI = 2 \end{aligned}\right\} \rightarrow SN_3 = 3.1$$

$$SN_3 = a_1 D_1 + a_2 D_2 m_2 + a_3 D_3 m_3$$

$$3.1 = 0.44 \times 3 + 6 \times 0.17 + 0.109 \times D_3 \times 0.8.$$

$R = 50\%$, $\quad D_3 = 8.7 \simeq \underline{9\ in}$ ✓

11-11. Given $W_{18} = 5 \times 10^6$, $M_R = 5{,}000$ psi, and $\Delta PSI = 1.7$, from Fig. 11.25
SN for main line pavement = $\underline{4.2}$

Given $P_e = 2.5\%$ and $P_p = 0.02\%$, $W_{18} = 5 \times 10^6 (0.025 + 0.0002)$
$= 0.126 \times 10^6$, from Fig. 11.25
SN for shoulder pavement = $\underline{2.4}$

Chapter 12
Rigid Pavement Design

12-1. Given: a concrete pavement on untreated subbase without concrete shoulders. $h = 10$ in., $k = 150$ pci, and $n = 2 \times 10^6$ repetitions.

Estimate: Allowable corner deflection.

From Eq. 12.9 $\quad$ % erosion damage = $100 \sum \frac{C_2 n_i}{N_i}$

When damage is 100 %, allowable number of repetitions $N = C_2 n$

$C_2 = 0.06$ for pavements with concrete shoulders, so

$N = 0.06 \times 2 \times 10^6 = 0.12 \times 10^6$

From Eq. 12.7 $\quad \log N = 14.524 - 6.777(C_1P - 9.0)^{0.103}$

$C_1 = 1$ for untreated subbase

$\log (0.12\text{x}10^6) = 14.524 - 6.777(P - 9.0)^{0.103}$

$P = 34.0946$ $\quad$ From Eq. 12.8

$$P = 268.7 \frac{p^2}{hk^{0.73}}$$

$$p = \sqrt{\frac{Phk^{0.73}}{268.7}} = \sqrt{\frac{34.0946\text{x}10\text{x}(150)^{0.73}}{268.7}} = 7.014 \text{ psi}$$

$$w = \frac{p}{k} = \frac{7.014}{150} = \underline{0.04676} \text{ in.}$$

12-2. Same as Problem 12-1 but with concrete shoulders.

$C_2 = 0.94$, so $N = 0.94 \times 2 \times 10^6 = 1.88 \times 10^6$

$\text{Log}(1.88 \times 10^6) = 14.524 - 6.777(P - 9.0)^{0.103}$

$P = 15.7485$ $\quad$ From Eq. 12.8 $\quad p = 4.767$ psi or $w = 4.767/150 = \underline{0.0318}$ in.

12-3. Total number of trucks during design period on design lane

$= 2500 \times 365 \times 20 \times 0.35 \times 0.5 = 3,193,750$

Calculation of Pavement Thickness

Project Problem 12-3

Trial thickness 8 in — Doweled joints: yes ✓ no ___

Subbase-subgrade k 200 pci — Concrete shoulder: Yes ___ no ✓

Modulus of rupture, MR 650 psi — Design period 20 years

Load safety factor, LSF 1.1

Axle load kips	Multiplied by LSF	Expected repetitions	Fatigue analysis: Allowable repetitions	Fatigue analysis: Fatigue damage %	Erosion analysis: Allowable repetitions	Erosion analysis: Erosion damage %
1	2	3	4	5	6	7

Single Axles

8. Equivalent stress 242
9. Stress ratio factor 0.372
10. Erosion factor 2.80

28	30.8	2874	19,000	15.1	900,000	0.3
26	28.6	6068	45,000	13.5	1,400,000	0.4
24	26.4	7346	160,000	4.6	2,100,000	0.4
22	24.2	49,823	800,000	6.2	3,500,000	1.4
20	22.0	208,871	—		7,200,000	2.9
18	19.8	353,868	—		16,000,000	2.2
16	17.6	418,062	—		40,000,000	1.0

Tandem Axles

11. Equivalent stress 208
12. Stress ratio factor 0.320
13. Erosion factor 2.93

48	52.8	30,660	10,000,000	0.3	950,000	3.2
44	48.4	33,534	—		1,600,000	2.1
40	44.0	53,655	—		2,600,000	2.1
36	39.6	54,933	—		5,600,000	1.0
32	35.2	76,650	—		12,000,000	0.6
28	30.8	109,865	—		40,000,000	0.3
24	26.4	256,139	—		—	
			Total	39.7	Total	17.9

12-4. Determine the thickness of a concrete pavement using the PCA procedure and check the result by the simplified procedure.

Trial thickness = 8.5 in.
K = 150 pci
MR = 650 psi
LSF = 1.2

Doweled joints: yes
Shoulders: yes
Design period = 20 years

Total no. of trucks on the design lane during the design period = 3460 x 365 x 20 =25,258,000

Load kips	Multiplied by LSF	Expected Repetition	Fatigue Analysis Allowable R.	Fatigue Analysis % Damage	Erosion Analysis Allowable R.	Erosion Analysis % Damage
Single Axle						
30	36	11,383	110,000	11.4	680,000	1.67
28	33.6	21,500	300,000	7.17	1,200,000	1.79
26	31.2	45,024	1,750,000	2.57	2,000,000	2.25
24	28.8	131,784			5,000,000	2.63
22	26.4	198,562			15,000,000	1.32
20	24	413,059				
18	21.6	636,157				
16	19.2	804,871				
14	16.8	1,207,306				
12	14.4	4,604,105				
Tandem Axles						
52	62.4	30,100			680,000	4.43
48	57.6	73,607			1,300,000	5.66
44	52.8	202,609			3,000,000	6.75
40	48	539,026			8,000,000	6.74
36	43.2	1,422,816				
32	38.4	2,621,269				
28	33.6	3,066,199				
24	28.8	1,834,863				
20	24	2,173,809				
16	19.2	2,512,756				
			Total	21.1		33.2

Single Axle: Eq. Stress = 191; Stress Ratio F = 0.29; Erosion Factor = 2.32

Tandem Axles: Eq. Stress = 166; Stress Ratio F = 0.26; Erosion Factor = 2.45

For h = 8.0 in., the fatigue damage is greater than 100 %, so h = 8.5 in.

For the simplified procedure, from Table 12.15, the allowable ADTT is 5,700 for an 8-in. slab with medium support, which is greater than the actual ADTT of 3460, so the thickness required is 8 in.

12-5. Same as Problem 12-4 but without concrete shoulder

Trial thickness = 9.5 in.
K = 150 pci
MR = 650 psi
LSF = 1.2

Doweled joints: yes
Concrete shoulders: no
Design period = 20 years

Total no. of trucks on the design lane during the design period = 25,258,000

From Table 12.15, a thickness of 9.5 in. is required. A 9-in. slab is not adequate because an allowable ADTT of 2700 is smaller than the actual ADTT of 3460.

Trial thickness = 9.5 in.

Load kips	Multiplied by LSF	Expected Repetition	Fatigue Analysis Allowable R	Fatigue Analysis % Damage	Erosion Analysis Allowable R	Erosion Analysis % Damage
Single Axle						
30	36	11,383	40,000	28.5	1,400,000	0.81
28	33.6	21,500	120,000	17.92	2,000,000	1.08
26	31.2	45,024	400,000	11.26	3,400,000	1.32
24	28.8	131,784	3,000,000	4.4	5,800,000	2.27
22	26.4	198,562			10,000,000	1.99
20	24	413,059			21,000,000	1.97
18	21.6	636,157			60,000,000	1.06
16	19.2	804,871				
14	16.8	1,207,306				
12	14.4	4,604,105				
Tandem Axles						
52	62.4	30,100	4,000,000	0.75	900,000	3.34
48	57.6	73,607			1,400,000	5.26
44	52.8	202,609			2,100,000	9.65
40	48	539,026			4,000,000	13.48
36	43.2	1,422,816			8,000,000	17.79
32	38.4	2,621,269			20,000,000	13.11
28	33.6	3,066,199			80,000,000	3.83
24	28.8	1,834,863				
20	24	2,173,809				
16	19.2	2,512,756				
			Total	62.83		76.96

Single Axle:
Eq. Stress = 200
Stress Ratio F =0.308
Erosion Factor =2.59

Tandem Axles:
Eq. Stress =183
Stress Ratio F=0.282
Erosion Factor=2.775

12-6. Given: $W_{18}^* = 5\times10^6[(1.04)^Y - 1]$, $\Delta PSI_{FH} = 0.08(Y)^{0.6}$

$R = 90\%$, $S_o = 0.4$, $D = 8$ in, $\Delta PSI = 2.0 - \Delta PSI_{FH}$,

$S_c = 600$ psi, $C_d = 1.05$, $J = 3.2$, $E_c = 5\times10^6$, and $k = 100$ pci

From Table 11.15, $Z_R = -1.282$ From Eq 12.21

$$\log W_{18} = -1.282\times0.4 + 7.35\log(8+1) - 0.06 + \frac{\log(\Delta PSI/3)}{1+1.624\times10^7/(8+1)^{8.46}}$$
$$+(4.22-0.32\times2.5)\log\left\{\frac{600\times1.05[(8)^{0.75}-1.132]}{215.63\times3.2\left[(8)^{0.75}-\dfrac{18.42}{\left(\frac{5\times10^6}{100}\right)^{0.25}}\right]}\right\}$$

$$\log W_{18} = 6.347 + 0.879\log\left(\frac{\Delta PSI}{3}\right)$$

(a) Assume $Y = 8.5$ years, $W_{18}^* = 5\times10^6[(1.04)^{8.5}-1] = 1.98\times10^6$

$\Delta PSI_{FH} = 0.08(8.5)^{0.6} = 0.289$, $\Delta PSI = 2 - 0.289 = 1.711$

$\log W_{18} = 6.347 + 0.879\log\frac{1.711}{3} = 6.1326$, or $W_{18} = 1.36\times10^6$

$1.36\times10^6 = 5\times10^6[(1.04)^Y-1]$, or $(1.04)^Y = 1.272$

$$Y = \frac{\log 1.272}{\log 1.04} = 6.2 \text{ years}$$

(b) Assume $Y = 6.2$ years

$W_{18}^* = 5\times10^6[(1.04)^{6.2}-1] = 1.38\times10^6$

$\Delta PSI_{FH} = 0.08(6.2)^{0.6} = 0.239$, $\Delta PSI = 2 - 0.239 = 1.761$

$\log W_{18} = 6.347 + 0.879\log\frac{1.761}{3} = 6.144$ $W_{18} = 1.39\times10^6$

The actual ESAL of 1.38×10^6 is slightly smaller than the allowable ESAL of 1.39×10^6 so a performance period of 6.2 years is satisfactory

12-7. Given a concrete pavement with $S_c = 650$ psi, J = 3.3, $\Delta PSI = 4.5 - 2.0 = 2.5$, and poor drainage with 5% of time near saturation.

Determine W_{18} by Eq. 12.21 without the reliability term and compare the result with Figure 11.25.

From Table 12.20, C = 0.9 for poor drainage with 5% of time near saturation.

With D_{SB}= 8 in., M_R= 5000 psi, E_{SB} = 30,000 psi, from Figure 12.18, the composite modulus of subgrade reaction k = 350 pci. From Eq. 12.21

$$\log W_{18} = 7.35\log(8+1) - 0.06 + \frac{\log\left(\frac{2.5}{3}\right)}{1 + \frac{1.624\text{x}10^7}{(8+1)^{8.46}}} +$$

$$(4.22 - 0.32\text{x}2.0)\log\left\{\frac{650\text{x}0.9\left(8^{0.75} - 1.132\right)}{215.63\text{x}3.2\left[8^{0.75} - \frac{18.42}{\left(\frac{4\text{x}10^6}{350}\right)^{0.25}}\right]}\right\}$$

$\log W_{18} = 7.01368 - 0.06 - 0.069621 + 0.050309 = 6.9343678$

W_{18} = 8,597,413

By assuming a reliability of 50% and drawing a line along the scale of overall standard deviation, from the AASHTO design chart, $W_{18} = 8.5 \times 10^6$. Both solutions check very closely.

12-8. Given D = 8.5 in. and the subgrade modulus, M_R, for each month
Determine the effective modulus, k_{eff}, by assuming $k = M_R / 19.4$

$U_r = (D^{0.75} - 0.39\, k^{0.25})^{3.24}$

The computed k and U_r are listed below:

Month	MR (psi)	k (pci)	Ur (%)
JAN	15,900	819.6	31.2
FEB	27,300	1407.2	21.8
MAR	38,700	1994.8	16.4
APR	50,000	2577.3	12.9
MAY	900	46.4	86.4
JUN	1,620	83.5	75.5
JUL	2,340	120.6	68.5
AUG	3,060	157.7	63.2
SEP	3,780	194.8	59.0
OCT	4,500	232.0	55.6
NOV	4,500	232.0	55.6
DEC	4,500	232.0	55.6
		Sum	601.8

$\overline{U_r}$ = 60.18/12 = 50.15 50.15 = $[8.5^{0.75} - 0.39\,(k_{eff})^{0.25}]^{3.24}$ or k_{eff} = 305 pci

12-9. Same as Problem 12-8 except that the relationship between M_R and k is

$$k = 0.95\left(\frac{E_f}{E}\right)^{\frac{1}{3}} \frac{E_f}{\left(1 - \nu_f^2\right)h}$$

with $E = E_c = 4 \times 10^6$, ν_f= 0.45, and h = D = 8.5 in.

The computed k and U_r are listed below:

Month	MR (psi)	k (pci)	Ur (%)
JAN	15,900	353.0	47.3
FEB	27,300	725.7	33.4
MAR	38,700	1155.6	25.1
APR	50,000	1626.2	19.5
MAY	900	7.7	115.3
JUN	1,620	16.8	103.6
JUL	2,340	27.4	95.6
AUG	3,060	39.2	89.4
SEP	3,780	52.0	84.4
OCT	4,500	65.6	80.1
NOV	4,500	65.6	80.1
DEC	4,500	65.6	80.1
		Sum	853.9

$\overline{U_r}$ = 853.9/12 = 71.16 71.16 = $[8.5^{0.75} - 0.39\,(k_{eff})^{0.25}]^{3.24}$ or k_{eff} = 105 pci

12-10.

(a) Determine thickness of slab

Given $K = 75$ pci, $E_c = 4\times10^6$ psi, $S_c = 650$ psi, $J = 2.9$

$C_d = 1.05$, $R = 95\%$, $S_o = 0.3$, $ESAL = 10\times10^6$,

and $\Delta PSI = 2$, from Figure 12.17

Thickness of slab $D = \underline{9.5}$ in.

(b) Determine number of No. 5 bar per 12-ft lane

Given $D = 9.5$ in; Wheel Load due to construction traffic $= 18{,}000$ lb, and $k = 75$, from Fig 12.22

$\sigma_w = 235$ psi

The minimum amount of steel P_{min} must satisfy the following three criteria: $\bar{X} < 8$ ft, $CW < 0.04$ in, and $\sigma_s < 62{,}000$ psi

Given $f_t = 0.86\, S_c = 559$ psi, $\alpha_s = 5\times10^{-6}/°F$,

$\alpha_c = 3.8\times10^{-6}/°F$ (Limestone coarse aggregate, see Table 12.23)

$\phi = \frac{5}{8}$ in. $= 0.625$ in. $Z = 0.00036$ (See Table 12.2)

From Eq. 12.33 (based on $\bar{X} = 8$ ft)

$$P_{min} = \frac{1.062\left(1+\frac{559}{1000}\right)^{1.457}\left(1+\frac{5\times10^{-6}}{2\times3.8\times10^{-6}}\right)^{0.25}(1+0.625)^{0.476}}{(8)^{0.217}\left(1+\frac{235}{1000}\right)^{1.13}(1+1000\times0.00036)^{0.389}} - 1$$

$$= \frac{2.8997}{2.2465} - 1 = 0.29\ \%$$

From Eq. 12.34 (based on $CW = 0.04$ in.)

$$P_{min} = \frac{0.358\left(1+\frac{559}{1000}\right)^{1.435}(1+0.625)^{0.484}}{(0.04)^{0.220}\left(1+\frac{235}{1000}\right)^{1.079}} - 1$$

$$= \frac{0.8564}{0.6186} - 1 = 0.38\ \%$$

From Eq. 12.35 (Based on $\sigma_s = 62{,}000$ psi, $DT_D = 60°F$)

$$P_{min} = \frac{50.834\left(1+\frac{60}{100}\right)^{0.155}\left(1+\frac{559}{1000}\right)^{1.493}}{(62{,}000)^{0.365}\left(1+\frac{235}{1000}\right)^{1.146}\left(1+1000\times 0.00036\right)^{0.180}} - 1$$

$$\simeq \frac{106.099}{75.563} - 1 = 0.40\%$$

use $P_{min} = \underline{0.4}\,\%$

The maximum amount of steel P_{max} should be based on a crack spacing not less than 3.5 ft.

From Eq. 12.33 (Based on $\bar{X} = 3.5$ ft

$$P_{max} = \frac{1.062(1.559)^{1.435}(1.658)^{0.25}(1.625)^{0.476}}{(3.5)^{0.217}(1.235)^{1.13}(1.36)^{0.389}} - 1$$

$$= \frac{2.8716}{1.8776} - 1 = \underline{0.53}\,\%$$

$N_{min} = 0.01273 \times 0.4 \times 12 \times 12 \times 9.5/(0.625)^2 = 17.8$

use a minimum of 18 bars per 12-ft lane

$N_{max} = 0.01273 \times 0.53 \times 12 \times 12 \times 9.5/(0.625)^2 = 23.6$

use a maximum of 24 bars per 12-ft lane.

Calculation of Pavement Thickness

Project Problem 12-11

Trial thickness 8.5 in — Doweled joints: yes ✓ no

Subbase-subgrade k 150 pci — Concrete shoulder: Yes no ✓

Modulus of rupture, MR 650 psi — Design period 20 years

Load safety factor, LSF 1.2

Axle load kips	Multiplied by LSF	Expected repetitions	Fatigue analysis: Allowable repetitions	Fatigue analysis: Fatigue damage %	Erosion analysis: Allowable repetitions	Erosion analysis: Erosion damage %
1	2	3	4	5	6	7
Single Axles			8. Equivalent stress 234 / 9. Stress ratio factor 0.36		10. Erosion factor 2.73	
30	36	227	2400	9.5	610,000	0.0
28	33.6	429	8000	5.4	850,000	0.1
26	31.2	900	23,000	3.9	1,400,000	0.1
24	28.8	2632	52,000	5.1	2,100,000	0.1
22	26.4	3966	300,000	1.3	2,400,000	0.2
20	24.0	8249	4,000,000	0.2	7,000,000	0.1
18	21.6	12,705	—		14,000,000	0.1
16	19.2	16,074	—		39,000,000	0.0
14	16.8	24,111	—		—	
12	14.4	91,949	—		—	
Tandem Axles			11. Equivalent stress 208 / 12. Stress ratio factor 0.32		13. Erosion factor 2.90	
52	62.4	601	190,000	0.3	430,000	0.1
48	57.6	1470	800,000	0.2	630,000	0.2
44	52.8	4046	10,000,000	0	1,000,000	0.4
40	48.0	10,765	—		1,900,000	0.6
36	43.2	28,415	—		3,800,000	0.7
32	38.4	52,350	—		8,000,000	0.7
28	33.6	61,235	—		20,000,000	0.3
24	28.8	36,644	—		100,000,000	0
20	24	43,413	—		—	
16	19.2	50,183	—		—	
			Total	25.9	Total	3.7

Calculation of Pavement Thickness

Project Problem 12-12

Trial thickness 7 in.
Subbase-subgrade k 150 pci
Modulus of rupture, MR 650 psi
Load safety factor, LSF 1.2

Doweled joints: yes ✓ no
Concrete shoulder: yes ✓ no
Design period 20 years

Axle load, kips	Multiplied by LSF	Expected repetitions	Fatigue analysis		Erosion analysis	
			Allowable repetitions	Fatigue, percent	Allowable repetitions	Damage, percent
1	2	3	4	5	6	7

8. Equivalent stress 248
9. Stress ratio factor 0.382
10. Erosion factor 2.54

Single Axles

30	36	228	730	31.2	150,000	0.15
28	33.6	430	2,600	16.5	220,000	0.20
26	31.2	900	7,800	11.5	320,000	0.28
24	28.8	2,636	30,000	8.8	1,520,000	0.51
22	26.4	3,971	100,000	4.0	1,000,000	0.40
20	24.0	8,261	600,000	1.4	2,500,000	0.33
18	21.6	12,723			7,000,000	0.18
16	19.2	16097				
14	16.8	24,146				
12	14.4	92,082				

11. Equivalent stress 210
12. Stress ratio factor 0.323
13. Erosion factor 2.62

Tandem Axles

52	62.4	602	140,000	0.43	180,000	0.33
48	57.6	1,472	700,000	0.21	280,000	0.53
44	52.8	4052			500,000	0.81
40	48.0	10,781			1,000,000	1.07
36	43.2	28,446			2,000,000	1.42
32	38.4	52,425			10,000,000	0.52
28	33.6	61,324				
24	28.8	39,697				
20	24.0	43,476				
16	19.2	50,255				
			Total	74.0	Total	6.7

Chapter 13
Design of Overlays

13-1.

(a) With mean pavement temperature of 80°F and a granular base of 12 in., from Fig. 13.3 $F = 0.95$

Given $\bar{\delta} = 0.034$ in. and $s = 0.0041$ in., from Eq. 13.7

$$\delta_{rrd} = (0.034 + 2 \times 0.0041) \times 0.95 \times 1 = 0.04 \text{ in.}$$

With $ESAL = 10{,}000{,}000$, from Fig. 13.5,

HMA overlay thickness = <u>4.5</u> in. (By design chart)

(b) Check by Eqs 13.9 and 13.10

$$E_2 = \frac{1.5 \times 70 \times 6.4}{0.04} = 16{,}800 \text{ psi} \qquad \text{From Eq. 13.9}$$

$$\delta_a = \frac{1.5 \times 70 \times 6.4}{16{,}800} \left(\left\{ 1 - \left[1 + 0.8 \left(\frac{4.5}{6.4} \right)^2 \right]^{-0.5} \right\} \times \frac{16{,}800}{500{,}000} + \left\{ 1 + \left[0.8 \times \frac{4.5}{6.4} \left(\frac{500{,}000}{16{,}800} \right)^{\frac{1}{3}} \right]^2 \right\}^{-0.5} \right)$$

$$= 0.04\,(0.00516 + 0.4996) = 0.02011$$

From Eq. 13.10

$$\log 0.02011 = \log 1.0363 - 0.2438 \log ESAL$$

$ESAL = 10{,}529{,}707$, which is slightly greater than the 10,000 given, so the use of 4.5 in. is satisfactory. If the computed ESAL is smaller than 10,000,000, a larger thickness by trial and error should be used.

13-2.

Given $\delta_{rrd} = 0.055$ in., from Eq. 13.11

$$(ESAL)_r = \left(\frac{1.0363}{0.055} \right)^{4.1017} = 169{,}891$$

Given annual growth rate of 6 % and a design period of 5 years, from Table 6.13, growth factor = 5.64

From Eq. 13.12, $(ESAL)_0 = \frac{169{,}891}{5.64} = \underline{30{,}123}$

13-3

Given a slab length of 10 ft and a temperature differential of 80 °F, from Figure 13.7, a minimum overlay thickness of $\underline{4}$ in. should be used

Deflection after overlay = 0.0007 − 4 × 0.05 × 0.0007

= 0.00056 (Assume each inch of HMA can reduce deflection by 20 %)

Because the deflection is less than 0.0006 in., no undersealing is required.

13-4 (a) Bonded Case

$$\bar{f}_t = \frac{1}{12}(500 + 453 + 554 + 450 + 513 + 488 + 512$$
$$+ 468 + 532 + 520 + 420 + 556) = 497.2 \text{ psi}$$

$$V[f_t] = [(2.8)^2 + (44.2)^2 + (56.8)^2 + (47.2)^2 + (15.8)^2$$
$$+ (9.2)^2 + (14.8)^2 + (29.2)^2 + (34.8)^2 + (22.8)^2 + (77.2)^2$$
$$+ (58.8)^2]/11 = 1814.76$$

$$s = \sqrt{1814.76} = 42.6 \text{ psi}$$

From Eq. 13.13

$$f_{te} = 497.2 - 1.65 \times 42.6 = 426.9 \text{ psi}$$

From Eq. 13.14 $S_c = 1.45 \times 0.9 \times 426.9 = 557$ psi

So curve 1 in Fig. 13.14 should be used.

From Fig. 13.14, Combined thickness = 11.5 in.

So thickness of bonded overlay = 11.5 - 8 = <u>3.5</u> in.

(b) Unbonded case

use Fig. 13.12 for case 3 (existing pavement in good condition) overlay thickness = <u>9</u> in.

13-5.

(a) Determine SN_f for new pavement From Eq. 13.22

$M_R = \frac{0.24 \times 9000}{0.00608 \times 36} = 9868$ psi $M_R = 0.33 \times 9868 = 3257$ psi

Given $R = 95\%$, $S_o = 0.45$, ESAL = 100,000, $M_R = 3.3$ ksi and $\Delta PSI = 4.2 - 2.5 = 1.7$, from Fig. 11.25

$SN_f = 3.4$ (For more accurate results, solve Eq. 11.37 by trial and error, and $SN_f = \underline{3.47}$

(b) Determine D_{OL} by NDT method

Given $d_o = 16.1$ mil, $M_R = 9868$ psi, $P = 9000$ lb, and $D = 7.5$ in., $M_R d_o / P = 9868 \times 16.1 / 9000 = 17.7$

From Fig. 13.17; $E_p / M_R = 50$ or $E_p = 9868 \times 50$

= 493,400 psi. From Eq. 13.26

$SN_{eff} = 0.0045 \times 7.5 \sqrt[3]{493,400} = 2.67$. From Eq. 13.32,

$D_{OL} = \frac{3.47 - 2.67}{0.44} = 1.82$ in. use $\underline{1.9}$ in.

(c) Determine D_{OL} by condition survey

$SN_{eff} = 0.35 \times 1.5 + 0.25 \times 6 = 2.03$

$D_{OL} = \frac{3.47 - 2.03}{0.44} = 3.27$ in., use $\underline{3.3}$ in.

(d) Determine D_{OL} by remaining life

$SN = 0.44 \times 1.5 + 0.33 \times 6 = 2.64$ From Eq 11.37

$\log N_{1.5} = 0 + 9.36 \log(2.61+1) - 0.2 + 0 + 2.32 \log 3257 - 8.07$

$= 5.218 - 0.2 + 8.150 - 8.07 = 5.098$

$N_{1.5} = 125,314$ From Eq 13.30

$RL = 100\left(1 - \frac{95,000}{125,314}\right) = 24.19$ From Fig 13.23

$CF = 0.78$ From Eq 13.31 $SN_{eff} = 0.78 \times 2.64 = 2.06$

$D_{OL} = \frac{3.47 - 2.06}{0.44} = \underline{3.2}$ in.

13-6.

(a) From Eq 13.22 $M_R = \frac{0.24 \times 9000}{0.0027 \times 36} = 22,222$ psi

with $M_R d_0 / P = 22,222 \times 4.1 / 9000 = 10.12$ and $D = 16$ in.

from Fig 13.17, $E_p / M_R = 39$ or $E_p = 39 \times 22,222 = 866,658$ psi

with $\frac{d_0 M_R}{q a} = \frac{0.0041 \times 22,222}{\frac{9000}{\pi (5.9)^2} \cdot 5.9} = 0.188$ and $\frac{D}{a} = \frac{16}{5.9} = 2.71$

from Fig 13.20 $E_p / M_R = 50$ or $E_p = 50 \times 22,222 = \underline{1,111,100}$ psi

(b) With $C = 0.167$, $M_R = 0.167 \times 22,222 = 3711$ psi

With $R = 95\%$, $S_0 = 0.49$, $W_{18} = 6,700,000$, $M_R = 3711$ psi,

and $\Delta PSI = 2.0$, from Fig 11.25 $SN_f = \underline{6}$

(c) $SN_{eff} = 0.25 \times 10 + 0.05 \times 6 = 2.8$

$D_{OL} = \frac{6.0 - 2.8}{0.44} = 7.27$ in Use $\underline{7.3}$ in.

13-7 (a) Determine E_c and Static K-Value

$AREA = 6\left[1 + 2\left(\frac{4.5}{5.2}\right) + 2\left(\frac{3.5}{5.2}\right) + \frac{2.9}{5.2}\right] = 27.81$

From Fig. 13.21, dynamic $K = 300$ pci, so

Static $K = \underline{150}$ pci, From Fig 13.22, with $K = 300$ pci

$E_c D^3 = 1.75 \times 10^9 \quad E_c = \frac{1.75 \times 10^9}{8^3} = \underline{3.4 \times 10^6}$ psi

(b) Determine D_{OL}

From Eq. 7.56a $S_c = \frac{43.5 \times 3.4 \times 10^6}{10^6} + 488.5 = 636.4$ psi

With $K = 150$ pci $E_c = 3.4 \times 10^6$, $S_c = 636$ psi, $J = 2.2$,

$C_d = 1$, $\Delta PSI = 2.0$, $R = 95\%$, $S_o = 0.3$, and $W_{18} = 80 \times 10^6$

from Fig. 12.17 $D_f = 11.6$ in. $D_{eff} = 8 \times 0.95 \times 0.95 = 7.22$ in.

$D_{OL} = 11.6 - 7.22 = 4.38$ in. of PCC.

From Eq. 13.36 $A = 2.2233 + 0.0099 \times (4.38)^2 - 0.1534 \times 4.38$

$= 1.741 \quad D_{OL} = 1.741 \times 4.38 = \underline{7.6}$ in.

13-8 From Eq. 13.37, with $F_{jc} = 0.8$, $F_{dur} = 0.8$, and $F_{ac} = 0.85$

$D_{eff} = 0.8 \times 0.8 \times 7 + (3 - 0.75) \times 0.5 \times 0.85 = 5.44$ in.

With $K = 362/2 = 181$ pci, $E_c = 2.1 \times 10^6$ psi, $J = 2.6$, $C_d = 1$

$S_c = \frac{43.5 \times 3.1 \times 10^6}{10^6} + 488.5 = 623$ psi, $\Delta PSI = 2$

$R = 95\%$, $S_o = 0.35$, and $W_{18} = 1{,}000{,}000$, from Fig. 12.17

$D_f = 9.5$ in.

$D_{OL} = 9.5 - 5.44 = 4.06$

$A = 2.2233 + 0.0099(4.06)^2 - 0.1534 \times 4.06 = 1.764$

$D_{OL} = 1.764 \times 4.06 = 7.16$ in. use $\underline{7.2}$ in.

13-9. From previous problem $D_f = 9.5$ in.

$D_{eff} = 0.9 \times 7 = 6.3$ in.

$D_{OL} = \sqrt{(9.5)^2 - (6.3)^2} = 7.11$ in. use $\underline{7.2}$ in.

13-10.

(a) Determine E_c and static K

$AREA = 6\left[1 + 2\left(\frac{3.08}{3.68}\right) + 2\left(\frac{2.64}{3.68}\right) + \frac{2.23}{3.68}\right] = 28.3$

From Figure 13.21, with $d_o = 3.68 \times 9{,}000 / 8{,}500 = 3.9$ mil

dynamic $K = 380$ pci so static $K = \underline{190}$ pci

From Figure 13.22 $E_c D^3 = 2.5 \times 10^9$ $E_c = \underline{4.6 \times 10^6}$ psi

(b) Determine D_{OL}

With $K = 190$ pci, $E_c = 4.6 \times 10^6$ psi, $J = 4$, $C_d = 1$

$S_c = \dfrac{43.5 \times 4.6 \times 10^6}{10^6} + 488.5 = 688.6$ psi, $\Delta PSI = 2$

and $W_{18} = 11{,}000{,}000$, $R = 95\%$ and $S_o = 0.35$,

from Fig. 12.17 $D_f = 11.6$ in.

$D_{eff} = 8.2 \times 0.95 = 7.8$ in.

$D_{OL} = 11.6 - 7.8 = \underline{3.8}$ in.

13-11. From previous problem $D_f = 11.6$ in.

$D_{eff} = 0.98 \times 8.2 = 8.04$ in.

$D_{OL} = \sqrt{(11.6)^2 - (8.04)^2} = 8.36$ in. Use $\underline{8.4}$ in.

13-12.

Given $r = 36$ in. $d_r = 0.00445$ in. From Eq. 13.22

$$M_R = \frac{0.24 \times 9000}{0.00445 \times 36} = 13,483 \text{ psi}$$

With $M_R d_0 / P = 13,483 \times 24.1 / 9000 = 36.1$ and

$D = 5.5 + 12 = 17.5$ in., from Fig 13.17

$E_p / M_R = 3$ or $E_p = 3 \times 13,843 = 41,500$ psi

With $D_{SB} = 17.5$ in. From Fig 12.18 dynamic $K = 900$ pci

Static $K = 450$ pci.

With $K = 450$ pci, $E_c = 4.2 \times 10^6$ psi, $S_c = 690$ psi

$J = 3.2$, $C_d = 1$, $\Delta PSI = 2$, $R = 95\%$, $S_0 = 0.35$ and

$W_{18} = 4,200,000$, from Fig 12.17, $D = \underline{8.3}$ in.

From Eq. 12.21

$$\log W_{18} = -1.645 \times 0.35 + 7.35 \log(8.3+1) - 0.06$$

$$+ \frac{\log 0.6667}{1 + 1.624 \times 10^7 / (8.3+1)^{8.46}} + (4.22 - 0.32 \times 2.5) \times$$

$$\log\left\{\frac{690 \times 1 (8.3^{0.75} - 1.132)}{215.63 \times 3.2 \left[(8.3)^{0.75} - 18.42 / (4.2 \times 10^6 / 450)^{0.25}\right]}\right\}$$

$$= -0.576 + 7.118 - 0.06 - 0.159 + 0.327$$

$$= 6.65$$

$W_{18} = 4,466,836$ which checks with the given traffic of 4,200,000

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