Open-File Report

PETAL3: PEnetration Testing And Liquefaction, An Interactive Computer Program

Albert T. F. Chen

U.S. Geological Survey
Menlo Park, California 94025

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INTRODUCTION

PETAL is an interactive computer program developed for the purpose of estimating/analyzing the seismic behavior of cohesionless soil deposits on the basis of their penetration resistance. Two earlier versions of PETAL were released to incorporate major advances in the state of the art in this particular area of geotechnology (Chen, 1984; Chen, 1986). This report presents the most current version of PETAL in which estimates of volumetric strains associated with seismic pore-pressure build-ups of cohesionless soil deposits are included. Such estimates of volume change are a feature not considered in the earlier versions.

GENERAL DESCRIPTION

PETAL3 consists of a main program and five subroutines. In contrast to PETAL2, PETAL3 combines subroutine GETFAC with subroutine PPRES and adds a new subroutine STRAIN to compute volumetric strains. As with earlier versions, the program is coded in FORTRAN and programmed to run interactively with VAX 11/785 computers. The program requires less than 14K bytes of storage to execute and contains approximately 600 executable statements. Various components of PETAL3 are described briefly.

Input. -- For each computer run, fixed input required are the site characteristics and earthquake specifications. These include the layering, density and ground water depths of the site, the magnitude of the earthquake and the design peak horizontal surface acceleration at the site. Other input such as the penetration resistance, the fine/gravel content, and/or grain size information are entered for each soil deposit/layer considered.

Provision is made to distinguish between the test ground-water condition and the design ground-water condition in the analysis. The former is the depth to the water table at the time of penetration measurement and the latter is the water table expected during the design earthquake. Overburden pressures for each ground-water condition can be quite different and may significantly alter the outcome of liquefaction evaluation.

If input penetration resistance is given in SPT blowcounts, the program corrects them to 60% hammer efficiency readings according to (Seed and others, 1985):

$$N_{60} = N_m \, ERm/60 \qquad (1)$$

where N_m = SPT N-values measured; and ERm = rod energy ratio for the SPT procedure used. If the penetration resistance is given in cone penetration test (CPT) tip-resistance, q_c (in kg/cm^2), it is first converted to N_{60} according to the relation suggested by Robertson and Campanella (1985) as shown in Fig. 1. The median grain size, D_{50} (in mm), required for this conversion becomes an additional input. Alternatively, the user may opt for the conversion factor proposed by Seed and Idriss (1982) by entering D_{50} as a negative value. If the absolute value of D_{50} is greater than 0.2, PETAL3 assigns 4.5 as the conversion factor. Otherwise, the value of 4.0 is assigned.

SPT blowcounts are also subject to correction for shallow depth. If the testing depth is less than 10 ft (3 m) from the surface, the input blowcounts are multiplied by 0.75 to compensate for the energy loss due to the short length of drive rods (Seed and Idriss, 1982).

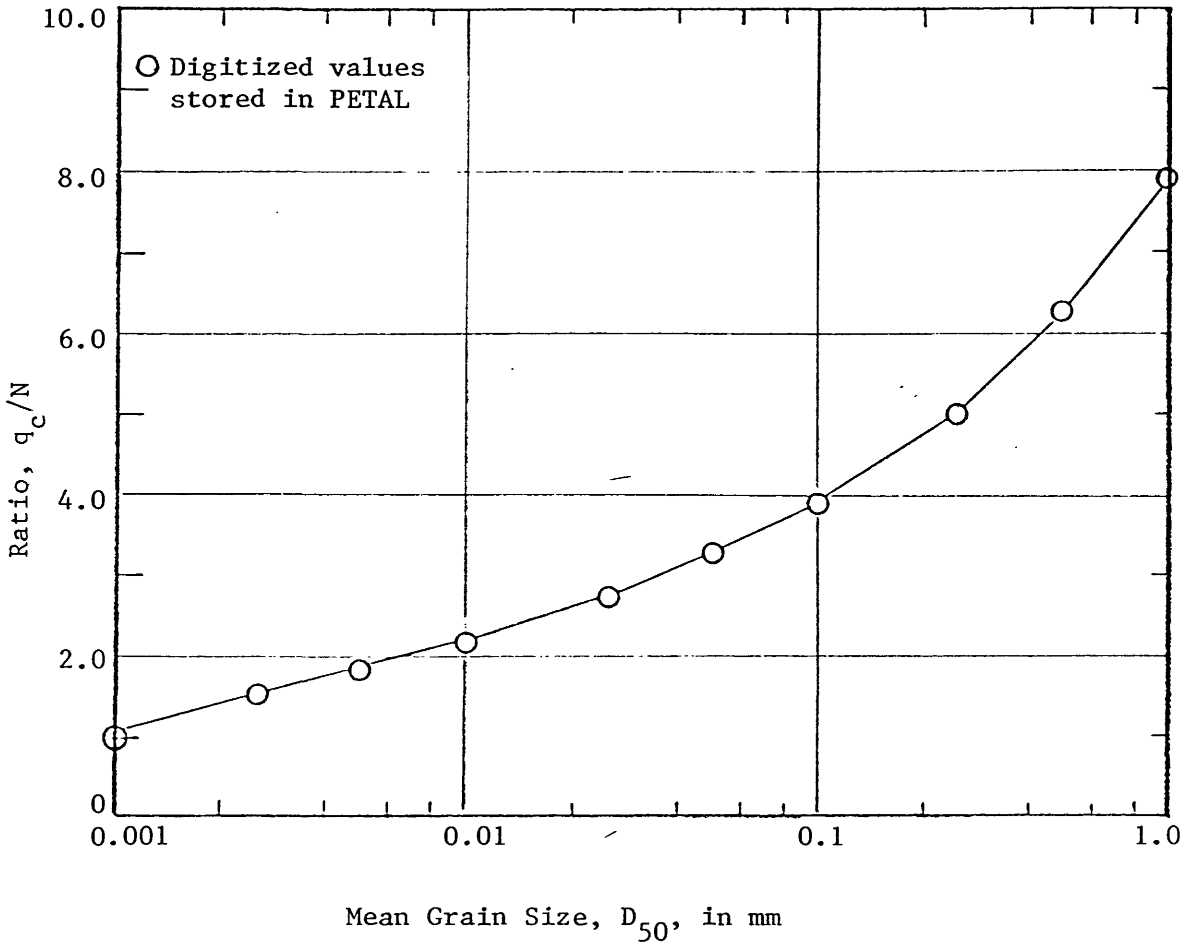

Figure 1. -- Variation of q_c/N ratio with mean grain size (Robertson and Campanella, 1985)

Normalized Standard Penetration Resistance. -- The correlation between liquefaction characteristics and penetration resistance is expressed in terms of a normalized blowcount, $(N_1)_{60}$, which is defined as the equivalent penetration resistance under an effective overburden pressure of 1 ton/ft^2 (1 kg/cm^2). This normalized blowcount is determined from:

$$(N_1)_{60} = C_N \, N_{60} \tag{2}$$

where C_N is a correction coefficient from the curves shown in Fig. 2. The relative density value required in Fig. 2 is obtained by iteration using subroutine RELDEN according to the empirical curve shown in Fig. 3 (Tokimatsu and Seed, 1987).

Average Cyclic Stress Ratio. -- The magnitude of the seismic stress acting on a soil element is expressed in terms of the induced average cyclic stress ratio, τ_{av}/σ'_o, determined from:

$$\frac{\tau_{av}}{\sigma'_o} = 0.65 \, \frac{a_{max}}{g} \, \frac{\sigma_o}{\sigma'_o} \, r_d \tag{3}$$

where a_{max} = (input) maximum acceleration at the ground surface; σ_o = total overburden pressure at depth under consideration; σ'_o = effective overburden pressure at depth under consideration; g = gravitational acceleration; and r_d = a stress reduction factor shown in Figure 4.

Liquefaction Resistance. --The determination of the liquefaction resistance, $(\tau/\sigma'_o)_l$, also expressed in terms of a stress ratio, is based on the relations proposed by Seed and others (1985). Such relations for 7.5-magnitude earthquakes are shown in Fig. 5 which illustrates how $(\tau/\sigma'_o)_l$

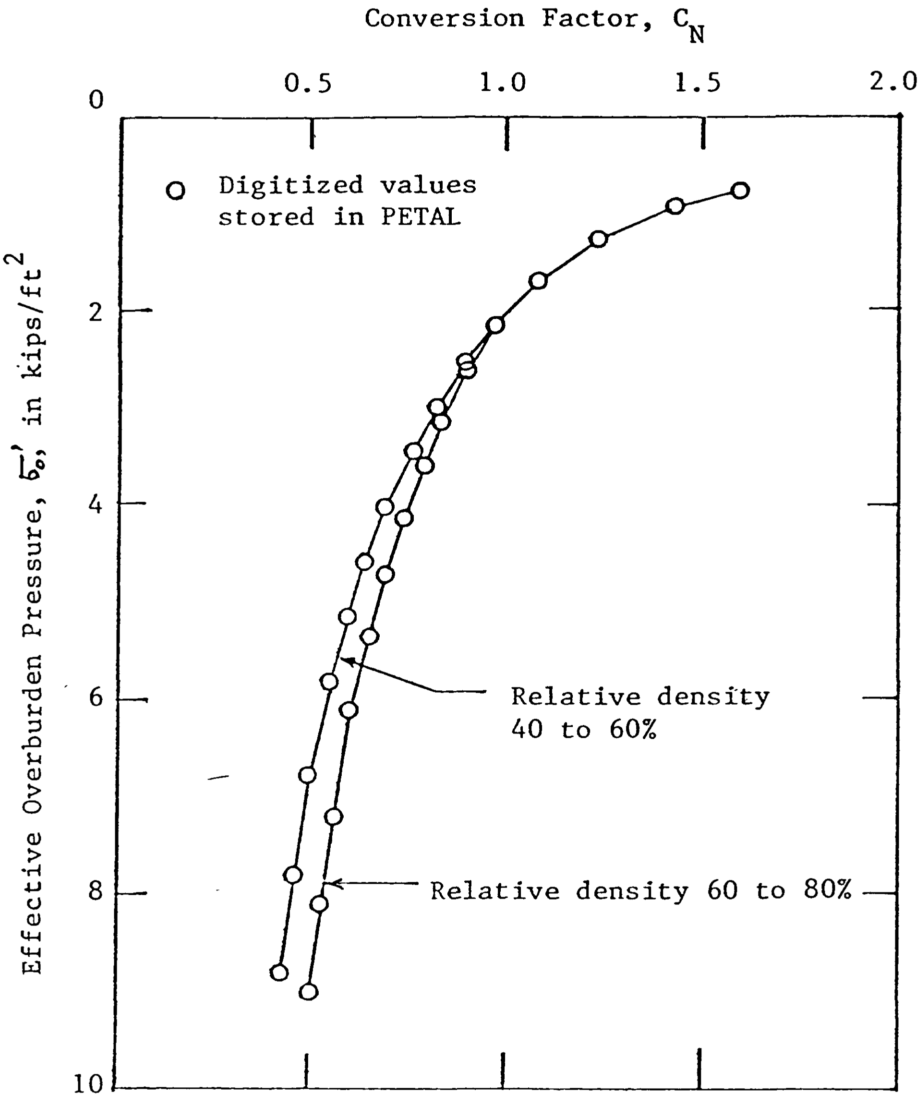

Figure 2. -- Conversion factor as a function of the effective overburden pressure and relative density (Seed and Idriss, 1982)

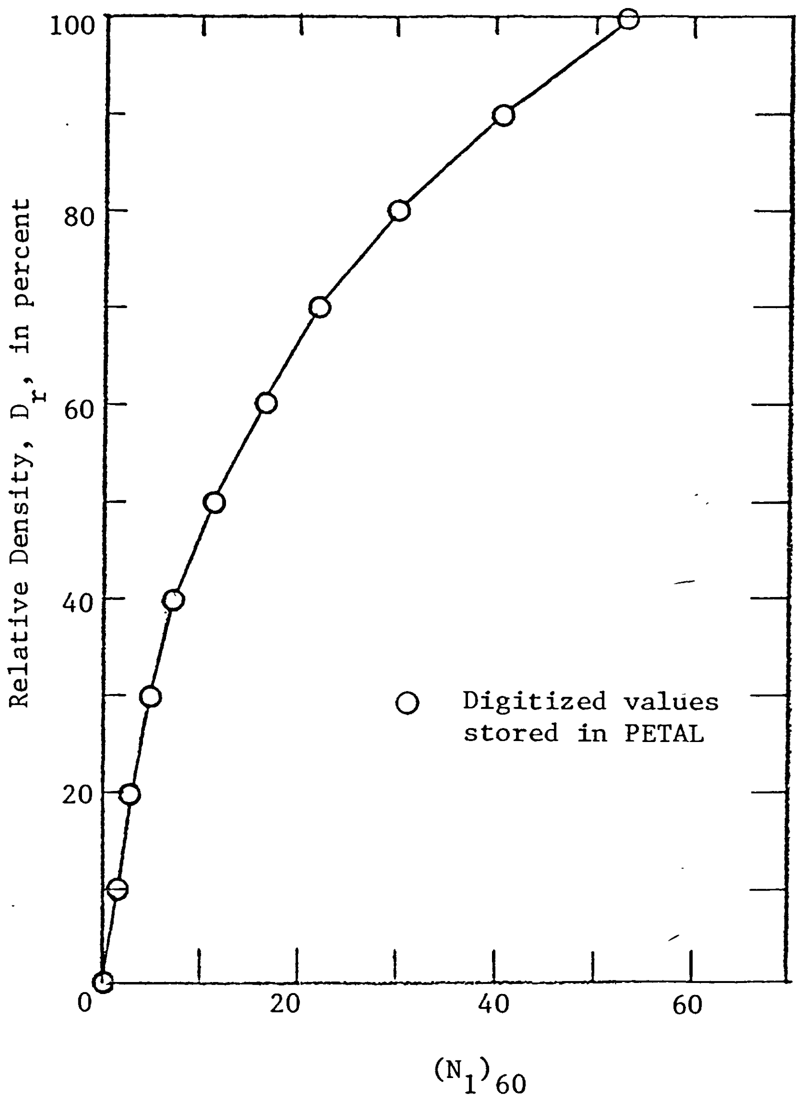

Figure 3. -- Variation of relative density with penetration resistance (Tokimatsu and Seed, 1987)

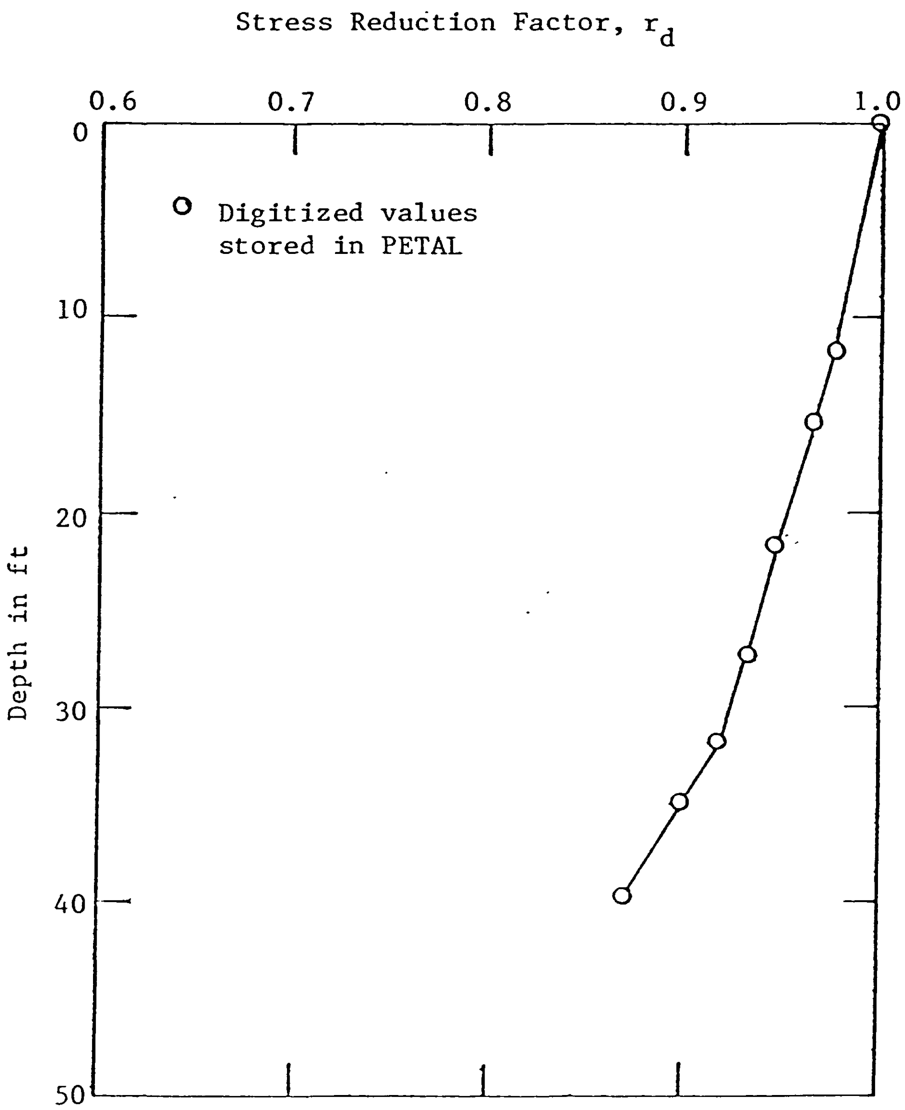

Figure 4. -- Stress reduction factor as a function of depth (Seed and Idriss, 1982)

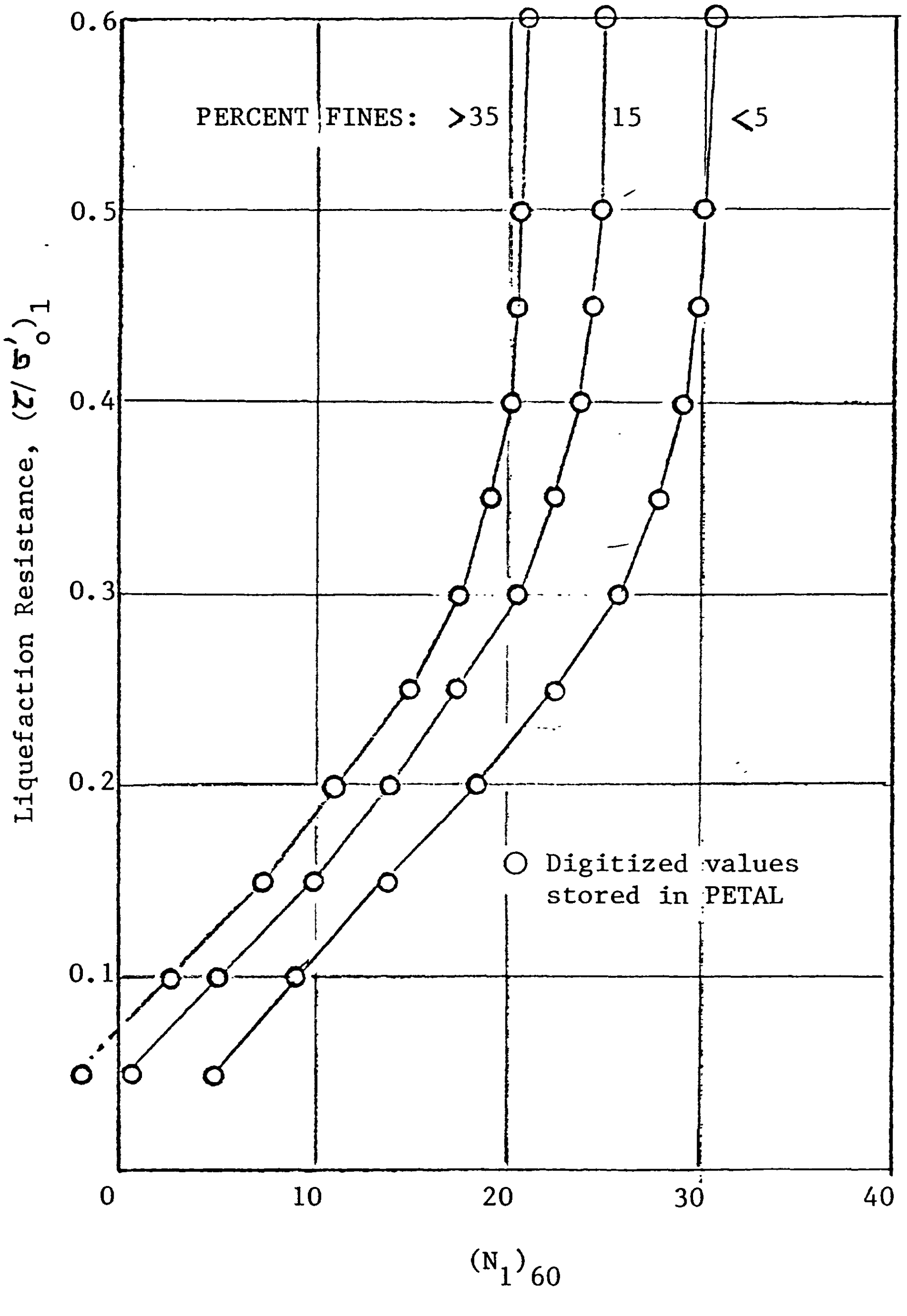

Figure 5. -- Variation of liquefaction resistance with $(N_1)_{60}$ in silty sands for M=7.5 earthquakes (Seed and others, 1985)

depends on both the normalized blowcount, $(N_1)_{60}$, and the fine content of the soil deposit/layer in question. In PETAL3, the scaling factor shown in Fig. 6 is first determined in subroutine PPRES to correct for the magnitude of the input earthquake and a new relation of $(\tau/\sigma'_0)_1$ versus $(N_1)_{60}$ is generated by iterations for each given fine content in subroutine ADJFIN.

Gravelly Sands. -- From laboratory results, Ishihara (1985) suggests that the effect of gravel inclusion on the liquefaction resistance of gravel-containing sands can be extrapolated from the liquefaction resistance of sands of identical depositional conditions. The extrapolation can be made according to the gravel content (fractions greater than 2 mm mesh size) as shown in Fig. 7 and is included in PETAL3.

Correction for Excessive Overburden Pressure. -- Liquefaction resistance is known to decrease as the overburden pressure increases. The $(\tau/\sigma'_0)_1$ as described above should be further corrected when σ'_0 is greater than 1.5 ton/ft^2 (1.5 kg/cm^2). The factor, K_σ, used for such correction is shown in Fig. 8. The same figure also shows the range in K_σ as established by Seed (1983).

Factor of Safety and Pore Pressure Built-up. -- The factor of safety against liquefaction is defined as

$$F.S. = (\tau/\sigma'_0)_1/(\tau_{av}/\sigma'_0) \qquad (4)$$

The pore-pressure build-up during an earthquake may be estimated from this factor of safety and the number of effective (stress) cycles induced by the earthquake (Seed and Idriss, 1982). Subroutine PPRES generates an excess pore-pressure ratio, $\Delta u/\sigma'_0$, versus F.S. curve according to the magnitude of

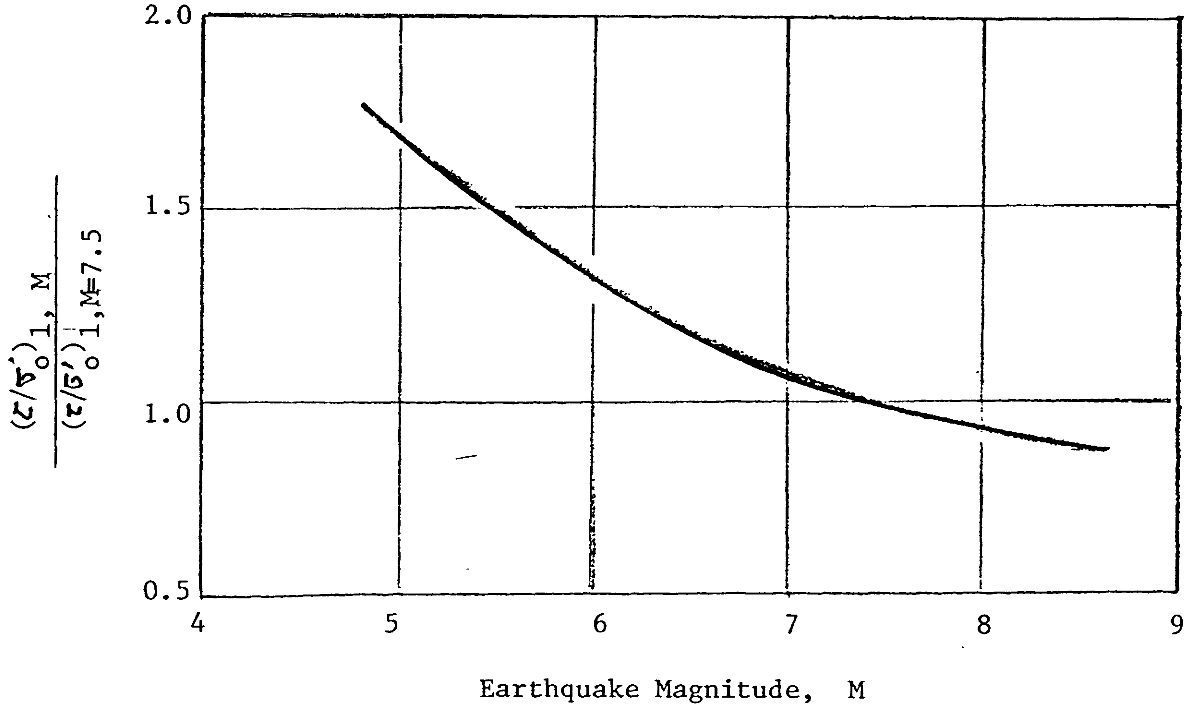

Figure 6. -- Scaling factor for modifying Fig. 5 for earthquakes with magnitudes other than 7.5

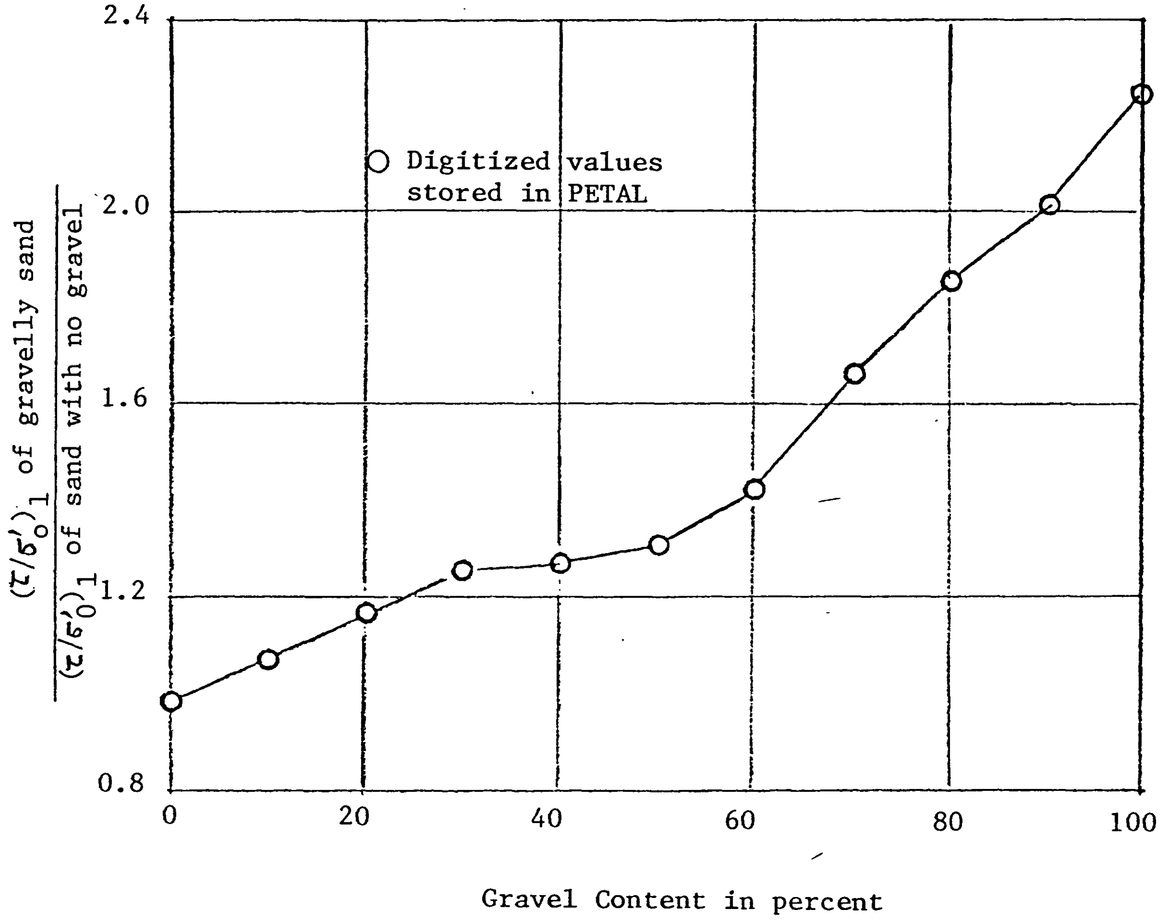

Figure 7 -- Variation of liquefaction resistance with gravel content (Ishihara, 1985)

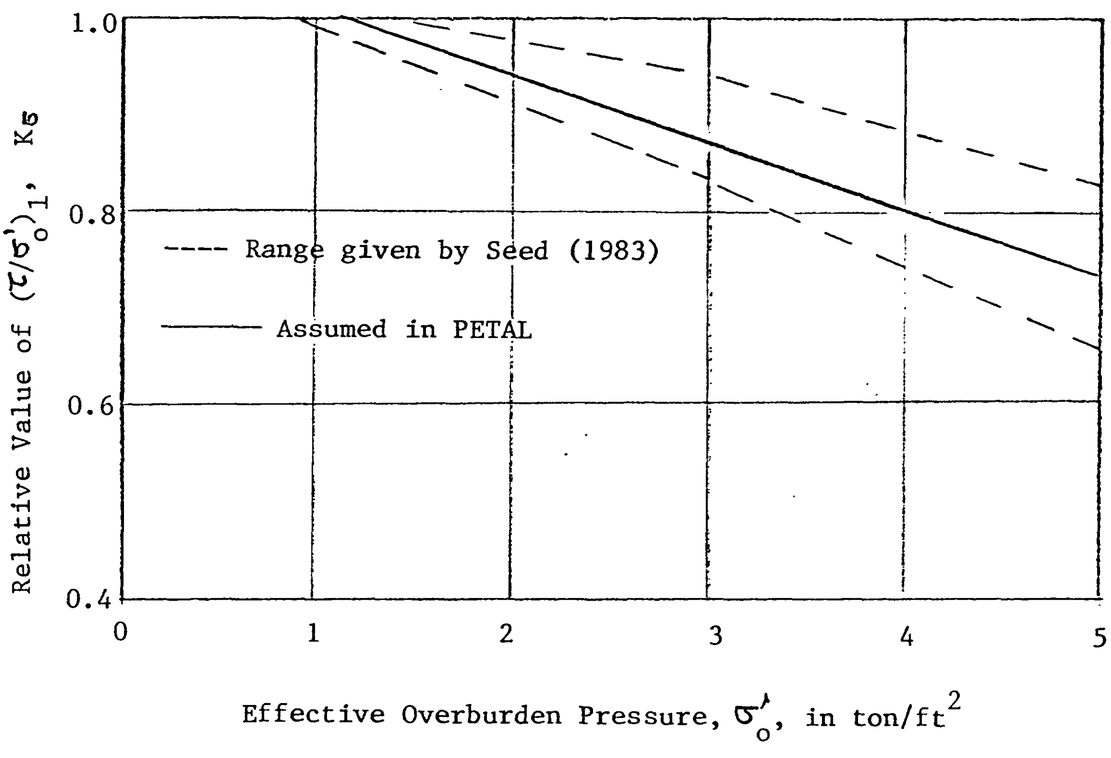

Figure 8. -- Reduction of liquefaction resistance with increase of overburden pressure

the earthquake considered. Such curves for different earthquake magnitudes are illustrated in Fig. 9. As seen in this figure, the estimate is good only for a very limited range of F.S. and PETAL3 will assign special values to identify the following different circumstances:

- if soil is gravelly, pore-pressure ratio, $\Delta u/\sigma'_o$=-0.01;
- if F.S.>2.0, $\Delta u/\sigma'_o$=0.02;
- if F.S.<1.02, $\Delta u/\sigma'_o$=1.0; and
- if $(N_1)_{60}$ is out of range to allow a reasonable extrapolation of $(\tau/\sigma'_o)_1$, then $(\tau/\sigma'_o)_1$=1.99, F.S.=4.99, and $\Delta u/\sigma'_o$=0.0

Estimates of volumetric strains. --For clean sands, Tokimatsu and Seed (1987) proposed that volumetric strains associated with pore-pressure build-ups and liquefaction can be estimated from the penetration resistance of each soil deposit/layer and the cyclic stress ratio, τ_{av}/σ'_o, for each earthquake. The chart shown in Fig. 10 provides the basis for making such estimates in PETAL3. Subroutine STRAIN first modifies the computed cyclic stress ratio for the given earthquake into an equivalent value for 7.5 magnitude earthquakes using the relationship:

$$(\tau_{av}/\sigma'_o)_{M=7.5} = (\tau_{av}/\sigma'_o)_{M=M}/r_M \qquad (5)$$

where r_M is the scaling factor shown in Fig. 6. The same subroutine then proceeds to find the value of volumetric strain by iteration according to the chart given in Fig. 10. This procedure, however, is not operational if the deposit is input as a gravelly sand or may lead to considerable errors if the fine content of the deposit is high (say, greater than 10%). Otherwise, the procedure has been shown to provide reasonable estimates of settlement in saturated sands (Tokimatsu and Seed, 1987, Chen, 1988).

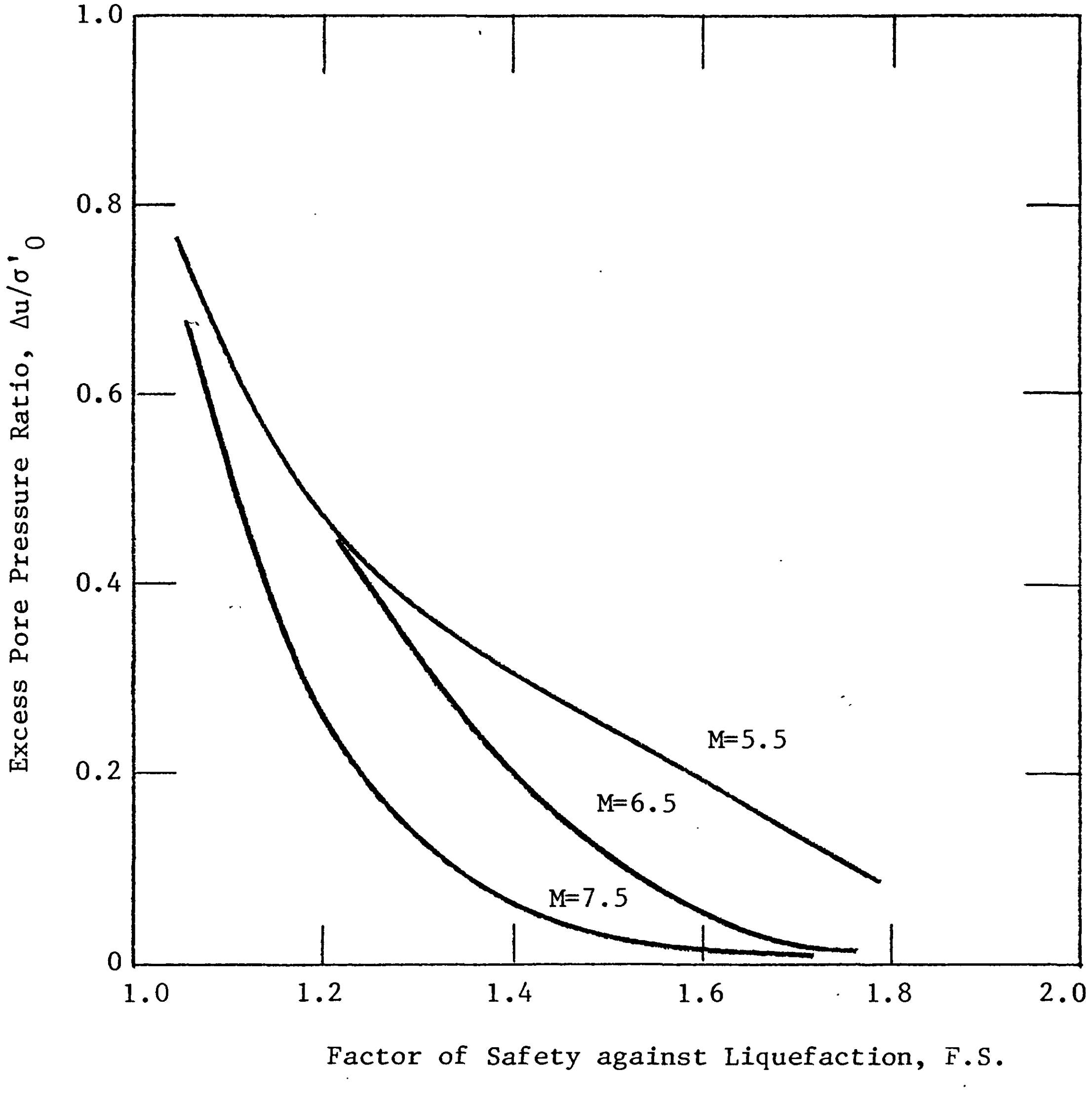

Figure 9. -- Excess pore pressure versus factor of safety against liquefaction for earthquakes of different magnitudes

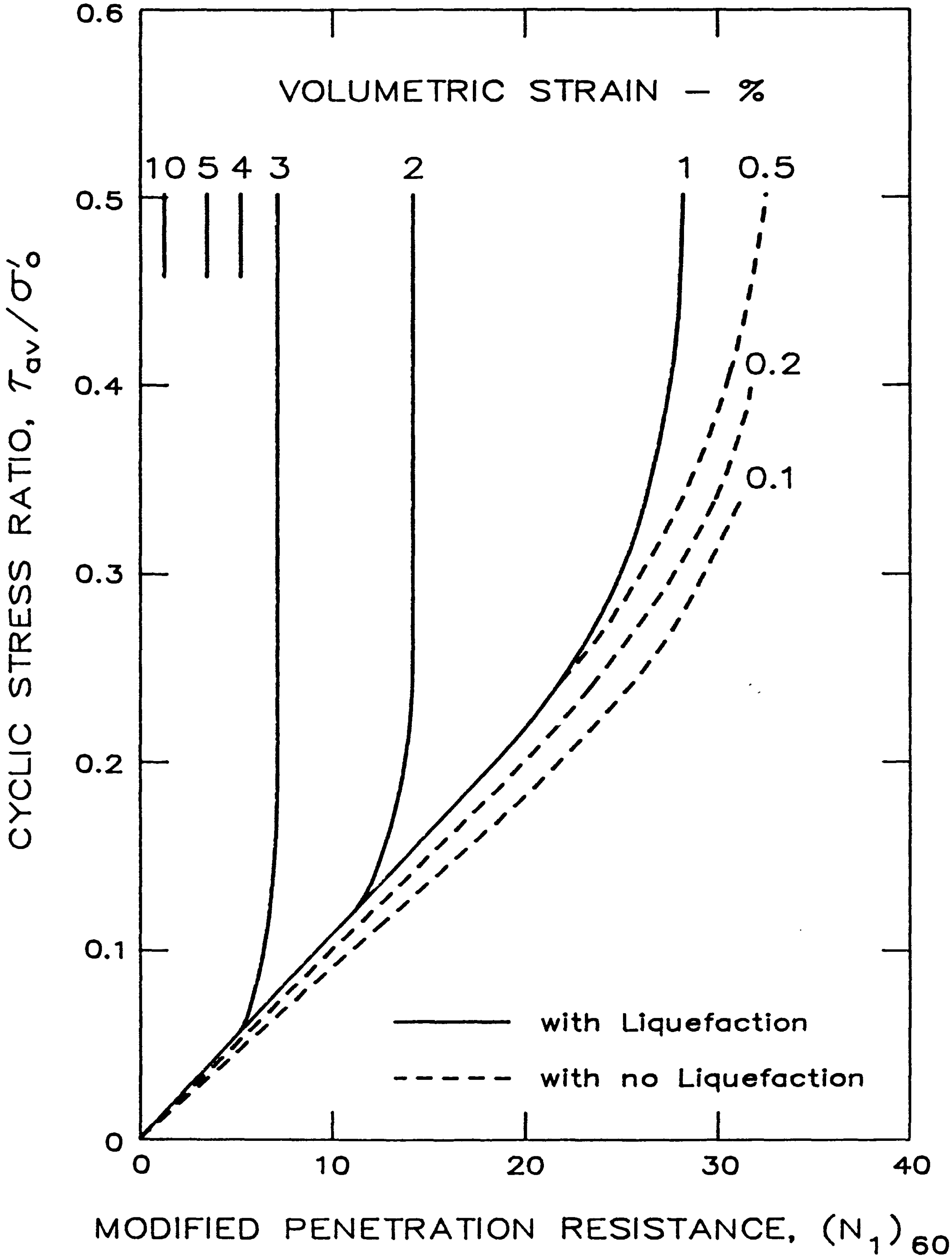

Figure 10. -- Proposed chart for evaluation of volumetric strain for saturated clean sands during 7.5-magnitudes earthquakes (Tokimatsu and Seed, 1987).

COMPUTATIONAL DATA

In contrast to the original version, no plot subroutine is included in the later versions of PETAL. Instead, all relevant data are stored in the array RESU(j,i) for additional output/plotter manipulation at users' own discretion. For RESU(j,i) in PETAL3, i refers to a group of data associated with the soil deposit at a given depth, and j=1,22 refers to the following quantities:

RESU(1,i) = depth in ft

RESU(2,i) = effective overburden pressure (in psf) at design ground-water condition

RESU(3,i) = total pressure (psf), design ground-water condition

RESU(4,i) = effective overburden pressure (psf) at test ground-water condition

RESU(5,i) = total pressure (psf), test ground-water condition

RESU(6,i) = input penetration resistance

RESU(7,i) = input fine content or gravel content

RESU(8,i) = input D_{50} (in mm), if applicable

RESU(9,i) = $(N_1)_{60}$

RESU(10,i) = estimated relative density, D_r

RESU(11,i) = τ_{av}/σ'_o, computed average cyclic stress ratio

RESU(12,i) = $(\tau/\sigma'_o)_l$, computed liquefaction resistance

RESU(13,i) = F.S., factor of safety against liquefaction

RESU(14,i) = $\Delta u/\sigma'_o$, excess pore-pressure ratio

RESU(j,i), j=15,20 and j=22 are reserved for remarks

RESU(21,i) = volumetric strain in percent.

SAMPLE RUN

For a demonstration run, consider a site consisting of 3 layers:

	Depth	Saturated Density	Moist Density
Layer 1	10.0 ft	102.0 pcf	98.0 pcf
Layer 2	25.0 ft	110.0 pcf	105.0 pcf
Layer 3	50.0 ft	120.0 pcf	120.0 pcf

The ground-water table is at the depth of 10 ft during SPT testing and assumed at 0.5 ft during the design earthquake. The design earthquake magnitude is 6.5 with the maximum surface acceleration at the site of 0.22g.

Deposits at three depths are being evaluated:

	Depth	Type	SPT Blow Count	Fine/Gravel Content
1	8.0 ft	sand	20.0	0.1
2	20.0 ft	gravelly sand	20.0	0.3
3	30.0	sand	20.0	varies from 0.2 to 0.05

All input are entered from the keyboard. Following is a reproduction of the interactive session for this computer run. In addition, output stored in I/O unit 16 produced from this run are also included.

(REPRODUCTION OF THE INTERACTIVE SESSION FOR THE SAMPLE RUN; LINES PRECEDED BY THE SIGN "→→" INDICATE INPUT FROM THE USER.)

```
   PETAL3: basic units are in LBS and FT

    enter title of this run in 72 characters or less

→→ PETAL3 demo run, 11/15/87

    site description: enter no. of layers (<10)

→→ 3
   enter depth(ft), saturated density(pcf), and wet density(pcf)
     with decimals of layer  1

→→ 10., 102., 98.
   enter depth(ft), saturated density(pcf), and wet density(pcf)
     with decimals of layer  2

→→ 25., 110., 105.
   enter depth(ft), saturated density(pcf), and wet density(pcf)
     with decimals of layer  3

→→ 50., 120., 120.

    enter expected depth of ground water during
    the design earthquake, and ground water depth
    when penetration test was performed -- 7.0, 20.0

→→ 0.5, 10.

    enter equake mag. and max acc (g) -- 7.5, 0.25

→→ 6.5, 0.22

    class=1 for SPT input and sandy/gravelly layers
         =2 for CPT and sandy deposits
    enter class (1 or 2) --

→→ 1

    enter SPT hammer efficiency (0.68 for 68%):

→→ 0.65

   use depth<0.0 to terminate execution

    enter depth (ft, <0. to exit), spt blow count
     (w/ neg sign, if gravelly), and fine content
      or gravel content if gravelly (0.1 for 10%) --
     for example -- 12.5, 25.0, 0.1

→→8.0, 20.0, 0.1
```

```
stress ratio insitu = 0.332 required to cause liq. = 0.466
factor of safety = 1.40
pore pressure ratio generated = 0.186
volumetric strain (%) =  0.04

 again? enter depth, blow count, fine content --

→→  20.0, -20.0, 0.3

stress ratio insitu = 0.320 required to cause liq. = 0.440
factor of safety = 1.37
pore pressure ratio generated =-0.010
volumetric strain (%) =  0.05

 strength ratio for gravel content given = 1.25

 again? enter depth, blow count, fine content --

→→  30.0, 20.0, 0.2

stress ratio insitu = 0.303 required to cause liq. = 0.493
factor of safety = 1.63
pore pressure ratio generated = 0.040
volumetric strain (%) =  0.01

 again? enter depth, blow count, fine content --

→→  30.0, 20.0, 0.15

stress ratio insitu = 0.303 required to cause liq. = 0.403
factor of safety = 1.33
pore pressure ratio generated = 0.297
volumetric strain (%) =  0.06

 again? enter depth, blow count, fine content --

→→ 30.0, 20.0, 0.05

stress ratio insitu = 0.303 required to cause liq. = 0.290
factor of safety = 0.96
pore pressure ratio generated = 1.000
volumetric strain (%) =  1.08

 again? enter depth, blow count, fine content --

→→ -5.0, 0., 0.
FORTRAN STOP
```

(OUTPUT FILE ON I/O UNIT 16)

```
PETAL3 demo run, 11/15/87

the site consists of  3 layers w/ depths, saturated and wet densities:
                      1      10.0 (ft)        102.0 (pcf)        98.0 (pcf)
                      2      25.0 (ft)        110.0 (pcf)       105.0 (pcf)
                      3      50.0 (ft)        120.0 (pcf)       120.0 (pcf)

input eq. mag.= 6.50   max. acc. = 0.22 g
correction factor (to M=7.5) = 1.18
design ground water table depth =   0.5 ft.
testing ground water table depth =  10.0 ft.

SPT hammer efficiency assigned = 0.65
```

count	depth (ft)	design stress (psf) effective	design stress (psf) total	testing stress (psf) effective	testing stress (psf) total	SPT blow count	fine/gravel content	remark
1	8.0	346.0	814.0	784.0	784.0	20.0	0.10	
2	20.0	901.2	2118.0	1456.0	2080.0	20.0	0.30	gravelly
3	30.0	1427.2	3268.0	1982.0	3230.0	20.0	0.20	
4	30.0	1427.2	3268.0	1982.0	3230.0	20.0	0.15	
5	30.0	1427.2	3268.0	1982.0	3230.0	20.0	0.05	

count	modified bc-N1,60	relative density	shear s. ratio	liq. resistance	factor safety	pore press. ratio	%, vol. strain	correction applied
1	25.8	0.75	0.33	0.47	1.40	0.19	0.04	shallow
2	25.4	0.74	0.32	0.44	1.37	-0.01(NA)	0.05(NA)	
3	21.9	0.70	0.30	0.49	1.63	0.04	0.01(NA)	
4	21.9	0.70	0.30	0.40	1.33	0.30	0.06	
5	21.9	0.70	0.30	0.29	0.96	1.00	1.08	

* * NA = not applicable or not accurate **

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Tokimatsu, K., and Seed, H. B., 1987, Simplified procedures for the evaluation of settlements in clean sands: Journal of Geotechnical Engineering, ASCE, Vol. 113, no. 8, pp.861-878.

PROGRAM LISTING

If the user has access to the VAX 11/785 computer of the Office of Earthquakes, Volcanoes, and Engineering, U.S. Geological Survey in Menlo Park, California, he/she can execute PETAL3 by typing the command:

```
run publ:[chen.liq]petal
```

and the computer will prompt for appropriate input. Listing of PETAL3 and its subroutines are reproduced in the following pages.

```
c         PETAL3:  PEnetration Test And Liquefaction
c
c                program to estimate liquefaction potentials and
c                volumetric strains of cohesionless deposits
c
c         ref: seed, journal of geotechnical engineering, asce,
c                   vol. 109, no. 3, march, 1983
c              seed, tokimatsu, harder, and chung, jour. of geotech.
c                   eng., asce, vol. 111, no. 12, dec., 1985
c              nrc, LIQUEFACTION OF SOILS DURING EARTHQUAKES, national
c                  academy press, 1985
c              ishihara, proc., 11th int. conf. on soil mech., & fdn.
c                  eng., vol.1, pp.321-376, 8/85
c              tokimatsu and seed, jour. of geotech. eng., asce,
c                  vol. 113, no. 8, aug., 1987
c
c         modified from programs PETAL2 and WET
c         by a. chen, oeve, usgs, menlo park, ca 94025, 11/87
c
      dimension dref(9),rd(9),rmk(8),dm(10),dcp(10),gx(11),gy(11),
     &          gyy(11)
      common /blka/x(9),y(9),xn(11),yt(11),title(18),resu(22,30)
      common /blkb/den(9),denwet(9), th(9), depth(9), nlayer, zgw, zgwt
      common /blkc/sy(6),qx(6),cy(6),sf(30),prat(30)
c
      data rmk/'    ',' sha','llow','o*bu','rden','grav','elly','(NA)'/
      data rd/1.0,0.9794,0.9668,0.9478,0.9346,0.9189,0.9009,
     &        0.8709,0.40/
      data dref/0.0,11.825,15.469,21.643,27.268,31.752,34.813,
     &          39.535,100.0/
      data dm/0.001,0.0025,0.005,0.01,0.025,0.05,0.1,0.25,0.5,1.0/
      data dcp/1.0,1.47,1.78,2.14,2.71,3.25,3.87,5.03,6.27,7.87/
      data gx/0.0,0.1,0.2,0.3,0.4,0.5,0.6,0.7,0.8,0.9,1.0/
      data gy/1.0,1.065,1.165,1.247,1.276,1.318,1.429,
     &        1.659,1.853,2.059,2.235/
      data gyy/0.05,0.1,0.15,0.2,0.25,0.3,0.35,0.4,0.45,0.5,0.6/
c
    2 format(18a4)
    4 format('    ')
    6 format(' enter depth(ft), saturated density(pcf), and wet ',
     & 'density(pcf)'/'   with decimals of layer',i3)
   10 format('  strength ratio for gravel content given =',f5.2/)
   12 format(i4,f9.1,2f11.1,2f12.1,f8.1,f12.2,f10.3,f8.1)
   14 format(/' stress ratio insitu =',f6.3,' required to cause liq. =',
     & f6.3/' factor of safety =',f5.2/
     & ' pore pressure ratio generated =',f6.3/
     & ' volumetric strain (%) =',f6.2/)
   16 format(/' the site consists of',i3,' layers w/ depths, ',
     & 'saturated and wet densities:')
   18 format(20x,i4,f10.1,' (ft)',f15.1,' (pcf)',f15.1,' (pcf)')
```

```
   20 format(/' input eq. mag.=',f5.2,'   max. acc. =',f5.2,' g'/
     & ' correction factor (to M=7.5) =',f5.2/
     & ' design ground water table depth =',f6.1,' ft.'/
     & ' testing ground water table depth =',f6.1,' ft.'/)
   22 format(' count   depth   design stress (psf)   testing stress ',
     & '(psf)   SPT blow  fine/gravel   remark'/10x,'(ft)     ',
     & 'effective   total     effective    total',
     & 6x,'count',5x,'content'/)
   24 format(i4,f9.1,2f11.1,2f12.1,f8.1,f12.2,6x,2a4)
   28 format(' SPT hammer efficiency assigned =',f5.2/)
   32 format(' count   depth   design stress (psf)   testing stress ',
     & '(psf)   CPT - Qc     fine',8x,'D50   CPT/SPT'/10x,'(ft)   ',
     & 'effective   total    effective    total',
     & 4x,'(kg/cm2)',5x,'content',5x,'(mm)   factor'/)
   34 format(//' count   modified  relative    shear s.',
     & '    liq.       factor   pore press.  %, vol.   correction'/
     & 8x,' bc-N1,60   density    ratio    resistance  ',
     & ' safety      ratio      strain     applied'/)
   36 format(/' * * NA = not applicable or not accurate **')
   38 format(i4,f10.1,f10.2,f11.2,f11.2,a4,f7.2,a4,f7.2,a4,
     & f7.2,a4,3x,a4,a4)
c
      write(6,4)
      write(6,*) 'PETAL3: basic units are in LBS and FT'
      write(6,4)
      write(6,*) ' enter title of this run in 72 characters or less'
      write(6,4)
      read(5,2) title
      write(6,4)
      write(6,*) ' site description: enter no. of layers (¼10)'
      write(6,4)
      read*, nlayer
      do  40 i=1,nlayer
      write(6,6) i
      write(6,4)
      read*, depth(i), den(i),denwet(i)
   40 continue
      th(1) = depth(1)
      do  60 i=2,nlayer
      th(i) = depth(i) - depth(i-1)
   60 continue
      write(6,4)
      write(6,*) ' enter expected depth of ground water during'
      write(6,*) ' the design earthquake, and ground water depth'
      write(6,*) ' when penetration test was performed -- 7.0, 20.0'
      write(6,4)
      read*, zgw, zgwt
      write(6,4)
      write(6,*) ' enter equake mag. and max acc (g) -- 7.5, 0.25'
      write(6,4)
      read*, eqm, amax
      write(6,4)
c
      call ppres(eqm,fac)
```

```
      do 70 i=1,11
      yt(i) = gyy(i)*fac
   70 continue
c
      write(6,*) ' class=1 for SPT input and sandy/gravelly layers'
      write(6,*) '      =2 for CPT and sandy deposits'
      write(6,*) ' enter class (1 or 2) --'
      write(6,4)
      read*, itype
      if(itype .ne. 1) go to 80
      write(6,4)
      write(6,*) ' enter SPT hammer efficiency (0.68 for 68%):'
      write(6,4)
      read*, hameff
      write(6,4)
   80 continue
      write(6,*)'use depth<0.0 to terminate execution'
      write(6,4)
c
      ic = 0
  100 ic = ic+1
      igrav = 0
      kdpt = 0
      if(itype .eq. 1) go to 250
      hameff = 0.6
      if(ic .ne. 1) go to 105
      write(6,*)' enter depth (ft, <0. to exit), Qc (kg/sq.cm),'
      write(6,*)'       D50 (mm), and fine content (0.1 for 10%) --'
      write(6,*)' for example -- 12.5, 88.0, 0.35, 0.1'
      write(6,4)
      go to 110
  105 write(6,*)' again? enter depth (<0. to exit), Qc, d50, fc'
      write(6,4)
  110 read*, z,qc,d50,fc
      if(z .lt. 0.0) go to 825
c
c        seed's criteria on conversion if d50 is entered w/ a neg. sign
c
      if(d50 .gt. 0.0) go to 140
      if(abs(d50) .lt. 0.2) go to 120
      xcpt = 4.5
      go to 200
  120 xcpt = 4.0
      go to 200
  140 do 160 loop=1,9
      if(d50 .lt. dm(loop+1)) go to 180
  160 continue
  180 j = loop
      if(loop .eq. 10) j=9
      phy = (dcp(j+1)-dcp(j))/(alog10(dm(j+1))-alog10(dm(j)))
      xcpt = dcp(j) + phy*(alog10(d50)-alog10(dm(j)))
  200 bc = qc/xcpt
      resu(6,ic) = qc
      resu(7,ic) = fc
```

```
      resu(8,ic) = d50
      resu(17,ic) = xcpt
      go to 300
  250 continue
      if(ic .ne. 1) go to 260
      write(6,*)' enter depth (ft, <0. to exit), spt blow count'
      write(6,*)'  (w/ neg sign, if gravelly), and fine content'
      write(6,*)'   or gravel content if gravelly (0.1 for 10%) --'
      write(6,*)'  for example -- 12.5, 25.0, 0.1'
      write(6,4)
      go to 270
  260 write(6,*)' again? enter depth, blow count, fine content --'
      write(6,4)
  270 continue
      read*, z, bct, ffc
      if(z .lt. 0.0) go to 825
      bc = abs(bct)
      resu(6,ic) = bc
      fc = ffc
      resu(7,ic) = ffc
      resu(8,ic) = rmk(1)
      resu(17,ic) = rmk(1)
      if(bct .gt. 0.0) go to 300
      igrav = 1
      gct = ffc
      resu(8,ic) = rmk(6)
      resu(17,ic) = rmk(7)
  300 if(z .lt. 10. .and. itype .eq. 1) bc=0.75*bc
c
      call adjfin(fc,igrav)
      call stress(z,sum1,sum2,s3,s4)
      ysig = s3/1000.
      call relden(ysig,bc,hameff,bcmod,rden)
c
c        to determine stress reduction factor rd & ave stress-ratio
c
      j = 1
      do 420 loop=1,8
      j = j+1
      if(dref(j) .gt. z) go to 440
  420 continue
  440 fac1 = rd(j-1) + (z-dref(j-1))*(rd(j)-rd(j-1))/(dref(j)-dref(j-1))
      atau = 0.65*fac1*amax*sum2
      taur = atau/sum1
c
c        to determine stress ratio at 100% pore pressure ratio
c
      xn12 = xn(11) + 1.0
      kppna = 0
      if(bcmod .lt. xn12) go to 590
      ratiof = 1.99
      fs = 4.99
      pratio = 0.0
      kppna = 1
```

```
      go to 680
  590 continue
      j = 1
      do 600 loop=1,10
      j = j+1
      if(xn(j) .gt. bcmod) go to 620
  600 continue
c
  620 ratiof = yt(j-1) + (yt(j)-yt(j-1))*(bcmod-xn(j-1))/(xn(j)-xn(j-1))
      facdpt = 1.0
      if(sum1 .gt. 3000.) kdpt=1
      if(kdpt .ne. 0) facdpt=1.07-3.348*0.01*0.001*sum1
      ratiof =ratiof*facdpt
      if(igrav .ne. 1) go to 635
      do 625 loop=1,10
      if(gct .le. gx(loop+1)) go to 630
  625 continue
  630 j = loop
      facgrv=gy(j)+(gct-gx(j))*(gy(j+1)-gy(j))/(gx(j+1)-gx(j))
      ratiof = ratiof*facgrv
  635 fs = ratiof/taur
c
c         to estimate pore pressure ratio generated
c
      pratio = -0.01
      if(igrav .eq. 1) go to 680
      pratio = 1.0
      if(fs .lt. 1.02) go to 680
      pratio = 0.02
      if(fs .gt. 2.0) go to 680
      do 650 loop=1,20
      if(fs .le. sf(loop+1)) go to 660
  650 continue
  660 j = loop
      pratio = prat(j)+(fs-sf(j))*
     &                 (prat(j+1)-prat(j))/(sf(j+1)-sf(j))
  680 continue
c
      call strain(fs,bcmod,taur,fac,eps)
c
      write(6,14) taur, ratiof, fs, pratio, eps
      if(igrav .eq. 1 .and. kppna .ne. 1) write(6,10) facgrv
c
c        store results in array resu(j,ic),j=1,20
c
      resu(1,ic) = z
      resu(2,ic) = sum1
      resu(3,ic) = sum2
      resu(4,ic) = s3
      resu(5,ic) = s4
      resu(9,ic) = bcmod
      resu(10,ic) = rden
      resu(11,ic) = taur
      resu(12,ic) = ratiof
```

```
      resu(13,ic) = fs
      resu(14,ic) = pratio
      resu(15,ic) = rmk(1)
      resu(16,ic) = rmk(1)
      resu(18,ic) = rmk(1)
      resu(19,ic) = rmk(1)
      resu(20,ic) = rmk(1)
      resu(21,ic) = eps
      resu(22,ic) = rmk(1)
      if(kppna .ne. 1) go to 720
      resu(18,ic) = rmk(8)
      resu(19,ic) = rmk(8)
  720 if(kdpt .eq. 0) go to 740
      resu(15,ic) = rmk(4)
      resu(16,ic) = rmk(5)
  740 if(igrav .ne. 1) go to 760
      resu(20,ic) = rmk(8)
  760 if(itype .ne. 1 .or. z .gt. 10.) go to 780
      resu(15,ic) = rmk(2)
      resu(16,ic) = rmk(3)
  780 if(igrav .ne. 1 .and. fc .le. 0.15) go to 800
      resu(22,ic) = rmk(8)
  800 continue
c
      go to 100
c
  825 continue
c
c         save results onto file for016.dat
c
      write(16,2) title
      write(16,16) nlayer
      write(16,18) ((i,depth(i),den(i),denwet(i)),i=1,nlayer)
      write(16,20) eqm, amax,fac, zgw,zgwt
      if(itype .eq. 1) write(16,28) hameff
c
      ic = ic-1
      if(itype .ne. 1) go to 900
      write(16,22)
      do 850 i=1,ic
      write(16,24) i,(resu(j,i),j=1,8),resu(17,i)
  850 continue
      go to 980
  900 write(16,32)
      do 920 i=1,ic
      write(16,12) i,(resu(j,i),j=1,8),resu(17,i)
  920 continue
  980 continue
      write(16,34)
      do 990 i=1,ic
      write(16,38)i,(resu(j,i),j=9,12),resu(18,i),resu(13,i),resu(19,i),
     & resu(14,i),resu(20,i),resu(21,i),resu(22,i),resu(15,i),resu(16,i)
  990 continue
      write(16,36)
```

```
c
      stop
      end




      subroutine adjfin(fc,igrav)
      dimension z(11,3)
      common /blka/x(9),y(9),xn(11),yt(11),title(18),resu(22,30)
      data z/-2.,2.5,7.17,10.93,14.67,17.33,19.0,20.0,20.26,
     &        20.49,20.82,0.5,5.0,9.67,13.73,17.21,20.23,22.3,
     &        23.54,24.1,24.59,24.92,4.67,8.92,13.61,18.17,22.3,
     &        25.51,27.7,28.92,29.51,29.84,30.5/
c
      if(igrav .ne. 0) go to 40
      if(fc .gt. 0.055) go to 50
   40 itype = 3
      go to 500
   50 if(fc .le. 0.3) go to 100
      itype =1
      go to 500
  100 if(fc .ge. 0.155 .or. fc .le. 0.145) go to 200
      itype = 2
      go to 500
  200 do 300 i=1, 11
      c = (z(i,1)-z(i,2)*3.+z(i,3)*2.)/0.06
      b = (z(i,1)-z(i,2)-0.1*c)/0.2
      a = z(i,3) - 0.05*b -0.05*0.05*c
      xn(i) = a + b*fc + c*fc*fc
  300 continue
      go to 600
  500 do 550 i=1,11
      xn(i) = z(i,itype)
  550 continue
  600 continue
      return
      end




      subroutine ppres(eqm,fac)
c
c         subroutine to calculate pore pressure ratio versus
c         factor of safety for a given earthquake magnitude
c
c         from program ppres.for by a. chen
c
      dimension ppr(11)
      common /blkc/sy(6),qx(6),cy(6),sf(30),prat(30)
      data ppr/0.0,0.136,0.212,0.294,0.367,0.435,0.506,
     &          0.600,0.694,0.812,1.00/
      data sy/1.6,1.32,1.13,1.0,0.89,0.80/
```

```
      data qx/5.25,6.0,6.75,7.5,8.5,9.9/
      data cy/3.0,6.0,10.0,15.0,26.0,100.0/
c
      do 50 i=1,30
      sf(i) = 1.0 + 0.05*i
   50 continue
      do 100 i=1,4
      if(eqm .le. qx(i+1)) go to 120
  100 continue
  120 cyn=cy(i)+(eqm-qx(i))*(cy(i+1)-cy(i))/(qx(i+1)-qx(i))
      do 140 i=1,4
      if(cyn .le. cy(i+1)) go to 160
  140 continue
  160 continue
      delx = cyn/cy(i)
      dx = cy(i+1)/cy(i)
      fac = sy(i)+(sy(i+1)-sy(i))*alog(delx)/alog(dx)
      do 300 ii=1,30
      fak = fac/sf(ii)
      do 220 i=1,4
      if(fak .ge. sy(i+1)) go to 240
  220 continue
  240 dx = cy(i+1)/cy(i)
      temp = (fak-sy(i))*alog(dx)/(sy(i+1)-sy(i))
      temp = temp + alog(cy(i))
      cym = exp(temp)
      cycrat = cyn/cym
      if(cycrat .lt. 1.0) go to 245
      pratio = 1.0
      go to 300
  245 continue
      temp = -0.1
      do 260 i=1,10
      temp = temp+0.1
      temq = temp+0.1
      if(cycrat .le. temq) go to 280
  260 continue
  280 pratio = ppr(i) +
     &         (ppr(i+1)-ppr(i))*(cycrat-temp)*10.0
  300 prat(ii) = pratio
      return
      end



      subroutine stress(z,s1,s2,s3,s4)
      common /blkb/den(9),denwet(9),th(9),depth(9),nlayer,zg,zgwt
c
      iseq = 1
      zgw = zg
c
  100 continue
      if(iseq .eq. 2) zgw=zgwt
```

```
      sum1 = 0.0
      sum2 = 0.0
      if(z .gt. zgw) go to 220
      j = 0
      do 120 loop=1,nlayer
      j = j+1
      if(depth(j) .ge. z) go to 140
      sum1 = sum1+th(j)*denwet(j)
      sum2 = sum1
  120 continue
  140 if(j .gt. 1) go to 160
      sum1 = z*denwet(j)
      sum2 = sum1
      go to 400
  160 sum1 = sum1 + (z-depth(j-1))*denwet(j)
      sum2 = sum1
      go to 400
  220 continue
      j = 0
      do 240 loop=1,nlayer
      j = j+1
      if(depth(j) .ge. zgw) go to 250
      sum1 = sum1 + th(j)*denwet(j)
      sum2 = sum2 + th(j)*denwet(j)
  240 continue
  250 continue
      idry = j
      if(idry .gt. 1) go to 280
      if(z .gt. depth(1)) go to 260
c
c        z, zgw both in layer 1
      sum1 = zgw*denwet(1) + (z-zgw)*(den(1)-62.4)
      sum2 = zgw*denwet(1)+(z-zgw)*den(1)
      go to 400
c
  260 sum1 = zgw*denwet(1) + (depth(1)-zgw)*(den(1)-62.4)
      sum2 = zgw*denwet(1) + (depth(1)-zgw)*den(1)
      go to 320
  280 if(z .gt. depth(idry)) go to 300
      sum1 = sum1 + (zgw-depth(idry-1))*denwet(idry)
     &            + (z-zgw)*(den(idry)-62.4)
      sum2 = sum2 + (zgw-depth(idry-1))*denwet(idry)
     &            + (z-zgw)*den(idry)
      go to 400
  300 sum1 = sum1 + (zgw-depth(idry-1))*denwet(idry)
     &            + (depth(idry)-zgw)*(den(idry)-62.4)
      sum2 = sum2 + (zgw-depth(idry-1))*denwet(idry)
     &            + (depth(idry)-zgw)*den(idry)
  320 continue
      do 340 loop=idry,nlayer
      j = j+1
      if(depth(j) .gt. z) go to 360
      sum1 = sum1 + th(j)*(den(j)-62.4)
      sum2 = sum2 + th(j)*den(j)
```

```
  340 continue
  360 sum1 = sum1 + (z-depth(j-1))*(den(j)-62.4)
      sum2 = sum2 + (z-depth(j-1))*den(j)
  400 continue
      if(iseq .eq. 2) go to 500
      s1 = sum1
      s2 = sum2
      iseq = 2
      go to 100
  500 s3 = sum1
      s4 = sum2
      return
      end



      subroutine relden(ysig,bc,hameff,bcmod,rden)
c          to estimate relative density from spt blow counts
c        by a. chen, 5/85
c
      dimension sv8(16), cn8(16), sv4(16), cn4(16),  bc6(11),
     & xf(16), yf(16)
      data sv8/0.7732,0.9447,1.2934,1.7221,1.9845,2.2949,2.6744,3.1689,
     &         3.5984,4.1400,4.7297,5.3664,6.1172,7.2153,8.1312,9.0241/
      data cn8/1.5965,1.4295,1.2288,1.0780,1.0114,0.9536,0.8951,0.8357,
     &         0.7952,0.7400,0.6936,0.6513,0.6035,0.5619,0.5310,0.5003/
      data sv4/0.7732,0.9447,1.2934,1.7221,1.9845,2.1597,2.5362,2.9828,
     &         3.4533,4.0370,4.5796,5.1473,5.8070,6.7640,7.7940,8.7560/
      data cn4/1.5965,1.4295,1.2288,1.0780,1.0114,0.9685,0.8963,0.8281,
     &         0.7643,0.6903,0.6397,0.5980,0.5556,0.5014,0.4649,0.4337/
      data bc6/0.0,1.0,2.5,4.6,7.2,11.4,16.2,21.9,30.0,40.4, 53.0/
c
c
      do 150 i=1,16
      yf(i) = sv8(i)
      xf(i) = cn8(i)
  150 continue
      if(ysig .gt. yf(1)) go to 220
      cn1 = 1.8
      go to 280
  220 continue
      j = 1
      do 240 loop=1,15
      j = j+1
      if(yf(j) .gt. ysig) go to 260
  240 continue
  260 cn1 = xf(j-1) + (xf(j)-xf(j-1))*(ysig-yf(j-1))/(yf(j)-yf(j-1))
  280 continue
c
      do 350 i=1,16
      yf(i) = sv4(i)
      xf(i) = cn4(i)
  350 continue
```

```
      if(ysig .gt. yf(1)) go to 520
      cn2 = 1.8
      go to 580
  520 continue
      j = 1
      do 540 loop=1,15
      j = j+1
       if(yf(j) .gt. ysig) go to 560
  540 continue
  560 cn2 = xf(j-1) + (xf(j)-xf(j-1))*(ysig-yf(j-1))/(yf(j)-yf(j-1))
  580 continue
      cn = 0.5*(cn1+cn2)
c
  600 continue
c
c        first estimate on normalized blow count
c
      bcn = bc*cn*hameff/0.6
      if(bcn .lt. 53.0) go to 620
      go to 680
  620 j=1
      do 640 loop=1,10
      j=j+1
      if(bc6(j) .ge. bcn) go to 660
  640 continue
c
c        first estimate on relative density
c
  660 dr = 10.*(j-2) + 10.*(bcn-bc6(j-1))/(bc6(j)-bc6(j-1))
c
c       repeat same process with the correct cn
c
      if(dr .le. 60.) go to 720
  680 do 700 i=1,16
      xf(i) = cn8(i)
      yf(i) = sv8(i)
  700 continue
  720 continue
c
      if(ysig .gt. yf(1)) go to 740
      cn = 1.8
      go to 800
  740 continue
      j = 1
      do 760 loop=1,15
      j = j+1
      if(yf(j) .gt. ysig) go to 780
  760 continue
  780 cn = xf(j-1) + (xf(j)-xf(j-1))*(ysig-yf(j-1))/(yf(j)-yf(j-1))
  800 continue
c
      bcn = bc*cn*hameff/0.6
      if(bcn .lt. 53.0) go to 820
      dr = 100.
```

```
      go to 880
  820 j=1
      do 840 loop=1,10
      j=j+1
      if(bc6(j) .ge. bcn) go to 860
  840 continue
c
  860 dr = 10.*(j-2) + 10.*(bcn-bc6(j-1))/(bc6(j)-bc6(j-1))
  880 continue
  900 continue
      rden = dr/100.
      bcmod = bcn
      return
      end



      subroutine strain(fs,bcn,str,fac,ec)
c
c          to estimate volumetric strain from shear stress ratio
c          and (N1)60 a la tokimatsu and seed, 1987
c
      dimension xn(8,7), xt(8,7), num(7), vst(7), ufs(7), uvs(7)
      data xn/30.5,29.8,29.5,28.9,27.7,25.5,22.3,0.,
     &        28.05,27.8,27.4,26.5,24.8,22.3,18.3,13.9,
     &        14.04,14.0,13.71,12.65,9.11,0.,0.,0.,
     &        7.35,7.28,6.79,4.7,0.,0.,0.,0.,
     &        5.05,5.0,4.65,0.,0.,0.,0.,0.,
     &        3.35,3.3,0.,0.,0.,0.,0.,0.,
     &        1.05,1.0,0.,0.,0.,0.,0.,0./
      data xt/0.6,0.5,0.45,0.4,0.35,0.3,0.25,0.0,
     &        0.6,0.45,0.4,0.35,0.3,0.25,0.2,0.15,
     &        0.6,0.25,0.2,0.15,0.1,0.,0.,0.,
     &        0.6,0.15,0.10,0.05,0.,0.,0.,0.,
     &        0.6,0.10, 0.05,0.0,0.0,0.,0.,0.,
     &        0.6,0.037,0.,0.,0.,0.,0.,0.,
     &        0.6,0.01,0.,0.,0.,0.,0.,0./
      data num/7,8,5,4,3,2,2/
      data vst/0.75,1.0,2.0,3.0,4.0,5.0,10.0/
      data ufs/2.0,1.667,1.429,1.25,1.136,1.07,1.0/
      data uvs/0.0,0.01,0.03,0.08,0.15,0.23,0.75/
c
      tau = 0.0
      if(fs .le. 1.0) go to 300
      if(fs .le. 2.0) go to 220
      ec = 0.0
      go to 800
c
c         estimate of vert. strain for partial liquefaction
c
  220 do 250 i=1,6
      ic = i
      if(fs .ge. ufs(i+1)) go to 270
```

```
  250 continue
  270 slp = (fs-ufs(ic))/(ufs(ic+1)-ufs(ic))
      ec = uvs(ic) + slp*(uvs(ic+1)-uvs(ic))
      go to 800
c
c         estimate of vert. strain for complete liquefaction
c
  300 refn = 0.0
      refm = 0.0
      tau = str/fac
      if(tau .gt. 0.6) tau=0.6
      do 400 j=1,7
      jc = j
      ila = num(j)
      if(tau .lt. xt(ila,j)) go to 380
      do 320 i=1,ila-1
      ic = i
      if(tau .ge. xt(ic+1,j)) go to 340
  320 continue
  340 slp = (tau-xt(ic,j))/(xt(ic+1,j)-xt(ic,j))
      temp = xn(ic,j) + slp*(xn(ic+1,j)-xn(ic,j))
      if(refn .ne. 0.0) go to 350
      refn = temp
      go to 380
  350 if(bcn .ge. temp) go to 360
      refn = temp
      go to 380
  360 refm = temp
      go to 450
  380 continue
  400 continue
      ec = 10.0
      go to 800
  450 slp = (bcn-refm)/(refn-refm)
      ec = vst(jc) + slp*(vst(jc-1)-vst(jc))
  800 continue
      return
      end
```