Open-File Report

PETAL2: PEnetration Testing And Liquefaction, An Interactive Computer Program

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INTRODUCTION

Since the earlier release of program PETAL (Chen, 1984), much progress in the interpretation of penetration test data has been made with respect to the liquefaction resistance of cohesionless deposits. Considerations now can be given to the fine/gravel content and the mean grain size of a deposit as well as the efficiency of the standard penetration test (SPT) hammer (Ishihara, 1985; Robertson and Campanella, 1985; Seed and others, 1985). The importance of considering these factors in liquefaction analyses was made apparent during a special workshop sponsored by the National Research Council (1985) and at various sessions during the 11th International Conference on Soil Mechanics and Foundation Engineering held in August of 1985.

To incorporate the latest developments in estimating liquefaction resistance using penetration data, the original version of program PETAL was extensively revised. This report provides the documentation of the revised program PETAL2.

GENERAL DESCRIPTION

PETAL2 consists of a main program and five subroutines. It is coded in FORTRAN and programmed to run interactively with VAX 11/780 computers. The program requires 14K bytes of storage to execute and contains approximately 600 statements. Important aspects of PETAL2 are described briefly.

Input. -- PETAL2 is designed to provide, from each run, estimates of liquefaction resistance and related quantities for a given site during a designated earthquake. Consequently, input concerning the site geology (layering, density, and ground water), the earthquake magnitude and the maximum surface acceleration are unchanged for each run. The penetration resistance, the fine/gravel content, and other depth-dependent input are entered for each depth 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 groundwater 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):

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

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 relationship 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 mm (sands), PETAL2 assigns 4.5 as the conversion factor. Otherwise, the value of 4.0 is assigned.

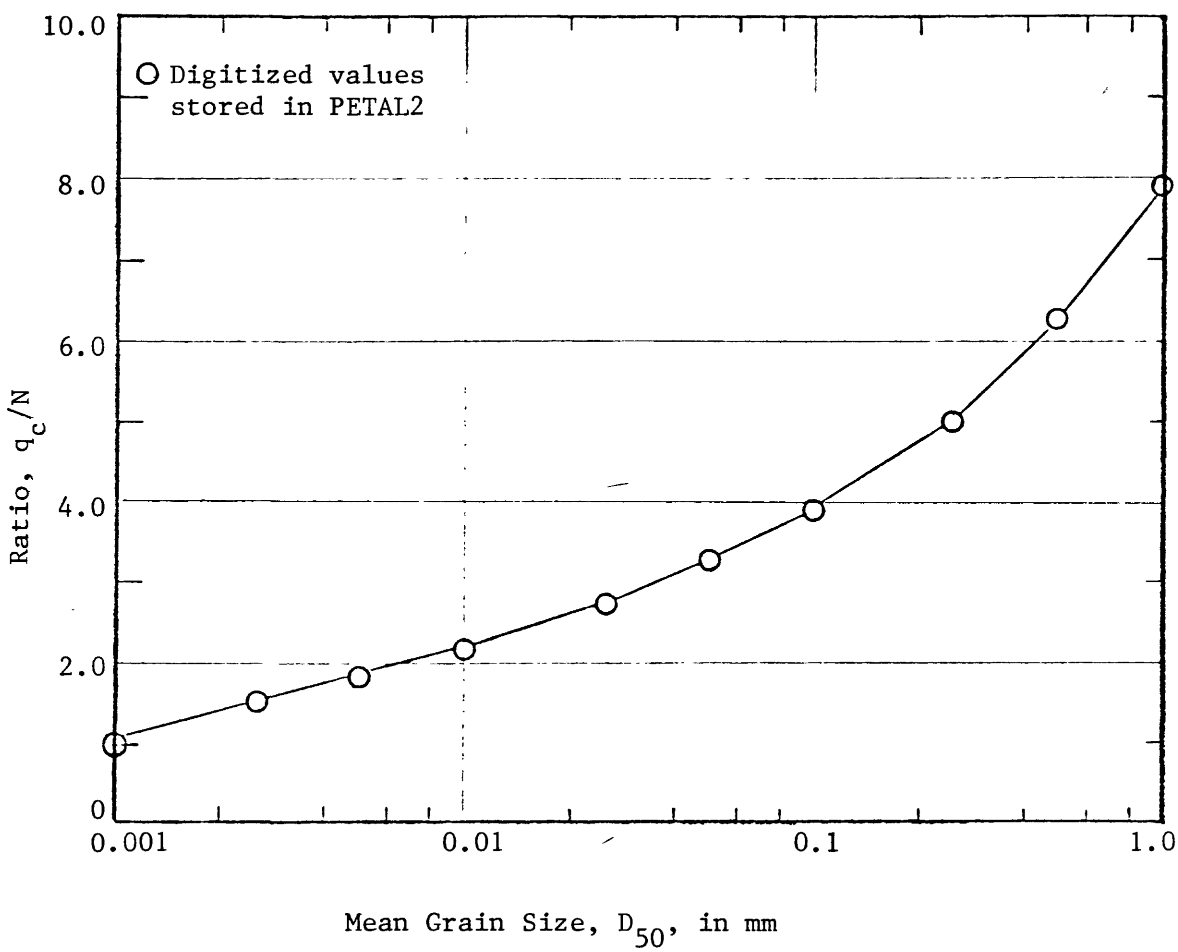

Figure 1. -- Variation of q_c/N ratio with mean grain size (Robertson and Campanella, 1985)

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 blow counts are multiplied by 0.75 to compensate for the energy loss due to the short length of drive rods (seed and Idriss, 1982)

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

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

where C_N is a correction coefficient from the curves shown in Fig. 2. Subroutine RELDEN estimates the relative density D_r according to the empirical curve shown in Fig. 3 (Tokimatsu and Seed, 1984) and thus eliminates the need to input D_r separately.

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

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

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.

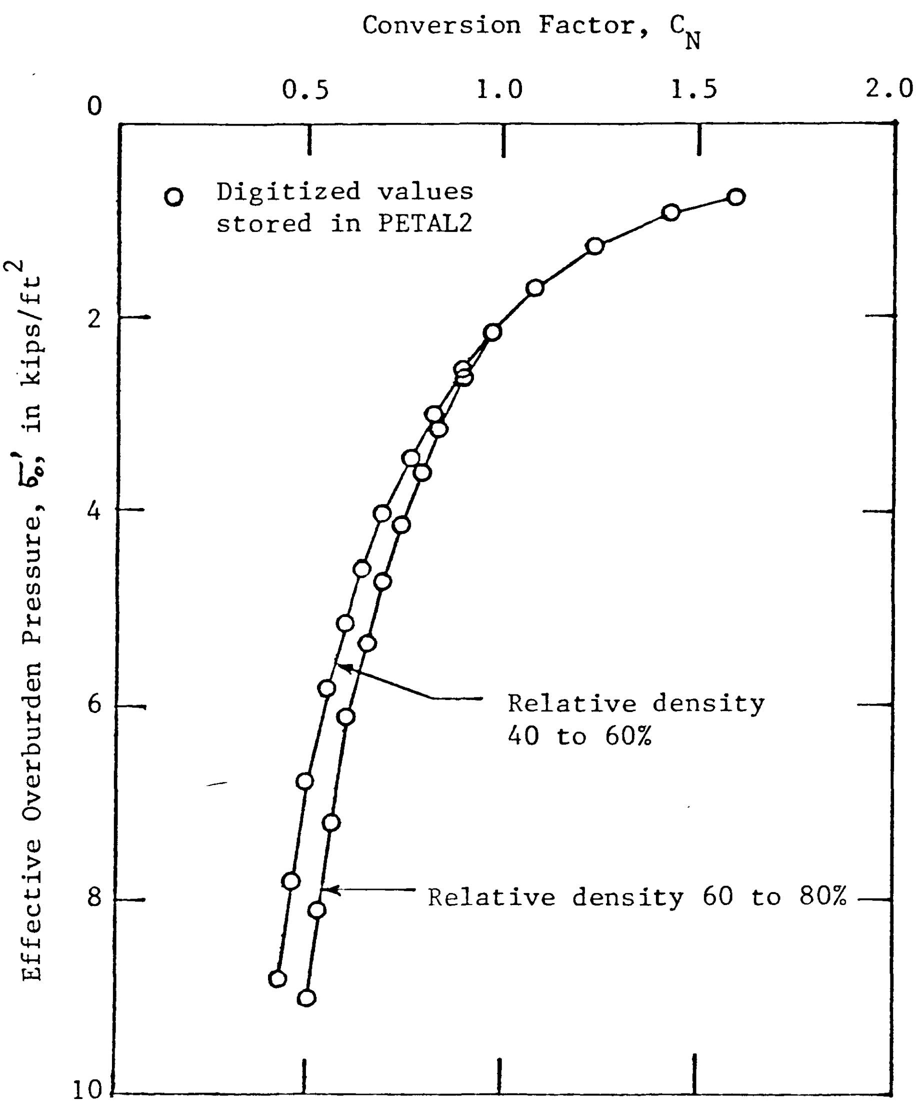

Figure 2. -- Conversion factor as a function of the effective overburden pressure and relative density (Seed and Idriss, 1982)

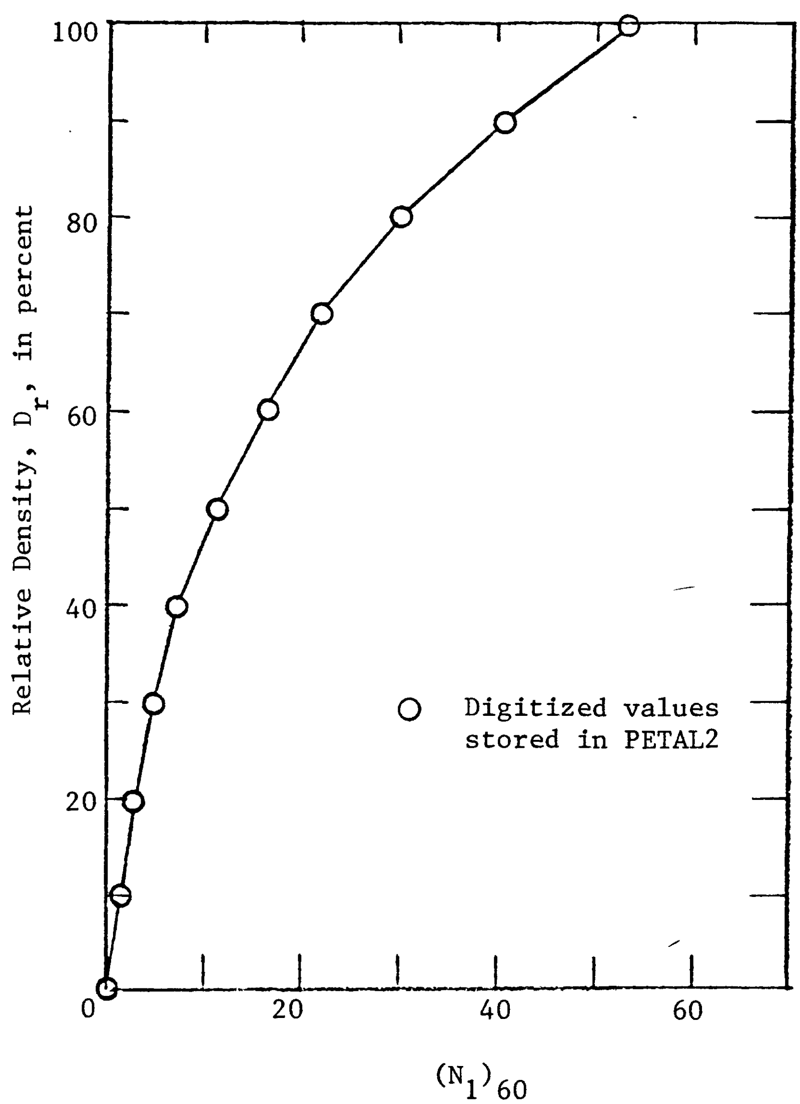

Figure 3. -- Variation of relative density with penetration resistance (Tokimatsu and Seed, 1984)

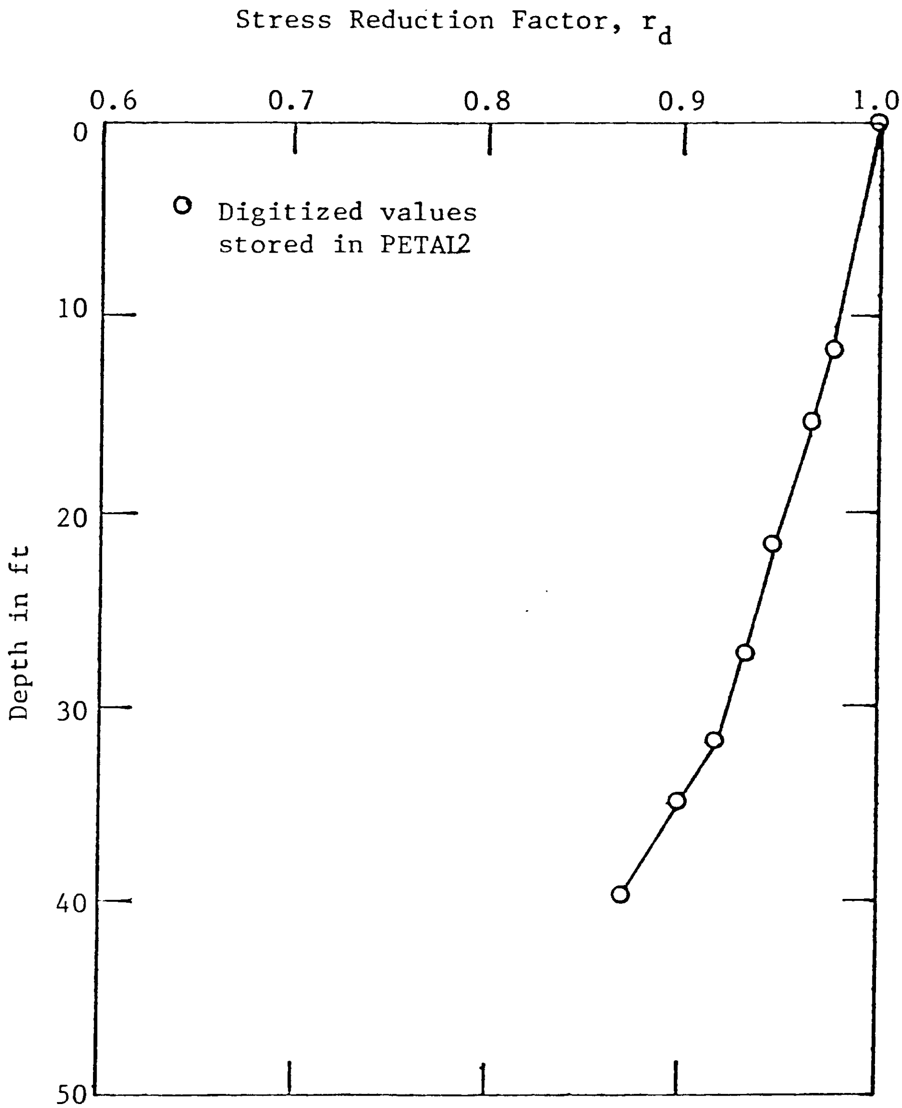

Figure 4. -- Stress reduction factor as a function of depth (Seed and Idriss, 1982)

Liquefaction Resistance. -- Liquefaction resistance, $(\tau/\sigma'_o)_1$, is also expressed in terms of a stress ratio. PETAL2 uses the relations proposed by Seed and others (1985) in which $(\tau/\sigma'_o)_1$ is a function of both the normalized blowcount, $(N_1)_{60}$, and the fine content of the soil element in question. Such relations for 7.5-magnitude earthquakes are shown in Fig. 5. For earthquakes with magnitudes other than 7.5 and fine contents not shown in Fig. 5, PETAL2 uses the scaling factor shown in Fig. 6 and performs iterations to generate a new relation for each case. These steps are carried out in subroutines GETFAC and ADJFIN.

Correction for Excessive Overburden Pressure. -- Liquefaction resistance is known to decrease as the overburden pressure increases. The $(\tau/\sigma'_o)_1$ as described above should be further corrected when σ'_o is greater than 1.5 ton/ft^2 (1.5 kg/cm^2). The factor, K_σ, used in PETAL2 for such correction is shown in Fig. 7. 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

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

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). For convenience, PETAL2 generates an excess pore-pressure ratio, $\Delta u/\sigma'_o$, versus F.S. curve in subroutine PPRES for use in each computer run. Such a curve for 6.5-magnitude earthquakes is illustrated in Fig. 8. As seen in this figure, the estimate is good only for

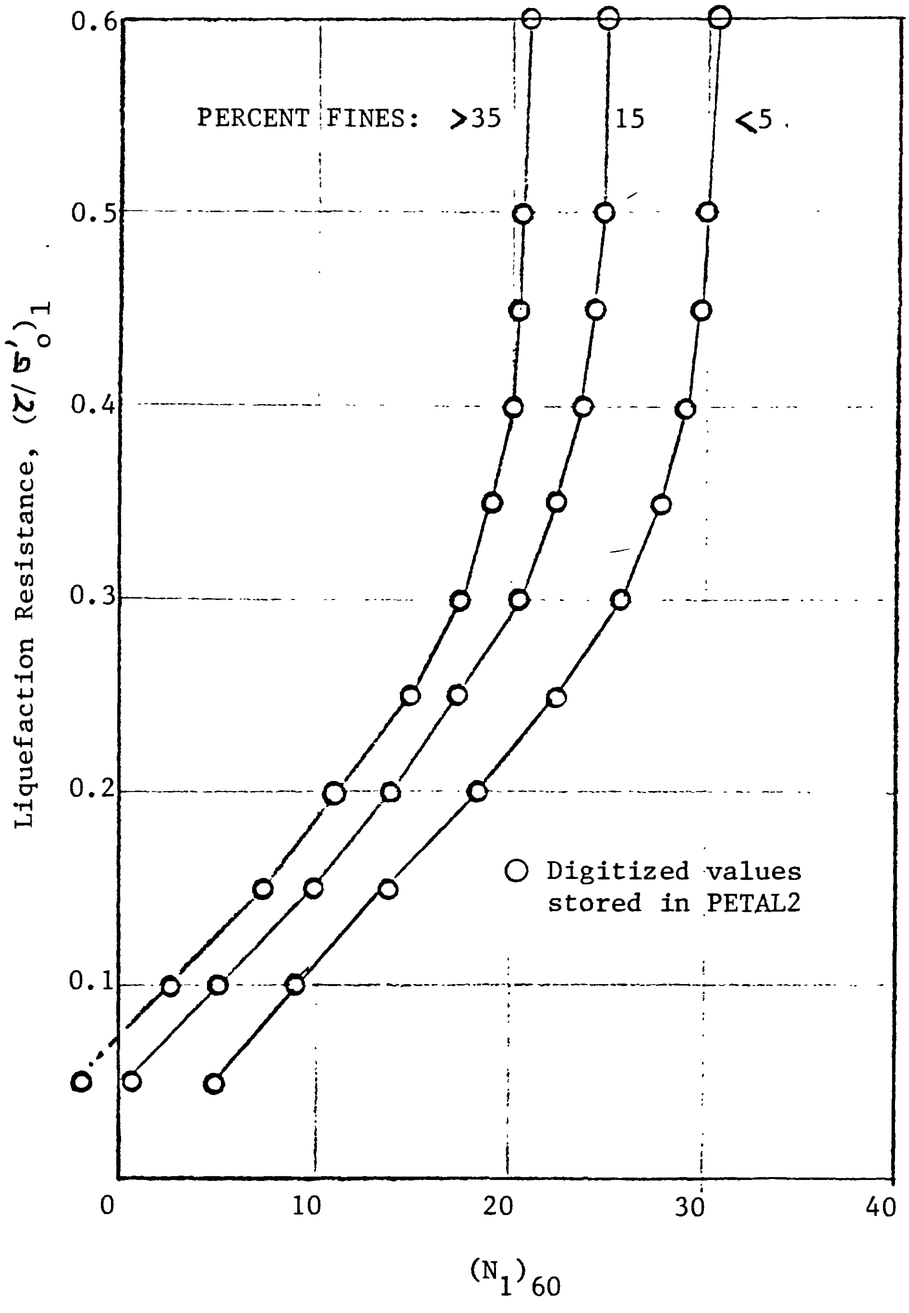

Figure 5. -- Variation of liquefaction resistance with $(N_1)_{60}$ in silty sands for M=7.5 earthquakes (Seed and others, 1984)

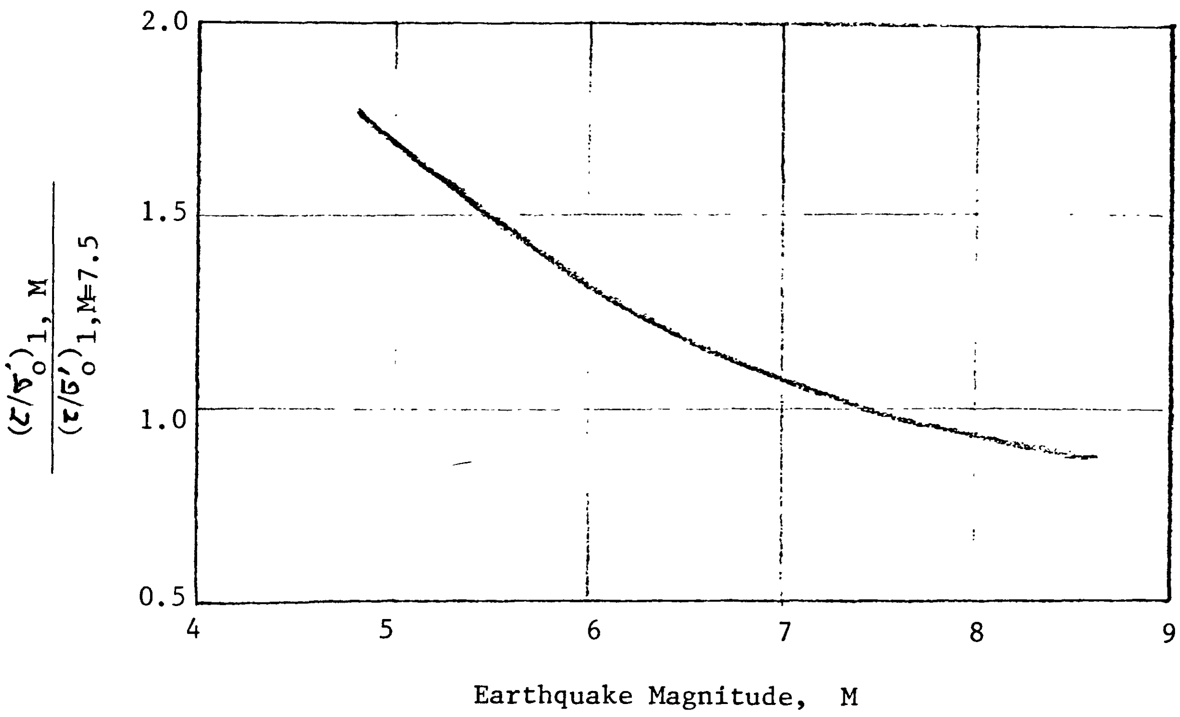

Figure 6. -- Scaling factor for modifying Fig. 5 for earthquakes with magnitudes other than 7.5

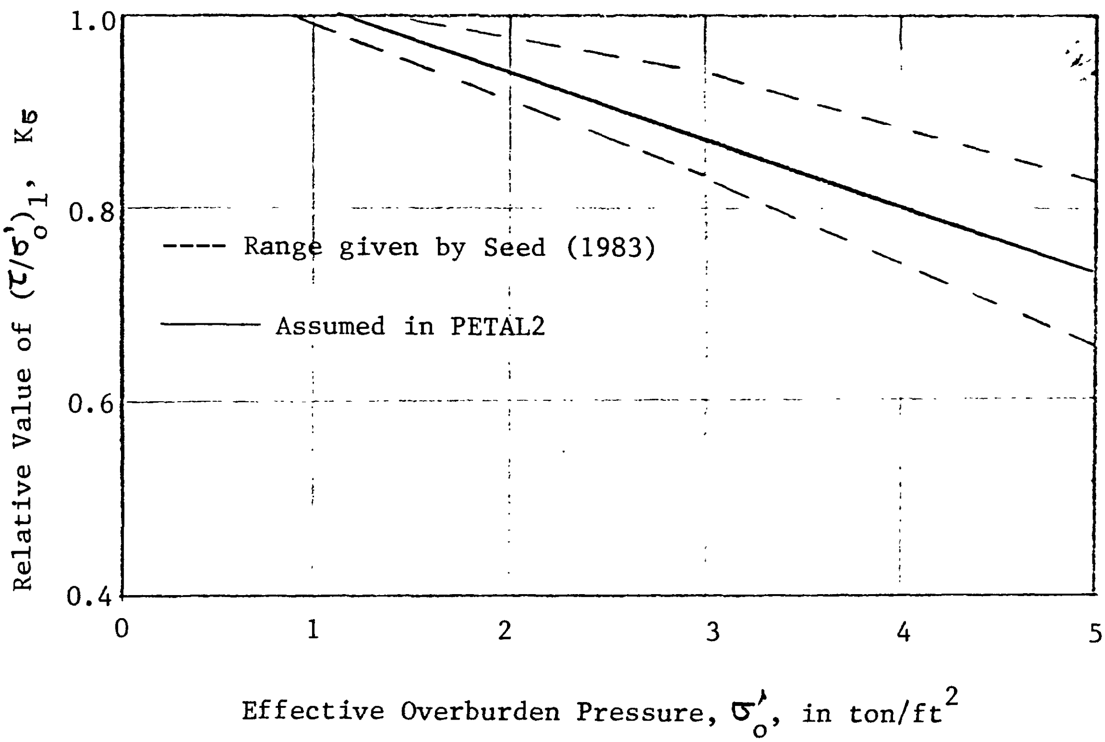

Figure 7. -- Reduction of liquefaction resistance with increase of overburden pressure

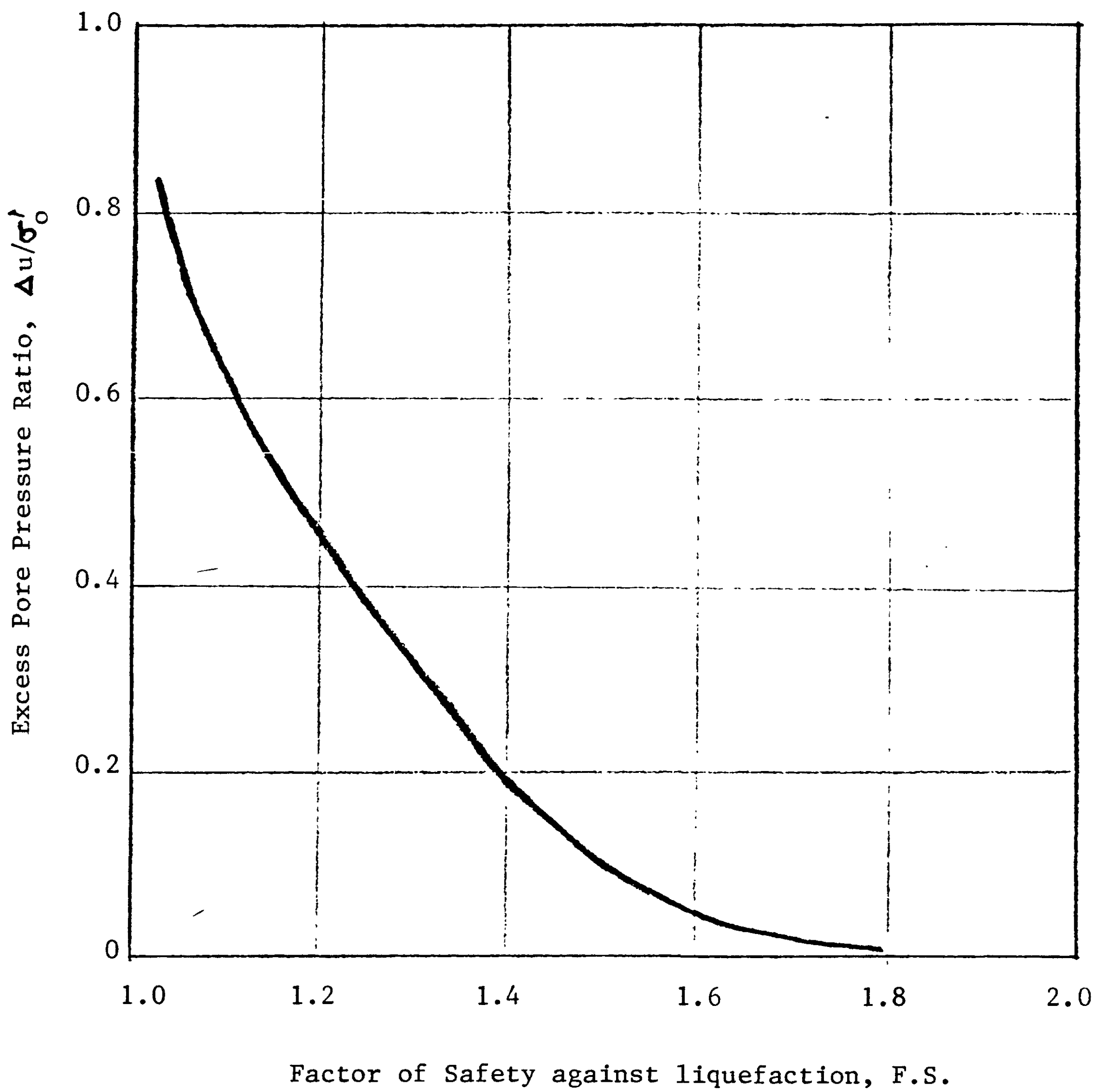

Figure 8. -- Variation of excess pore pressure ratio with factor of safety against liquefaction for M=6.5 earthquakes

a very limited range of F.S. and PETAL2 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 $\Delta u/\sigma'_o=0.0$

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. 9. This approach is used in PETAL2.

COMPUTATIONAL DATA

In contrast to the original version, no plot subroutine is included in PETAL2. Instead, all relevant data are stored in the array RESU(j,i) for additional output/plotter manipulation at users' own discretion. In RESU(j,i), i refers to a group of data associated with the soil deposit at a given depth, and j=1,20 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

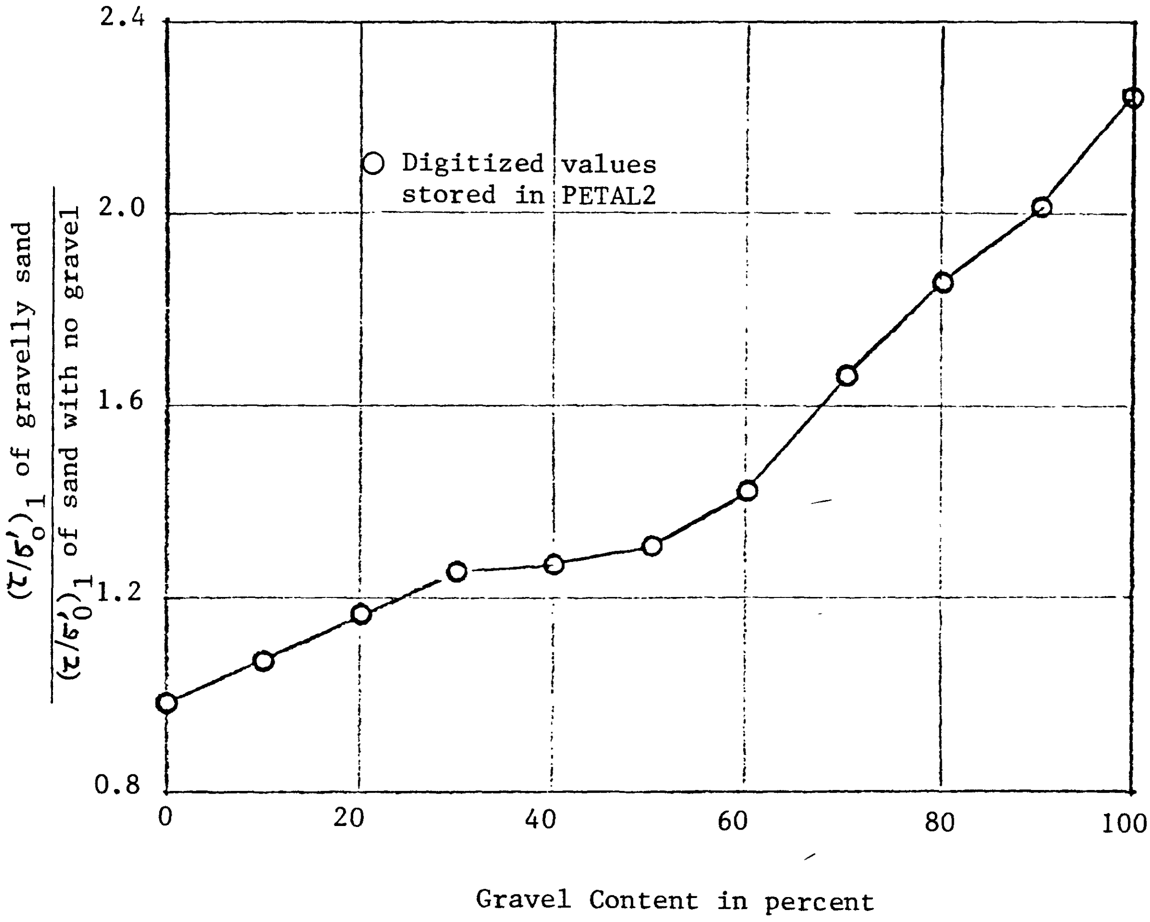

Figure 9. -- Variation of liquefaction resistance with gravel content (Ishihara, 1985)

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) = $(\tau/\sigma'_o)_1$, 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 are reserved for remarks.

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)

```
PETAL2:  basic units are in LBS and FT
enter title of this run in 72 characters or less
PETAL: demonstration run, 01/10/86

 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

25.0, 110., 105.0
enter depth(ft), saturated density(pcf), and wet density(pcf) with decimals of
layer  3

50.0, 120.0, 120.0

 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, 10.0

 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
```

```
 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

 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

 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

 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

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

☞ -5.0, 0.0, 0.0
FORTRAN STOP
```

* * * NOTE: Lines preceded by the sign ☞ indicate input from the user.

(OUTPUT FILE ON UNIT 16)

PETAL: demonstration run, 01/10/86

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
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	depth (ft)	modified bc, N1	relative density	in-situ stress ratio	liquefaction stress ratio	factor of safety	pore press. ratio	correction applied
1	8.0	25.8	0.75	0.33	0.47	1.40	0.19	shallow
2	20.0	25.4	0.74	0.32	0.44	1.37	-0.01(NA)	
3	30.0	21.9	0.70	0.30	0.49	1.63	0.04	
4	30.0	21.9	0.70	0.30	0.40	1.33	0.30	
5	30.0	21.9	0.70	0.30	0.29	0.96	1.00	

* * NA = not applicable or not accurate **

REFERENCES CITED

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Ishihara, K., 1985, Stability of Natural Deposits during earthquakes: Proceedings, 11th International Conference on Soil Mechanics and Foundation Engineering, San Francisco, CA, Vol. 1, pp.321-376.

National Research Council, 1985, Liquefaction of soils during earthquakes: Report No. CETS-EE-001, National Technical Information Service, Springfield, VA 22161.

Robertson, P. K., and Campanella, R. G., 1985, Liquefaction potential of sands using the CPT: Journal of Geotechnical Engineering, ASCE, Vol.111, No. 3, pp.384-403.

Seed, H. B., 1983, Earthquake-resistant design of earth dams: Proceedings, ASCE Symposium on Seismic Design of Embankments and Caverns, American Society of Civil Engineers, New York, New York.

Seed, H. B., and Idriss, I. M., 1982, Ground Motions and Soil Liquefaction during Earthquakes: EERI Monograph Series, Earthquake Engineering Research Institute.

Seed, H. B., Tokimatsu, K., Harder, L. F., and Chung, R. M., 1985, Influence of SPT procedures in soil liquefaction resistance evaluations: Journal of Geotechnical Engineering, ASCE, Vol. 111, No. 12, pp. 1425-1445.

Tokimatsu, K., and Seed, H. B., 1984, Simplified procedures for the evaluation of settlements in clean sands: Report No. UCB/EERC-84/16, Earthquake Engineering Research Center, University of California, Berkeley, California.

PROGRAM LISTING

If the user has the access to the VAX 11/780 computer of the Office of Earthquakes, Volcanos, and Engineering, USGS in Menlo Park, California, he can execute PETAL2 by typing the command:

```
run pub1:[chen.tom]petal
```

and the computer will prompt for appropriate input.

Listing of PETAL2 and its subroutines are reproduced in the following pages.

```
c         PETAL2:  PEnetration Test And Liquefaction
c
c                program to estimate liquefaction potentials from
c                SPT/CPT data and fine/gravel content of deposit
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
c         by a. chen, oeve, usgs, 01/86
c         modified from programs NEWPET, NEWRELA, RDEN, TOKI and FICAL
c
      dimension dref(9), rd(9), rmk(8),dm(10),dcp(10),gx(11),gy(11)
      common /blka/x(9),y(9),xn(11),yt(11),title(18),resu(20,30)
      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/
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/)
   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'/
     & ' 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',7x,'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   depth  modified  relative     in-situ',
     & '     liquefaction    factor    pore press.   correction'/
     & 10x,'(ft)  bc, N1    density   stress ratio  stress ratio',
     & '  of safety    ratio       applied'/)
   36 format(/' * * NA = not applicable or not accurate **')
   38 format(i4,2f9.1,f10.2,f13.2,2(f9.2,a4),f7.2,a4,6x,a4,a4)
c
      write(6,4)
      write(6,*) 'PETAL2: 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 (<10)'
      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)
      call getfac(eqm,fac)
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
      kdpt = 0
      igrav = 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
      write(6,14) taur, ratiof, fs, pratio
      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)
      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 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, 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(1,i),(resu(j,i),j=9,12),resu(18,i),resu(13,i),
     & resu(19,i),resu(14,i),resu(20,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(20,30)
      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)
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 getfac(eqm,fac)
c
c        subroutine to compute scaling factor, fac, for a
c        given earthquake magnitude, eqm
c
      common /blkc/sy(6),qx(6),cy(6),sf(30),prat(30)
      common /blka/x(9),y(9),xn(11),yt(11),title(18),resu(20,30)
      data yt/0.05,0.1,0.15,0.2,0.25,0.3,0.35,0.4,0.45,0.5,0.6/
c
      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 180 i=1,11
      yt(i) = yt(i)*fac
  180 continue
      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
```