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Evaluation of Randomness of Earthquake Motion for Cyclic Undrained Strength of Sand

by

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ABSTRACT

The correction factor C_2 which accounts for the difference in cyclic undrained strength of sand between random loading and sinusoidal loading was studied by using earthquake motions. The factor C_2 which is defined as the ratio of the maximum stress ratio of a random loading to the stress ratio of a 20 cycles uniform sinusoidal loading for the identical cyclic shear stress amplitude was found to be a function of depth in the ground concerned, earthquake magnitude and epicentral distance.

INTRODUCTION

The in situ cyclic undrained shear resistance R at a depth Z of interest can be estimated from laboratory cyclic undrained triaxial strength by applying several correction factors:

$$R = C_1 \cdot C_2 \cdot C_3 \cdot C_4 \cdot C_5 \cdot R_{\ell_{20}} \tag{1}$$

in which $R_{\ell_{20}}$ is defined as

$$R_{\ell_{20}} = \sigma_{dp}/2\bar{\sigma}_c \tag{2}$$

the stress ratio for which double amplitude axial strain becomes 5 or 6 percent at the number of cyclic loading $N_c = 20$.

In Eq. (1), C_1 is the correction factor for the difference between in situ confining pressure and laboratory confining pressure. It has been confirmed by Ishihara and Li (1972), Ishibashi and Sherif (1976) and Tatsuoka et al. (1980 a, b and c) that C_1 is

$$C_1 = (1 + 2K_0)/3 \tag{3}$$

for a soil deposit which was made by a similar way to the laboratory pluviation through air or water. However, it was shown by Tatsuoka et al. (1980 a, b and c) that Eq. (3) can not be applied to a soil

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deposit which was deposited in a manner similar to the laboratory wet tamping procedure. It is likely that Eq. (3) is applicable to alluvial deposits or uncompacted hydraulic fills. C_1 by Eq. (3) equals 1.62 for an earthpressure coefficent at rest K_0 of 0.5.

C_2 is the correction factor which accounts for the difference between random and sinusoidal loading. This factor will be analyzed in this paper by using recorded earthquake motions and the two methods which will be described later. Factors C_3 and C_4 correct for the effects of soil disturbance and densification, respectively, during sampling, transportation and handling of samples. For loose to medium deposits, it was assumed by Iwasaki et al. (1978) that the multipulation $C_3 \times C_4$ equals 1.0. Factor C_5 allows for the effects of multi-directional shaking, which is 0.9 by Seed (1976).

In this paper, the values of C_2 which were calculated for earthquake motions recorded on ground surface and at the depth of 27 m at an identical location for identical earthquakes will be first shown and some discussions on the relationship among C_2, magnitude and epicentral distance will be followed

VARIATION OF FACTOR C_2 WITH DEPTH

The value of C_2 can be estimated by using a considerable amount of earthquake records on ground surface. Then, the relationship among C_2 on ground surface, magnitude, epicentral distance and ground condition can be established. However, it is evident that the value of C_2 for an underground location may be different from that on ground surface.

Among several stations where borehole accelerometers are stalled along Tokyo Bay in Japan, the Ukishima station was selected to study the variation of C_2 with depth (Fig. 1). The Ukishima station is placed on a deep soft deposit; several records at several depths for different earthquakes have been recorded here. Usually, liquefaction becomes a problem for such a deept soft deposits. The soil profile of the Ukishima station are shown in Fig. 2. From several earthquake records, three records on ground surface and three records at the depth of 27 m were selected. Each pair of records on ground surface and at the depth of 27 m are for the same earthquake. The three earthquakes have different magnitude and epicentral distance as listed in Table 1. The time histories of acceleration of these earthquake motions are shown in Fig. 3.

It was assumed that the time history of soil stress ratio at a point near the instrument is proportional in its amplitude to the time history of acceleration recorded by the instrument. From the time histories of acceleration shown in Fig. 3, histograms of normalized pulse amplitude, which is the ratio of the amplitude of each pulse to the maximum amplitude L_i/L_{max}, were obtained as shown in Figs. 5 through 7.* In this procedure, one pulse was counted when

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* Refer to Appendix 1

there are one positive peak between zerocrossings and one negative peak between next zerocrossings as illustrated in Fig. 4. The amplitude for this pulse was obtained as the average of the positive peak a_p and the negative peak a_n. In obtaining the histograms of pulse size, the range of L_i/L_{max} of 0.05 was selected. It may be seen from Figs. 5 through 7 that the distributions of pulse size for ground surface and for a depth of 27 m are slightly different for each case. There are more pulses for larger values of L_i/L_{max} for the depth of 27 m than on ground surface. By using these distributions, the values of L_{max} to cause 7.5 % double amplitude shear strain in a simple shear specimen of wet tamped Monterey No. 0 sand of D_r = 45 % and 60 % were computed by the cumulative damage concept (Valera and Donovan (1976)) and by the deteriorating stress-strain concept as follows. The value of L_{max} is obtained so that the sequence of pulse (L_1, L_2, ···, L_i, ···, L_{max}, ···, L_n) satisfies the following two equations by the cumulative damage concept as

$$1 = \sum_{i=1}^{n} (1/N_i) \tag{4}$$

$$N_i = \alpha_2 (1.452)^{\frac{1}{L_i}} + \frac{1}{\alpha_1 L_i} \frac{\log(DA_{max}/15)}{\log 5} \tag{5}$$

where DA_{max} = 7.5 %.* Eq. (5) is obtained from a series of cyclic undrained simple shear tests on wet tamped Monterey No. 0 sand of D_r = 45 %, 60 %, and 80 % (Tatsuoka et al. (1980 a, b and c)). The parameters α_1 and α_2 in Eq. (5) are empirical ones which are

D_r(%)	α_1	α_2
45	5	0.461
60	2	0.763
80	0.625	1.590

The deteriorating stress-strain concept was developed by the author to predict the time history of dynamic shear strain for random loading. This method is summarized in Figs. 8 and 9. When the values of L_a and DA_a for a certain pulse among a random loading are given, the double amplitude shear strain DA* for the next pulse of amplitude L_b is obtained by following the procedure illustrated in Fig. 8. In Fig. 9, the relationship between double amplitude shear strain DA and number of cyclic loading N_c for a uniform loading is represented by

$$DA = 15 \times 5^{(N_c - \alpha_2 (1.452)^{1/L})\alpha_1 L} \quad \text{for } DA > 1.5\ \% \tag{5}$$

in which α_1 and α_2 are values listed above and L is the amplitude of

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* Refer to Appendix 2

cyclic load which equals stress ratio $\tau/\overline{\sigma}_{vc}$ in cyclic simple shear test. A linear relation between DA and L is assumed for DA less than 1.5 % in this theory. By repeating the procedure illustrated in Fig. 8 from the first cycle of a random loading time history, the time history of double amplitude shear strain can be traced. Then, the value of L_{max} which is the maximum pulse of the random loading(L_1, L_2, ···, L_i, ···, L_{max}, ···, L_n) which causes DA_{max} of 7.5 % in a specified simple shear specimen can be calculated.* The procedure is explained in detail elsewhere (Tatsuoka and Silver (1980)). Then, the value of C_2 can be obtained by dividing the value of L_{max} by the value of $\tau/\overline{\sigma}_{vc}$ of a uniform loading which causes DA_{max} of 7.5 % at the number of cyclic loading of 20. The results of computation are listed in Table 1. Also in Table 1 are listed the values of C_2 when DA_{max} of 15 % is used as a criteria of failure. The values C_2 for DA_{max} of 15 % is almost equal to those for DA_{max} of 7.5 %. The relationships between the value of C_2 for earthquake motion recorded on ground surface and that at the depth of 27 m are shown in Fig. 10 for the cumulative damage concept and in Fig. 11 for the deteriorating stress-strain concept, respectively. It can be seen from these figures that the values of C_2 for earthquake motion on ground surface are, in general, larger than these at the depth of 27 m. This occurs because earthquake motions recorded on ground surface are, in general, more like shock type than those at deeper portions. Therefore, it seems that the value of C_2 which is determined by using earthquake motions recorded on ground surface is, in general, an overestimation for deeper portions. Based on the present information shown in Figs. 10 and 11, it is suggested that the value of C_2 determined by using earthquake motions recorded on ground surface be reduced by 5 % for liquefaction potential analyses at a depth.

In addition, it may be seen from Figs. 10 and 11 that the difference of C_2 between for D_r = 45 % and for D_r = 60 % is not significant. Additional studies are necessary to estimate the effect of density on the value of C_2.

RELATION AMONG FACTOR C_2, MAGNITUDE AND EPICENTRAL DISTANCE

In addition to the earthquake motions listed in Table 1, some strong earthquake motions recorded on ground surfaces of alluvial deposits were used to compute the value of C_2 for wet tamped Monterey No. 0 sand of D_r = 60 % by the cumulative damage concept (see Table 2). The results are shown in Fig. 12. Unfortunately, since the number of data is limited, any distinct trend can not be seen from the results shown in Fig. 12. However, it is likely that C_2 is not a simple function of magnitude, but is also affected by epicentral distance. The relationship among C_2, magnitude and epicentral distance can be established using earthquake motions which have been recorded on ground surface by applying either the cumula-

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* Refer to Appendix 3

tive damage concept or the deteriorating stress-strain concept.

CONCLUSIONS

The correction factor C_2 accounts for the difference in strength between random loading and sinusoidal loading. Based on cyclic undrained simple shear test results, earthquake motions and some theoretical computations, it was found that this correction factor C_2 is about 5 % larger on the ground surface than at a depth of 27 m, for a site on a deep alluvial deposit. The factor C_2 depends on both magnitude and distance of the earthquake.

ACKNOWLEDGEMENTS

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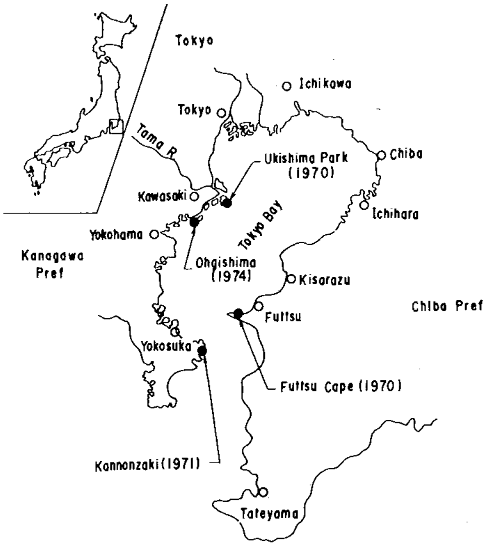


Fig.1. Stations of Borehole Accelerometer Installation (Iwasaki et al. (1976))

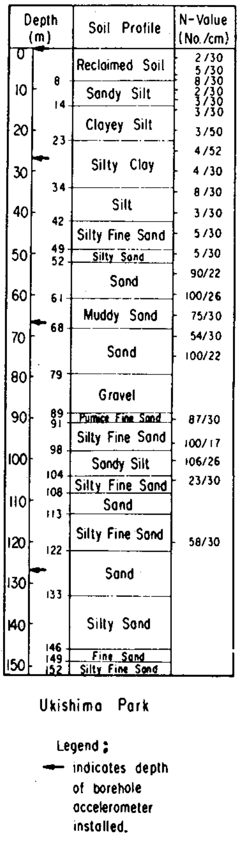
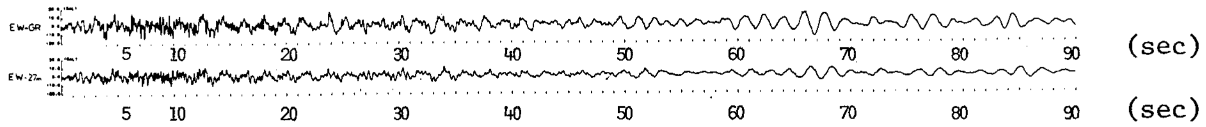
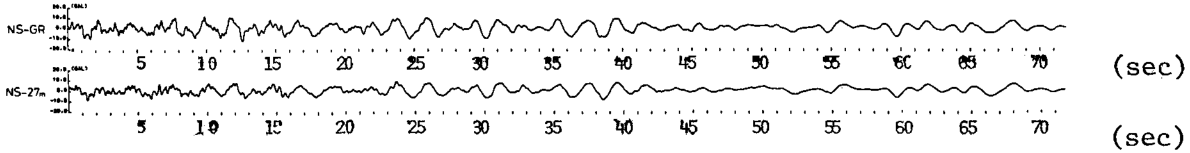


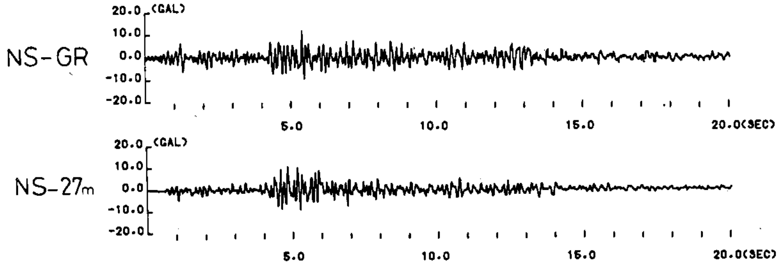
Fig.2. Soil Profile at the Station at Ukishima Park (Iwasaki et al. (1976))



Earthquake Motion 1



Earthquake Motion 2



Earthquake Motion 3

Fig.3. Time Histories of Acceleration for Three Earthquake

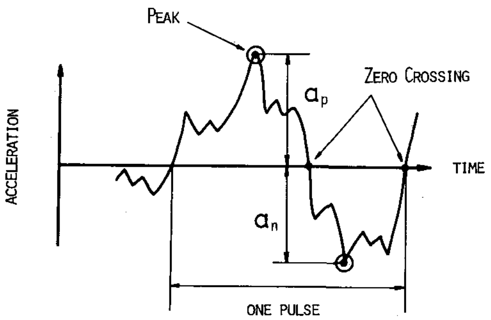


Fig.4. Method of Counting Pulses for Data Shown in Figs.5, 6 and 7

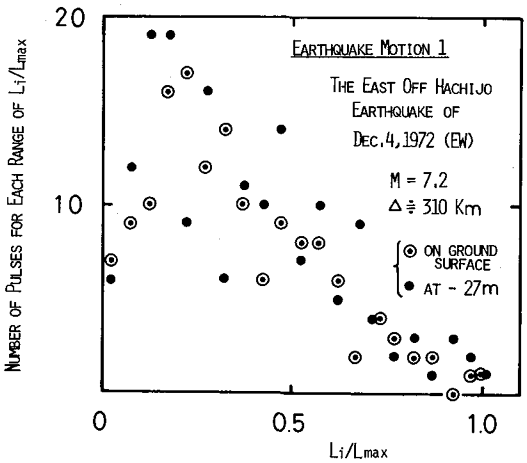


Fig.5. Distribution of Pulse for Earthquake Motion 1

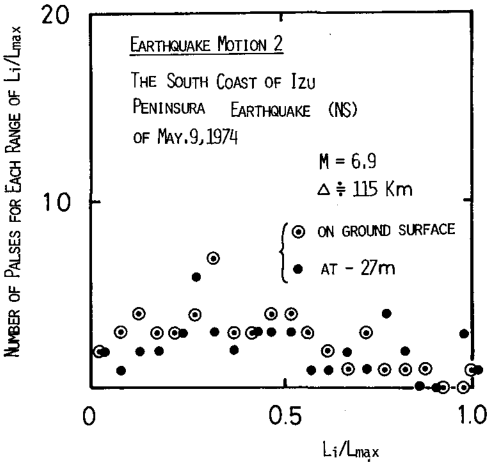


Fig.6. Distribution of Pulse for Earthquake Motion 2

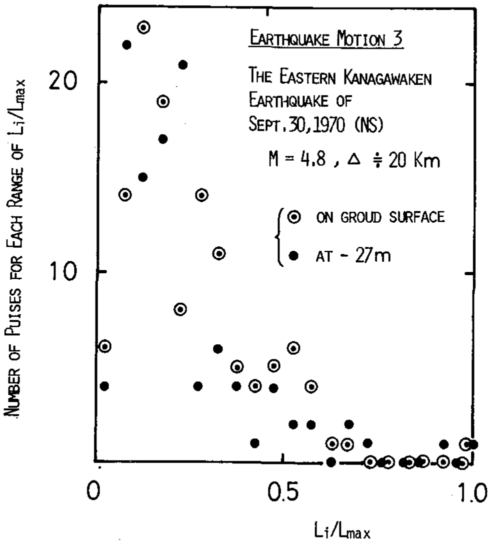


Fig.7. Distribution of Pulse for Earthquake Motion 3

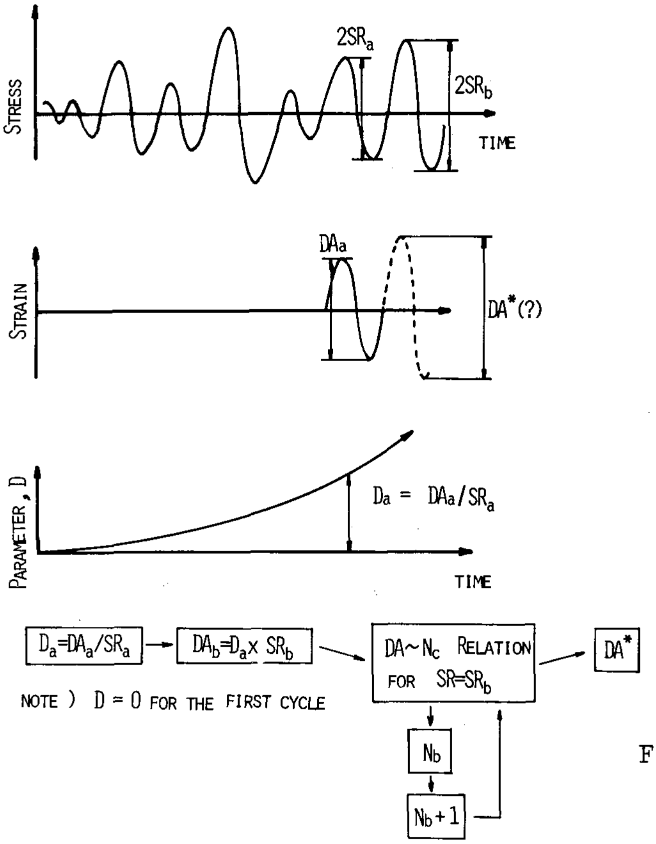


Fig.8. Method to predict Shear Strain for the Next Pulse

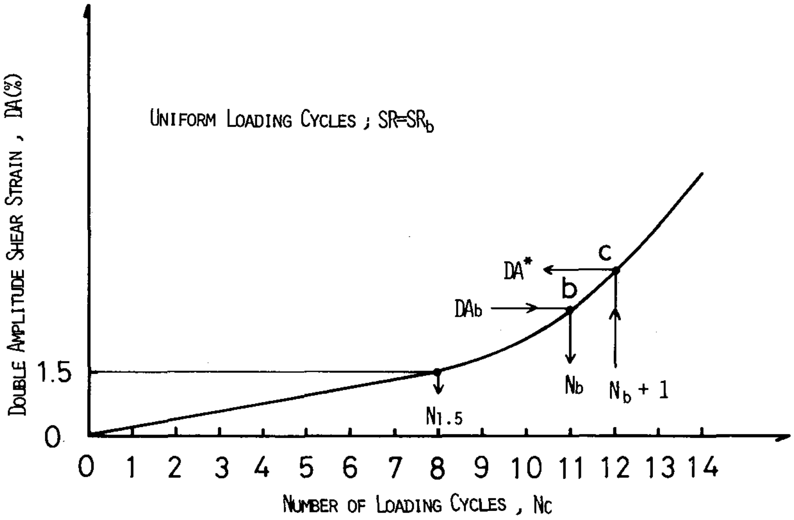


Fig.9. Number of Cyclic Loading, N_c Relationship between Double Amplitude Shear Strain DA and Number of Cyclic Loading Used in the Deteriorating Stress-Strain Concept

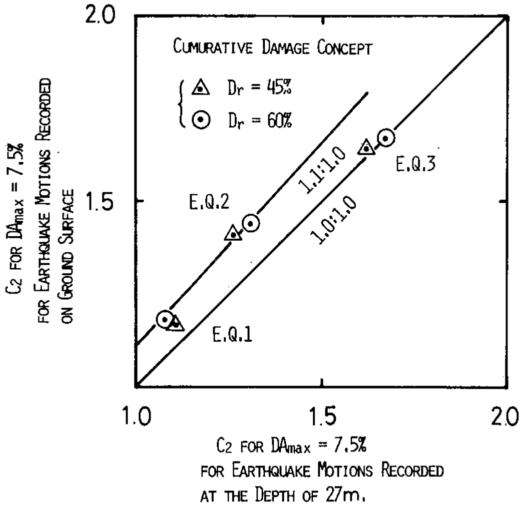


Fig.10. C_2 on Ground Surface versus C_2 at the Depth of 27m by Cumulative Damage Concept

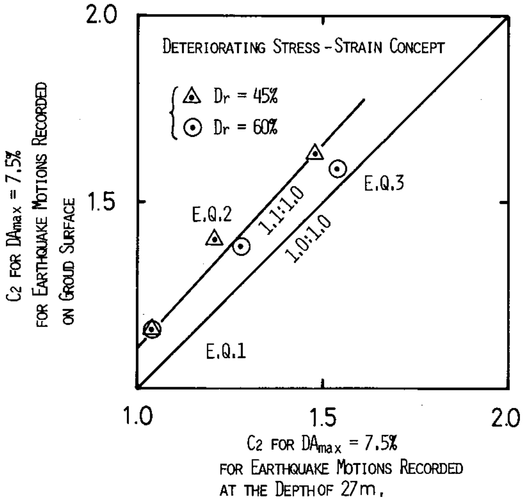


Fig.11. C_2 on Ground Surface versus C_2 at the Depth of 27m by Deteriorating Stress-Strain Concept

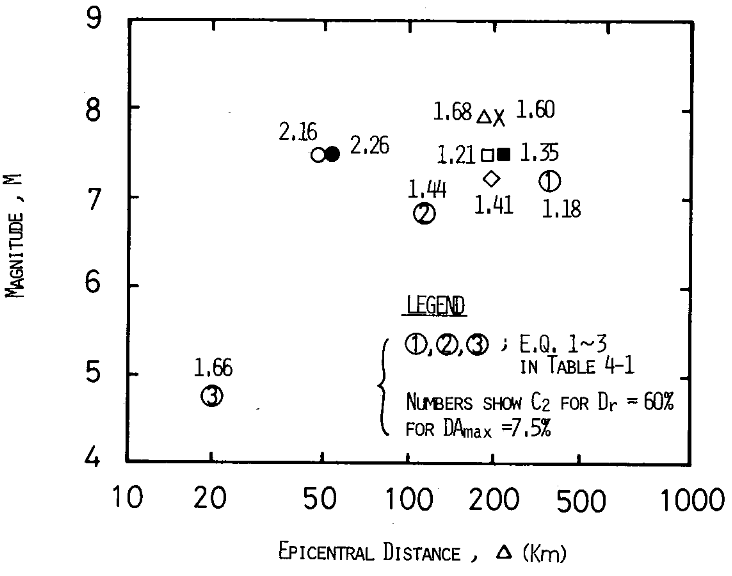


Fig.12. Relationship among C_2, Magnitude and Epicentral Distance for Earthquake Motions Recorded on Ground Surface by the Cumulative Damage Concept

No	Earthquake			Earthquake Motion			L_{max} for DA_{max}=7.5% and 15%				C_2 for DA_{max}=7.5% and 15%			
	Name	Date	Magnitude M	Epicentral Distance (km)	Component	Maximum Acceleration max (gals)	Cumulative Damage Concept		Deteriorating Stress-Strain Concept		Cumulative Damage Concept		Deteriorating Stress-Strain Concept	
							D_r=45%	D_r=60%	D_r=45%	D_r=60%	D_r=45%	D_r=60%	D_r=45%	D_r=60%
1	East off Hachijo	Dec. 4, 1972	7.2	310	EW, ground surface	15.6	$\frac{0.119^{*}}{0.122}$	$\frac{0.134}{0.137}$	$\frac{0.118}{0.118}$	$\frac{0.132}{0.132}$	$\frac{1.17^{**}}{1.20}$	$\frac{1.18}{1.20}$	$\frac{1.16}{1.16}$	$\frac{1.16}{1.16}$
					EW, -27m	11.3	$\frac{0.113}{0.113}$	$\frac{0.123}{0.125}$	$\frac{0.106}{0.106}$	$\frac{0.118}{0.121}$	$\frac{1.11}{1.11}$	$\frac{1.08}{1.10}$	$\frac{1.04}{1.04}$	$\frac{1.04}{1.06}$
2	South Coast of Izu Peninsular	May, 9, 1974	6.9	115	NS, ground surface	12.2	$\frac{0.144}{0.147}$	$\frac{0.164}{0.170}$	$\frac{0.143}{0.143}$	$\frac{0.156}{0.158}$	$\frac{1.41}{1.44}$	$\frac{1.44}{1.49}$	$\frac{1.40}{1.40}$	$\frac{1.37}{1.39}$
					NS, -27m	9.2	$\frac{0.129}{0.131}$	$\frac{0.149}{0.152}$	$\frac{0.123}{0.123}$	$\frac{0.146}{0.147}$	$\frac{1.26}{1.28}$	$\frac{1.31}{1.33}$	$\frac{1.21}{1.21}$	$\frac{1.28}{1.29}$
3	Eastern Kanagawa-ken	Sept. 30, 1970	4.8	20	NS, ground surface	11.6	$\frac{0.167}{0.170}$	$\frac{0.189}{0.195}$	$\frac{0.166}{0.166}$	$\frac{0.181}{0.182}$	$\frac{1.64}{1.67}$	$\frac{1.66}{1.71}$	$\frac{1.63}{1.63}$	$\frac{1.59}{1.60}$
					NS, -27m	10.4	$\frac{0.165}{0.169}$	$\frac{0.190}{0.200}$	$\frac{0.161}{0.161}$	$\frac{0.175}{0.175}$	$\frac{1.62}{1.66}$	$\frac{1.67}{1.75}$	$\frac{1.58}{1.58}$	$\frac{1.54}{1.54}$

* L_{max} for DA_{max}=7.5% / L_{max} for DA_{max}=15%

** C_2 for DA_{max}=7.5% / C_2 for DA_{max}=15%

$$\begin{cases} \text{at } N_c=20,\ \tau/\bar{\sigma}_v=0.102 \text{ for DA=7.5\% and 15\% for } D_r=45\% \text{ for uniform cyclic loading} \\ \text{at } N_c=20,\ \tau/\bar{\sigma}_v=0.114 \text{ for DA=7.5\% and 15\% for } D_r=60\% \text{ for uniform cyclic loading} \end{cases}$$

Table 1. List of Earthquake Motions Analyzed

Symbols	Earthquake (Magnitude)	Record Site (Component, Δ= epicentral distance (km), α = maximum acceleration (gals)		C_2 for DA_{max}=7.5% for D_r=60%	Liquefaction
○	Niigata* (7.5)	Kawagishi-cho	(NS, Δ=51, α = 155)	2.16	YES
●			(EW, Δ=51, α = 159)	2.26	YES
△	Tokachioki-Main Shock (7.9)**	Hachinohe (NS, Δ = 189, α = 95)		1.68	NO
×	Tokachioki-After Shock ** (7.5)	Muroran (NS, Δ = 196, α = 95)		1.60	NO
□		Aomori	(NS, Δ=193, α=56)	1.21	NO
■			(EW, Δ=193, α=86)	1.35	NO
◇	Tokachioki-After Shock (7.2)**	Hachinohe (EW, Δ = 194, α = 30)		1.41	NO

* The Niigata Earthquake (1964)
** The Tokachioki Earthquake (1968)

Table 2. C_2 Computed for Some Strong Motions on Ground Surface by the Cumulative Damage Concept

<u>Apendix 1</u> A computer Program to Obtain the Distribution of Pulse in Random Earthquake Motions

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C
C             COMPUTER PROGRAM TO OBTAIN THE DISTRIBUTION
C               OF PULSES IN EARTHQUAKE MOTIONS
C
C◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆C
C         PULSEP:POSITIVE PULSE
C         PULSEN:NEGATIVE PULSE
C         NOPLS(I):NUMBER OF PULSE OF PULSE/PULSEMAX:0.05(I-1) TO 0.05I
                 DIMENSION PULSEP(500),PULSEN(500),NOPLS(50),PULSE(500)
        READ(12,400)NOEQMO
  400   FORMAT(I5)
        WRITE(14,410)NOEQMO
  410   FORMAT("          EARTHQUAKE MOTION:NO=",I5)
        PLSMAX=0.0
        I=1
        WRITE(14,500)
  500   FORMAT(" POSITIVE HALF PULSE,NEGATIVE HALF PULSE")
   10   READ(12,100)PULSEP(I),PULSEN(I)
  100   FORMAT(2F10.3)
        IF(PULSEP(I).GT.1000.0)GO TO 20
        PULSE(I)=(PULSEP(I)+PULSEN(I))/2.0
        IF(PULSE(I).GT.PLSMAX)PLSMAX=PULSE(I)
        WRITE(14,501)I,PULSEP(I),PULSEN(I)
  501   FORMAT(I5,F10.3,"      -",F10.3)
        I=I+1
        GO TO 10
   20   I=I-1
        NUMBER=I
        WRITE(14,502) PLSMAX
  502   FORMAT(" MAXIMUM PULSE=",F10.4)
        WRITE(14,505)
  505   FORMAT(" NORMALIZED PULSES")
        DO 21 M=1,NUMBER
        PULSE(M)=PULSE(M)/PLSMAX
   21   WRITE(14,506)PULSE(M)
  506   FORMAT(F10.3)
        DO 25 K=1,20
   25   NOPLS(K)=0
        DO 30 J=1,21
        PLSL=0.05◆(J-1)
        PLSU=0.05◆J
        DO 40 N=1,NUMBER
        IF(PULSE(N).LT.PLSL) GO TO 40
        IF(PULSE(N).GE.PLSU) GO TO 40
        NOPLS(J)=NOPLS(J)+1
   40   CONTINUE
   30   CONTINUE
        WRITE(14,503)
  503   FORMAT(" GE.L/LMAX LT.L/LMAX NUMBER OF PULSE")
        DO 50 L=1,21
        PLSL=0.05◆(L-1)
        PLSU=0.05◆L
   50   WRITE(14,504)PLSL,PLSU,NOPLS(L)
  504   FORMAT(2F10.3,I5)
        STOP
        END
```

Apendix 2 A Computer Program for Calculating Maximum Double Amplitue Shear Strain for Random Loading by the Cumulative Damage Concept

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      DIMENSION PULSED(100),PULSE(100),ALMAX(100)

C **********************************************************************
C                 PROGRAM FOR CALCULATION OF MAXIMUM SHEAR
C                  STRAIN AMPLITUDE BY CUMULATIVE DAMAGE CONCEPT
C ***********************************************************************
C IRD=1,2 OR 3 FOR RD=45,60 OR 80%.
C NOPLS=NUMBER OF PULSE.
C NOWAVE=NUMBER OF WAVE.
C NOREPT=NUBER OF REPETION

      READ(14,100)IRD,NOPLS,NOWAVE,NOREPT
  100 FORMAT(4I10)
      WRITE(15,200)
  200 FORMAT(" NORMALIZED PULSES")
      DO 6 I=1,NOPLS
      READ(14,101)PULSED(I)
  101 FORMAT(F10.3)
    6 WRITE(15,101)PULSED(I)
      DO 7 J=1,NOWAVE
    7 READ(14,102)ALMAX(J)
  102 FORMAT(F10.4)

      IF(IRD-2)45,60,80
   45 ALFA1=5.0
      ALFA2=0.461
      IRD=45
      GO TO 1
   60 ALFA1=2.0
      ALFA2=0.763
      IRD=60
      GO TO 1
   80 ALFA1=0.625
      ALFA2=1.59
      IRD=80

    1 WRITE(15,201)IRD
  201 FORMAT(" RD=",I10,"%")
      DO 300 I=1,NOWAVE
      WRITE(15,202)ALMAX(I)
  202 FORMAT(" LMAX=",F 10.4)
      DA=0.0001
      DA1=0.0
      DA2=0.0
    2 DAMAGE=0.0
      DO 301 II=1,NOPLS
      PULSE(II)=1.0/(PULSED(II)*ALMAX(I))
      IF(PULSE(II).GT.88.0) PULSE(II)=88.0
      AN15=ALFA2*(1.452**PULSE(II))
      ANII=AN15+((ALOG10(DA)-ALOG10(15.0))/(ALOG10(5.0)*ALFA1))*PULSE
     1(II)
      IF(ANII.LT.0.000001)ANII=0.000001
  301 DAMAGE=DAMAGE+1.0/ANII
      DAMAGE=DAMAGE*NOREPT
      IF(DA2.GT.0.0)GO TO 5
      IF(DAMAGE.GT.1.0)GO TO 4
      IF(AA.GT.0.5)GO TO 9
      DA=0.0
      GO TO 10
    4 DA1=DA
      AA=1.0
      DA=DA*10.0
```

```
      GO TO 2
    5 IF(DAMAGE.GT.1.0)GO TO 8
      IF(DAMAGE.LT.0.9999)GO TO 9
   10 DAMAX=DA
  300 WRITE(15,302)DAMAX
  302 FORMAT(" MAXIMUM DA(%)=",F10.3)
      STOP
    8 DA1=DA
      DA=(DA+DA2)/2.0
      GO TO 2
    9 DA2=DA
      DA=(DA+DA1)/2.0
      GO TO 2
      END
```

```
R 1100 0.263 1.298 48
```

Apendix 3 A Computer Program for Calculating of Time History of Double Amplitude Shear Strain and the Maximum Double Amplitude Shear Strain for Random Loading by the Deteriorating Stress Strain Relation Concept

This computer program has several options as to the relationship between double amplitude shear strain and number of loading cycles for uniform loading and as to the deteriorating stress-strain relationship as follows.

The Relationship between Double Amplitude Shear Strain and Number of Loading Cycles for Uniform Loading

KLM=1 The relationship between amplitude of stress ratio L and double amplitude shear strain DA is

$$L = DA \qquad \text{(Ap-1)}$$

up to DA=1.5 % as explained in this paper.

KLM=2 This relationship is valid only for the number of cyclic loading less than unity.

The Deteriorating Stress-Strain Relationship

IJK=1 The deteriorating stress-strain relationship is

$$L = DA/D \qquad \text{(Ap-2)}$$

as explained in Section 3.

IJK=2 This is expressed by

$$L = DA^2/D \qquad \text{(Ap-3)}$$

```
            DOUBLE PRECISION DD,EE,FF
            DIMENSION PULSED(500),PULSE(500),ALMAX(100),DA(500),EPSLON
     1  (100)
C ◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆
C
C         A PROGRAM FOR CALCULATION OF TIME HISTORY OF SHEAR STRAIN
C            AMPLITUDE BY DETERIORATING STRESS-STRAIN RELATIONSHIP
C
C            BY FUMIO TATSUOKA, AUGUST,1979 IN GOLDEN,COLORADO
C ◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆
C  IRD=1,2 OR 3 FOR RD=45,60 OR 80%
C  NOPLS=NUMBER OF PULSE
C  NO WAVE=NUMBER OF WAVE.
C  NOEPSL=NUMBER OF EPSLON
C  NOREPT=NUMBER OF REPETITION OF LOADING FOR SINGLE WAVE
C  IPR=1 MEANS PRINT OUT OF TIME HISTORY OF SHEAR STRAIN AMPLITUDE
C       DETERIORATING STRESS-STRAIN RELATIONSHIP
C       IJK=1: L=DA/DD,  IJK=2: L=DA◆◆2/DD
C     KLM=1: L=DA UP TO DA=1.5%
C      KLM=2:  L=DA UP TP NC=1
CKLM.GT.1: L-DA UP TO NC=1
      READ(14,100) IRD,NOPLS,NOWAVE,NOREPT,IPR
  100 FORMAT(5I10)
      READ(14,300) IJK,KLM
  300 FORMAT(2I5)
      WRITE(15,400) IJK
  400 FORMAT(" DETERIORATING L-DA: L=DA◆◆",I1,"/DD")
      IF(KLM.GT.1) GO TO 750
      WRITE(15,401)
  401 FORMAT(" DA IS PROPORTIONAL TO NC UP TO DA=1.5%")
      GO TO  760
  750 WRITE(15,402)
  402 FORMAT("  DA IS PROPORTIONAL TO NC UP TO N=1.0")
  760 WRITE(15,200)
  200 FORMAT("    NORMALIZED PULSES")
      DO 6 LL=1,NOPLS
    6 READ(14,101) PULSED(LL)
  101 FORMAT(F10.3)
      DO 7 K=1,NOREPT
      DO 8 JJ=1,NOPLS
      L=JJ+NOPLS◆(K-1)
      PULSED(L)=PULSED(JJ)
    8 WRITE(15,101) PULSED(L)
    7 CONTINUE
      NOPLS=NOPLS◆NOREPT
      DO 10 N=1,NOWAVE
   10 READ(14,103) ALMAX(N)
  103 FORMAT(F10.4)
      IF(IRD-2)45,60,80
   45 ALFA1=5.0
      ALFA2=0.461
      IRD=45
      GO TO 1
   60 ALFA1=2.0
      ALFA2=0.763
      IRD=60
      GO TO 1
   80 ALFA1=0.625
      ALFA2=1.59
      IRD=80
    1 WRITE(15,201)IRD
  201 FORMAT(" RELATIVE DENSITY=",I10,"%")
      DO 301 I=1,NOWAVE
      WRITE(15,203) ALMAX(I)
  203 FORMAT("    LMAX=",F10.4)
      DAMAX=0.0
      DDMAX=0.0
      DATIO=0.0
      DO 302 II=1,NOPLS
      PULSE(II)=1.0/(PULSED(II)◆ALMAX(I))
```

```
      IF(PULSE(II).GT.88.0) PULSE(II)=88.0
      IF(II.GT.1)GO TO 2
      FF=(1.0-ALFA2*1.452**PULSE(II))*ALFA1/PULSE(II)
      IF(FF.GT.20.0)FF=20.0
      IF(FF.LT.-50.0)FF=-50.0
      DA(II)=5.0**FF
      DA(II)=DA(II)*15.0
      ANIIO=0.0
      IF(KLM.GT.1) GO TO 4
      IF(DA(II).GT.1.5) GO TO 4
      AN15=ALFA2*(1.452**PULSE(II))
      CC=ALOG10(0.10)/ALOG10(5.0)/ALFA1
      AN1P5=AN15+CC*PULSE(II)
      DA(II)=1.5/AN1P5
      GO TO 4
    2 AN15=ALFA2*(1.452**PULSE(II))
      IF(DA(II-1).LT.0.0000001) DA(II-1)=0.0000001
      IF(IJK.GT.1) GO TO 90
      DD=DA(II-1)*PULSE(II-1)
      IF(DD.LT.DDMAX) DD=DDMAX
      DAIIO=DD/PULSE(II)
      GO TO 70
   90 DD=DA(II-1)**2*PULSE(II-1)
      IF(DD.LT.DDMAX) DD=DDMAX
      DAIIO=SQRT(1.0/PULSE(II))*SQRT(DD)
   70 IF(DD.GT.DDMAX) DDMAX=DD
      IF(KLM.GT.1) GO TO 910
      IF(DAIIO.GT.1.5) GO TO 20
      CC=ALOG10(0.10)/ALOG10(5.0)/ALFA1
      AN1P5=AN15+CC*PULSE(II)
      ANIIO=AN1P5*DAIIO/1.5
      GO TO 3
  910 DAONE=(1.0-AN15)*ALFA1/PULSE(II)
       IF(DAIIO.LT.0.0000001) GO TO 30
      YOKO=ALOG10(15.0)+DAONE*ALOG10(5.0)-ALOG10(DAIIO)
      IF(YOKO.LT.0.0000001) GO TO 20
      IF(DAONE.GT.20.0)DAONE=20.0
      IF(DAONE.LT.-50.0)DAONE=-50.0
   30 DAONE=5.0**DAONE
      DAONE=15.0*DAONE
      ANIIO=DAIIO/DAONE
      GO TO 3
   20 CC=(ALOG10(DAIIO)-ALOG10(15.0))/(ALOG10(5.0)*ALFA1)
      ANIIO=AN15+CC*PULSE(II)
      DA(II)=DAIIO*5.0**(ALFA1/PULSE(II))
      GO TO 4
    3 EE=(ANIIO+1.0-AN15)*ALFA1/PULSE(II)
      IF(EE.GT.20.0) EE=20.0
      IF(EE.LT.-50.0)EE=-50.0
      DA(II)=5.0**EE
      DA(II)=DA(II)*15.0
      IF(KLM.GT.1) GO TO 4
      IF(DA(II).GT.1.5) GO TO 4
      DA(II)=1.5/AN1P5*(ANIIO+1.0)
    4 IF(DA(II).GE.DAMAX)DAMAX=DA(II)
      PLS=1.0/PULSE(II)
      IF(IPR.EQ.1) GO TO 303
      GO TO 302
  303 WRITE(15,204)II,ANIIO,DAIIO,PLS,DA(II)
  204 FORMAT(I5,"  N(I0)=",F10.3," DA(I0)(%)=",F10.3," L=",F10.3,
     2 "DA(%)=",F10.3)
  302 CONTINUE
  301 WRITE(15,205)ALMAX(I),DAMAX

  205 FORMAT(" LMAX=",F10.3,"DAMAX(%)=",F10.3)
      STOP
      END
```