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CYCLIC UNDRAINED STRENGTHS OF SATURATED SAND UNDER RANDOM AND UNIFORM LOADING AND THEIR RELATION

by

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SYNOPSIS

Cyclic undrained torsional shear tests on hollow cylindrical specimens of saturated sand were performed by changing both density values of specimens and types of random loading patterns. Two time histories of acceleration recorded on ground during an earthquake were used as the time histories of input shear stresses. Their results were compared with the results of cyclic undrained torsional shear tests on the specimens of the same sand using uniform sinusoidal loadings. It was found that for these two types of random loading patterns used the ratio of the maximum shear stress during a given random loading pattern to the amplitude of uniform sinusoidal loading pattern having a certain number of pulses to cause the same value of shear strain in the similar specimen depends strongly on the density of the specimen. It was also found that the difference in this ratio for different types of random loadings increases with the increase in density of specimen.

INTRODUCTION

Usually uniform cyclic undrained tests using sinusoidal loading patterns are performed on saturated sand specimens to evaluate strengths against liquefaction in laboratories. On the other hand, earthquake motions are random. Therefore, some measures are necessitated to account for this difference, uniform or random, in the procedure of evaluation of liquefaction potential for a given sand element, for which the resistance or liquefaction strength against uniform loading is known as a function of the number of cycles. In the method proposed by Seed and Idriss (1971)[5], an input random cyclic loading pattern is converted into an equivalent uniform loading pattern having a certain number of loading cycles N_{eq} which are defined depending on the magnitude of earthquake M. The effects of wave form of input cyclic stresses on liquefaction potentials are taken into account by using different values of N_{eq}. It is to be noted that to determine the values of N_{eq} as a function of M, both the randomness of earthquake motions and the characteristics of the relationship between cyclic stress ratio and the number of cycles by cyclic undrained tests using uniform loading patterns were taken into account. On the other hand, in the method proposed by Ishihara (1977)[3], the behavior of a given sand element for a given random loading pattern is predicted from the liquefaction strength of this sand element against uniform cyclic loading. For this purpose, a correction factor c_2 have been experimentally determined by Ishihara and Yasuda (1975)[2]. (Note that the notation c_2 was not used by Ishihara (1977)[3] but used by Tatsuoka, et al (1980)[7]).

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These two methods are schematically described in Fig.1. In the Ishihara's method, the equivalent random loading pattern ERL is defined as the one which induces the same degree of liquefaction in a given soil element with that caused by the uniform loading pattern having 20 cycles. The ratio of the amplitude of the random loading pattern ERL to the amplitude of the uniform loading pattern having 20 cycles is defined as c_2. It was shown by Tatsuoka, et al (1980)[7] that these two methods give similar results. We followed the Ishihara's method in this study.

Only available experimental data for the value of c_2 are those by Ishihara and Yasuda (1975)[2] for loose samples of one kind of sand having a relative density value of 55%. It was shown that the value of c_2 be a function of randomness of random loading patterns.

In this study, the value of c_2 were experimentally obtained for a wide range of density by performing cyclic undrained torsional tests (by using uniform and two kinds of random loading patterns.). It was found that the values of c_2 shown by Ishihara and Yasuda (1975)[2] are valid only for loose sand, but the value of c_2 varies considerably by the variation in density.

TEST PROGRAM

Test procedures for random loading tests employed are similar to those for uniform loading tests (Muramatsu ans Tatsuoka (1981)[4] and Tatsuoka, Muramatsu and Sasaki (1982)[8]). Random loading patterns were produced from digitized acceleration values provided by Port and Harbour Research Institute (1969)[10] through a digital-analog converter (Fig.2). In this study, two kinds of time history acceleration recorded on the ground surface (Table 1) were used which are two of six random loading patterns used by Ishihara and Yasuda (1975)[2]. Irregular signals of DC type was supplied to a pneumatic cyclic loading system (Chan, 1982)[1] after adjusting the amplitudes of pulse to a prescribed value. Slow tests were performed by extending the time axis in loading patterns around 10 times to reproduce better random loading patterns by the pneumatic loading system. It was thought that this slow test be justified by the fact that the cyclic undrained triaxial tests on the test sand were identical for sinusoidal cyclic loadings of 0.5Hz and 0.05Hz (Fig.3). Hollow cylindrical specimens were 10cm in height, 10cm in outer diameter and 6cm in inner diameter. Test material was Toyoura Sand (G_s=2.64, e_{max}=0.977, e_{min}=0.605, D_{50}=0.162mm, $U_c=D_{60}/D_{10}$=1.46 and no content finer than 74μm). Specimens were prepared by the air-pluviation method. Density values were controlled by adjusting the height of fall. After being saturated, the specimens were consolidated isotropically to an effective confining pressure of 98 kN/m^2 with a back pressure of 98 kN/m^2.

TEST RESULTS

Typical test results for the two random loading patterns are shown in Figs. 4 and 5. It may be seen from these figures that these two wave patterns are quite different. The wave pattern "Main Shock" may be distinguished as of shock-type and the wave pattern "After Shock" may be distinguished as of vibrational type. To study the relationship among the wave pattern of cyclic stresses, site condition and earthquake patameters (magnitude, epicentral distance, source mechanism or so) is beyond the scope of this study. These two wave patterns were selected as typical of shock-and vibrational types. As described later, it was found that the degree of reproduction of wave form were generally satisfactory when the maximum shear strain was less than around 20%. After the shear strain value became more than this value, the pattern of measured shear stresses became different from the original input pattern. However, since the later analyses of these data were performed for the shear strain values equal to or less than 15%, the fact described above did not affect the results of this study. Then, such test results as shown in Figs. 4 and 5 were analysed based on the maximum values of double amplitude shear strain DA_{max} observed, not on the values of excess pore pressure measured or not on "initial liquefaction". Such a procedure as above was adopted in order to clearly define the cyclic undrained stress-strain behavior especially for dense samples. The maximum value of shear stress ratio $SR^*_{max} = (\tau/\sigma'_{mc})_{max}$ in single amplitude was also obtained for each test result. σ'_{mc} is the effective confining stress during consolidation equal to 98 kN/m^2 in this study. Since the samples were isotropically consolidated, the value of σ'_{mc} was identical to the value of effective vertical or horizontal stresses, σ'_{vc} or σ'_{hc}.

A series of tests were performed with changing density values for several different values of SR^*_{max}. Test results were summarized as relationships between the relative density values D_r of consolidated specimens and the maximum values of double amplitude shear strain DA_{max} for each value of SR^*_{max} as shown in Figs. 6 and 7. In these figures, the data points with symbols of arrow directing to right represent the cases where measured time histories of shear stress were attenuated after shear strain value became larger than sround 20%. Therefore it was considered that the shear strain values would have been larger than measured values if the time history of shear stress had simulated precisely the original input random loading pattern. The averaged relationship between D_r and DA_{max} was determined for each value of SR^*_{max} as shown in Figs. 6 and 7. From the relationship between Dr and DA_{max}, the values of D_r corresponding to the values of DA_{max} equal to 3%, 7.5% and 15% were obtained for each value of SR^*_{max}. The values of SR^*_{max} and D_r thus obtained for different values of DA_{max} were summarized as in Figs. 8 through 10. Also shown in these figures are the relationships between the stress ratio $SR = \tau_{cy}/\sigma'_{mc}$ and the relative density values D_r for different numbers of loading cycles where the values of double amplitude shear strain DA of 3%, 7.5% or 15% was observed which were obtained by uniform loading tests (see Tatsuoka, Muramatsu and Sasaki (1982)[8] for details). From these figures, the following facts can be found. First, the relationships between SR^*_{max} and D_r for random loading tests were more smooth than those between SR and D_r for uniform loading tests within the limit of tests performed. It may be seen from these figures that there were no sudden increase in the value of SR^*_{max} with the increase in D_r in the case of random loading. Therefore, it is clear that the ratios of SR^*_{max} to SR for identical values of DA_{max} and DA are not constant but vary with the variation in density of specimen. Secondly, the difference in the value of SR^*_{max} between two different types of random loading increases with the increase in density of specimen. This means that the effect of wave form on cyclic undrained stress-strain behaviors of saturated sand specimen increases with the increase in density of specimen. Furthermore, it may also be interesting that the values of SR^*_{max} thus defined become less than the value of SR for relative density values larger than certain values. This means that in such cases the value of c_2 become less than unity.

DISCUSSIONS

In order to find possible reasons for the facts described above, the wave forms of random loading patterns used were analysed. First, pulses were defined as the stresses between two adjacent zero crossings in the input random loading patterns (Fig.11). Then, the maximum pulse SR_{max} was defined as a half of the maximum double amplitude of τ/σ'_{mc}. Note that the value of SR_{max} was less than the value of SR^*_{max} for two original random loading patterns used in this study. Next, the pulses other than the maximum pulse were defined as illustrated in Fig.11. The cumulative curves of these pulses were plotted against the value of SR_i/SR_{max} as shown in Fig.12. In this figure, for example the points a, b and c represent the largest, the second largest and the third largest pulses for the wave pattern of After shock. As can be seen, the uniform cyclic stresses series of 20 cycles having a constant amplitude value is represented by a vertical straight line a-d in Fig.12. Therefore, when the cumulative curve for a given random loading pattern is steeper, this pattern is more vibrational and vice versa. It may be seen from Fig.12 that while for the wave pattern of Main shock the tenth largest pulse is as small as around 50% of the largest pulse, for the wave pattern of After shock the tenth largest pulse is still as large as around 75% of the largest pulse.

On the other hand, shown in Fig.13 are the relationships between SR and the number of loading cycles where 15% double amplitude shear strain values were observed in uniform loading tests for several different density values (Tatsuoka, Muramatsu and Sasaki, 1982)[8]. Combining the data shown in Figs. 12 and 13, the performances shown in Figs. 8 through 10 may be qualitatively explained as follows. When a specimen is in a loose condition with the relative density value being, say, 50%, the number of loading cycles to cause a certain value of DA, say 15%, increases substantially with the decrease in the value of SR. Assume that the amount of damage given by each pulse in a random loading pattern to cause a DA value of 15% can be represented by the inverse value of N_c shown in Fig.13 as suggested by the cumulative damage concept (Valera and Donovan, 1976)[11]. Suppose further that the largest pulse has a SR_{max} of 0.25 and the second largest pulse has a SR of $0.6\times SR_{max}$ =0.15. In the case of D_r=50%, the values of N_c for these two cases are 2.5 and 30, respectively (see Fig.13). Therefore, the damage by the second largest pulse is only 2.5/30 or 8% as large as that by the largest pulse. This may imply that for a loose sand element, the contributions of pulses other than the maximum pulse in respect of damaging sand decreases considerably with the decrease in the largeness of the pulse. Therefore, it seems natural that for looser sands the value of SR^*_{max} or SR_{max} for a given random loading pattern is the most important factor in respect of causing a certain amount of shear strain and the wave pattern has a less importance in this respect. On the other hand, in a dense sand, as shown in Fig.13, the relationship between SR and N_c for DA=15% is quite different from that of loose samples for SR larger than around 0.3. It may be seen from Fig.13 that the value of N_c increases only slightly with the decrease in the value of SR when SR is larger than around 0.3. Suppose that a sample has a D_r of 85%. The numbers of loading cycles for values of SR equal to 0.6 and 0.36(60% of 0.6) are around 10 and around 30, respectively. Thus the amount of damage by a pulse having a SR of 0.36 is still around 30% of that by the pulse of SR=0.6. This may imply that in such a dense sand pulses having SR-values larger than around 0.3 damage almost equally the sand. Therefore, it may be reasonable to consider that for dense sands the role of the major pulses other than the largest pulse is still very important in respect of damaging the samples. Therefore, it is likely that for dense sands the number of such major pulses or the wave form is as important as the magnitude of the largest pulse.

Furthermore, it may be noticed from Fig.10 that the value of SR which induces a DA of 15% at a certain number of loading cycles increases substantially with the increase in the value of D_r for values of D_r larger than a certain value. On the other hand, it is also true that the stress ratio for a certain number of loading cycles where a DA of 15% is induced does not represent the whole characteristics of such strength performances for a given value of D_r as shown in Fig.13. It may be seen that the difference in the whole shape of the strength curves shown in Fig.13 by the difference in density is not as large as in the value of SR at a certain number of cycles especially for dense sands. It seems that the response of a sand element against such random loading pattern as earthquake motions reflect the characteristics of whole shape of such strength curves as shown in Fig.13. Such a discussion as above may partly explain why there are difference between the $SR \sim D_r$ relationship for a certain value of N_c and the $SR^*_{max} \sim D_r$ relationship shown in Fig.10. Such discussions may be valid also for the cases of DA equal to 3% and 7.5%.

CORRECTION FACTOR c_2

The correction factor c_2 will be defined as the ratio of the maximum single amplitude of pulses SR^*_{max} in a given random loading pattern to the amplitude of a uniform cyclic stress series having 20 pulses SR_{20}, with both inducing an identical shear strain value in an identical sample (see Fig.1). The values of c_2 can be readily obtained from the values of SR^*_{max} and SR_{20} shown in Figs. 8 through 10. The value of c_2 thus obtained for the values of DA of 3%, 7.5% and 15% are plotted against the value of relative density in Fig.14. Also in Fig.15 plotted are the value of c_2 against the value of $SR_{20}=(\tau_{cy}/\sigma'_{vc})_{20}$ to cause double amplitude shear strains (DA) of 3%, 7.5% or 15% at N_c=20 in uniform loading tests. For the purpose of comparison, the data by Ishihara and Yasuda (1975)[2] were also plotted in Fig.15. For the case of their study the value of c_2 were defined such that when SR_{20} is defined as the stress ratio of uniform cyclic stresses at the 20th cycle of which initial liquefaction occurs in a given sample, only random loading patterns having values of SR^*_{max} larger than or equal to $c_2 \times SR_{20}$ induce initial liquefaction in the same sample. The followings may be pointed out from the data shown in Figs. 14 and 15.

First, it is seen from Fig.14 that the value of c_2 is functions of not only the randomness of input cyclic shear stresses but also the density of sample and the definition of liquefaction or the magnitude of shear strain amplitude for which liquefaction is defined. It may further be seen from Fig.15 that when the values of c_2 are plotted against tha value of SR_{20} with both the values of c_2 and SR_{20} being defined for an identical value of DA, the scatterings in the relationshios between c_2 and SR_{20} among different values of DA are small. This fact may suggest that the values of c_2 for digferent kinds of sand have to be summarized in such a form as in Fig.15 to obtain unique relationships which are valid for many different kinds of sand. In fact, it may be seen from Fig.15 that while there are several different factors between in the tests by Ishihara and Yasuda (1975)[2] and in the tests performed in this investigation, the values of c_2 for a SR_{20} of 0.2 are quite similar between these two kinds of data for these two kinds of random loading patterns employed.

Next, it may be seen from Fig.15 that the relationship between c_2 and SR_{20} depends considerably on the kind of random loading pattern. For Main shock pattern, the value of c_2 increases to its maximum value at a SR_{20} of around 0.28 and then decreases with the increase in SR_{20}. For After shock pattern, on the other hand, the value of c_2 decreases gradually with the increases in SR_{20} ranging from around 0.2 to around 0.75. It is likely that the facts shown in Fig.15 suggest that the values of c_2 by Ishihara and Yasuda (1975)[2] may or may not be conservative depending on the wave form of a given random loading pattern and the liquefaction strength for uniform loading of a given soil. It may also be seen from Fig.15 that for SR_{20} less than around 0.15 the difference in c_2 between these two kinds of random loading patterns is diminishing with the decrease in SR_{20}. This may imply that such loose sands as that their values of SR_{20} are less than around 0.15, the wave forms of loading patterns has almost no significance.

Considering that the value of c_2 ahown in Fig.15 has a wide variation it seems that the method in which the liquefaction characteristics against random loading patterns is predicted by using the correction factor c_2 and the value of SR_{20} has a limitation in respect of the accuracy of prediction. A method should be found in which the liquefaction characteristics against a given random loading pattern be predicted precisely based on both the time history of a given rsndom loading pattern or an appropriate parameter or parameters representing its randomness and data by uniform loading tests.

EQUIVALENT NUMBER OF CYCLES N_{eq}

In the simplified method proposed by Seed and Idriss (1971)[5], a given irregular stress pattern is converted into an equivalent uniform cyclic stress series the amplitude of which is 65% of the maximum single amplitude of this irregular stress pattern and its number of cycles (the equivalent number of cycles N_{eq}) is given as a function of the specified magnitude of earthquake M (see Fig.1). The values of N_{eq} can be obtained from Fig.9 of Seed (1976)[6], which are

M	6	6.5	7	7.5	8
N_{eq}	4	6	10	15	21

The values of N_{eq} were also experimentally determined from the test results by this investigation as follows. First, for a given density and for a given value of DA the value of 65% of the value of SR^*_{max} was obtained for each of the two random loading patterns used from the results shown in Figs. 8, 9 and 10. Then, the corresponding equivalent number of cycles N_{eq} was obtained by reading the number of cycles N_c which corresponded to the value of 0.65 SR^*_{max} from such relationships between SR and N_c obtained by uniform loading tests as shown in Fig.13. The values of N_{eq} thus obtained for the two random loading patterns were plotted against the relative density D_r in Fig.16 and against the stress ratio to cause DA=3%, 7.5% or 15% at N_c=20 by uniform loading SR_{20} in Fig.17. It may be seen from these figures that the value of N_{eq} is not a constant value for each of the two random loading patterns but is functions of shear strain value used for defining strength and density or strength by uniform loading. Furthermore, it may also be seen that the values of N_{eq} obtained by this investigation are not necessarily similar to those values suggested by Seed (1976)[6].

It seems important to know the effect of inaccuracy in estimating the value of N_{eq} on evaluation of liquefaction potential when the simplified procedure suggested by Seed and Idriss (1971)[5] is employed. For this purpose, the factor of safety against liquefaction F_{LS} when the values of N_{eq} suggested by Seed (1976)[6] be used were calculated for the case where the true factor of safety against liquefaction was unity as

$$F_{LS} = (SR)_{N_{eq}}/(0.65 \times SR^*_{max}) \qquad (1)$$

in which N_{eq} are 20 for Main shock loading pattern (M=7.9) and 15 for After shock loading pattern (M=7.5) based on Seed (1976)[6], $(SR)_{N_{eq}}$ is the value of stress ratio which causes a specified value of DA at the number of cycles

N_{eq}, 15 or 20 in this case, in a uniform loading test on a specimen having a given density and SR^{*}_{max} is the maximum single amplitude of stress ratio in a given random loading pattern which causes the same specified value of DA_{max} as above in the same specimen. Therefore, if the values of N_{eq} were appropriate, the value of F_{LS} should be equal to unity. However, it was not true as shown in Figs. 18 and 19. It may be seen from Figs. 18 and 19 that the values of F_{LS} thus obtained are not equal to unity but vary with the variation in D_r or SR_{20}. It is to be noted that the relationship between F_{LS} and SR_{20} is rather independent of the value of DA for the range between 3% and 15%. This may imply that when the value of N_{eq} is defined as a function of SR_{20}, then the value of N_{eq} is at least independent of the value of DA for which liquefaction is defined. However, it should be emphasized again that the value of N_{eq} has to be defined as a function of density or liquefaction strength by uniform loading at least.

CONCLUSIONS

On the basis of the limited number of tests reported in this paper, the followings were found:

(1) The correction factor c_2 depends strongly on the density of sand especially for more shock type random loading patterns.

(2) There are unique relationships between c_2 and SR_{20} irrespectively of the value of DA for which the values of c_2 and SR_{20} are defined.

(3) The ratio of the value of c_2 for Main shock loading pattern to that for After shock loading pattern increases with the increase in SR_{20}. For a very low value of SR_{20} of around 0.15, this ratio is almost unity. This ratio increases with the increase in SR_{20} of up to around 0.28 and then becomes almost constant with being around 1.4 to 1.6 for SR_{20} larger than around 0.28.

(4) The equivalent number of cycles N_{eq} for uniform cyclic stress series having an amplitude of 0.65 of the maximum amplitude of a given random loading pattern is not independent of the density of sand or the liquefaction strength by uniform loading tests. The simplified method by Seed and Idriss (1971)[5] combined with the suggested values of N_{eq} by Seed (1976)[6] may give underestimation or overestimation of liquefaction potential depending on the case, because the values of N_{eq} are given only as a function of the magnitude of earthquake in the simplified method.

SUGGESTIONS FOR FUTURE WORK

The trend of variation in the value of c_2 or N_{eq} shown in Fig.15 or in Fig.19 has to be explained theoretically. When a theoretical method is found by which the value of c_2 shown in Fig.15 or the value of N_{eq} shown in Fig.19 can be predicted based on both a given loading pattern and given results by uniform loading tests, this method may be used to predict the liquefaction strength against a given random loading pattern in place of the methods shown in Fig.1. However, it will be very often in the simplified design procedure that the design random loading pattern is not given, but only the design maximum acceleration at the ground surface is given. For such cases, the simplified methods illustrated in Fig.1 will have to be employed as an expedient method. For such a design method, it will be needed to know the values of c_2 or N_{eq} as functions of not only liquefaction strength but also the magnitude of earthquake, epicentral distance, other earthquake parameters and the ground condition. The theoretical method cited above may be used to obtain such functions by combining with such data by uniform loading tests as shown in Fig.13 with many earthquake motion records accumulated so far as suggested Tatsuoka (1980)[9].

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Table 1 Random Loading Patterns Used as Input Cyclic Stresses

Earthquake : 1968 Tokachioki Earthquake

	Recording Site	Component	Epicentral distance Δ	Maximum Acceleration α_{max}
Main Shock (M=7.9)	Hachinohe	N-S	Δ=189 km	αmax=235 gals
After Shock (M=7.5)	Aomori	E-W	Δ=193 km	αmax=86 gals

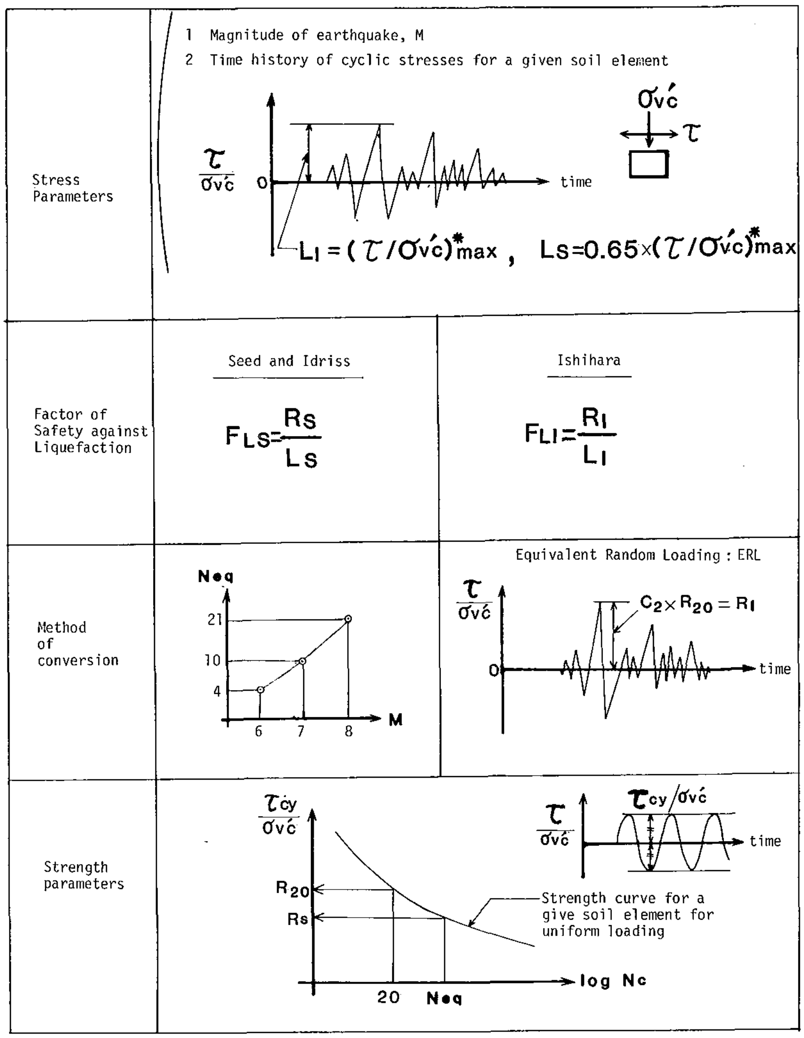

Fig.1 Schematic Diagram Showing Two Different Procedures for Simplified Evaluation of Liquefaction Potential.

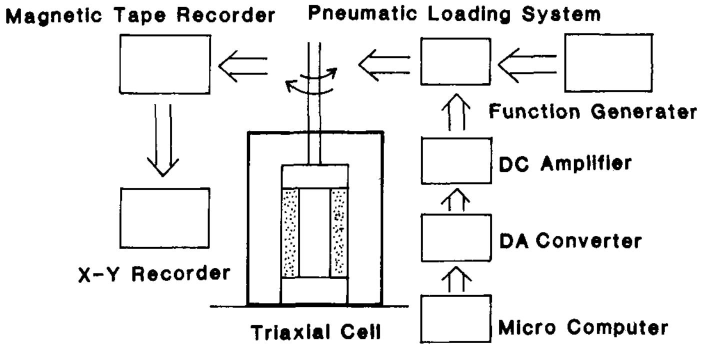

Fig.2 Loading and Measuring Systems Used for Random Loading Tests.

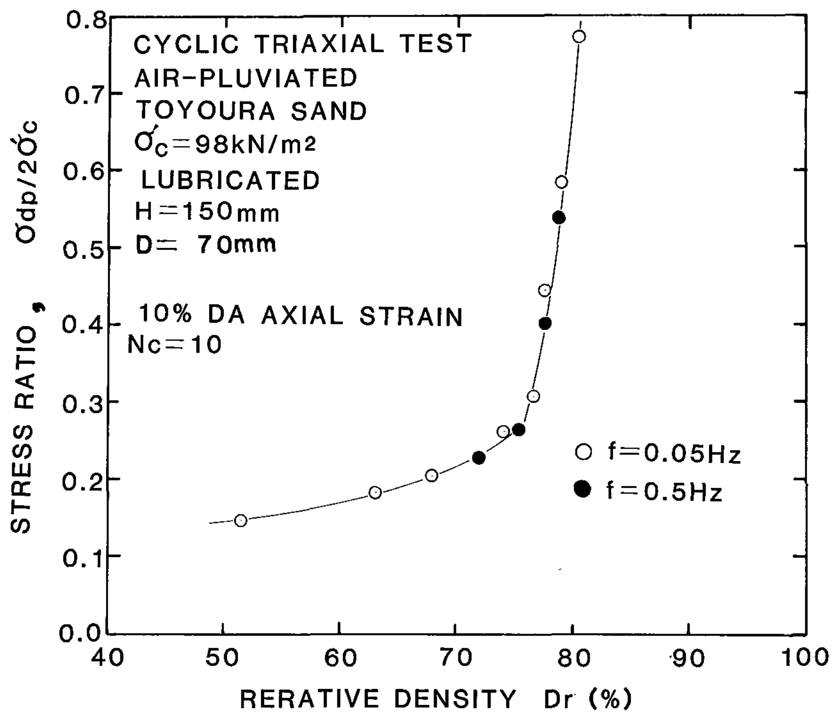

Fig.3 Results of Uniform Cyclic Undrained Triaxial Test for Different Input Frequencies.

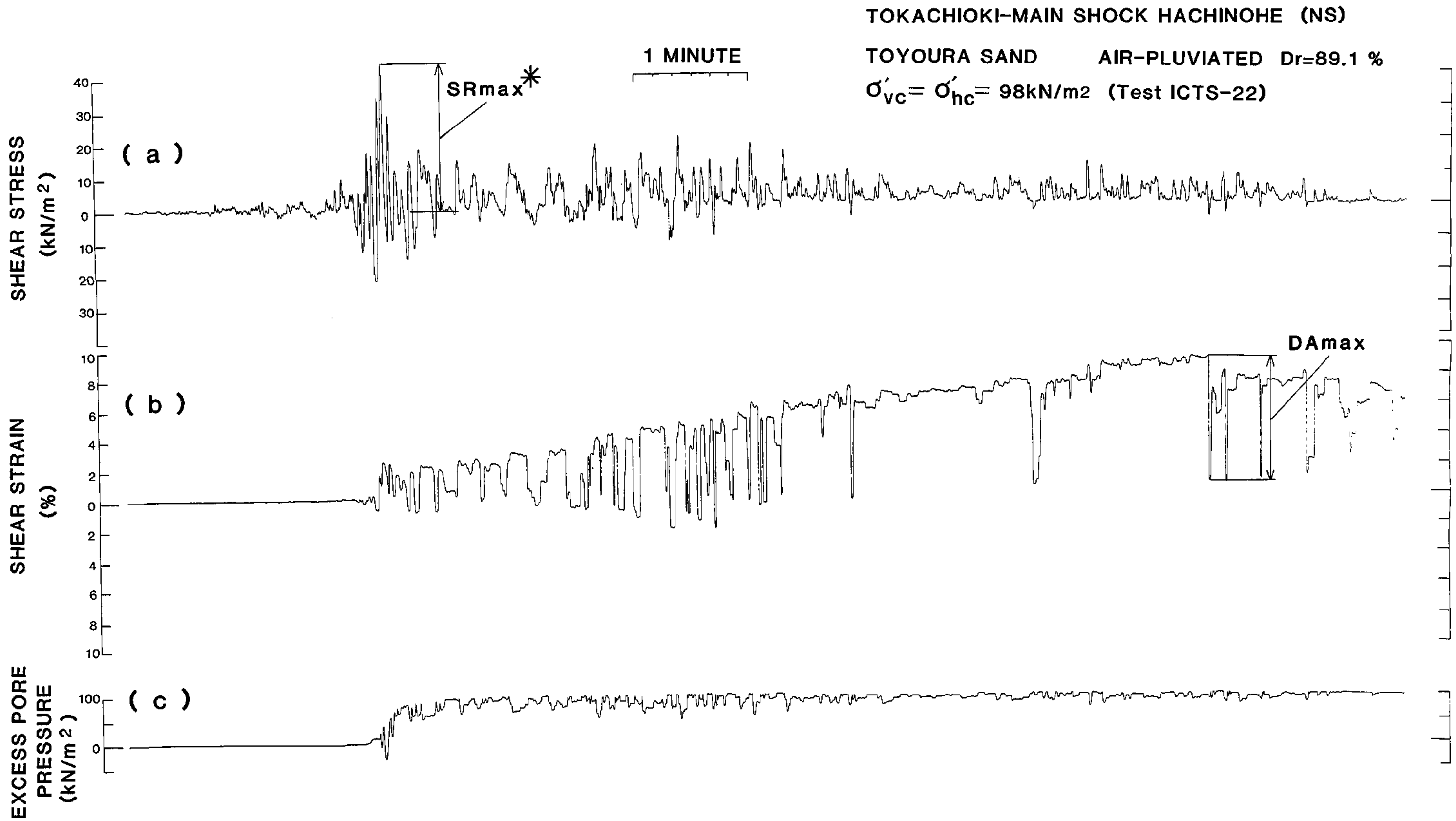

Fig.4 Typical Recorded Time Histories of (a) Shear Stress, (b) Shear Strain and (c) Excess Pore Pressure, (d) Effective Stress Path and (e) Shear Stress - Shear Strain Relations for Main Shock Loading Pattern (to be continued).

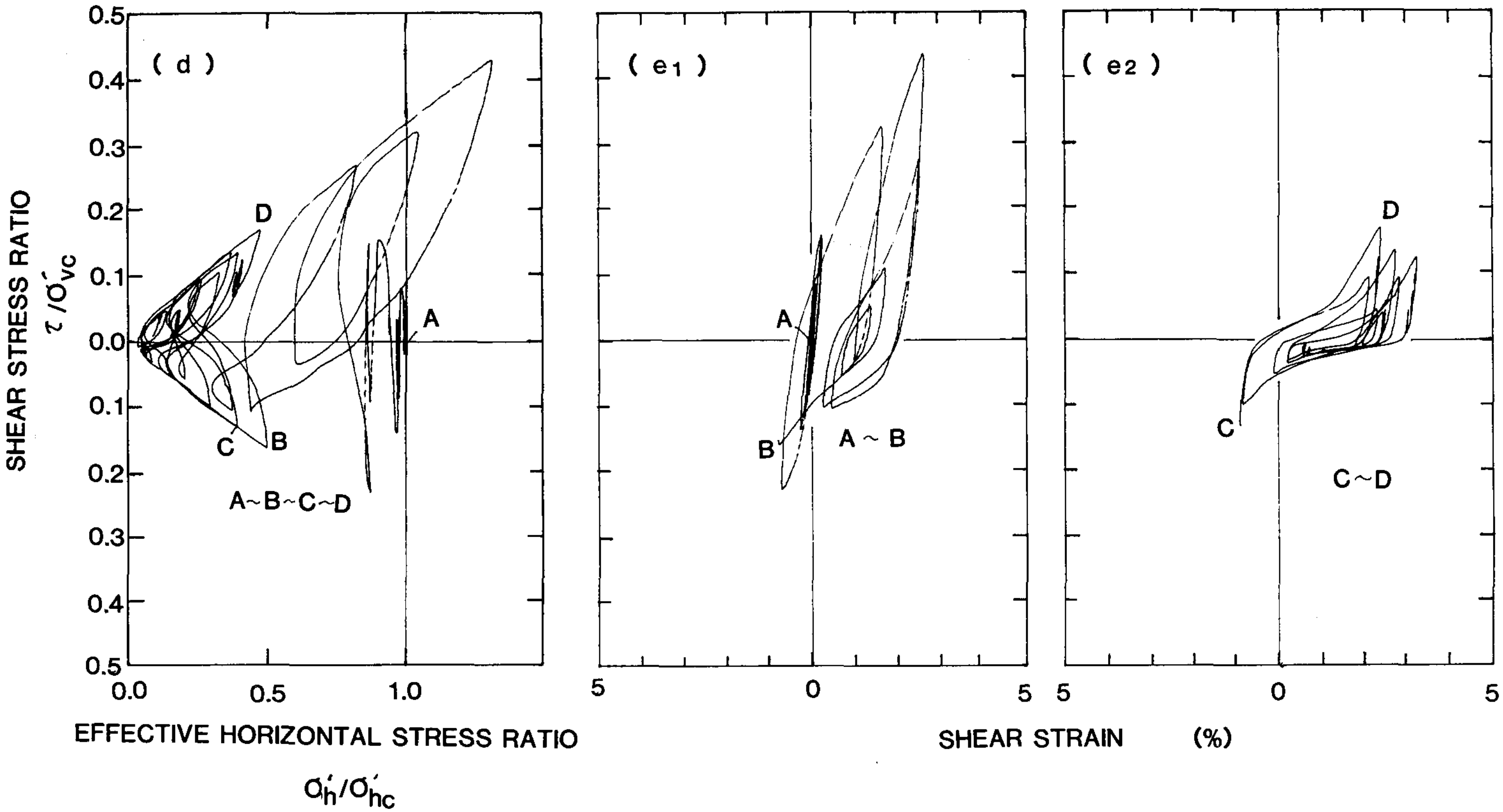

Fig.4(continued) Typical Recorded Time Histories of (a) Shear Stress, (b) Shear Strain and (c) Excess Pore Pressure, (d) Effective Stress Path and (e) Shear Stress - Shear Strain Relations for Main Shock Loading Pattern.

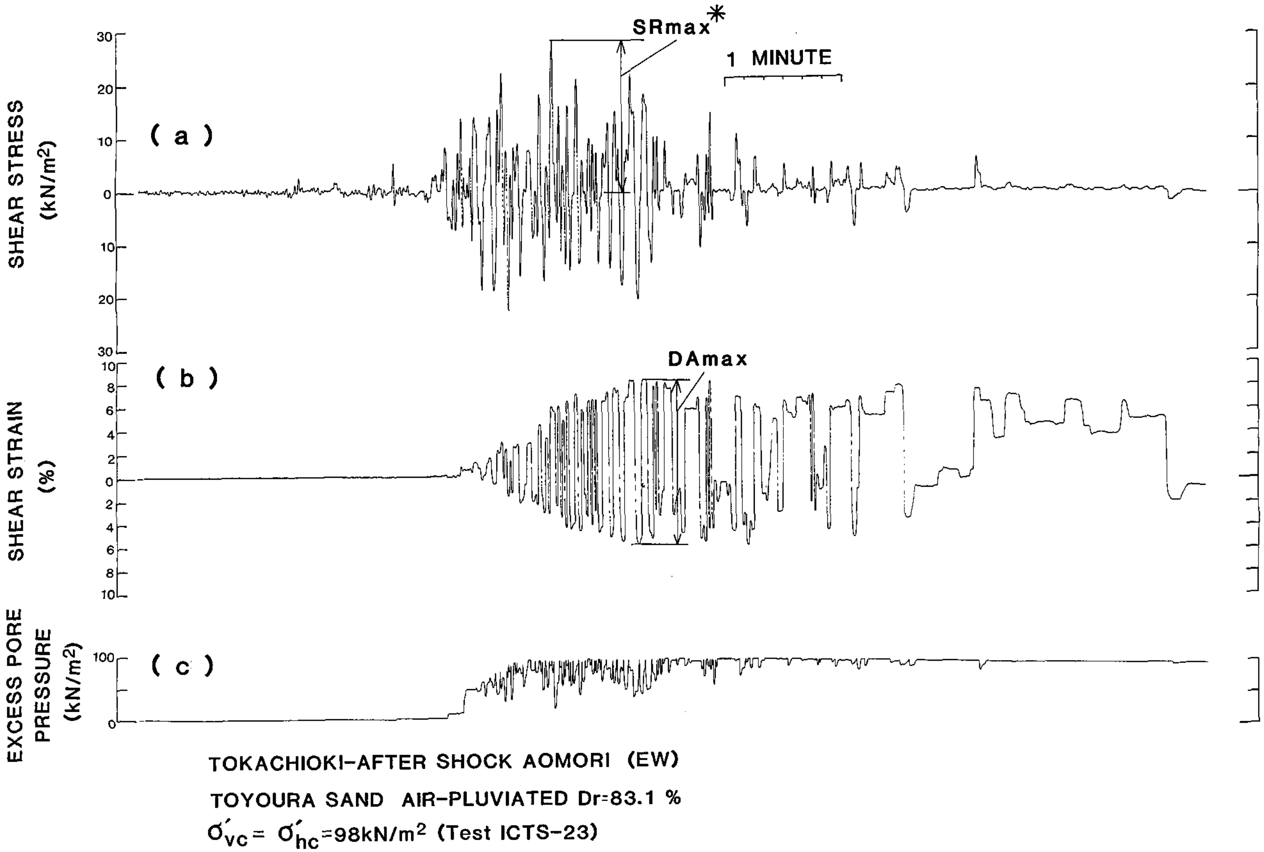

Fig.5 Typical Recorded Time Histories of (a) Shear Stress, (b) Shear Strain and (c) Excess Pore Pressure, (d) Effective Stress Path and (e) Shear Stress - Shear Strain Relations for After Shock Loading Pattern (to be continued).

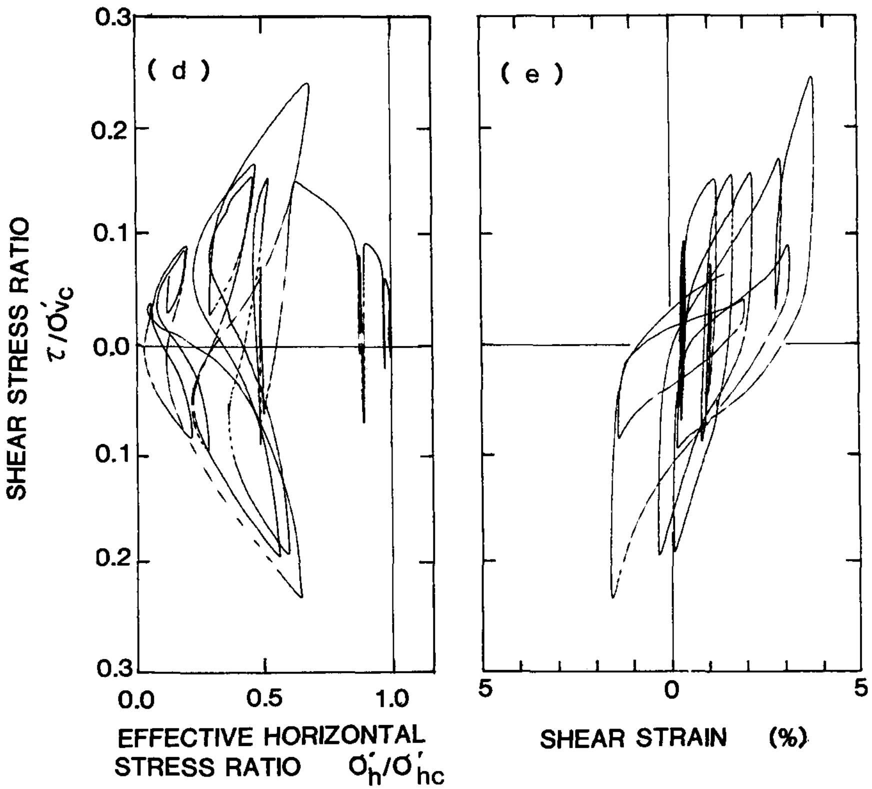

Fig.5(continued) Typical Recorded Time Histories of (a) Shear Stress, (b) Shear Strain and (c) Excess Pore Pressure, (d) Effective Stress Path and (e) Shear Stress - Shear Strain Relations for After Shock Loading Pattern.

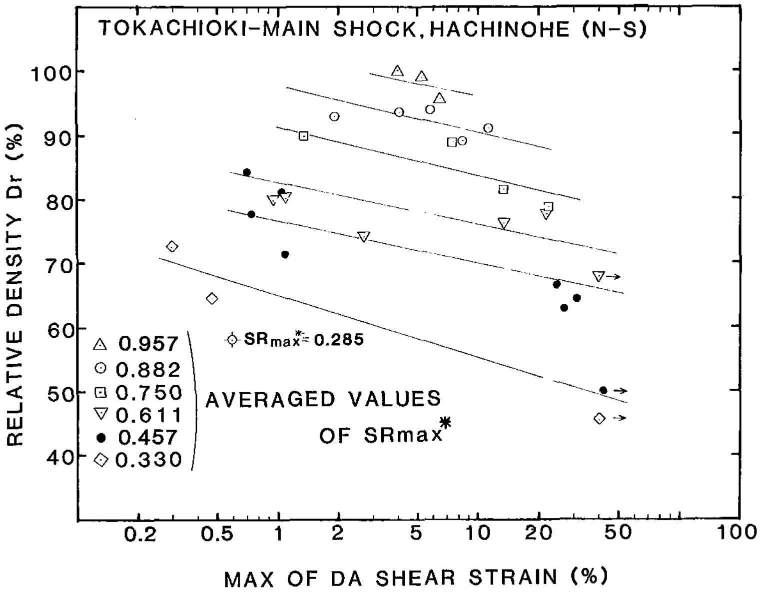

Fig.6 Relationships between Relative Density D_r and Maximum Double Amplitude Shear Strain DA_{max} for Different Maximum Single Amplitude Shear Stress Ratio Values SR^*_{max} for Main Shock Loading Pattern.

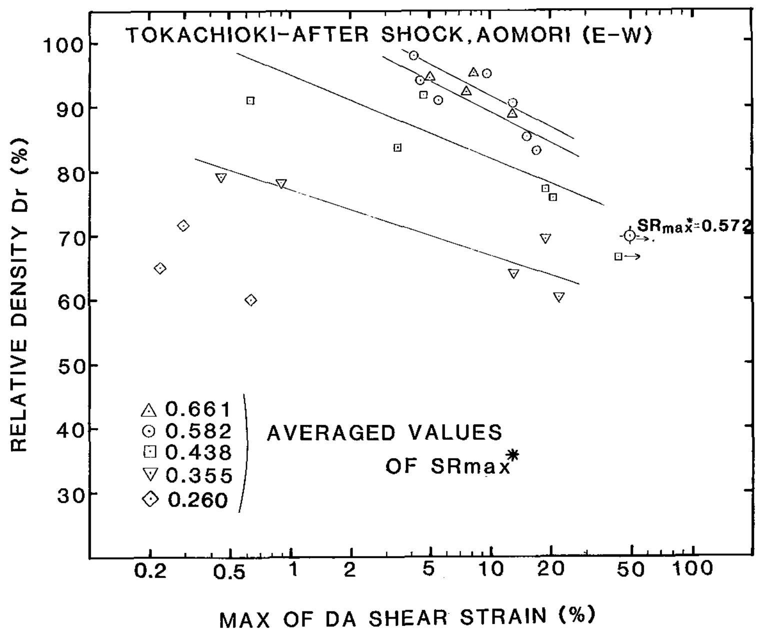

Fig.7 Relationships between Relative Density D_r and Maximum Double Amplitude Shear Strain DA_{max} for Different Maximum Single Amplitude Shear Stress Ratio SR^*_{max} for After Shock Loading Pattern.

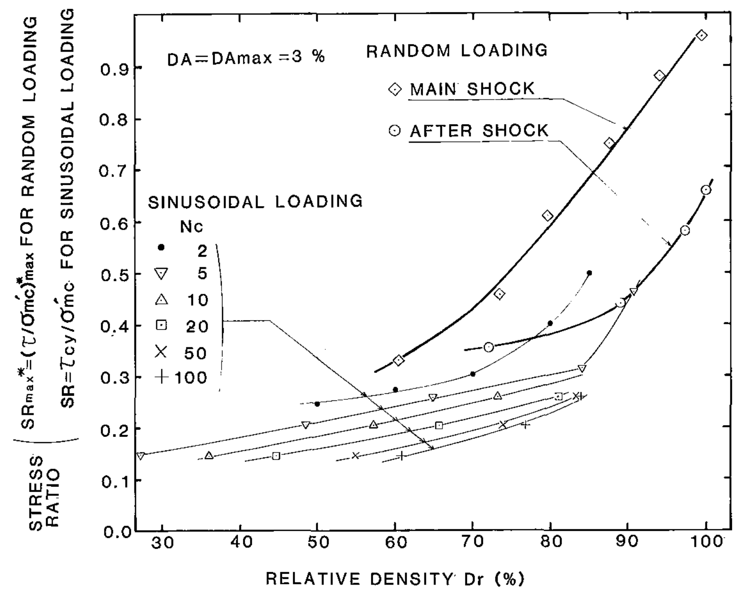

Fig.8 Relationships between Stress Ratios, SR^{*}_{max} or SR, and Relative Density D_r by Random and Uniform Cyclic Loadind Tests for DA or DA_{max} = 3%.

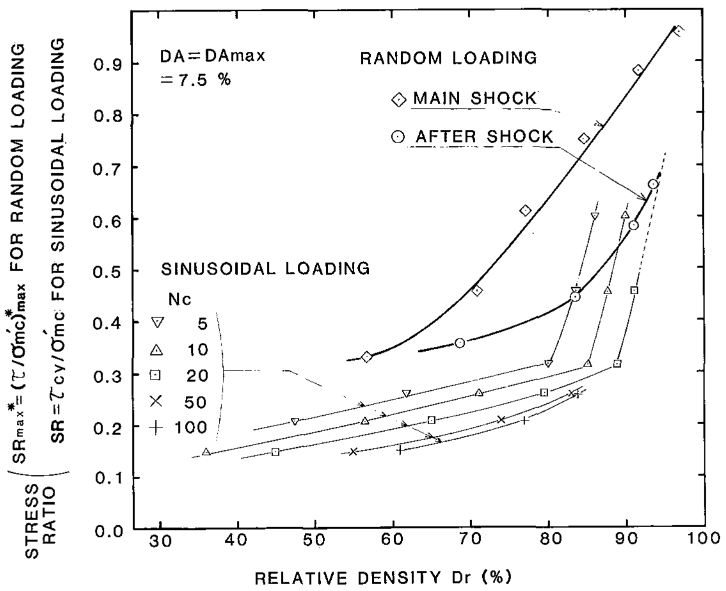

Fig.9 Relationships between Stress Ratios, SR^{*}_{max} or SR, and Relative Density D_r by Random and Uniform Cyclic Loading Tests for DA or DA_{max} = 7.5%.

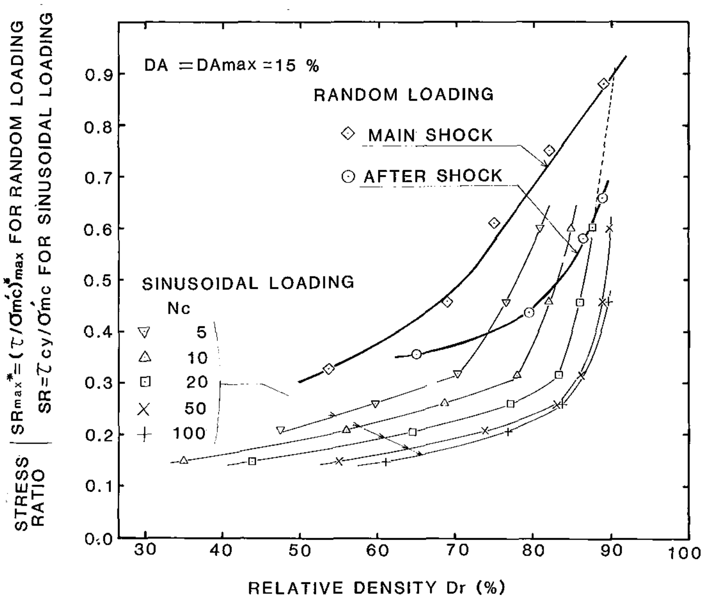

Fig.10 Relationships between Stress Ratios, SR^*_{max} or SR, and Relative Density D_r by Random and Uniform Cyclic Loading Tests for DA or $DA_{max} = 15\%$.

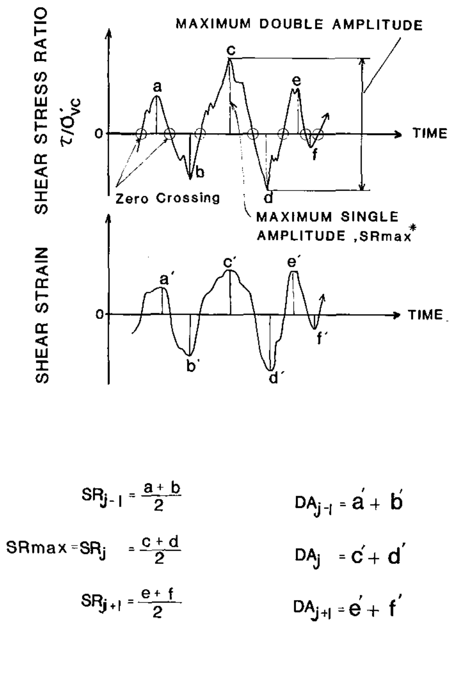

Fig.11 Schematic Diagram Showing Definitions of SR_i and DA_i.

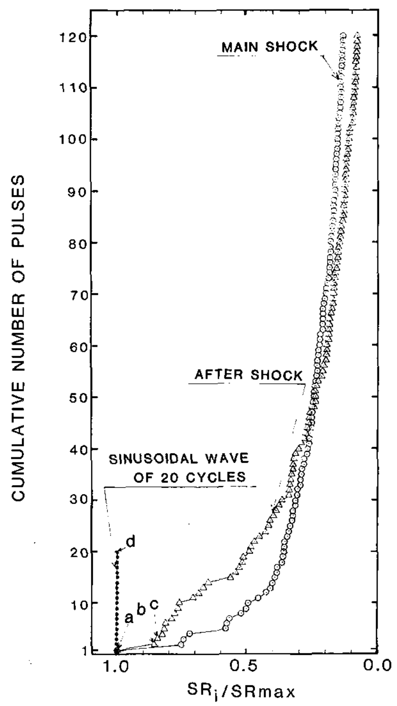

Fig.12 Cumulative Curves of Pulses for Uniform and Random Loading Patterns.

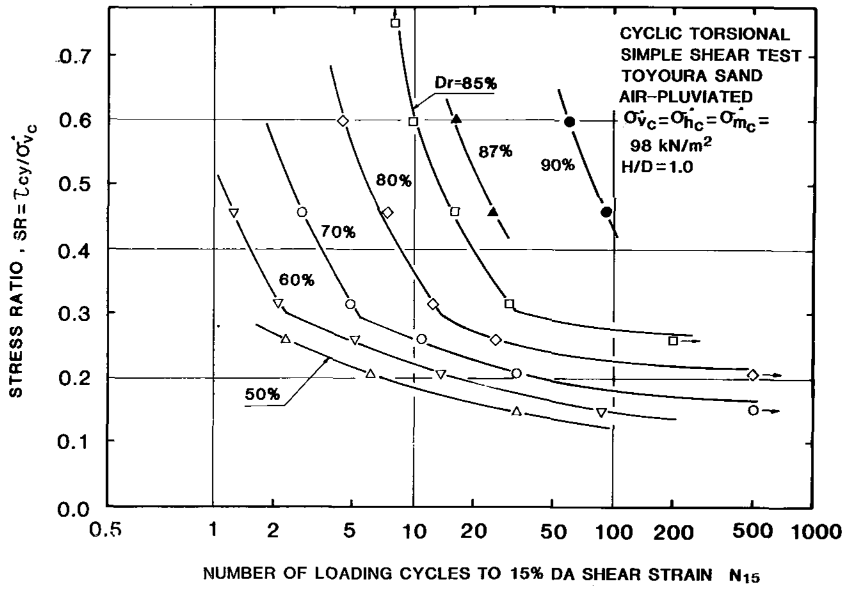

Fig.13 Relationships between Stress Ratio SR and Number of Loading Cycles N_c to 15% Double Amplitude Shear Strain by Uniform Cyclic Tests.

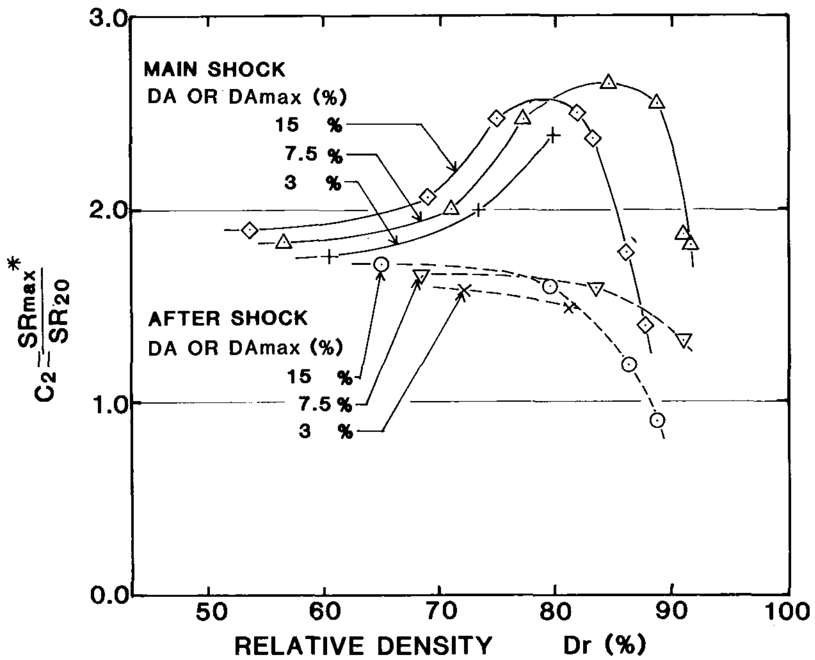

Fig.14 Correction Factor c_2 as a Function of Relative Density D_r for Different Values of DA or DA_{max}.

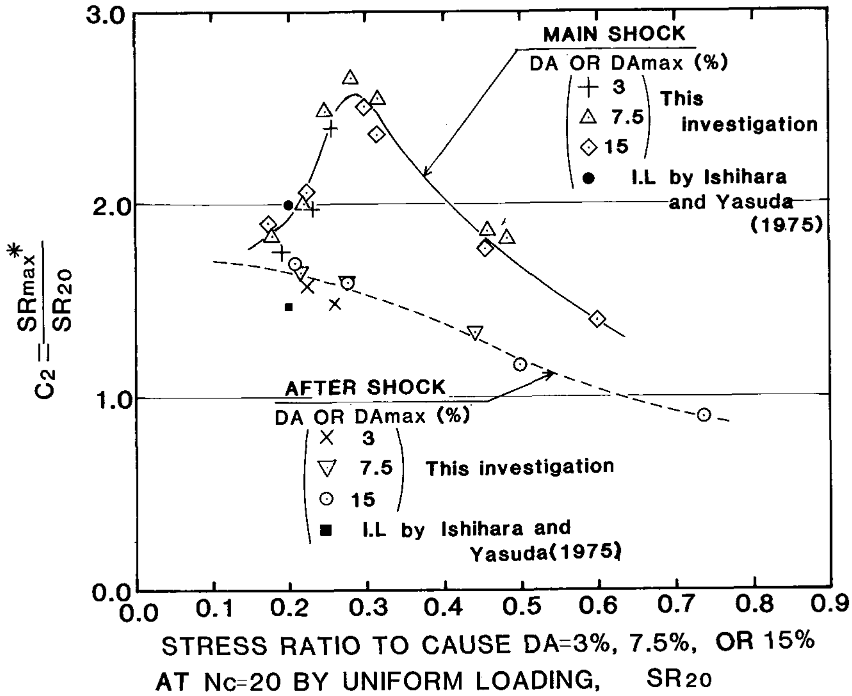

Fig.15 Correction Factor c_2 as a Function of Stress Ratio to Cause DA or DA_{max} = 3%, 7.5% or 15% at N_c=20 by Cyclic Uniform Loading, SR_{20} .

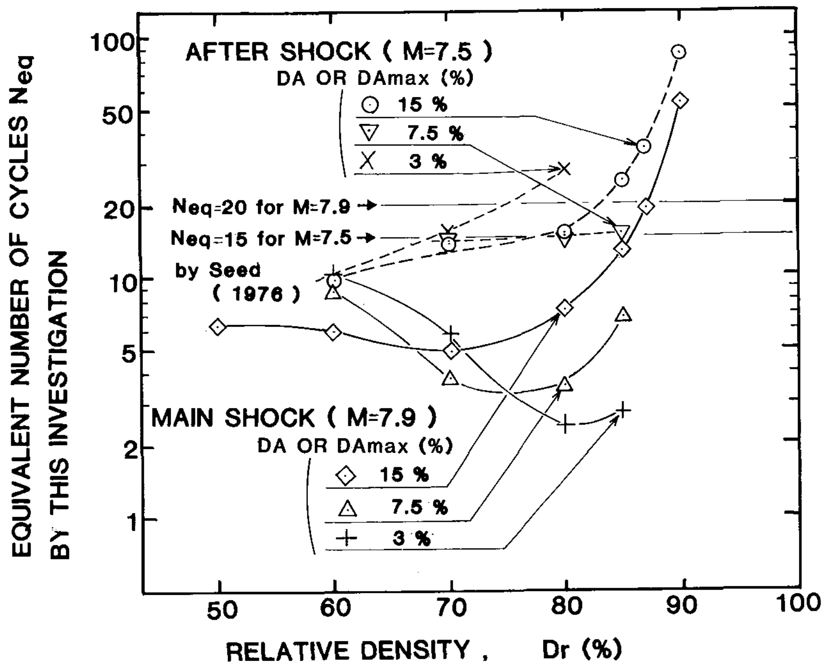

Fig.16 Equivalent Numbers of Cycles N_{eq} at $0.65 \times SR_{max}^*$ as a Function of Relative Density D_r for Different Values of DA or DA_{max}.

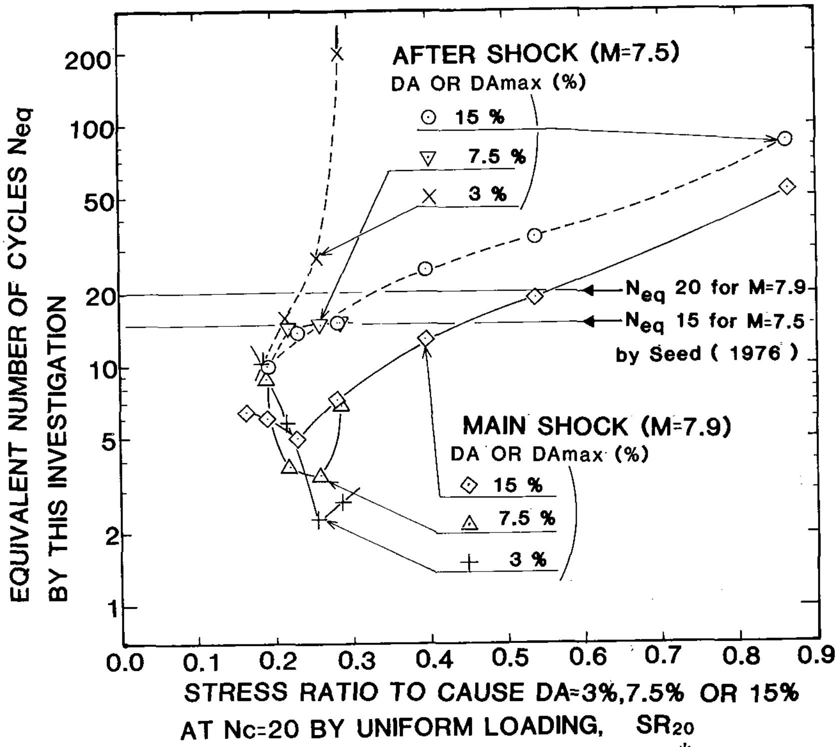

Fig.17 Equivalent Numbers of Cycles N_{eq} at $0.65 \times SR^{*}_{max}$ as a Function of Stress Ratio to Cause DA or DA_{max}=3%,7.5% or 15% at N_c=20 by Cyclic Uniform Loading, SR_{20}

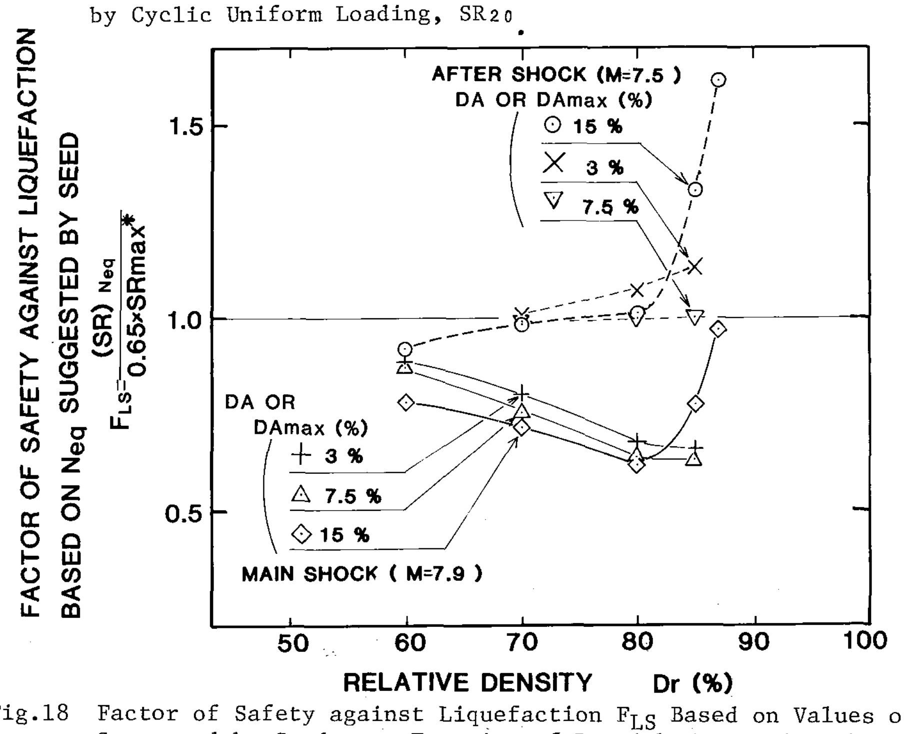

Fig.18 Factor of Safety against Liquefaction F_{LS} Based on Values of N_{eq} Suggested by Seed as a Function of Dr with True Values being Unity.

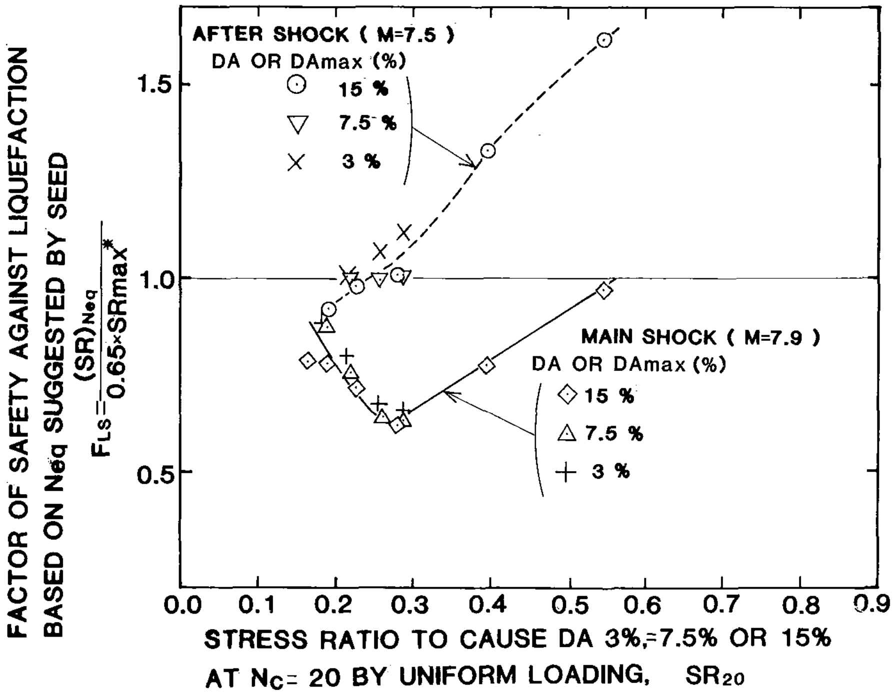

Fig.19 Factor of Safety against Liquefaction F_{LS} Based on Values of N_{eq} Suggested by Seed as a Function of SR_{20} with True Valued being Unity.