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A Study on Magnitude Scaling Factors and Screening Limits of Liquefaction Potential Assessment in Moderate Earthquake Regions

중진지역에 적합한 액상화 평가 생략기준 및 지진규모 보정계수에 관한 연구

Park, Keun-Bo[1] 박 근 보 Park, Young-Geun[2] 박 영 근
Choi, Jae-Soon[3] 최 재 순 Kim, Soo-Il[4] 김 수 일

요 지

기존의 액상화 평가법은 대부분 미국, 일본, 그리고 유럽과 같이 지진 발생빈도가 높고 그로 인한 액상화 피해가 빈번한 국가에서 주도적으로 연구되어왔다. 이런 지역적 특성을 토대로 개발된 액상화 평가방법들은 높은 지진규모(M=7.5)에 바탕을 두고 있다. 국내의 경우, 1997년 실제적인 내진 연구가 시작된 이래 액상화 평가의 구체적 규정은 항만시설의 내진설계 표준서(1999)에 언급된 바 있으나 이는 문헌연구를 통해 제시된 것으로 실제적이지 못하다. 그러므로, 국내 적합한 설계기준을 작성하기 위해서는 지진피해자료의 부족을 국내 지반을 대상으로 한 동적실내시험을 통하는 것이 바람직하며, 일반적인 정현하중 진동시험 보다 실제 지진하중 재하 시험이 훨씬 효과적일 수 있다. 본 연구에서는 실제 지진파 고유의 특성을 적용한 진동삼축 시험을 통하여 상대밀도와 세립분함유량의 변화에 따른 액상화 저항강도를 산정하였다. 실험결과를 국내의 대표적인 항만지역의 지진응답 해석 결과와 비교 분석하고 중진지역에 적합한 액상화 평가의 생략기준을 제시하였다. 또한 실제 지진하중 삼축 실험 결과를 이용하여 국내 여건에 적합한 지진규모 보정계수를 제안하였다.

Abstract

Conventional methods for the assessment of liquefaction potential were primarily for areas of severe earthquake zones (M=7.5) such as North America and Japan. Detailed earthquake related researches in Korea started in 1997, including development of the seismic design standards for port and harbour structures, which was later completed in 1999. Because most contents in the guidelines were quoted through literature reviews from North America and Japan, which are located in strong earthquake region, those are not proper in Korea, a moderate earthquake region. This requires further improvement of the present guidelines. Considering earthquake hazard data in Korea, use of laboratory tests based on irregular earthquake motion appears to be effective to reflect the dynamic characteristics of soil more realistically than those using simplified regular loading. In this study, cyclic triaxial tests using irregular earthquake motions are performed with different earthquake magnitudes, relative densities, and fines contents. Assessment of liquefaction potential in moderate earthquake regions is discussed based on various laboratory test results. Effects of these components on dynamic behavior of soils are discussed as well. From the test results, screening limits and magnitude scaling factors to determine the soil liquefaction resistance strength in seismic design were re-investigated and proposed using normalized maximum stress ratios under real irregular earthquake motions.

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1 Member, Graduate Student, Dept. of Civil Engrg., Yonsei Univ. (uscake@yonsei.ac.kr)
2 Member, Lieutenant Commander, Republic of Korea Navy
3 Member, Post Doc., Dept. of Civil Engrg., Yonsei Univ.
4 Member, Prof., Dept. of Civil Engrg., Yonsei Univ.

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1. Introduction

During the past 40 years the liquefaction of saturated sand under sinusoidal loadings has been studied and a sound understanding of its mechanisms and the parameters that control it have been developed. However, the understanding of the liquefaction potential of saturated sand under irregular earthquake loading is less complete. In most laboratory cyclic triaxial tests, sinusoidal types of cyclic loadings equivalent to field irregular earthquake motions are employed as an approximated and simplified approach. The application of the sinusoidal loading is based on the concept of the equivalent uniform stress suggested by Seed et al. (1975). One of the significant advantages for cyclic tests using the sinusoidal loading is that a single test can represent various earthquake loading patterns. In addition, the test requires simpler loading devices. For this reason, test results using sinusoidal loadings have been quite popular among many earthquake engineers for assessing of liquefaction potential. However, as the equivalent uniform stress concept is an approximate approach, the liquefaction resistance under irregular earthquake motions in field may differ from that obtained from laboratory tests using the sinusoidal cyclic loading.

Current Magnitude scaling factors (MSFs) and screening limits for assessing of liquefaction potential are largely based on knowledge gained from laboratory research on clean sands, field observations of liquefied ground, and correlations of normalized penetration resistance data with field liquefaction observations. Because MSFs and screening limits currently available are primarily for earthquakes with large magnitudes and clean sands, uncertainties still exist for moderate earthquake areas and silty sand deposits. In this study, laboratory cyclic tests using both regular sinusoidal and irregular earthquake loadings were performed and compared. Effects of fines content and relative density were also analyzed based on cyclic triaxial test results under real irregular earthquake motions. In particular, a series of cyclic tests under various soil conditions were carried out expecting to be used for future modification of the Korean seismic design standards in two aspects: criteria for screening limits and MSFs of liquefaction analysis. The final goal of this paper is to propose MSFs and to evaluate criteria for the earthquake screening limits under which detailed liquefaction analysis could be omitted in a design process.

2. Screening Limits and MSFs of Liquefaction Analysis in Korea

Saturated loose sandy deposits are susceptible to liquefaction during an earthquake. Past significant earthquakes indicate that liquefaction should be one of most critical factors for seismic design and construction of structures. Therefore, the assessment of liquefaction potential should be performed prior to the main structure design. The procedure for the assessment of liquefaction potential in Korea is shown in Fig. 1. For the assessment of liquefaction potential, the performance level of prevention of collapse is considered first. However, this procedure can be omitted in the design process through the screening procedure. The conditions for the screening are as follows (EESK, 1999):

- soils above the ground water table
- soils with N > 20
- soils at depths greater than 20 m
- soils that have a clay content greater than 20% with plasticity index > 10
- soils that have a fines content greater than 35%
- soils that have a relative density greater than 80%

The screening limits of liquefaction analysis are proposed for nations located in severe earthquake zone (M=7.5). Existing methods for assessment of liquefaction potential using field tests such as SPT or CPT are based

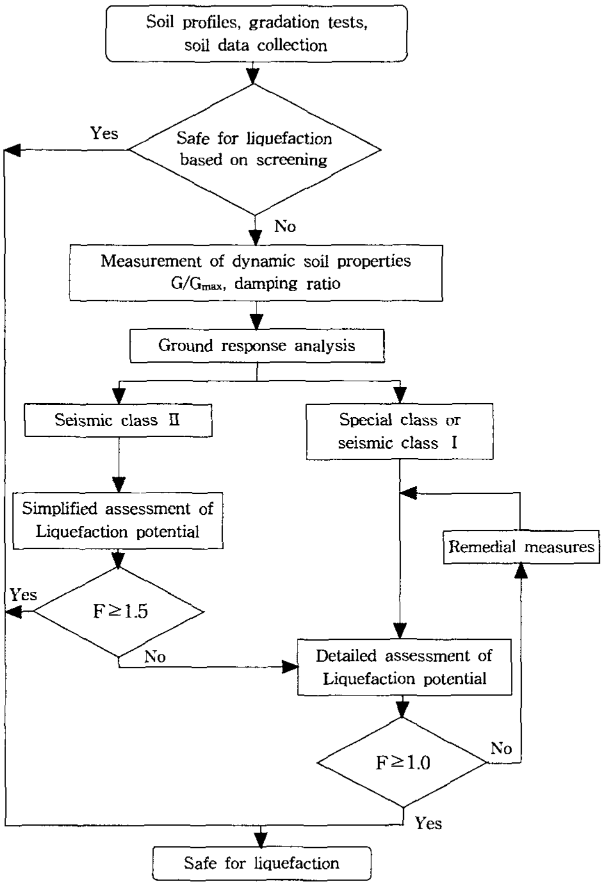


Fig. 1. Flow chart of assessment of liquefaction potential

on earthquakes of 7.5 magnitude. Therefore, these screening limits for assessing of liquefaction potential need to be modified and investigated for the compatible level of earthquake in Korea.

In Korea, the modified Seed & Idriss method (Kim 1998) has been suggested as an appropriate liquefaction evaluation method for the seismic design. Fig. 2 shows a flow chart of the simplified assessment of liquefaction potential based on modified Seed & Idriss method. As shown in Fig. 2, the grain size distribution and SPT N values are used in the simplified assessment method. For more accurate assessment, a cyclic stress ratio (CSR) is estimated and used based on results of ground response analysis. In addition, a MSF is adopted to consider the Korean standard earthquake magnitude of 6.5 in calculation of the cyclic resistance ratio (CRR). The use of magnitude of 6.5 is based on past earthquake history of Korea, which has shown only 4 cases of earthquake magnitudes stronger than 5.0 on the Richter scale.

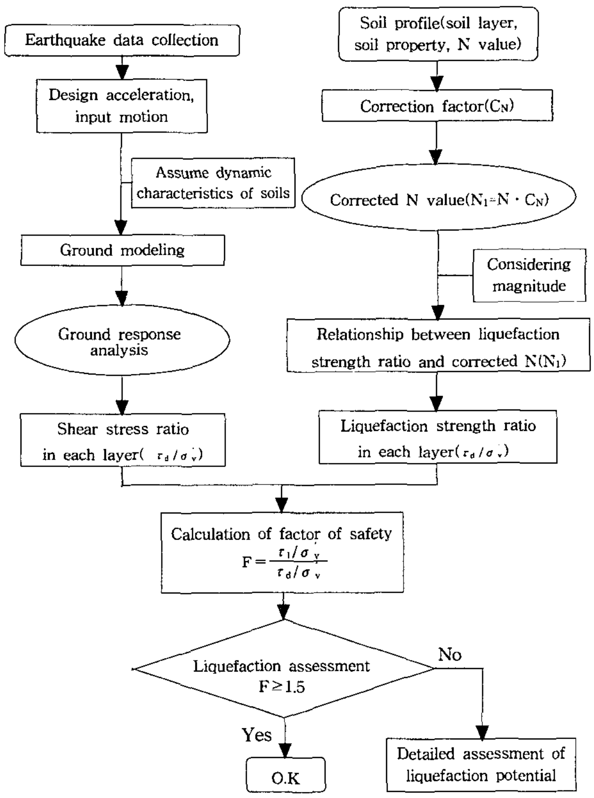


Fig. 2. Flow chart of simplified assessment of liquefaction potential

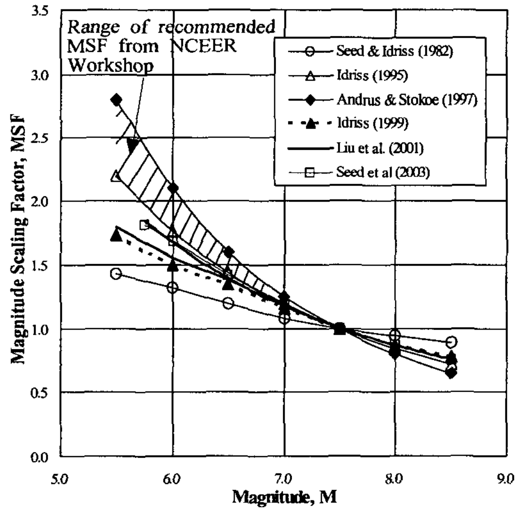


Fig. 3. Magnitude scaling factors

Since 1982, the MSFs based on laboratory testing, analysis of case history, and statistical analysis of observed liquefaction have been studied. Fig. 3 shows MSFs proposed by several engineers. In Korea, MSF is used as that of Seed and Idriss (1982). Recently, to adjust the liquefaction resistance strength to earthquake magnitudes smaller or larger than 7.5, a range of scaling factors were proposed in NCEER/NSF workshop (1997). In addition Seed et al. (2003) presented suggestions regarding further improvement needed.

3. Experimental Procedures

Soils used in cyclic triaxial tests were the Jumunjin sand, a representative silica sand in Korea, with four different fines contents equal to 0, 10, 20, and 30%. Tests with clean sand samples (i.e., fines content of 0%) were used for investigation of MSF while criteria for liquefaction screening limits were analyzed using both clean and silty sand samples of fines contents equal to 0, 10, 20, and 30%. The silty sands were prepared by mixing regular Jumunjin sands and silt-sized crushed Jumunjin sands at desired weight ratios. Fig. 4 shows grain size distribution curves of the test soils along with a range of liquefaction possibility proposed by Tsuchida in 1970. It is seen that all the grain size distribution curves of the test soils fall within the range of high liquefaction possibility. Basic property tests were performed for each test soil, and results are shown in Table 1. The maximum and minimum index densities (i.e., minimum and maximum index void ratios) of soils with different fines contents were determined by the procedure specified in ASTM-4253 vibratory table and ASTM-4254 method B, respectively.

Triaxial soil specimens tested in this study are of 70 mm in diameter and 140 mm in height. Water sedimentation method (Dobry 1991) was adopted for sample preparations. For the water sedimentation method, dry sands are poured through a nozzle from just above the water surface and allowed to sediment through a height of 2 to 3 cm under water. In this procedure, sands are deposited continuously under water without appreciable segregation of material. If a denser sample is to be prepared, compaction energy is applied by hitting the side of the mold stepwise during the process of sample placement. In this study, densification of the sample was accomplished by carefully and symmetrically tapping the sides of the sample mold immediately after soil deposition. Because the mass of sand and silt used in sample preparation could be accurately estimated, it was possible to obtain a relative density that was reasonably close to a target value by measuring the height of the sample as it densifies. The test specimen had no particle segregation, regardless of gradation or fines content during the sample preparation and was initially saturated by applying back pressure and all the specimens exhibited the pore water pressure parameter B equal to 0.97 or greater. The triaxial test specimen was then isotropically consolidated to a desired effective confining pressure prior to applying cyclic loading. All the triaxial tests were carried out at isotropically consolidated conditions with an effective confining pressure level equal to 100 kPa.

The cyclic triaxial test distribution diagram used in this

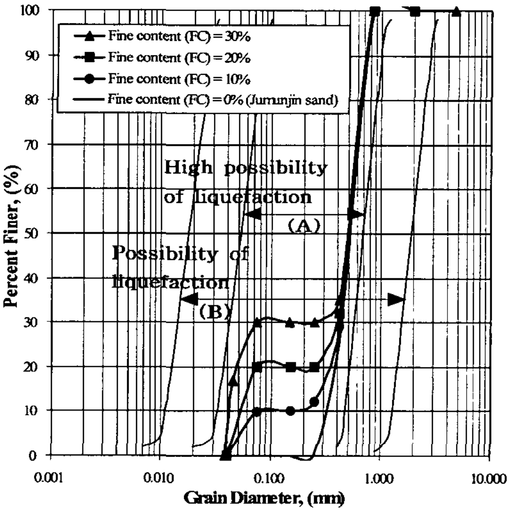


Fig. 4. Grain size distribution

Table 1. Properties of soils tested

Fines content (silt crushed) FC(%)	Max. index density $\gamma_{max}(kg/cm^3)$	Min. index density $\gamma_{min}(kg/cm^3)$	Max. index void ratio e_{max}	Min. index void ratio e_{min}	Mean grain size D_{50}(mm)	Coeff. of uniformity C_u	Coeff. of curvature C_c	Plasticity index
0	1.60	1.39	0.885	0.638	0.52	1.35	1.14	NP
10	1.76	1.46	0.795	0.489	0.51	7.30	3.11	NP
20	1.86	1.51	0.748	0.419	0.50	10.39	6.07	NP
30	2.06	1.56	0.692	0.282	0.50	12.44	0.58	NP

study is shown in Fig. 5. Two different types of triaxial loadings were used: irregular earthquake and regular sinusoidal loadings. For tests with irregular earthquake motions, 11 acceleration records were selected from recent major earthquakes of magnitudes between 6.1 and 8.1. Durations for the tests were significant durations (Abrahmson & Silva 1996), which are 5-95% RMS (Root-Mean-Square) durations. Values of magnitude and significant durations for earthquakes used in this study are shown in Table 2. In the table, Ormond, Big Bear, and Hyogo-Ken Nanbu earthquakes were adopted for analysis of criteria for liquefaction screening limits, while all of earthquake motions were used for the investigation of MSFs. Each irregular earthquake motion was generated using user-defined facilities of the triaxial system software. The maximum possible frequency allowed in the system

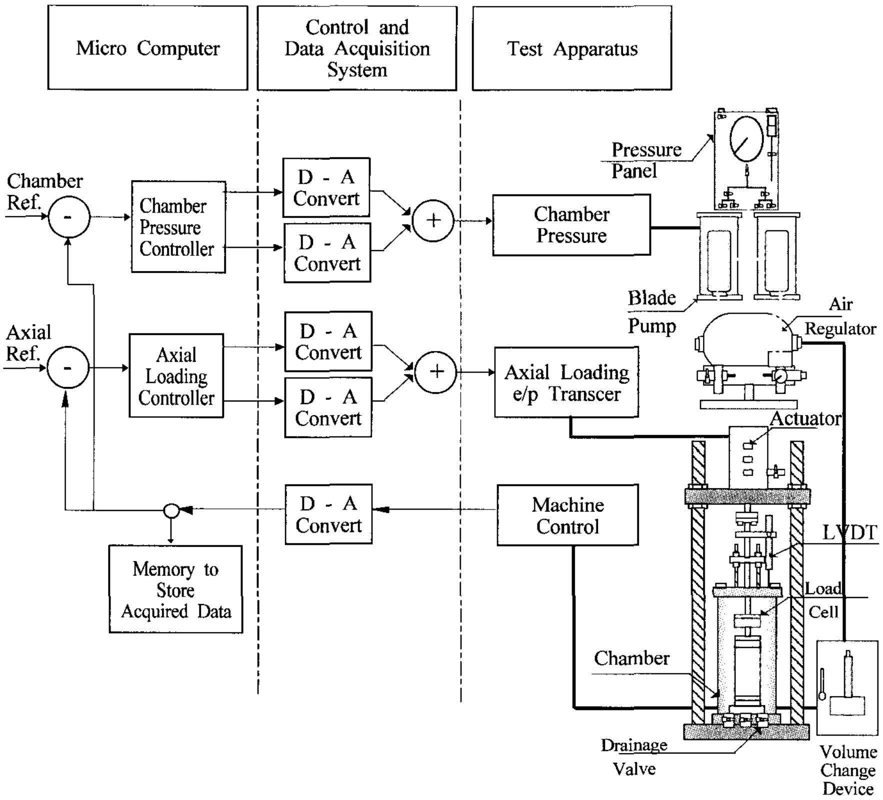


Fig. 5. Cyclic triaxial test distribution diagram used in this study

Table 2. Earthquake motions used in this study

Earthquake	Magnitude	Significant duration (sec)	Year and location
Parkfield	6.1 (M_w)	6.4	1966, California, USA
Ormond*	6.2 (M_w)	21.4	1993, New Zealand
Kamitsuki	6.3 (M_w)	16.3	2000, Kamitsuki, Japan
Baja-California	6.4 (M_w)	19.7	1934, Mexico
Big Bear*	6.5 (M_w)	10.2	1992, California, USA
Alaska	6.6 (M_w)	15.2	2001, Alaska, USA
Hyogo-Ken Nanbu*	6.9 (M_w)	8.1	1995, Kobe, Japan
Loma Prieta	7.0 (M_w)	7.8	1989, California, USA
El Centro	7.2 (M_w)	23.8	1940, California, USA
Ofunato	7.4 (M_w)	3.6	1978, Miyagi-ken-oki, Japan
Hachinohe	8.2 (M_w)	7.7	1968, Tokachi-oki, Japan

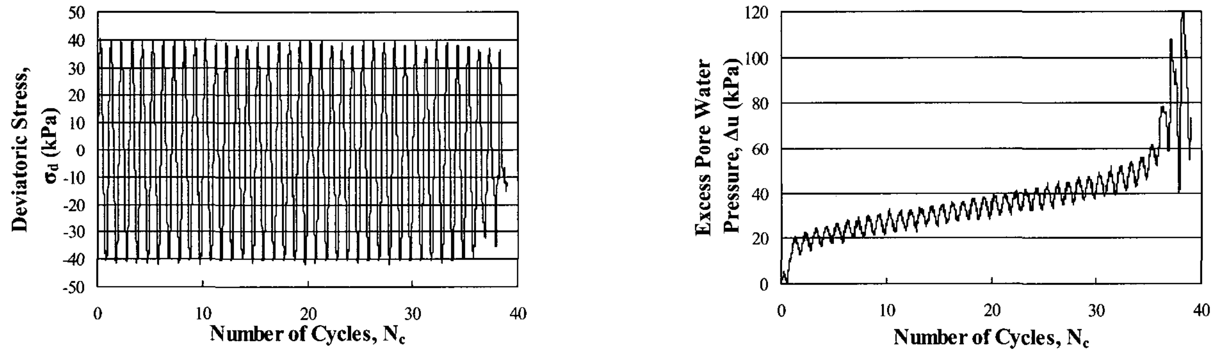
※ M_w : Moment magnitude, * : Earthquake motions used in test for criteria of screening limits is 70 Hz. Measurements in the tests include axial deformations, volume changes, deviatoric stresses, and pore water pressures with time. Triaxial tests under sinusoidal loading were also carried out for the comparison of results between irregular earthquake and regular sinusoidal loadings. For these tests with sinusoidal loadings, Jumunjin sands with no fines were used.

4. Test Results

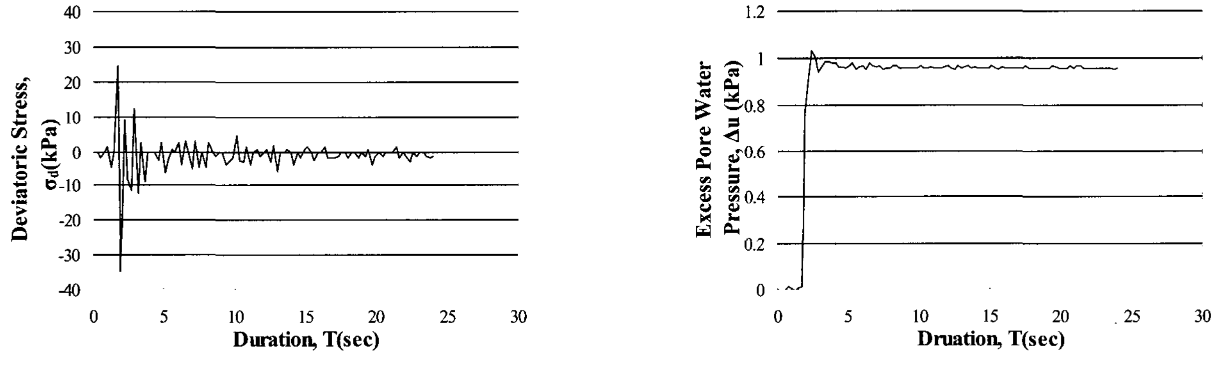
4.1 Comparison of Test Results between Irregular and Sinusoidal Motions

In conventional cyclic triaxial tests, specimens are in general loaded with sinusoidal deviatoric stresses at appropriate cyclic stress ratios until they liquefy. For irregular earthquake motions, however, unlike the sinusoidal loading case, it is necessary to evaluate a magnitude of stress, at which liquefaction is first generated by repeating tests using the same earthquake motion with varying acceleration levels. Fig. 6 shows the effect of loading types on the liquefaction behavior. Cyclic triaxial test result using the regular sinusoidal loading shows that the pore water pressure builds up steadily as the number of cyclic stress increases, and eventually reaches a value equal to the initially applied confining pressure. Such a state has been referred to as an initial liquefaction. In irregular earthquake loading tests, in particular for impact type motions, it is noted that the pore pressure does not increase in earlier stages, but suddenly jumps up when the maximum deviatoric stress is reached, whereupon liquefaction sets in.

In order to evaluate the maximum deviatoric stress at which liquefaction is first generated under irregular earthquake loadings, the following steps are implemented. In the first step, the test is carried out using a certain deviatoric stress level, which is small enough not to cause liquefaction. In the next step, the level of the deviatoric stress is increased slightly with the same wave form as used in the previous step. By repeating this procedure, error of the target relative density is less than 1% and liquefaction eventually occurs showing an induced residual pore pressure equal to the confining



(a) Sinusoidal loading



(b) Irregular earthquake loading

Fig. 6. Deviatoric stress and excess pore water pressure under sinusoidal and irregular earthquake loadings

pressure. The stress at this point is defined as the maximum deviatoric stress for a given earthquake wave form. This procedure is shown in Fig. 7.

An example of test results obtained using the procedure described above with different earthquake motions is shown in Fig. 8. In Fig. 8, test results are expressed in terms of the maximum stress ratio (i.e., liquefaction resistance ratio) = $\sigma_{d(max)}/2\sigma_c'$ where $\sigma_{d(max)}$ = cyclic deviatoric stress and σ_c' = initial effective confining pressure under which samples are consolidated.

For the simplified assessment of liquefaction potential using regular cyclic loadings, it is necessary to determine equivalent number of significant uniform stress cycles for an earthquake that has an irregular time history. The basic procedure associated with determination of equivalent stress cycles is fairly simple as described by Seed et al. (1975). Fig. 9 shows equivalent numbers of uniform stress cycles for earthquakes with magnitudes between 5.3 and 7.7 proposed by Seed et al. (1975). Results for the earthquakes used in this study are also included in Fig. 9. In Fig. 9, it is observed that most test results in this study fall outside the range of one standard deviation from the mean value. It is, meanwhile, noticeable that test results for magnitude of around 6.5 are in the range of tenth loading cycle.

In order to compare liquefaction resistances between irregular earthquake and equivalent sinusoidal cyclic loadings, additional tests were performed. Jumunjin sand samples with no fines were tested under confining pressure of 100 kPa and relative density of 60%. Three

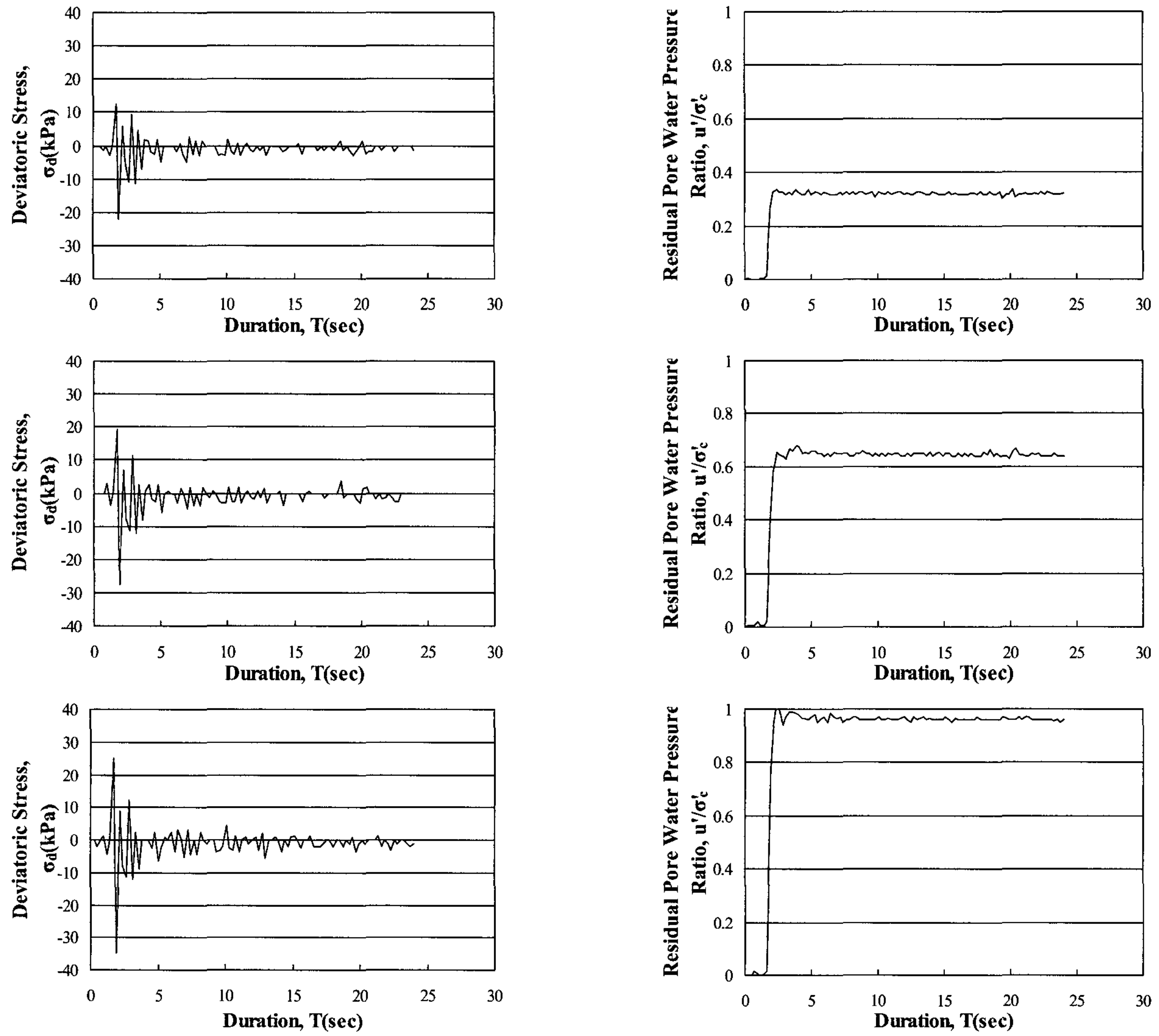


Fig. 7. Test steps for evaluation of the maximum stress ratio at liquefaction under irregular earthquake motion

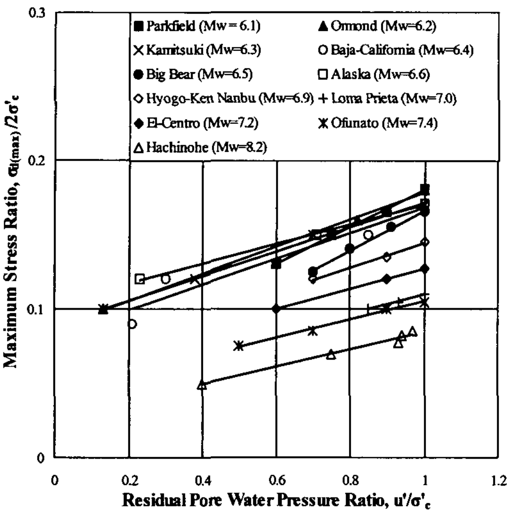


Fig. 8. Relationships between stress ratio and pore water pressure ratio

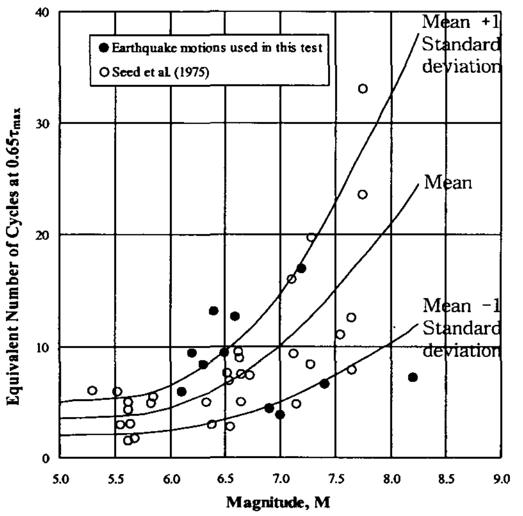


Fig. 9. Equivalent number of uniform stress cycles

liquefaction resistance ratios (i.e., the capacity of the soil to resist liquefaction) equal to 0.19, 0.23, and 0.26 were employed for the tests. Magnitudes and equivalent numbers of cycles in these tests were 6.0 and 5, 6.75 and 10, and 7.5 and 20, respectively. Fig. 10 shows liquefaction resistance ratios between irregular earthquake motions and sinusoidal loadings. In Fig. 10, test results for sinusoidal loading were divided by 1.5, following the equivalent uniform stress concept by Seed et al. (1975). From test results, it is found that liquefaction resistances under sinusoidal loadings coincide with those under irregular earthquake loadings at around magnitude 6.8, while showing different liquefaction resistances at other range of earthquake magnitudes.

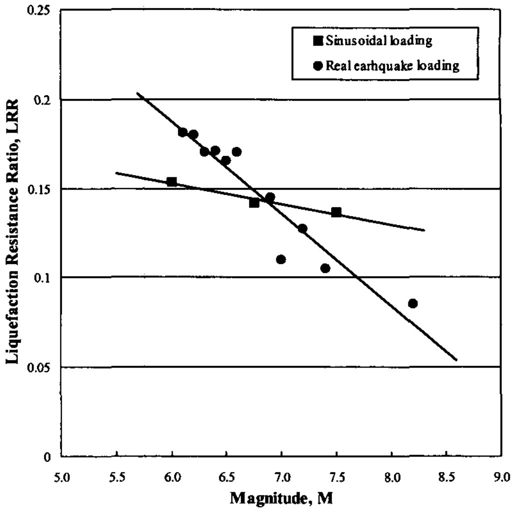


Fig. 10. Comparison of liquefaction resistance ratio between sinusoidal and irregular earthquake loadings

4.2 Magnitude Scaling Factors

Existing methods for evaluation of liquefaction resistance using in-situ tests such as SPT and CPT are mostly based on an earthquake magnitude of around 7.5. In order to adjust liquefaction resistance to magnitudes smaller or larger than 7.5, a range of scaling factors were proposed in the NCEER/NSF workshop in 1997 (Youd & Idriss 1997) and Seed et al. (2003). Those are based on (1) laboratory tests (Seed & Idriss 1982; Idriss 1999); (2) statistical analysis of observed liquefactions (Ambraseys 1988; Andrus & Stokoe 1997); (3) statistical analysis of case history data using a regression equation (Youd & Noble 1997); and (4) evaluation of distant liquefaction sites from earthquakes of various magnitudes and peak accelerations at those sites (Arango 1996) as described in Liu et al. (2001). The NCEER/NSF workshop also recommended factors suggested by Idriss (1995, see Youd et al. 2001) and by Andrus & Stokoe (1997) as to lower and upper limits for MSFs, respectively.

In Korea, seismic design standards adopt an earthquake magnitude of 6.5 for earthquake-related design without detailed specification of MSFs. In this study, MSFs were re-investigated based on laboratory cyclic triaxial test results given in Fig. 8 using method derived by Seed and Idriss (1982). To propose MSFs in this study, the amplitudes of the applied loading, as quantified by maximum stress ratio, were determined as a function of

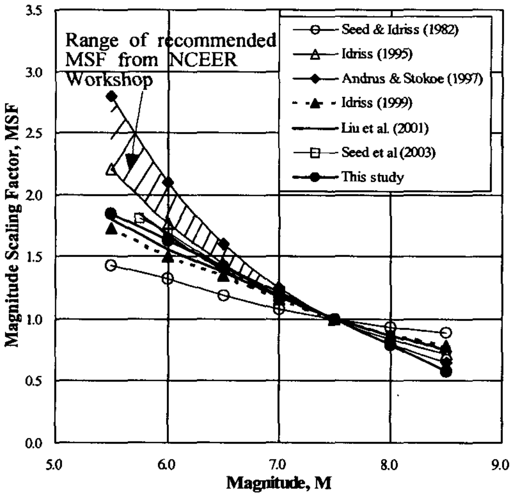
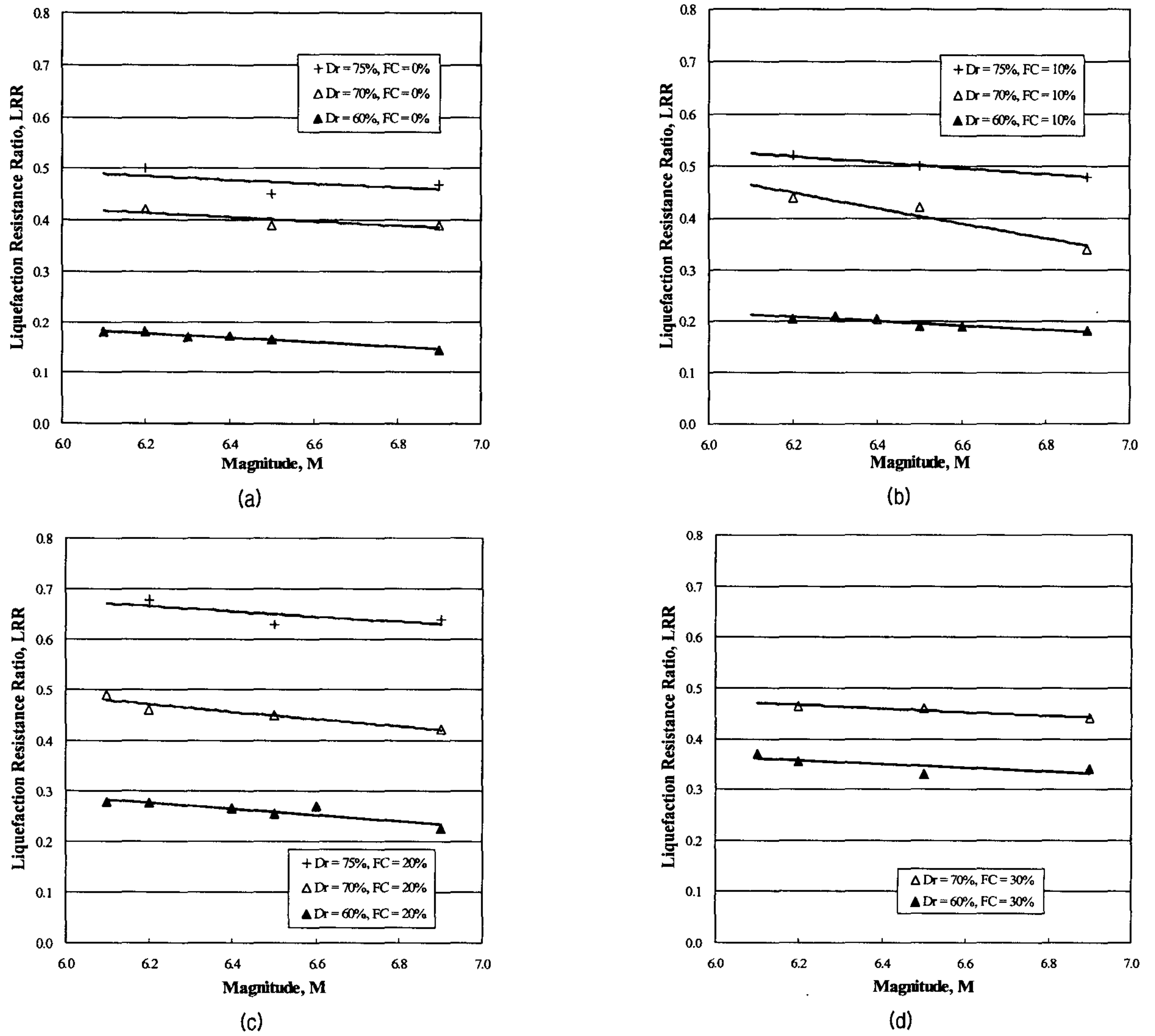


Fig. 11. Comparison of magnitude scaling factors

the earthquake magnitudes required causing liquefaction in Fig. 8. Magnitude 7.5 was used as the base value (i.e., the liquefaction value at which MSF=1.0) and MSFs were re-plotted in Fig. 11. Fig. 11 shows the relationships between MSFs and earthquake magnitudes obtained from this study and other authors. MSFs evaluated in this study were 1.42 and greatly consistent with MSFs recently proposed by Seed et al. (2003), while lower than a range of those recommended by NCEER.

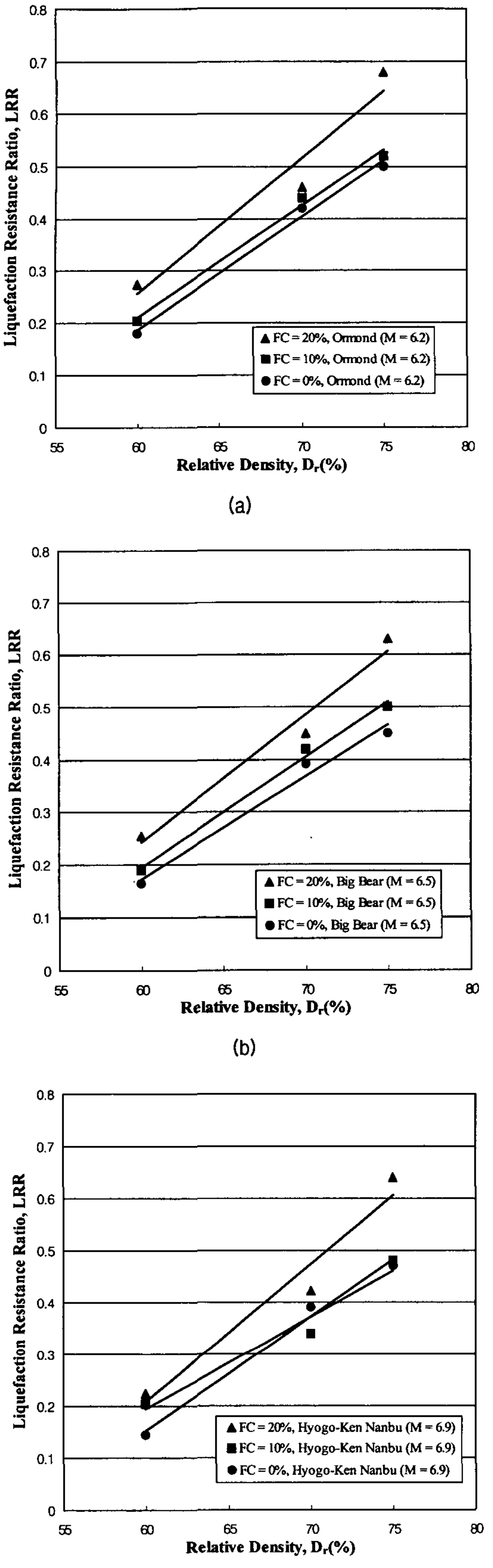
4.3 Effects of Relative Density and Fines Content on Liquefaction Resistance under Irregular Earthquake Motions

Fig. 12 shows liquefaction resistances at three different relative densities under various earthquake motions. It is seen that the higher relative densities, the greater liquefaction resistance results in. Fig. 13 shows effects



(a) (b) (c) (d)

Fig. 12. Effect of relative density on liquefaction resistance under various earthquake magnitudes

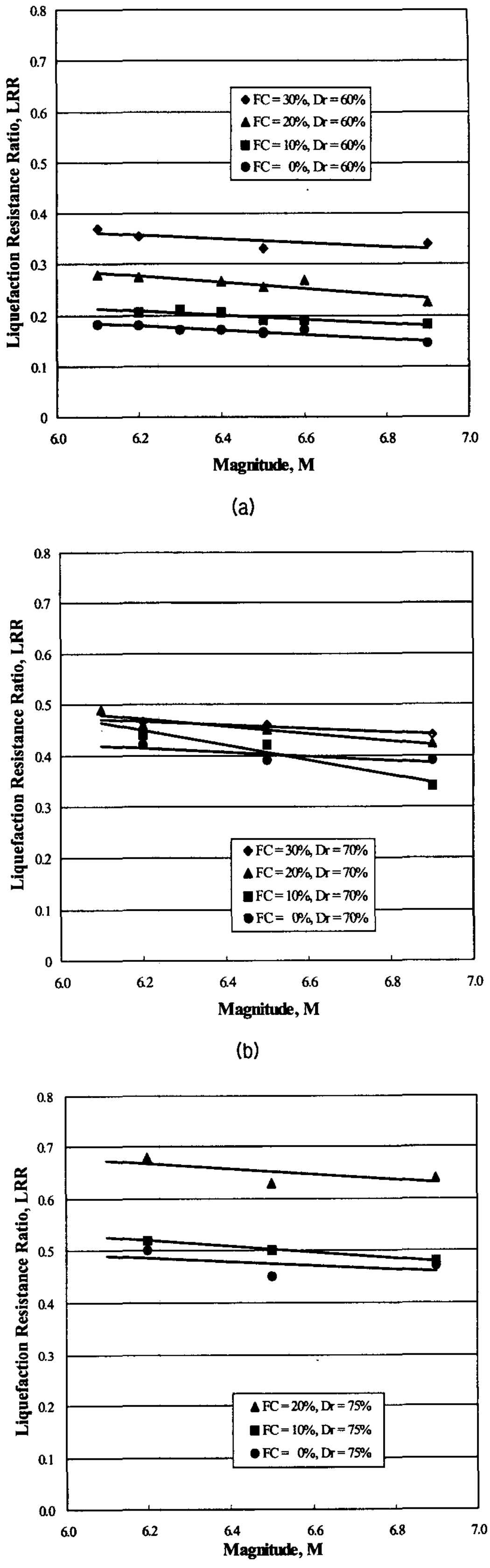


(a)

(b)

(c)

Fig. 13. Effect of relative density on liquefaction resistance for different fines contents

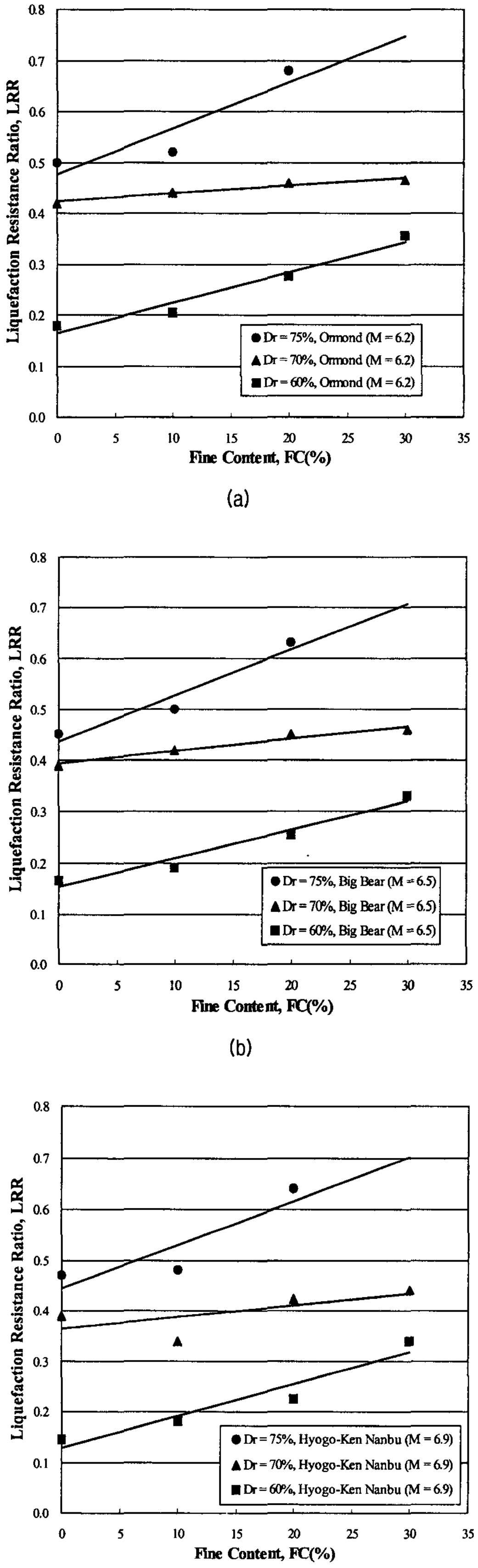


(a)

(b)

(c)

Fig. 14. Effect of fines contents on liquefaction resistance with earthquake magnitudes



(a)

(b)

(c)

Fig. 15. Effect of fines contents on liquefaction resistance ratio for different magnitudes and relative densities

of the relative density on the liquefaction resistance with different fines contents equal to 0 and 20%. For both clean and silty sands, effects of the relative density appear to be significant, representing higher liquefaction resistances with increasing relative densities. Results for silty sands obtained in this study are in reasonably good agreement with previous research results for clean sands (Mulilis 1975; Vaid & Sivathayalan 1996).

Figs. 14 and 15 show effects of fines contents on the liquefaction resistance. It is observed that the liquefaction resistance of silty sands increases with increasing fines contents. As shown in Fig. 14, changes of fines contents from 0 to 30% result in an approximate 90 and 30% increase of the liquefaction resistance at relative densities equal to 60 and 70%, respectively. About 70% increase of the liquefaction resistance at relative density equal to 75% results in for a change of fines content from 0 to 20%. These results are in good agreement with previous findings that the presence of fines produces higher liquefaction resistances (Chang et al. 1982; Dezfulian 1982; Amini & Qi 2000; Polito & Martin II 2001). This is due to the fact that adhesion between fine particles tends to prevent separation of individual particles when a sand is about to liquefy and as the silt content increases, sand particles are increasingly surrounded by silt, and the sand-grain-to-sand-grain contact decreases. Thus, the specimen behavior becomes somewhat similar to silty soils. Fig. 15 also shows the increase of liquefaction resistances with the increase of fines contents. As shown in Fig. 15, results for three different relative densities equal to 60, 70, and 75% show a similar dependency of the liquefaction resistance on the fines contents irrespective of earthquake magnitudes.

4.4 Criteria for Liquefaction Screening Limits

In order to investigate criteria of liquefaction screening limits, triaxial test results under irregular earthquake motions with magnitudes of around 6.5 were compared with seismic demands (i.e., the load imparted to the soil by the earthquake) calculated by equivalent-linear program SHAKE91 (Schnabel et al. 1972; Idriss & Sun 1992). If

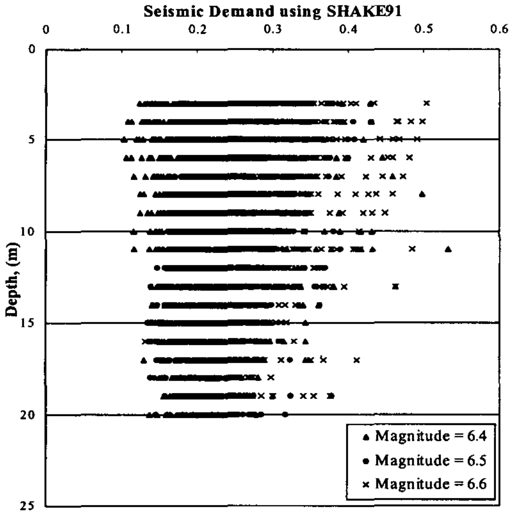


Fig. 16. Seismic demand from one-dimensional ground response analysis for different earthquake magnitudes

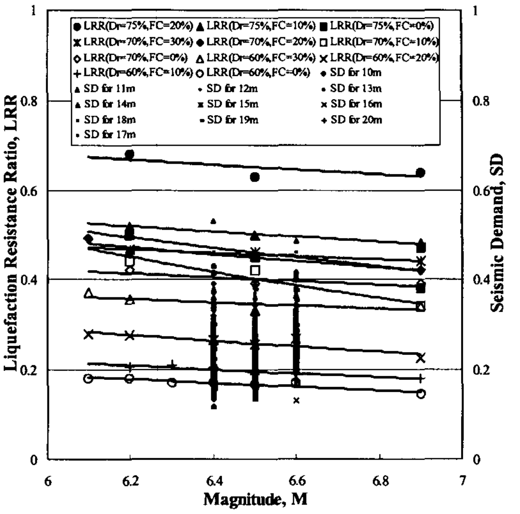


Fig. 17. Relationships between liquefaction resistance and seismic demand with earthquake magnitudes

the seismic demand is greater than the liquefaction resistance for a given earthquake magnitude, the soil will liquefy under the earthquake. In order to calculate the seismic demand for various soil conditions, one dimensional ground response analyses were performed for 132 profiles of 9 sites nearby ports and harbors located in Korea. Selected soil profiles represent different depths and various soil layers of CL, ML, and SM. In the SHAKE 91 analysis, three earthquake motions of magnitudes from 6.4 to 6.6 were selected as input motions for considering moderate earthquake magnitudes in Korea. The seismic demand can be determined for a soil profile at any desired depth based on results of maximum acceleration and stresses using the SHAKE91 analysis. In the SHAKE91 analysis, all the earthquake input motions with peak acceleration level of 0.11g equivalent to the seismic class II criteria in Korean standard were applied as the base rock motions. Fig. 16 shows seismic demands calculated for 132 soil profiles selected in this study at depths from 3 to 20 m. As shown in Fig. 16, most values of seismic demands are under 0.5. Fig. 17 shows liquefaction resistance strengths obtained from triaxial tests under irregular motions and seismic demands with earthquake magnitudes obtained from Fig. 16. From the figure it is observed that most seismic demands are smaller than liquefaction resistances. Considering test results with different relative densities and fines contents described earlier and stress analyses for typical soil conditions in port and harbor sites in the Korean peninsula, a relative density of 75% with no fines appears to be a condition above which no seismic hazards are expected and thus no liquefaction analysis is required. It is also found that soils of a relative density equal to 70% with a fines content of 20% represents a similar condition mentioned above. Although additional investigations are needed, results obtained in this study can be used for further development of the liquefaction screening limits in Korea.

5. Conclusions

To revise the present Korean seismic standards for the liquefaction potential assessment, cyclic triaxial tests using irregular earthquake motions, different earthquake magnitudes, relative densities, and fines contents were performed. The following primary conclusions are obtained as a result of this study:

(1) From laboratory cyclic triaxial test results, it is found that liquefaction resistances under sinusoidal loadings coincide with those under irregular earthquake loadings at around a magnitude of 6.8, while showing different liquefaction resistances at other ranges of earthquake magnitudes. It should be, therefore,

noticed that the use of uniform stress waves, such as sinusoidal loading, is also an approximated approach, and great care is required for analysis of test results at low and high range of earthquake magnitudes.

(2) Proposed MSFs were lower than those recommended from the NCEER workshop. But, proposed MSF obtained in this study is 1.42 and shows close agreement with that recently proposed by Seed et al. (2003).

(3) Triaxial Tests were carried at conditions of different relative densities (60, 70, and 75%) and fines contents (0, 10, 20, and 30%). In the test results for both clean and silty sands, effects of the relative density appear to be significant representing higher liquefaction resistances with increasing relative densities. It is also observed that the liquefaction resistance of silty sands increases with increasing fines contents.

(4) To revise the criteria for liquefaction screening limits in Korea, ground response analyses were carried out and most of the values of the seismic demands were under 0.5. Comparing triaxial test and ground response results, a relative density of 75% with no fines appears to be a condition above which no seismic hazards are expected and thus no liquefaction analysis is required. It is also found that soils of a relative density equal to 70% with a fines content of 20% represent a similar condition mentioned above.

(5) Conditions for the screening limits in moderate earthquake regions are proposed as soils that have fines contents greater than 20% and relative densities greater than 75%.

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