Evaluation of Site-dependent Ductility Factors for Elastic Perfectly Plastic SDOF Systems

토질조건에 따른 탄소성 단자유도 구조물의 연성계수 평가

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국문요약

반응수정계수의 핵심구성요소인 연성계수를 토질조건에 따라 제시하였다. 47개의 지진에서 얻어진 총 1,860개의 지진기록이 사용되었으며, 지반 전단파의 평균속도에 따라 4가지의 토질조건을 고려하였다. 이러한 분류는 현재 사용되고 있는 UBC(1997), NEHRP(1997) 및 IBC 2000(1997)의 토질조건과 일치한다. 통계적 회귀분석으로부터, 토질조건에 따른 연성계수를 평가하기 위한 단순화된 식이 제안되었다. 제안된 식은 상대적으로 간단하면서도 평균연성계수와 잘 일치하는 결과를 보였다. 제안된 식에 근거하여, 현재의 기준과 일치하는 토질조건에 따른 연성계수를 평가할 수 있을 것으로 기대한다.

주요어 : 연성계수, 전단파 속도, 토질조건, 제안식

ABSTRACT

This paper suggests the site-dependent ductility factor which is a key component of response modification factor(R). To compute the ductility factor, a group of 1,860 ground motions recorded from 47 earthquake was considered. Based on the local site conditions at the recording station, ground motions were classified into four groups according to average shear wave velocity. This site classification was consistent with site categories of the UBC(1997), NEHRP(1997) and IBC 2000(1997). Based on the results of regression analysis, a simplified equations were proposed to compute site-dependent ductility factors. The proposed equations were relatively simple and provide a good estimation of mean ductility factors. Based on the proposed equations, ductility factors considering the site conditions can be evaluated in accordance with the present building codes.

Key words : ductility factor, shear wave velocity, site condition, proposed equation.

1. Introduction

The design force levels currently specified by most seismic codes are calculated by dividing the base shear for elastic response by the response modification factor(R). The concept of a response modification factor was proposed based on the premise that well-detailed seismic framing systems could sustain large inelastic deformations without collapse and develop lateral strengths in excess of their design strength. It is well known that the response modification factor takes account for ductility, over-strength, redundancy and damping of the structural systems. However, several researchers, including Project ATC 19[1] and 34[2], have expressed their concerns about the lack of rationality in the response modification factors currently specified in seismic design codes. Therefore, it is necessary to re-evaluate the response modification factors in seismic design. Ductility factor has played an important role in seismic design as it is key component in response modification factor(R).

To evaluate systematically the response modification factors for existing or new buildings, it is necessary to get the ductility factor which is reflected by site conditions. Previous studies on ductility factors were suggested in various formulas (e.g. Nassar and Krawinkler 1991[3], Miranda 1993[4], 1997[5], Kim, M. H. 1997[6], KNHC 1998[7], Borzi and Elnashai 2000.[8] In these studies, the site conditions were roughly classified such as rock site, alluvium site and soft soil site, etc. (Miranda, Kim, M. H. etc)

This study suggest the site-dependent ductility factor which is a key component of response modification factor(R). Ductility factors were computed for perfect elastic plastic SDOF systems undergoing different level of inelastic deformation and period when subjected to a large number of recorded earthquake ground motions. Based on the local site conditions at the recording station, ground motions were classified into four groups according to the

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average shear wave velocity. This site classification was consistent with the site categories of UBC (1997)[9], NEHRP(1997)[10] and IBC 2000(1997).[11] Based on the results of regression analysis, a simplified equations were proposed to compute site-dependent ductility factors.

2. Ductility Factor

2.1 Definition of Ductility Factor

The ductility factor (i.e., the reduction in strength demand), R_μ, is defined as the ratio of the elastic strength demand to the inelastic strength demand,

$$R_\mu = \frac{F_y(\mu = 1)}{F_y(\mu = \mu_i)} \tag{1}$$

where $F_y(\mu = 1)$ is the lateral strength required to avoid yielding in the system under a given motion and $F_y(\mu = \mu_i)$ is the lateral strength required to maintain the displacement ductility ratio demand, μ, less than or equal to a pre-determined target ductility ratio, μ_i, under the same ground motion.

For a given ground motion and a maximum tolerable displacement ductility demand μ_i, the object problem is to compute the minimum lateral strength capacity $F_y(\mu = \mu_i)$ that has to be supplied to the structure in order to avoid ductility ratio demands larger than μ_i. Equation (1) can be rewritten as

$$R_\mu = \frac{C_y(\mu = 1)}{C_y(\mu = \mu_i)} \tag{2}$$

where $C_y(\mu = 1)$ is seismic coefficient (yield strength divided by the weight of the structure) required to avoid yielding; and $C_y(\mu = \mu_i)$ is minimum seismic coefficient required to control the displacement ductility demand to μ_i.

2.2 Literature Review

(1) Nassar and Krawinkler(1991)[3]

Nassar and Krawinkler studied the response of SDOF nonlinear systems when subjected to 15 ground motions recorded in the Western United States. The records used were obtained at alluvium and rock sites, but the influence of site conditions was not considered. Based on mean ductility factors the following expression was proposed to estimate ductility factors:

$$R_\mu = [c(\mu - 1) + 1]^{1/c} \tag{3}$$

where

$$c(T, \alpha) = \frac{T^a}{1 + T^a} + \frac{b}{T} \tag{4}$$

where α is the post-yield stiffness as percentage of the initial stiffness of the system, a and b are constants.

(2) Miranda(1993, 1997)[4, 5]

The equation for ductility factor introduced by Miranda was obtained from 124 ground motions recorded on a wide range of soil conditions(1993). The soil conditions were classified as rock(38 records), alluvium(62 records), and very soft sites(24 records). It is given as :

$$R_\mu = \frac{\mu - 1}{\Phi} + 1 \geq 1 \tag{5}$$

where Φ is a function of μ, T and the soil conditions at the site, and is given by

For rock sites

$$\Phi = 1 + \frac{1}{10T - \mu T} - \frac{1}{2T}\exp\left[\frac{-3}{2}\left(\ln T - \frac{3}{5}\right)^2\right] \tag{6}$$

For alluvium sites

$$\Phi = 1 + \frac{1}{12T - \mu T} - \frac{2}{5T}\exp\left[-2\left(\ln T - \frac{1}{5}\right)^2\right] \tag{7}$$

For soft soil sites

$$\Phi = 1 + \frac{T_g}{3T} - \frac{3T_g}{4T}\exp\left[-3\left(\ln\frac{T}{T_g} - \frac{1}{4}\right)^2\right] \tag{8}$$

where T_g is the predominant period of the ground motion.

Based on previous study, Miranda concluded that although some differences exist between ductility factors for rock and firm alluvium sites, for practical application these differences are relatively small and can be neglected(1997). He proposed the following simplified expression in the design of structures built on rock or firm sites:

$$R_\mu = \mu + (1 - \mu)\exp\left(\frac{-16T}{\mu}\right) \tag{9}$$

where μ is the displacement ductility ratio and T is the period of vibration.

(3) Kim M. H.(1997)[6]

Inelastic design spectra and ductility factors were performed using 101 ground motion data of weak and moderate earthquake recorded in several parts of the world. Inelastic mean spectra for each soil type (S1, S2, S3) and target ductility(1, 2, 4, 6, 8) were evaluated from inelastic response spectra, and spectral properties were analyzed. The proposed equation in this study was given by

$$R_\mu = 1 + \frac{\delta T}{\varepsilon + T} \tag{10}$$

where δ and ε are constants considering the site conditions and displacement ductility ratios.

(4) Korea National Housing Corporation(1998)[7]

This study considered the response of SDOF nonlinear systems when subjected to 40 ground motions recorded at stiff soil sites. In order to investigate the effect of hysteretic model of a system on ductility factors, elastic perfectly plastic model, bilinear and stiffness degradation models were used. The proposed equation for elastic perfectly plastic model was given by

$$R_\mu = A_0[1 - \exp(-B_0 \times T)] \tag{11}$$

where

$$A_0 = 0.99 \times \mu + 0.15 \tag{12}$$

$$B_0 = 23.69 \times \mu^{-0.83} \tag{13}$$

where μ is the displacement ductility ratio and T is the period of vibration.

(5) Borzi and Elnashai(2000)[8]

The relationship for ductility factor introduced by Borzi and Elnashai was obtained from analysis of 364 ground motions recorded on wide range of soil conditions. The study concluded that while displacement ductility may influence significantly the ductility factors, magnitude, distance and soil conditions have a negligible effect on mean ductility factors.

Based on mean ductility factors, the following trilinear expressions were proposed to estimate the ductility factors:

$$R_u = (q_1 - 1)\frac{T}{T_1} + 1 \ , \text{ when } \ T < T_1 \tag{14}$$

$$R_u = q_1 + (q_2 - q_1)\frac{T - T_1}{T_2 - T_1} \ , \text{ when } \ T_1 < T < T_2 \tag{15}$$

$$R_u = q_2 \ , \text{ when } \ T > T_2 \tag{16}$$

where T_1, T_2, q_1 and q_2 were expressions of displacement ductility ratio and hysteretic behavior functions.

3. Earthquake Ground Motions

There is a general consensus that one of the largest sources of uncertainty in the estimation of the response of inelastic structures during earthquakes is the prediction of the intensity and characteristics of future earthquake ground motions at a given site. In this study, an effort was made to consider a relatively large number of recorded ground motion to study the effects of the variability of the characteristics of ground motions on ductility factors.

To evaluate the ductility factors, a group of 1,860 ground motions recorded on a wide range of soil conditions during 47 different earthquakes was considered. A particularly large number of earthquake ground motions was selected in order to assess the dispersion of the ductility factors. Some of the ground motions used in this study were listed in <Table 1>. The others were omitted because of limited space. Complete listing of earthquake ground motions can be founded in Kang C. K.(2003).[12] All of the selected records represent free-field conditions, basement and ground level.

Based on the local site conditions at the recording station, ground motions were classified into four groups according to average shear wave velocity, $\overline{v_s}$, as follows.

(a) Site AB (Rock Site) : $\overline{v_s} \geq 760\, m/s$ (192 ground motions)

(b) Site C (Dense Soil) : $360\, m/s \leq \overline{v_s} < 760\, m/s$ (554 ground motions)

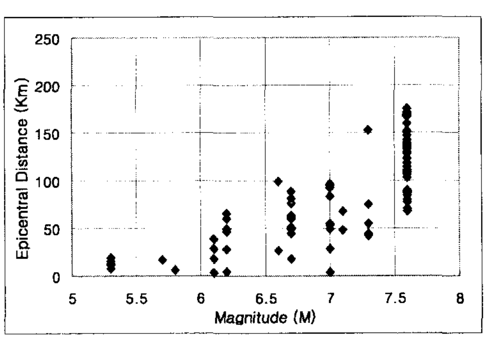
(c) Site D (Stiff Soil) : $180\, m/s \leq \overline{v_s} < 360\, m/s$ (892 ground motions)

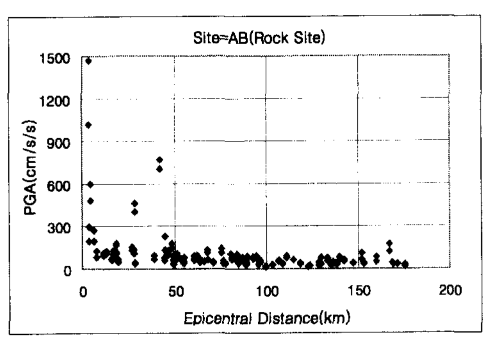
(d) Site E (Soft Soil) : $\overline{v_s} < 180\, m/s$ (222 ground motions)

<Table 1> Some of the Earthquake Ground Motions

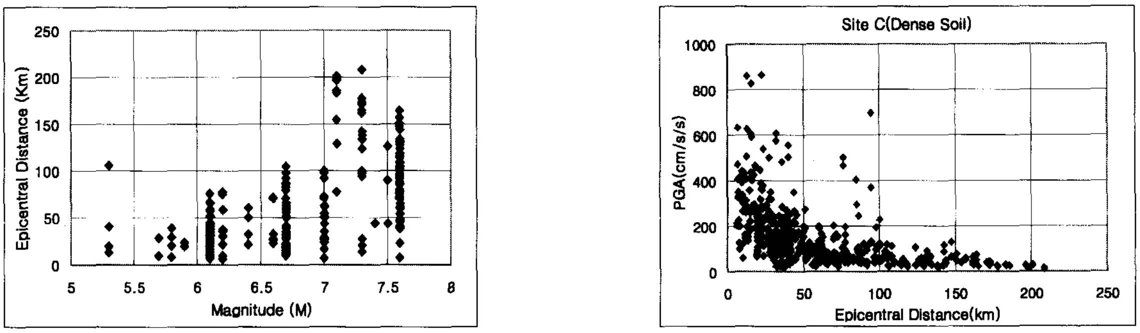
No	Earthquake	M	Station	Site Geology	Site Category	Dist. (km)	Compo-nent	PGA (a/g)
1	Anza, CA	5.3	Anza Array-fire station	Alluvium	AB006	15.9	315	0.0715
2	Borrego valley, CA	6.6	El Centro Arry Station 9	Deep Alluvium	D003	46.3	0	0.0597
3	Cape Mendocino, CA	7.0	Cape Mendodino Petrolla	Cretaceous Rock	AB008	3.8	90	1.0396
4	Chi Chi Taiwan	7.6	CWB station CHY002	S_E (1997 UBC)	E002	42.4	270	0.1169
5	Chi Chi Taiwan	7.6	CWB station HWA056	S_B (1997 UBC)	AB011	80.3	0	0.1070
6	Coyote, CA	5.7	Giloy Array Station 1	Rock	AB067	16.7	230	0.1029
7	Duzec, Turkey	7.1	Lamont 1061	-	C098	-	270	0.1339
8	Erzincan, Turkey	6.9	95 Erzincan	-	D248	-	90	0.4957
9	Hector Mine, CA	7.1	13123 Riverside Airport	Alluvium	C495	128.9	90	0.0260
10	Hollister	5.2	1028 Hollister City Hall	-	D251	-	181	0.0889
11	Imperial Valley, CA	6.4	6604 Cerro Prieto	Rock	C105	21.5	147	0.1689
12	Kobe, Japan	6.9	Kakogawa	-	E115	-	0	0.2509
13	Kocaeli, Turkey	7.4	Cekmece	Stiff Soil	D321	99.7	0	0.1789
14	Landers, CA	7.3	32075 Baker Fire Station	Alluvium	C135	123.9	50	0.1079
15	Loma Prieta, CA	7.0	58373 Apeel 10 - Skyline	Sandstone	C207	62.6	0	0.1029
16	Loma Prieta, CA	7.0	58163 Yerba Buena Island	Franciscan	AB104	95.4	90	0.0679
17	Lytle Creek, CA	5.3	Cedar Springs, Allen Ranch	Granitic	AB111	19.3	95	0.0710
18	Morgan Hill, CA	6.1	57383 Gilroy Array #6	Rock	C239	35.9	0	0.2219
19	Mt. Lewis, CA	6.2	57191 Halls Valley	Alluvium	D468	-	90	0.1589
20	Northridge, CA	6.7	90017 LA-Wonderland Ave	Granite Rocks	AB130	18.2	185	0.1719
21	Northridge, CA	6.7	14403 LA-116th St School	Terrace Deposits	C329	40.5	90	0.2078
22	Point Mugu, CA	5.3	272 Port Hueneme	Alluvium 300M	D609	17.9	180	0.1120
23	San Fernando, CA	6.6	127 Lake Hughes #9	Gneiss	AB157	26.7	21	0.1569
24	San Fernando, CA	6.6	111 Cedar Springs	Granitic	AB159	99.4	95	0.0200
25	San Francisco, CA	5.3	1117 Golden Gate Park	Chert	AB162	11.5	100	0.1120
26	Superstition Hills, CA	6.6	5060 Brawley	Alluvium	D631	22.1	225	0.1559
27	Trinidad, CA	7.2	1498 Rio Dell Overpass	-	C401	-	0	0.1629
28	Victoria, Mexico	6.4	6604 Cerro Prieto	Rock	C410	32.0	315	0.5867
29	Westmorland, CA	5.9	5060 Brawley Airport	Alluvium	D643	16.0	225	0.1689
30	Whitter Narrows, CA	6.1	14196 Inglewood - Union Oil	Terrace Deposit	C435	25.4	0	0.2988

In <Fig. 1>, the distribution of earthquake ground motions comprising the data-set with regard to magnitude, epicentral distance, peak ground acceleration and site classification are shown. The figures demonstrate that the data except site E(soft soil), is well-distributed with respect to all three parameters, hence results of analysis will not have significant bias.

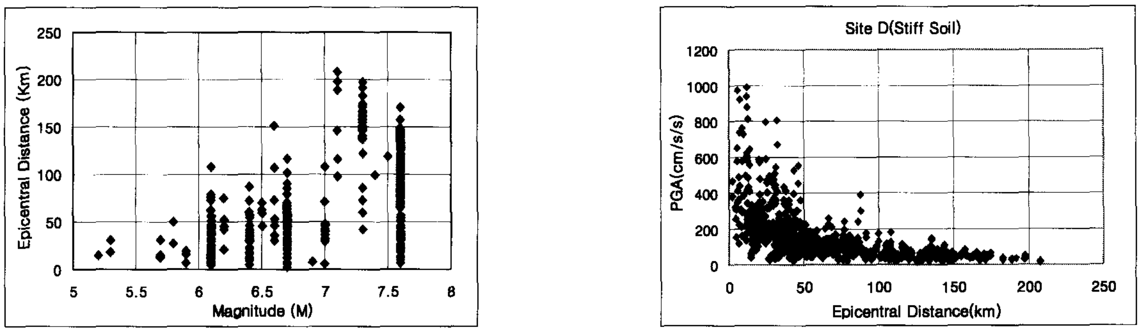




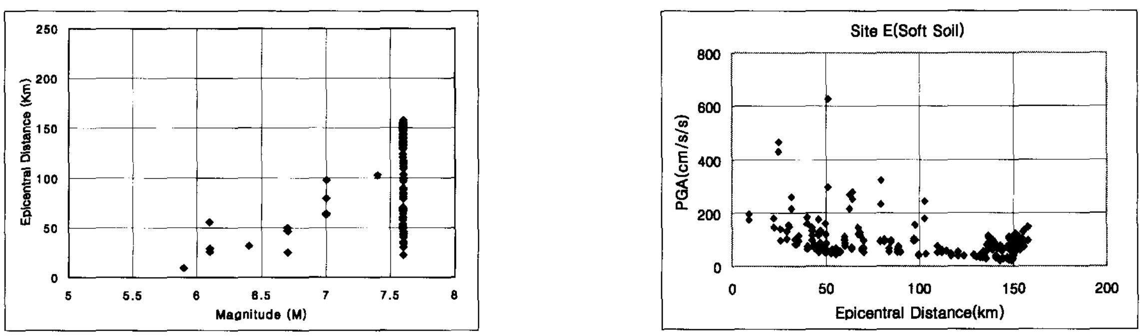
(a) Site AB(Rock Site)



(b) Site C(Dense Soil)



(c) Site D(Stiff Soil)



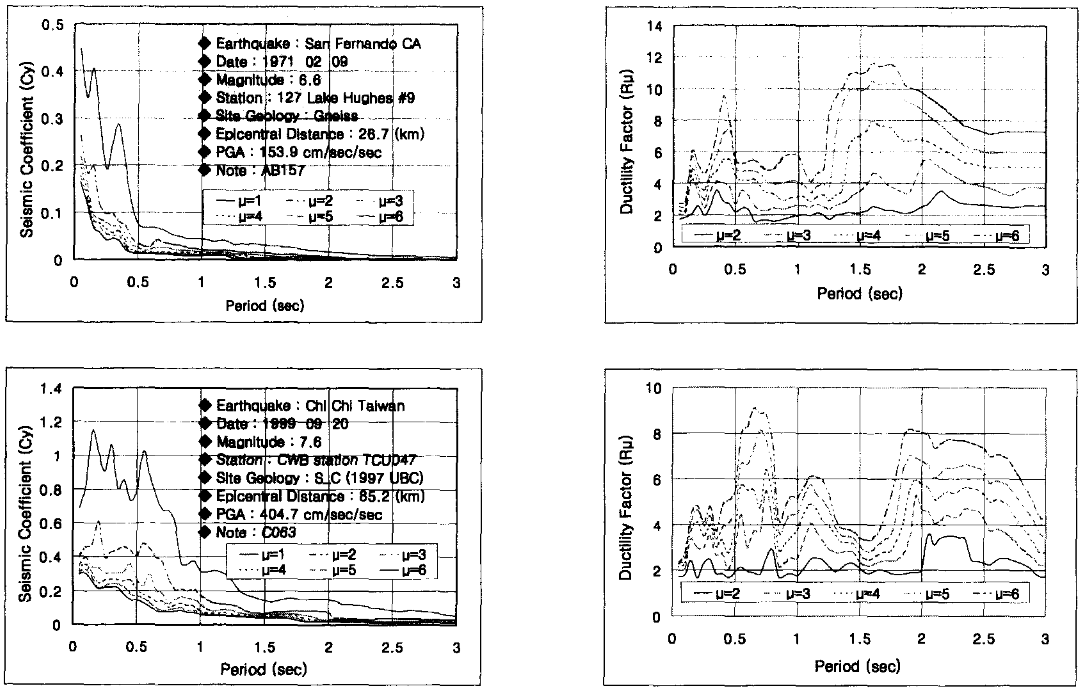
(d) Site E(Soft Soil)

Fig 1 Distribution of earthquake ground motions

4. Method of Analysis

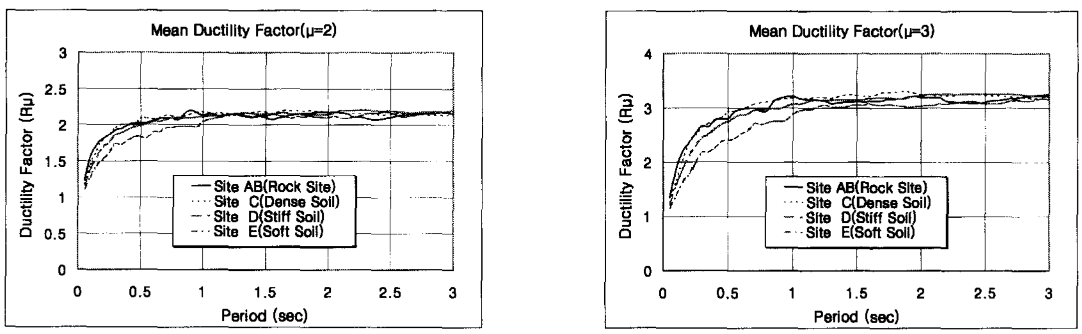
Nonlinear time history analysis were carried out on SDOF systems. BISPEC[13] was used to perform the dynamic analysis. For a given period of vibration and a given target ductility displacement ductility ratio, constant displacement ductility inelastic response spectrum was computed by iteration on the system's non-dimensional yielding strength $C_y(\mu = \mu_i)$ until the displacement ductility demand is, within a certain tolerance, the same as the target ductility. The tolerance is chosen such that $C_y(\mu \cdot = \mu_i)$ is considered satisfactory if the computed ductility is within 1% of target ductility.

The following values of target ductilities are selected for this study : 1(elastic), 2, 3, 4, 5 and 6. For each earthquake record and each target ductility, the inelastic response spectrum are computed for a set of 60 discrete periods ranging from 0.05 to 3.0 seconds. Considering the large number of records, ductilities, and periods of vibration and the large computational effort involved in calculating constant displacement ductility inelastic spectrum through iteration, this study is limited to SDOF systems that have a elastic perfectly plastic behavior and constant damping coefficient corresponding to a damping ratio ξ of 5% based on elastic properties. <Fig. 2> show the constant displacement ductility inelastic response spectra and ductility factors for some of the earthquake ground motions.

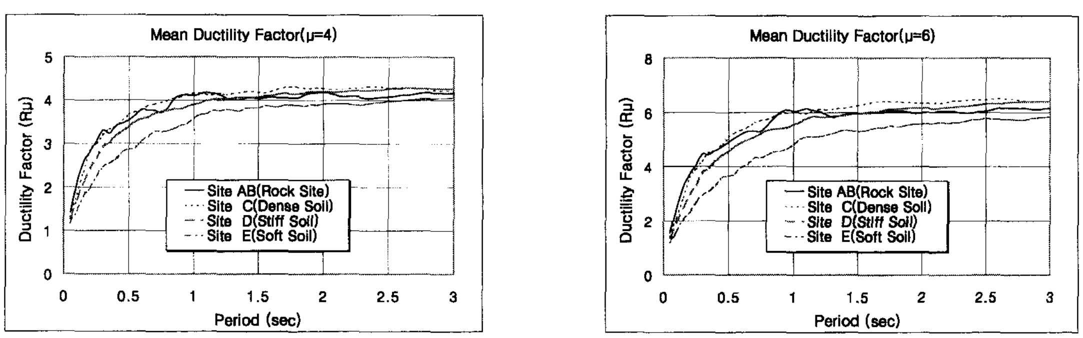


(a) Inelastic response spectra (b) Ductility factor

Fig 2 Example of inelastic response spectra and ductility factor



(a) μ=2 (b) μ=3



(c) μ=4 (d) μ=6

Fig 3 Site-dependent mean ductility factors

5. Evaluation of site-dependent ductility factor

5.1 $R_\mu - \mu - T$ relationship

The paper resulted in the ductility factor depends strongly on the target displacement ductility ratio(μ) and period(T). The mean of ductility factor spectra of all ground motions for elasto-plastic systems with target displacement ductility ratios $\mu = 2$, 3, 4, 5 and 6, at each site conditions, are shown in <Fig.

3>. As shown in this figure, the ductility factors (R_μ)-target displacement ductility ratios(μ)-period(T) relationship are characterized by the following features ;

- The ductility factors approach $R_\mu = 1$ as the periods tend to zero.
- The ductility factors increase with increasing target ductility where the rate of increase depends on periods.
- For a given target displacement ductility, the ductility factor exhibits an important variation with changes in period, particularly in the short-period range.
- For a long-period range, mean ductility factors are approximately constant and approach the target displacement ductility ratio.
- Periods at which ductility factors become approximately equal to the displacement ductility ratio, depend not only on site conditions but also on displacement ductility ratios.

5.2 Regression Analysis

For practical purposes, a simplified expression is desired to consider the ductility factor(R_μ)-displacement ductility ratio(μ)-period(T) relationship for each site condition. A study has been carried out on all data set to formulate regression equations representing the ductility factor(R_μ) as a function of the aforementioned parameters for elasto-plastic SDOF systems with 5% critical damping. The approximate ductility factor(R_μ) is assumed by

$$R_\mu = 1 + \frac{T}{\phi} \tag{17}$$

where ϕ is a function of displacement ductility ratio(μ), period(T) and the site condition. This proposed equation satisfies the following condition which is characteristics of $R_\mu - \mu - T$ relationships.

$$\lim_{T \to 0} R_\mu = \lim_{T \to 0}\left(1 + \frac{T}{\phi}\right) = 1 \tag{18}$$

$$\lim_{T \to \infty} R_\mu = \lim_{T \to \infty}\left(1 + \frac{T}{\phi}\right) \fallingdotseq constant \tag{19}$$

$$\lim_{\mu \to 1} R_\mu = \lim_{\mu \to 1}\left(1 + \frac{T}{\phi}\right) = 1 \tag{20}$$

Eq. (18) represents the extreme case of a very stiff system (yield displacement $\delta_y \to 0$) for which a very small reduction in its strength capacity brings the system to the prescribed target ductility ratio, i.e., $R_u = 1$. Eq. (19) is based on the other extreme case of a very soft system for which the maximum relative displacement tends to the peak ground displacement, PGD, regardless of the system yield level (i.e., equal displacements). Eq. (20) applies to elastic systems. Eqs. (18) through (20) require that the function ϕ fulfill the following conditions:

$$\lim_{T \to 0} \phi(\mu, T) \fallingdotseq 0 \tag{21}$$

$$\lim_{T \to \infty} \phi(\mu, T) \fallingdotseq \infty \tag{22}$$

$$\lim_{\mu \to 1} \phi(\mu, T) \fallingdotseq \infty \tag{23}$$

Several forms of the function for ϕ are considered, and regression analysis is conducted for each site condition separately in order to fit the function ϕ to the data obtained from nonlinear time-history analysis. For each site condition, the functions ϕ that fit best mean ductility factors and satisfy the above mentioned conditions are given by as follows.

For site AB(Rock site),

$$\phi = \frac{1}{4 + 16(LN\mu)} + \frac{0.92\,T}{\mu - 1} \tag{24}$$

For site C(Dense soil),

$$\phi = \frac{1}{8 + 9(LN\mu)} + \frac{0.83\,T}{\mu - 1} \tag{25}$$

For site D(Stiff soil),

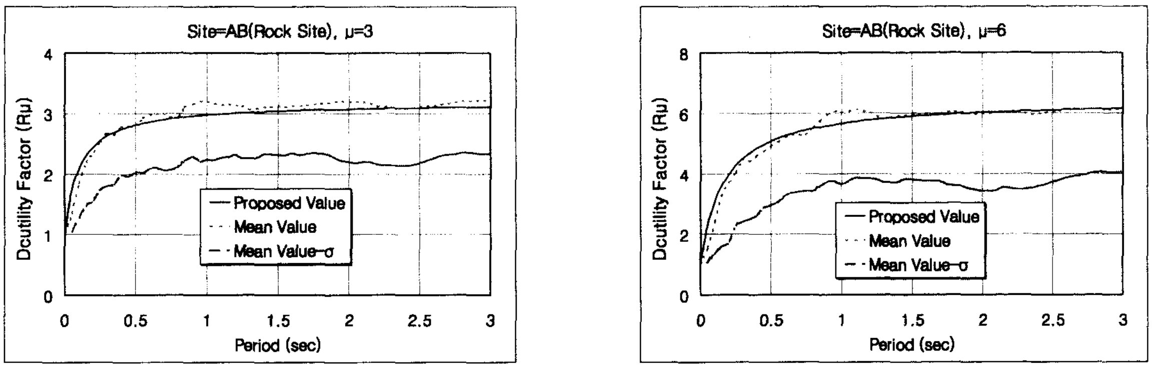
$$\phi = \frac{1}{3 + 7(LN\mu)} + \frac{0.79\,T}{\mu - 1} \tag{26}$$

For site E(Soft soil),

$$\phi = \frac{1}{2 + 4(LN\mu)} + \frac{0.82\,T}{\mu - 1} \tag{27}$$

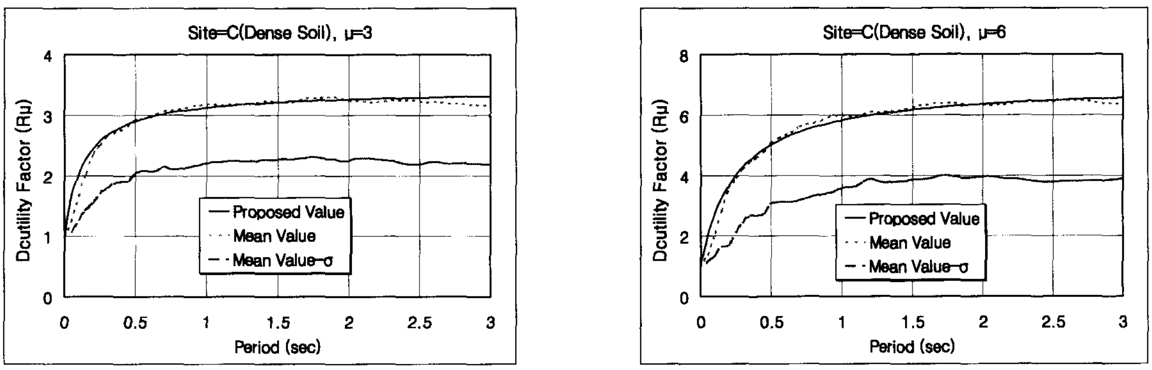
6. Presentation of Results

A comparison between mean ductility factors computed for systems subjected to ground motions recorded on each site condition with those computed using proposed equations is shown from <Fig. 4> to <Fig. 7>. In these figures, bottom lines



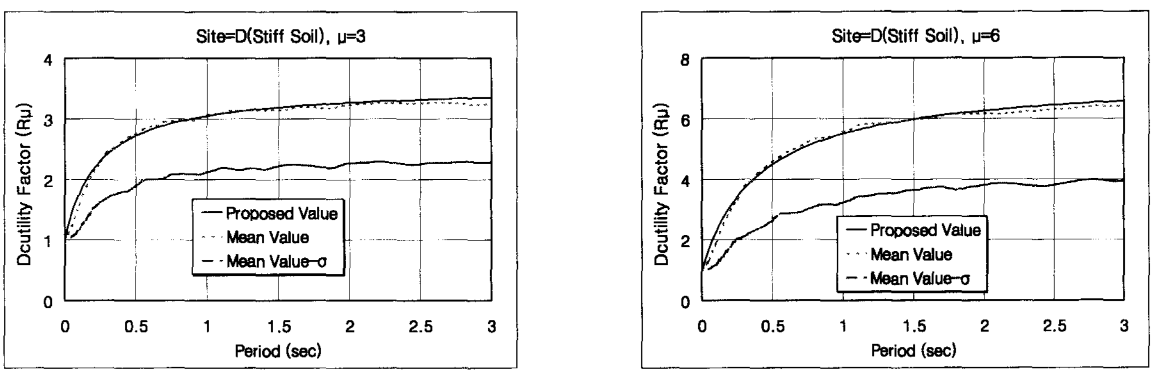
(a) μ=3 (b) μ=6

Fig 4 Mean and proposed ductility factors for site AB(Rock Site)



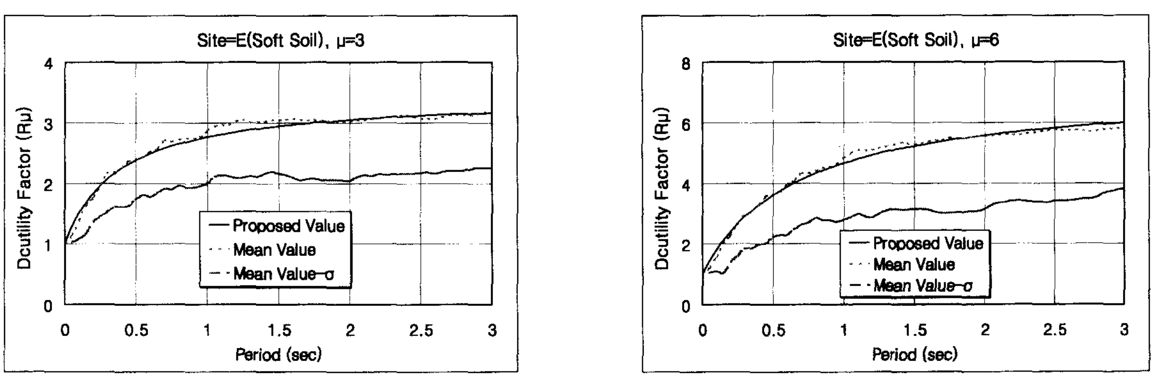
(a) μ=3 (b) μ=6

Fig 5 Mean and proposed ductility factors for site C(Dense Soil)



(a) μ=3 (b) μ=6

Fig 6 Mean and proposed ductility factors for site D(Stiff Soil)

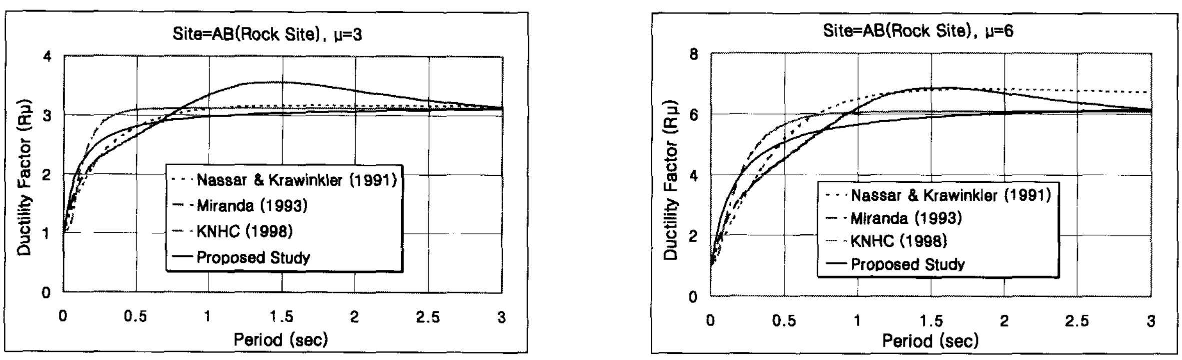


(a) μ=3 (b) μ=6

Fig 7 Mean and proposed ductility factors for site E(Soft Soil) present the mean value minus standard deviation(σ). It can be seen that the use of these simple equations leads to very good approximations of mean ductility factors due to inelastic behavior.

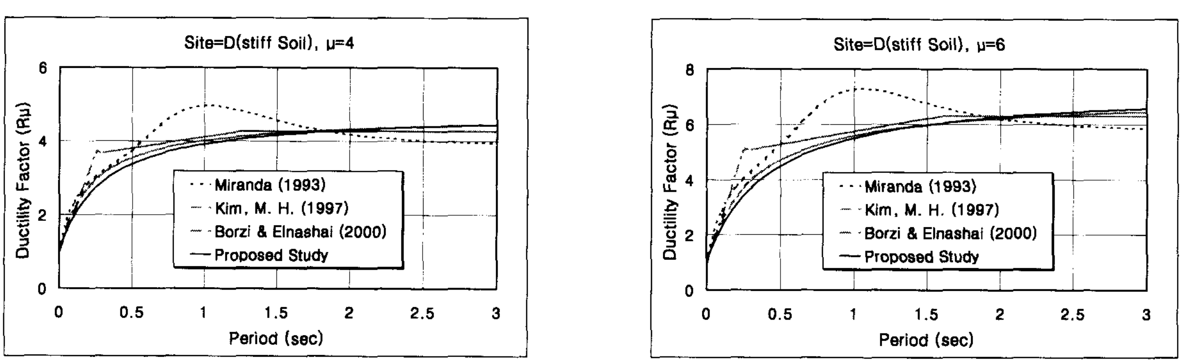
The accuracy of the proposed rule is compared with that of some selected estimation rules previously published in the literature, as presented in section 2. For site AB(rock site), three recently developed estimation rules are used. The first, by Nassar and Krawinkler(1991), is given by Eq. (3) and Eq. (4). The second rule, by Miranda(1993), is given by Eq. (5) and Eq. (6). The third rule, by Korea National Housing Corporation(KNHC, 1998), is given by Eqs. (11) through (13). A comparison between estimation rules previously published with those computed using the proposed equation in this study is shown in <Fig. 8>. As shown in these figures, Nassar and Krawinkler's equations overestimated the ductility factor in the long periods range when displacement ductility ratio, μ, is 6. Miranda's rules also overestimated the ductility factor where periods range from 1.0s to 2.5s. And, in Eq. (6), the calculation of function Φ are more troublesome than those of function ϕ proposed in this study.

For site D(stiff soil), three recently developed estimation rules are also used. The first rule, by Miranda(1993), is given by Eq. (5) and Eq. (7). The second rule, by Kim, M. H.(1997), is given by Eq. (10). The last rule, by Borzi and Elnashai(2000), is given by Eqs. (14) through (16). <Fig. 9> show that comparison between estimation rules previously published with those computed using the proposed equation in this study. As shown in these figures, Miranda's rules also overestimated the ductility factor where periods range from 0.6s to 1.6s. On the whole Kim's rules coincided with proposed equations in this study. However, this rules have shortcomings that ductility factors were only calculated when displacement ductility ratio, μ, is 2, 4, 6, and 8. Borzi and Elnashai's rules generally consistent with proposed rules except short period ranges. Kim, M. H. and Borzi and Elnashai's rules are inconvenient to calculate the ductility factor because these rules have to use the their own table.



(a) Site=AB(Rock Site), μ=3 (b) Site=AB(Rock Site), μ=6

Fig 8 Previous and proposed ductility factors for site AB(Rock Site)



(a) Site=D(Stiff Soil), μ=4 (b) Site=D(Stiff Soil), μ=6

Fig 9 Previous and proposed ductility factors for site D(Stiff Soil)

However, proposed simple equations are more convenient to compute the ductility factors than previous formulas. Moreover, proposed equations have an advantage that site classifications are consistent with present building codes (e.g. UBC, NEHRP and IBC 2000).

7. Conclusions

The primary purpose of this study was to suggest the site-dependent ductility factors. To evaluate the ductility factors, a group of 1,860 ground motions recorded on a wide range of soil conditions during 47 different earthquakes was considered. Based on the results of regression analysis, a simplified equations were proposed to compute site-dependent ductility factors. The proposed equations to compute site-dependent ductility factors are relatively simple and provide a good estimation of mean ductility factors. And, the proposed simple equations are more convenient to evaluate the ductility factors than previous formulas. Based on the proposed equations, ductility factors considering the site conditions which are consistent with present building codes (e.g. UBC, NEHRP and IBC 2000) can be evaluated.

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