Article ID: 1671-3664(2007)04-0351-05 **DOI**: 10.1007/s11803-007-0755-x

Study on inelastic displacement ratio spectra for near-fault pulse-type ground motions

Zhai Changhai†, Li Shuang1‡, Xie Lili1,2,§ and Sun Yamin1*

1. *School of Civil Engineering, Harbin Institute of Technology, Harbin 150090, China*
2. *Institute of Engineering Mechanics, China Earthquake Administration, Harbin 150080, China*

Abstract: In displacement-based seismic design, inelastic displacement ratio spectra (IDRS) are particularly useful for estimating the maximum lateral inelastic displacement demand of a nonlinear SDOF system from the maximum elastic displacement demand of its counterpart linear elastic SDOF system. In this study, the characteristics of IDRS for near-fault pulse-type ground motions are investigated based on a great number of earthquake ground motions. The influence of site conditions, ratio of peak ground velocity (PGV) to peak ground acceleration (PGA), the PGV, and the maximum incremental velocity (MIV) on IDRS are also evaluated. The results indicate that the effect of near-fault ground motions on IDRS are significant only at periods between 0.2 s - 1.5 s, where the amplification can approach 20%. The PGV/PGA ratio has the most significant influence on IDRS among the parameters considered. It is also found that site conditions only slightly affect the IDRS.

Keywords: near-fault pulse-type ground motion; inelastic displacement ratio spectrum; ground motion parameter; PGV/PGA; site condition

1 Introduction

In displacement-based seismic design (DBSD), the displacement rather than force is used as a basic demand parameter for the design, evaluation and rehabilitation of structures. It is essential to provide a simplified procedure to estimate the inelastic displacement demands of structures subjected to ground motions where the structure is expected to behave nonlinearly. This is particularly true when the design is based on design spectra rather than on acceleration time histories. The inelastic displacement ratio spectra (IDRS) provides a useful procedure for estimating the maximum lateral inelastic displacement demand of a structure from its corresponding maximum elastic displacement demand. Since the 1960's, many studies (Veletsos and Newmark, 1960; Veletsos *et al.*, 1965; Miranda 1993, 2000, 2001; Miranda and Jorge, 2002; Jorge and Miranda, 2004; Akkar and Miranda, 2005; Whittaker *et al.*, 1998; Chopra and Goel, 2000; Wang *et al.*, 2006) on IDRS have been performed for far-fault ground motions. In recent major earthquakes, such as the 1994 Northridge, 1995 Kobe, 1999 Chi-Chi, etc., the near-fault pulse-type ground motions caused serious damage to structures. Thus, the characteristics of IDRS for near-fault ground motions have recently received considerable attention in both seismology and earthquake engineering. The inelastic displacement ratio seems to be much larger than unity for structural periods less than the predominant period of near-fault pulse-type ground motions (Iwan *et al.*, 2000). Other similar studies on near-fault pulse-type ground motions, which can significantly influence structures with short periods, has been carried out (Baez and Miranda, 2000; MacRae *et al.*, 2001). For ground motions in near-fault regions, local site conditions, peak ground velocity (PGV), and maximum incremental velocity (MIV) are recognized as the most important factors influencing inelastic displacement ratios (Baez and Miranda, 2000; Huang and Zhu, 2003). Since the ratio of peak ground velocity to peak ground acceleration (PGV/PGA) is a very important parameter to characterize the damage potential of near-fault ground motions, the importance of the study of its effect on IDRS is evident. Additionally, most of the studies mentioned above are based on a limited number of near-fault ground motions, thus further study is necessary.

The objective of this paper is to present the results of a statistical study of the characteristics of IDRS for near-fault ground motions. The effects of local site conditions,

---

Correspondence to: Zhai Changhai, School of Civil Engineering, Harbin Institute of Technology, Harbin 150090, China
Tel: 86-451-86282027
E-mail: zch-hit@hit.edu.cn

†Doctor, Associate Professor; ‡Ph. D. Student; §Professor, Member of CAE; *Master Student

Supported by: National Natural Science Foundation of China Under Grants No. 50608024 and No.50538050; Opening Laboratory of Earthquake Engineering and Engineering Vibration Foundation Under Grant No.2007001

Received July 11, 2007; **Accepted** October 10, 2007

PGV/PGA, PGV and MIV are also investigated.

2 Inelastic displacement ratios

The inelastic displacement ratio, C_μ, is defined as the peak inelastic displacement demand of an inelastic SDOF system, with a ductility ratio μ, divided by the peak elastic displacement demand of the corresponding elastic SDOF system. This ratio is expressed as

$$C_\mu = \Delta_{\mathrm{ine}} / \Delta_{\mathrm{e}} \tag{1}$$

where Δ_{ine} and Δ_{e} denote the peak inelastic and elastic displacements, respectively.

3 Parameter value selection

The parameters used in the IDRS calculation and their values are as follows:

(1) Initial natural vibration period that varies between 0.07 - 5.5 s;

(2) Perfect elastoplastic hysteretic behavior is assumed for the inelastic system, and a viscous damping ratio of 5% is taken;

(3) Five ductility levels are used, i.e., 2, 3, 4, 5 and 6.

4 Ground motions used in the study

A total of 137 near-fault pulse-type ground motion records from 18 different earthquakes around the world are used in this study. The set of ground motions have the following features: (1) recorded at the stations having the closest distances within 20 km from the surface projection of the fault rupture; (2) contain distinct pulses in velocity-time histories; (3) recorded during earthquakes with magnitudes (M_{w}) larger than 5.0; and (4) recorded at the stations where detailed geotechnical information of the sites are available. In order to study the IDRS for near-fault ground motions, a total of 476 far-fault ground motions from 30 different earthquakes at stations having the closest distances larger than 20 km away from the surface projection of the fault rupture are selected. All the ground motions were recorded at free field stations or at the first floor of low-rise buildings. The PGAs of the ground motions are larger than 40 cm/s^2. These strong motion records are available from the Pacific Earthquake Engineering Research Center (PEER) strong motion database (http://peer.berkeley.edu/smcat) and the Institute of Engineering Mechanics (IEM) strong motion database (http://www.iem.cn/eeev) of China Earthquake Administration. In addition to the ground motions recorded in the well-known Loma Prieta (1989), Northridge (1994), and Kobe (1995) earthquakes, etc., the ground motions used in this study also include most of the records collected during major earthquakes that occurred in China, such as the Haicheng (1975), Tangshan (1976), Gengma (1988), Chi-Chi (1999), and Shidian (2001) earthquakes, etc. This is a high-quality dataset in terms of both accelerograms that have been individually corrected, and information regarding the

Table 1 Earthquake ground motions used in the study

Earthquake name	Year	Num. of records	Earthquake name	Year	Num. of records
El Centro	1940	2	Parkfield	1966	2(4)
San Fernando	1971	8(2)	Coalinga	1983	7
Mammoth Lakes	1980	5	Morgan Hill	1984	3(4)
Loma Prieta	1989	9(14)	Western Washington	1949	2
Landers	1992	8(4)	Mexico	1985	9
North Palm Springs	1986	28	Island of Hawaii	1975	1
Whittier Narrows	1987	23(4)	Kobe	1995	8(4)
Chalfant Valley	1986	6	Chi-Chi	1999	166(35)
Kern County	1952	1	Duzce	1999	0(2)
Southern Alaska	1976	7	Kocaeli	1995	0(6)
Imperial Valley	1979	31(30)	Tangshan	1976	18
Coyote Lake	1979	0(4)	Sunan	1976	13
Petrolia	1992	5	Lijiang	1996	14
Northridge	1994	22(16)	Nahanni	1985	0(2)
Livermore Valley	1980	22	Lancang	1988	20
Westmoreland	1981	12	Wusu	1995	12
Superstitn Hills (B)	1987	0(4)	ATushi	1996	5
Erzincan	1992	0(2)	Haicheng	1975	8

Note: The numbers in parentheses are the number of near-fault pulse-type ground motions recording stations and earthquake characteristics. The ground motions used in the study are listed in Table 1.

5 IDRS for near-fault ground motions

The IDRS for each near-fault and far-fault ground motion corresponding to five ductility levels are computed, and then the mean IDRS are obtained by averaging these results. Figure 1(a) shows a comparison between IDRS for near-fault ground motions and far-fault ground motions. Note that the IDRS for the two sets of ground motions are nearly the same. Figure 1(b) presents ratios of the IDRS for the two sets of ground motions. The smaller ratios at T between 0s-0.2s indicate that the near-fault has little effect in the extreme short period range. For periods larger than 1.5s, the IDRS for near-fault ground motions are generally smaller than those for far-fault ground motions and the ratios in this range are within 10%. It is important to note that the IDRS for near-fault ground motions are larger than those for far-fault ground motions at periods between 0.2-1.5s, where the largest difference of near 20% is observed. The large difference of IDRS in the period range of 0.2 -1.5 s between the two groups is primarily caused by the wider acceleration-sensitive regions of the near-fault ground motions.

6 Effects of local site condition, PGV/PGA, PGV and MIV on IDRS

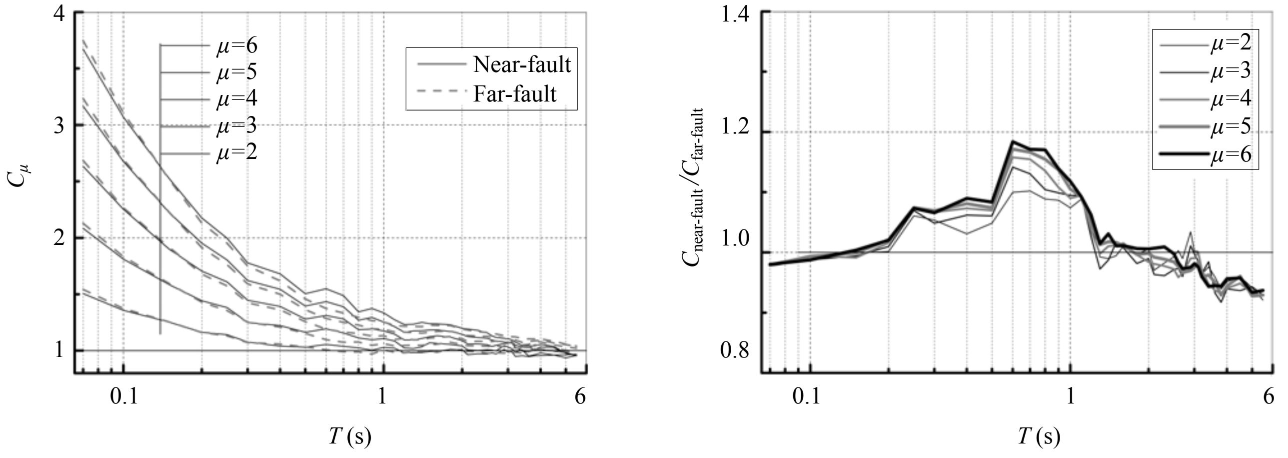
Because local site conditions PGV/PGA, PGV and MIV are important parameters for characterizing damage potential of near-fault ground motions, their impact on IDRS are investigated in this study. According to the shear wave velocity of the stations where the ground motions used in the analysis were recorded, the near-fault ground motions are classified into two groups depending on the site conditions. These are defined as: stiff soil site conditions with V_s>360 m/s and soft soil site conditions with V_s≤360 m/s.

Figure 2 presents a comparison of the ratios of IDRS for stiff site conditions to soft site conditions. Note that in most period ranges, the IDRS for soft site conditions are, on the contrary, larger than those for stiff site conditions and the maximum difference between them is about 10%. Thus, it can be concluded that site conditions are not significant for near-fault ground motions. In addition, the effect of site conditions on IDRS is not sensitive to the ductility levels.

Figure 3 compares the ratios of IDRS for near-fault ground motions with PGV/PGA≥0.2 to those with PGV/PGA<0.2 for different ductility levels. It is shown that the ratios of the mean IDRS for ground motions with PGV/PGA≥0.2 are larger than the ratios with PGV/PGA<0.2 over the entire period and the largest difference of IDRS for the two groups reaches 65%. For a given period, the PGV/PGA effect increases as the ductility level increases. Therefore, it can be concluded that the ratio of PGV/PGA has a significant influence on IDRS for near-fault ground motions.

A comparison of the ratios of IDRS for near-fault ground motions with PGV≥50 cm/s to those with PGV<50 cm/s for different ductility levels are shown in Fig. 4. Note that the IDRS for near-fault ground motions with PGV≥50 cm/s is larger than those with PGV<50 cm/s for the entire period. The largest difference of IDRS for the two PGV ranges occurs at the short periods, and can reach 30%. For periods larger than about 2 s, the difference decreases to less than 10%. Thus, PGV has little effect on the IDRS for near-fault ground motions at long periods.

Figure 5 shows the influence of MIV on IDRS for near-fault ground motions. It is seen that the MIV effect on IDRS is similar to the PGV effect. However,



(a) IDRS for near-fault ground motions and far-fault ground motions

(b) Ratios of IDRS for near-fault ground motions to those for far-fault ground motions

Fig. 1 Comparison of IDRS between near-fault ground motions and far-fault ground motions

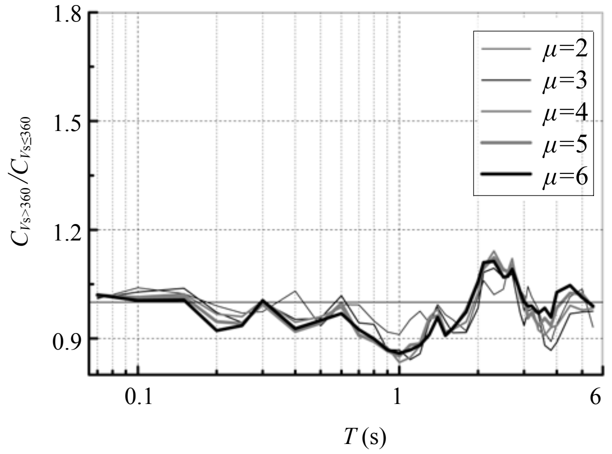


Fig. 2 Ratios of IDRS for near-fault ground motions of stiff site conditions to those of soft site condition

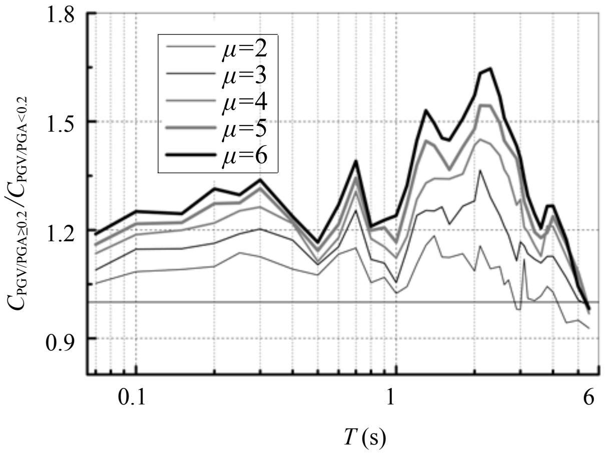


Fig. 3 Ratios of IDRS for near-fault ground motions with PGV/PGA≥0.2 to those with PGV/PGA<0.2

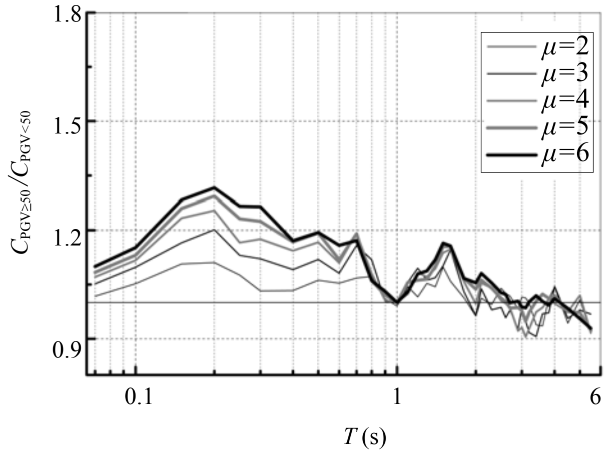


Fig. 4 Ratios of IDRS for near-fault ground motions with PGV≥50cm/s to those with PGV<50cm/s

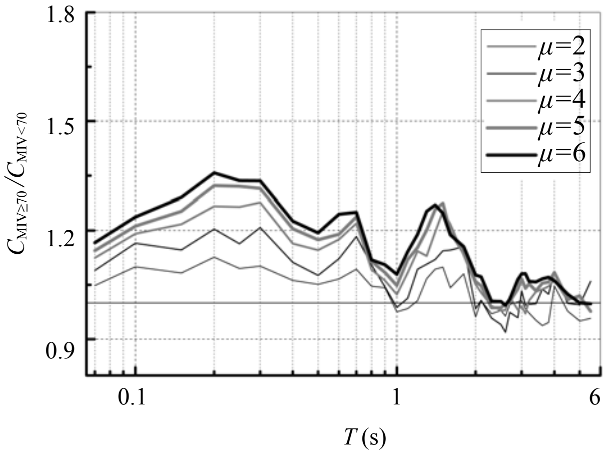


Fig. 5 Ratios of IDRS for near-fault ground motions with MIV≥70cm/s to those with MIV<70cm/s

MIV has a slightly greater effect. This observation may be illustrated from good correlation between the two parameters. The correlation between the two parameters can reach 0.95 (Zhai, 2005).

7 Conclusions

In this study, based on a great number of ground motions, the characteristics of IDRS for near-fault pulse-type ground motions are investigated. The effect of local site conditions, PGV/PGA, PGV and MIV on IDRS are discussed. The results are summarized as follows:

(1) The IDRS for the near-fault ground motions are nearly the same as those for the far-fault ground motions. For periods less than 0.2 s and longer than 1.5s, the near-fault pulse effect on IDRS is not significant, while in the period range between 0.2-1.5 s, the IDRS for near-fault ground motions are larger than those for far-fault ground motions, where the largest difference approaches 20%.

(2) Local site conditions have little influence on IDRS for near-fault ground motions. PGV and MIV have a larger impact on the IDRS at short period ranges and little effect at long period ranges. The ratio of PGV/PGA has the greatest influence on the IDRS for near-fault ground motions among the parameters considered in this study. Furthermore, the effect of PGV/PGA increase as the ductility level increases.

References

Akkar SD and Miranda E (2005), "Statistical Evaluation of Approximate Methods for Estimating Maximum Deformation Demands on Existing Structures," *Journal of Structural Engineering*, ASCE, **131**(1): 160-172.

Baez JI and Miranda E (2000), "Amplification Factors to Estimate Inelastic Displacement Demands for the Design of Structures in the Near Field," *Proceedings of the 12th Word Conference on Earthquake Engineering, Auckland*, New Zealand: New Zealand Society for Earthquake Engineering, pp. 1561.

Chopra AK and Goel RK (2000), "Evaluation of NSP to

Estimate Seismic Deformations: SDF systems," *Journal of Structural Engineering*, **126**(4):482-490.

Huang Jianwen and Zhu Xi (2003), "Inelastic Response Analysis for the SDOF Structures Under Near-fault Earthquakes," *China Safety Science Journal*, **13**(11): 59-65. (in Chinese)

Iwan WD, Huang Chingtung and Guyader AC (2000), "Important Features of the Response of Inelastic Structures to Near-field Ground Motion," *Proceedings of the 12th Word Conference on Earthquake Engineering*, Auckland, New Zealand: New Zealand Society for Earthquake Engineering, pp. 1740.

MacRae GA, Morrow DV and Roeder CW (2001), "Near-fault Ground Motion Effects on Simple Structures," *Journal of Structural Engineering*, **127** (9): 996-1004.

Miranda E (1993), "Evaluation of Site-dependent Inelastic Seismic Design Spectra," *Journal of Structural Engineering*, **119**(5):1319-1338.

Miranda E (2000). "Inelastic Displacement Ratios for Structures on Firm Sites," *Journal of the Structural Engineering*, ASCE, **126**(10):1150-1159.

Miranda E (2001), "Estimation of Inelastic Deformation Demands of SDOF Systems," *Journal of Structural Engineering*, **127**(9):1005-1012.

Miranda E and Jorge RG (2002), "Evaluation of Approximate Methods to Estimate Maximum Inelastic Displacement Demands," *Earthquake Engineering and Structural Dynamics*, **31**:539-560.

Veletsos AS and Newmark NM (1960), "Effect of Inelastic Behavior on the Response of Simple Systems to Earthquake Motions," *Proceedings of 2WCEE*, Tokyo, Japan.

Veletsos AS, Newmark NM and Chepalati CV (1965), "Deformation Spectra for Elastic and Elastoplastic Systems Subjected to Ground Shock and Earthquake Motion," *Proceedings of the 3WCEE*, Wellington, New Zealand.

Wang Dongsheng, Li Hongnan, Wang Guoxin, *et al.* (2006), "Study on Characters of Long Period Portion of Inelastic Spectra," *Earthquake Engineering and Engineering Vibration*, **26**(2): 49-55. (in Chinese)

Whittaker AS, Constantinou M and Tsopelas P (1998), "Displacement Estimates for Performance-based Seismic Design," *Journal of Structural Engineering*, ASCE, **124**(8): 905-912.

Zhai Changhai (2005), "Study on the Severest Design Ground Motions and the Strength Reduction Factors," Harbin: Harbin Institute of Technology. (in Chinese)