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NONLINEAR RESPONSE SPECTRA FOR STRONG GROUND MOTION RECORDS FROM THE 2004 NIIGATA-KEN CHUETSU EARTHQUAKES

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ABSTRACT: A sequence of destructive earthquakes struck mid-Niigata prefecture in central Japan during late October 2004. This paper examines some of the characteristics of the strong ground motions recorded during the main shock and aftershocks of the earthquakes, and the effects of these records on the linear and nonlinear dynamic response of single-degree-of-freedom systems. The studies suggest that a ground motion recorded close to the epicenter of the main shock produce larger response than those of the current design codes up to natural period of 2 seconds.

Key Words: Niigata-Ken Chuetsu Earthquakes, Strong Ground Motions, Elastic Response Spectra, Nonlinear Response Spectra, and Aftershocks.

INTRODUCTION

A sequence of destructive earthquakes struck mid-Niigata prefecture in central Japan during late October 2004. The main shock had a magnitude M_j of 6.8 according to Japan Meteorological Agency. The main shock occurred at 17:56 JST local time (8:56 UTC) on October 23rd, 2004, and more than five aftershocks with M_j > 5.5 occurred within 10 days of the main shock, as shown in Table 1 (K-NET/**N**ational Research **I**nstitute for **E**arthquake Science and **D**isaster Prevention). The epicenters of the main shock and some of the aftershocks are shown in Fig. 1. The hypocenter of the main shock is located at $37.29°$ N and $138.87°$ E with a depth of 13 km. The Japan Meteorological Agency named the earthquakes "Niigata-Ken Chuetsu Earthquakes." Forty-one people were reported to have been killed by the earthquakes and more than 100,000 people were forced to evacuate (11/14/04 according to Asahi Shimbun, 2004). The main shock caused the first derailment of a Shinkansen train in more than 40 years. Reports indicated 47 railway bridge columns were damaged near the site of the derailment (Asahi Shimbun, 2004).

During the main shock and aftershocks, ground motions were recorded as part of the K-NET strong motion instrumentation program (K-NET/NIED). These records provide highly valuable information to help understand the effects of near-fault ground motions on engineered structures and to upgrade seismic design criteria. This paper examines some of the characteristics of the strong ground motions, including aftershocks, recorded during the Niigata-Ken Chuetsu earthquakes and the effects of these records on the linear and nonlinear dynamic response of single-degree-of-freedom systems. Note that strong ground shaking might be expected to vary significantly over short distance due to a variety of factors including the nature of the fault rupture process, differing wave propagation paths, local topological features, and local soil conditions. Moreover, the motion at the base of an actual structure may be significantly altered by soil-structure interaction effects. Thus, such dynamic effects should be taken account of when damage evaluations of actual structures are performed.

Table 1 Main shock and aftershocks of Niigata-Ken Chuetsu earthquakes ($M_j > 5.5$) (K-NET/NIED)

Local Time (JST)	Epicenter	Depth (km)	M_j	PGA (m/sec^2)	Site Where PGA Recorded
2004/10/23 17:56	37.29N, 138.87E	13	6.8	17.16	NIG021
2004/10/23 18:03	37.35N, 138.99E	9	6.2	3.72	NIG017
2004/10/23 18:12	37.25N, 138.83E	12	6.0	2.76	NIG020
2004/10/23 18:34	37.30N, 138.93E	14	6.5	8.16	NIG021
2004/10/23 19:46	37.29N, 138.88E	12	5.7	4.32	NIG019
2004/10/25 06:05	37.33N, 138.95E	15	5.8	4.27	NIG020
2004/10/27 10:40	37.29N, 139.03E	12	6.1	5.30	NIG020

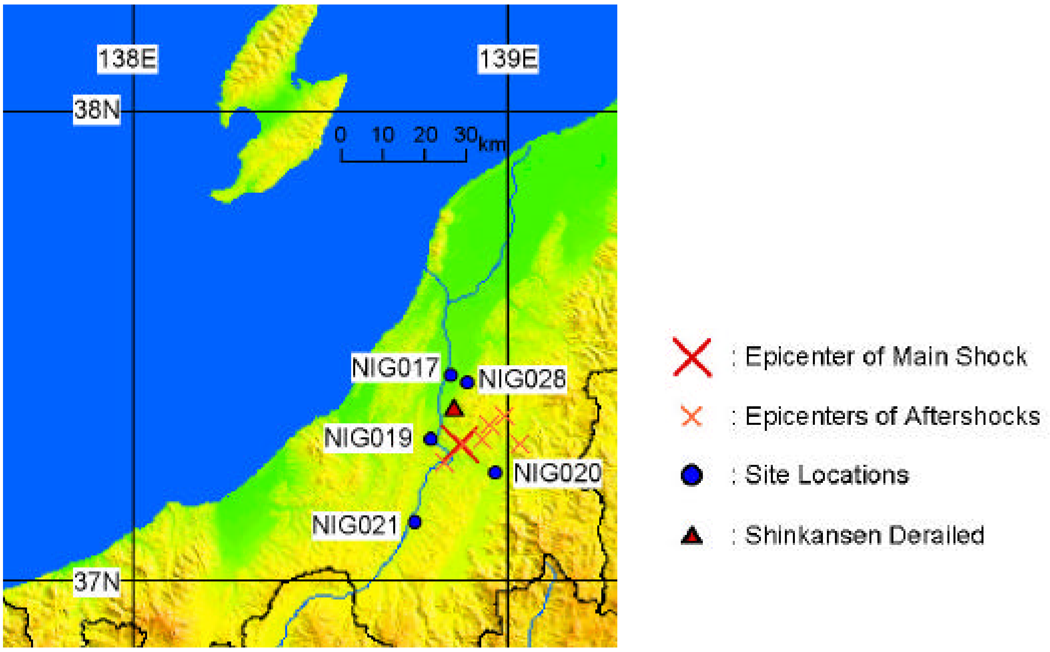
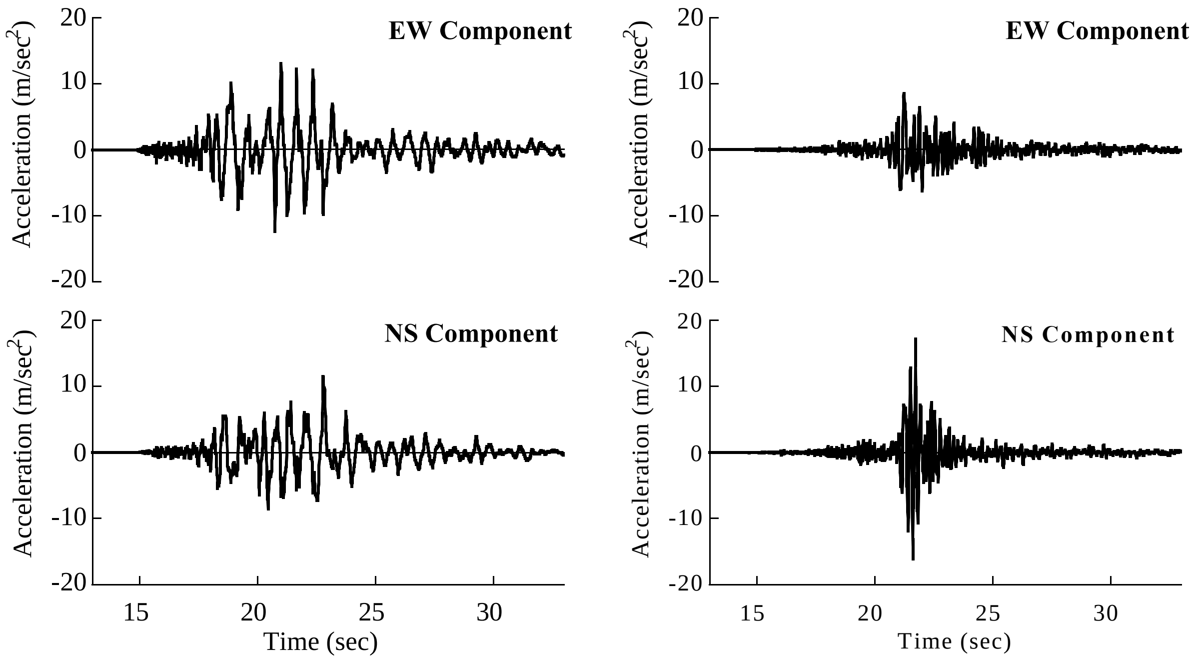


Fig. 1 Epicenters and K-NET stations near epicenters (K-NET/NIED)

GROUND MOTION ANALYZED AND ELASTIC RESPONSE SPECTRA

Six aftershocks with $M_j > 5.5$ occurred in the mid Niigata region within 10 days after the main shock with $M_j = 6.8$ occurred as shown in Table 1. Fig. 1 shows site locations of K-NET instruments near the epicenters where strong ground motions were recorded. A peak ground acceleration of 17.2 m/sec^2 was recorded at the Tohkamachi (NIG021) site during the main shock.



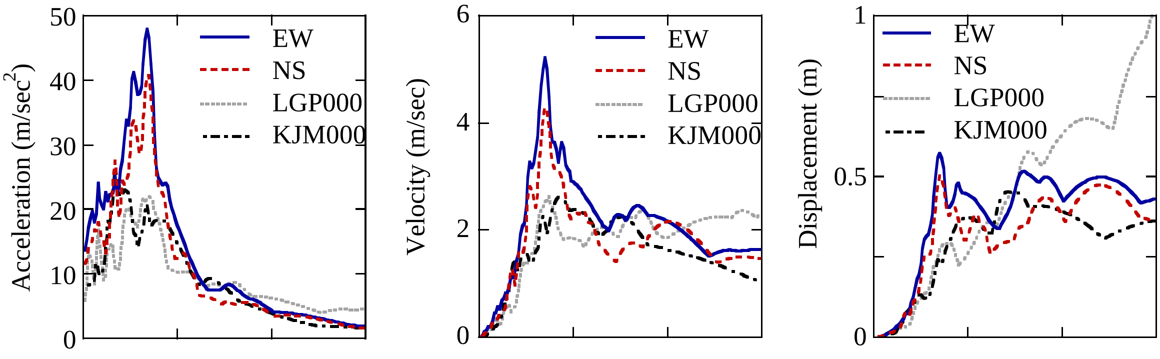
(a) Ojiya records (b) Tohkamachi records

Fig. 2 Strong ground motions recorded during main shock

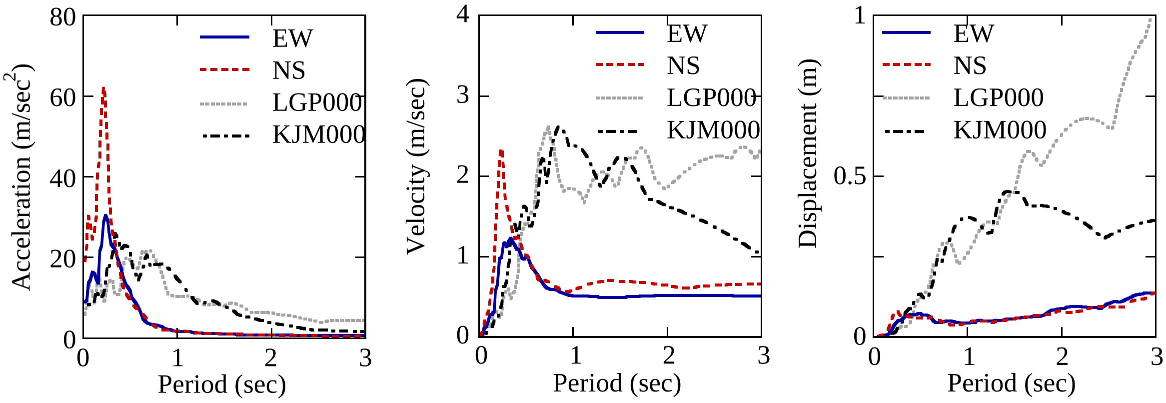
This study focuses on ground motions recorded at the Ojiya (NIG019) and Tohkamachi (NIG021) sites, where extremely strong ground motions with PGA in excess of 10 m/sec^2 were recorded during the main shock. Results from the other ground motions recorded in the earthquakes can be found in a report by Sakai and Mahin (2004). Figure 2 plots the ground accelerations recorded at the Ojiya (NIG019) and Tohkamachi (NIG021) sites. The peak ground accelerations were 17.2 m/sec^2 and 13.1 m/sec^2 for the NIG021 (NS) and NIG019 (EW) sites, respectively.

Figure 3 compares elastic response spectra for the ground motions recorded at the Ojiya (NIG019) and Tohkamachi (NIG021) sites during the main shock of the Niigata-Ken Chuetsu earthquakes with the Los Gatos (LGP000) record from the 1989 Loma Prieta, California, earthquake and the JMA Kobe (KJM000) record from the 1995 Hyogo-Ken Nanbu, Japan, earthquake (Regents of the University of California, 2000). These spectra are computed for elastic systems with periods ranging from nearly zero through 3 seconds and having a viscous damping ratio of 5%. Smooth design spectra representative of those used in California and Japan for this level of shaking are shown in Fig 4. In these figures, curves labeled ARS correspond to criteria used by the California Department of Transportation for a stiff soil (Soil profile type D) site, and for an earthquake magnitude of 6.5 ± 0.25 and a PGA= 0.6 g (California Department of Transportation, 2001). The curves labeled JRA correspond to a stiff soil (Soil condition I) site, a Level 2 and Type II ground motion in accordance with the Japanese Design Specification of Highway Bridges by Japan Road Association (2002).

The NIG019 records have peaks around 0.7 second in the acceleration, velocity and displacement response spectra. The peak spectral accelerations are 48 m/sec^2 and 41 m/sec^2, and peak displacements are 0.57 m and 0.5 m for EW and NS components, respectively. Both components of the NIG019 records have equivalent or larger spectral amplitudes than the Los Gatos and the JMA Kobe records up to 1.5 seconds, which indicates that the earthquakes could be more destructive to structures in that natural period range than other recent earthquakes in California and Japan. The NIG019 records also exhibit a relative peak in the spectral curves at a period of about 1.6 to 2 seconds. Such peaks may be representative of the effects of the rupture mechanism on records obtained at near-fault sites or the effect of soil or topological conditions at the recorded site. The NIG019 records also show larger

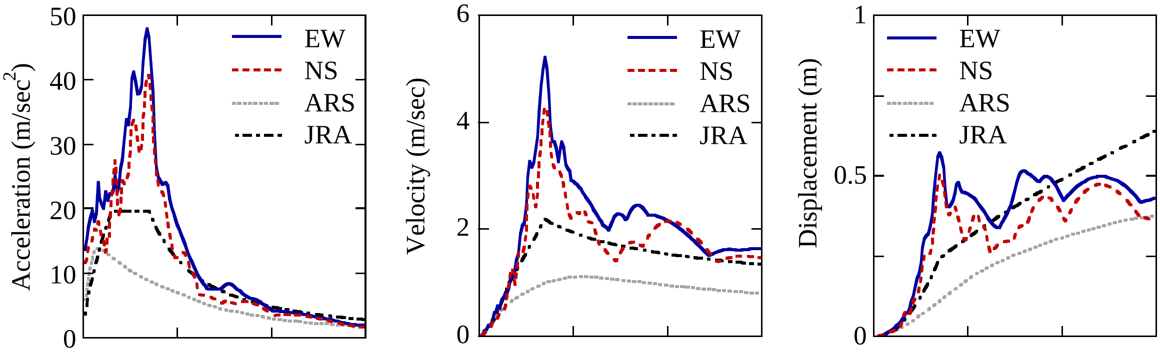


(a) Ojiya (NIG019) records

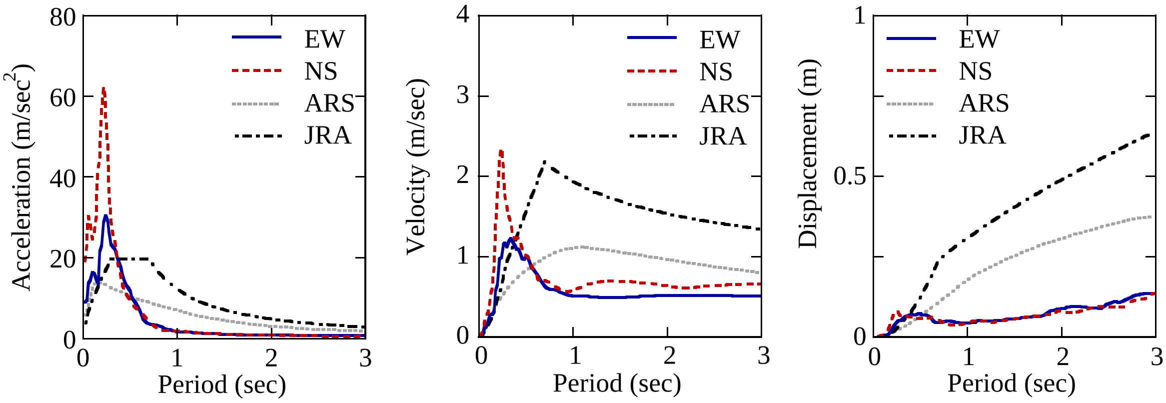


(b) Tohkamachi (NIG021) records

Fig. 3 Elastic response spectra compared with past earthquake records



(a) Ojiya (NIG019) records



(b) Tohkamachi (NIG021) records

Fig. 4 Elastic response spectra compared with design spectra spectral values than those of the current design codes up to natural period of 2 seconds.

The NS component of the NIG021 records has very large peak spectral acceleration response at around 0.2 second; however, it decreases sharply as the natural period increases, and the acceleration response is only 2 m/sec^2 at 1 second. Although the peak ground acceleration of the NS component was nearly 2 g, the narrow banded nature of the spectra suggests that this record may not be too damaging outside of the short period range.

NONLINEAR RESPONSE OF SDOF SYSTEMS

To investigate the nonlinear response of structures subjected to the records obtained from the main shock of the Niigata-Ken Chuetsu earthquakes, a series of nonlinear response analyses was conducted with using the BiSpec (Hachem, 2000; Hachem et al., 2003), a computer program that can generate nonlinear response spectra for single-degree-of-freedom systems having bilinear or stiffness degrading hysteretic characteristics. These models represent hysteretic behavior of steel structures and reinforced concrete structures, respectively. This paper shows results with stiffness degrading models although both hysteretic models are considered in the study. Stiffness degrading models tend to provide smaller maximum and residual displacements than bilinear models. Results with bilinear models can be found in the report by Sakai and Mahin (2004).

Figure 5 the stiffness degrading model used, which is so-called the Clough model and one of the simplest models for reinforced concrete structures. The unloading stiffness of the model is always the same as the initial elastic stiffness while the reloading stiffness decreases with increment of lateral displacement as the reloading path is directed to the point of the experienced maximum displacement. The post-yield tangent stiffness is fixed at zero, and 5% of viscous damping ratio is considered.

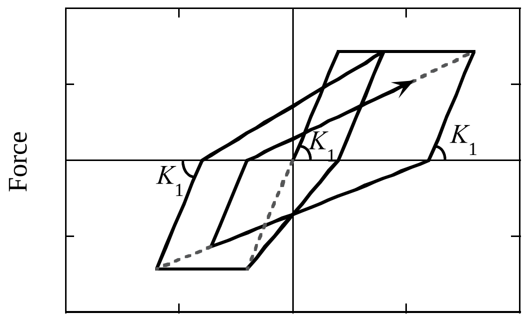
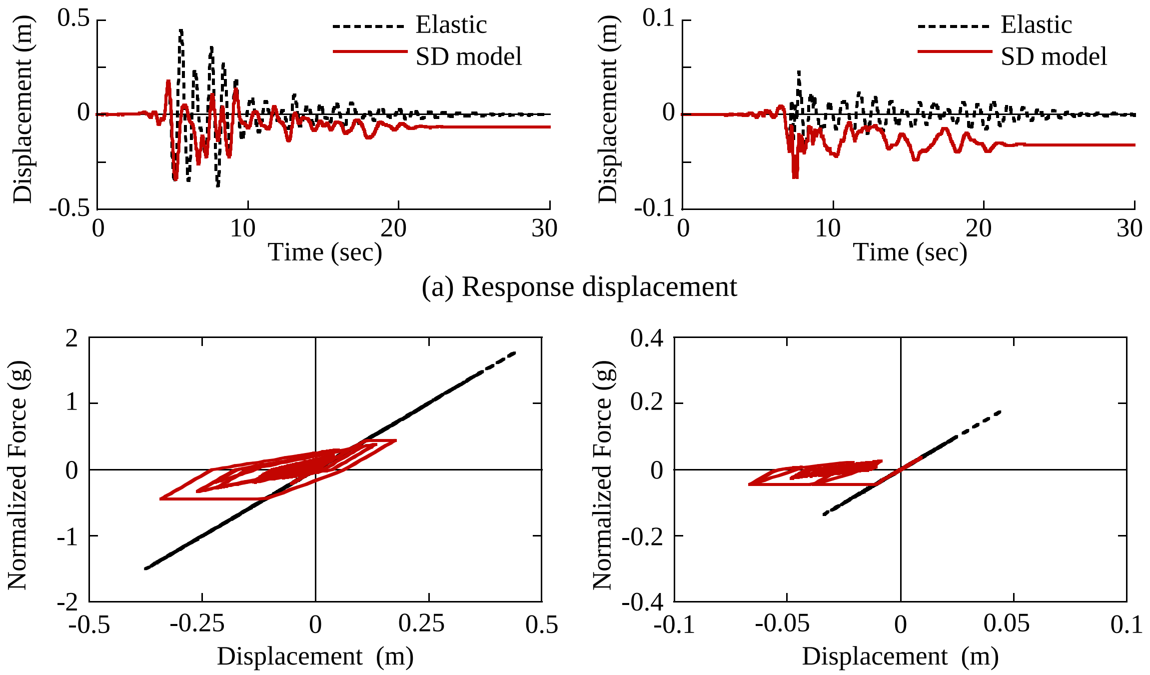


Fig. 5 Stiffness degrading models

Figure 6 shows examples of nonlinear response computed with the BiSpec for the EW component of Ojiya, NIG019, records and NS component of Tohkamachi, NIG021, records. The natural period of the single-degree-of-freedom system is 1 second, and R, which is defined below, is 4.

$$R = \frac{D_{el}}{D_y} \tag{1}$$

where D_{el} is the maximum displacement of elastic system with a corresponding natural period and D_y is the yield displacement of a nonlinear structure. Thus, the structure is only one-fourth as strong as it would have had to be to remain elastic.



(a) Response displacement

(b) Force-displacement hystereses

(1) Ojiya (NIG019) EW record (2) Tohkamachi (NIG021) NS record

Fig. 6 Nonlinear dynamic response of SDOF system

The nonlinear maximum response of the system subjected to the Ojiya record is smaller than the elastic response. The response ductility is about 3. On the other hand, when the Tohkamachi record is considered, the nonlinear responses become 50% larger than the elastic response, which results in a displacement ductility of more than 6. However, note that the nonlinear maximum displacement for the Tohkamachi record is only 25% of that for the Ojiya record. The elastic spectra in Figs. 3 and 4 show that response of a 1 sec. period structure to the Tohkamachi record is only about one-tenth of that to the Ojiya record. Even so, for an R of 4, the displacement ductility of the systems subjected to the Tohkamachi record is substantially larger than for the Ojiya record, suggesting that the Tohkamachi record has a more serious effect on nonlinear response in this period range. Consequently, the Tohkamachi record produces larger residual displacement ductility.

NONLINEAR RESPONSE SPECTRA

To evaluate such nonlinear response for various natural periods, nonlinear response spectra with constant R are generated. Four R values, 1, 2, 4 and 8, are considered in the study, and Figure 7 shows nonlinear response spectra of maximum displacements D_{max} and residual displacements D_{res} as well as for several normalized displacement quantities: displacement ductility (D_{max}/D_y), residual displacement ductility (D_{res}/D_y), gamma (D_{el}/D_{inel}), and D_{res}/D_{max} for an R of 4, which is a value that engineered structures would likely have as current seismic design codes require (e.g., California Department of Transportation, 2001). For the plots, four ground motions (NIG019EW, NIG021NS, LGP000 and KJM000) are considered. The structural systems are represented by stiffness degrading models with zero post-yield stiffness and 5% of viscous damping. The plots demonstrate how structures behave nonlinearly under the above ground motions, if structures are designed according to a corresponding ground motion with R = 4. Results for the other R values can be found in the report (Sakai and Mahin, 2004).

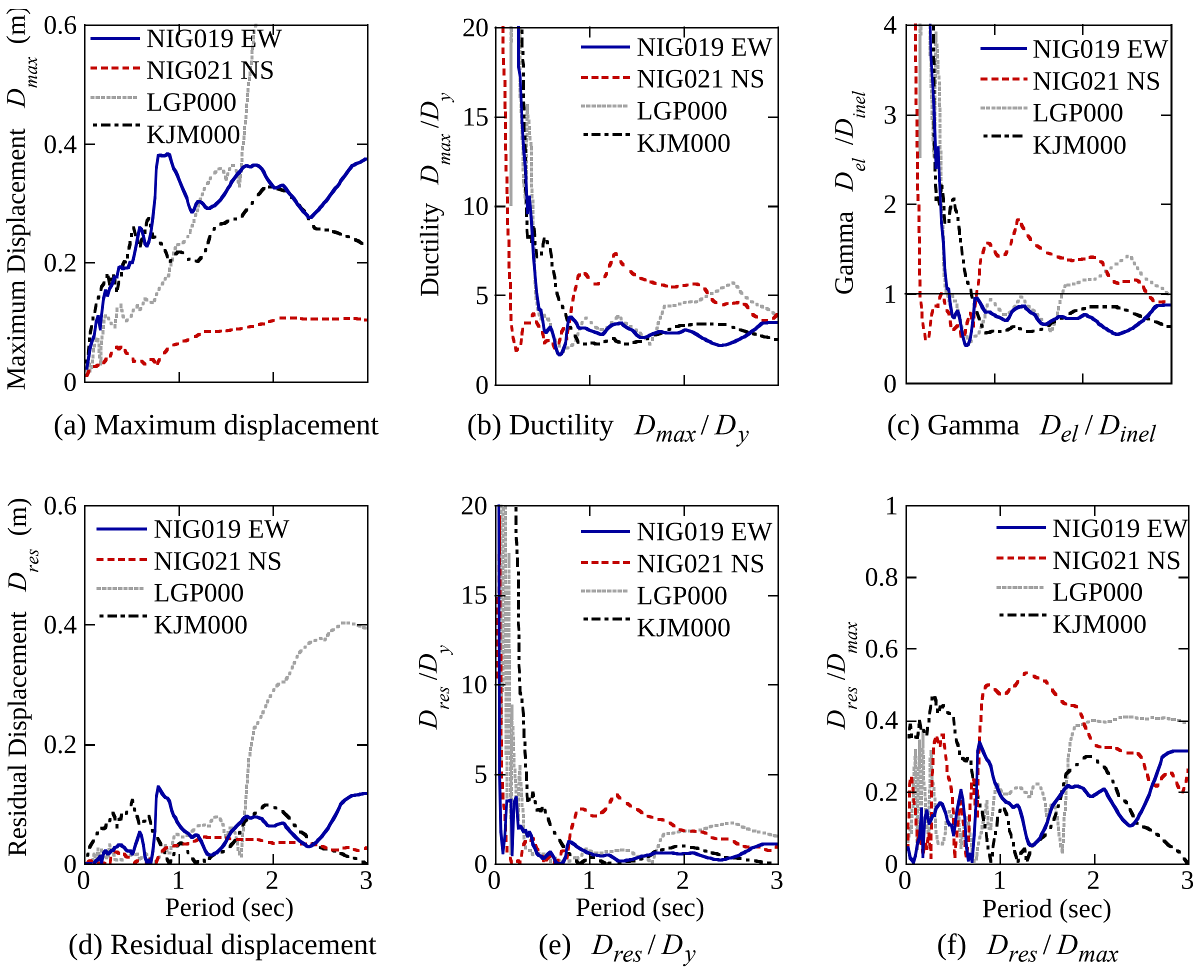


Fig. 7 Nonlinear response spectra with $R = 4$

The EW component of Ojiya (NIG019) records produces equivalent or larger nonlinear response than the other records for natural periods ranging between 0 and 1.7 seconds, and, in particular, relatively large displacements are predicted for natural periods between 0.7 and 1.25 seconds. The gamma value plots show the nonlinear response to NIG019EW is smaller than the elastic response when the natural period of structures is larger than 0.5 seconds. This can also be seen from the ductility plot where the computed displacement ductility in this range is less than the R value used (i.e., 4). This implies the equal displacement rule often used in design may be conservative in this range for the EW component of Ojiya records. For structures with periods less than about 0.5 sec., the nonlinear displacements significantly exceed those predicted elastically. Although the residual displacements have relatively larger values for structures with periods above 0.7 seconds, these displacements are generally smaller or equal to the yield displacements of the structure in this period range for NIG019EW.

The NS component of Tohkamachi (NIG021) records shows only about 40% of the maximum displacements of the other records considered; however, the response ductility and gamma values show this record tends to produce larger nonlinear response displacements than those predicted based on the equal displacement rule (except for periods between 0.2 and 0.8 seconds, where there is a peak followed by a descending branch in the spectral acceleration and spectral displacement curves). Residual displacements become relatively large, reaching about 4 times of the yield displacements or 50% of the peak displacements for periods between 0.75 and 1.75 seconds.

EFFECT OF AFTERSHOCKS

In the aftershocks of the Niigata-Ken Chuetsu earthquakes, strong ground motions with PGA > 4 m/sec^2 were recorded in several sites, as shown in Table 1. To evaluate the intensity and effects of the aftershocks on the accumulation of damage and drift of structures, further linear and nonlinear dynamic analyses were conducted. Figure 8 shows the combined ground motions resulting from the main shock and selected aftershocks for the Ojiya (NIG019) EW records and Tohkamachi (NIG021) NS records. Thirty seconds intervals from the strong motion portions of the original records are combined together to form one 90 or 60 second long ground motion record for use in these analyses.

Figure 9 shows the effect of aftershocks on elastic response spectra. The records at the Ojiya (NIG019) site show no effect of the aftershocks because the PGAs of the aftershocks are about 40% of the main shock. On the other hand, the aftershock recorded at the Tohkamachi (NIG021) site has larger intensity than the main shock according to the elastic response spectra although the PGA of the aftershock is only about half of the main shock.

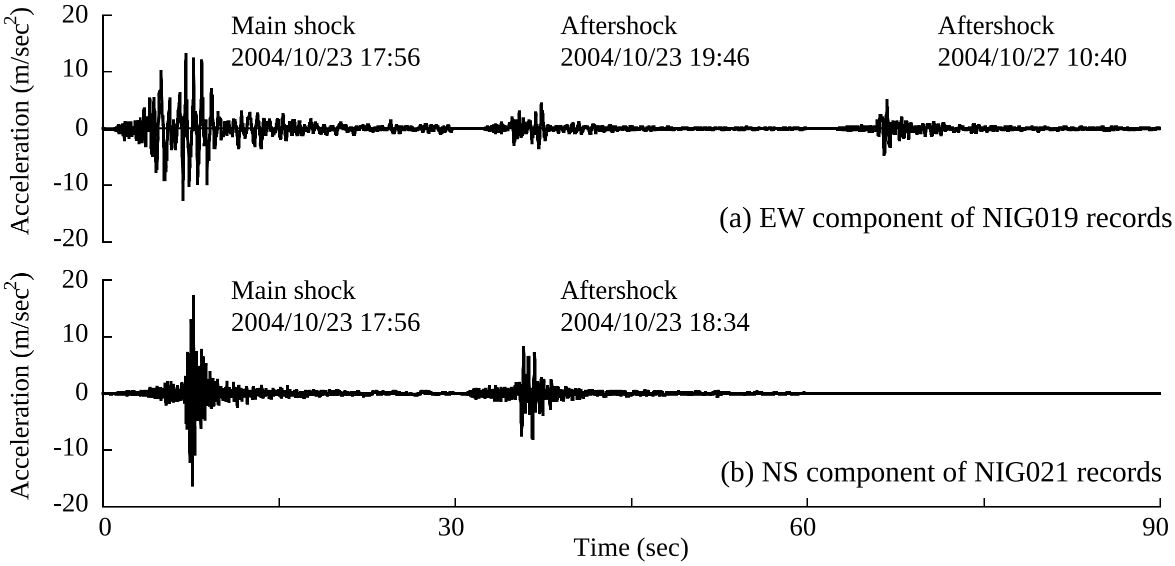
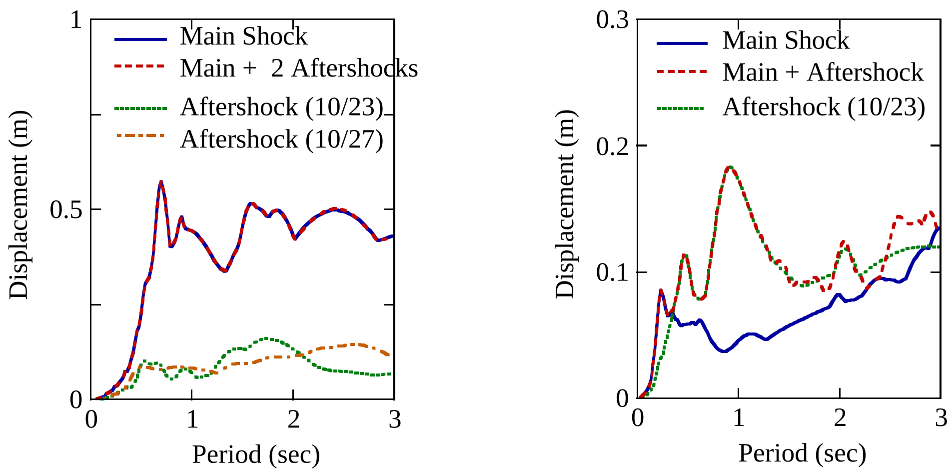
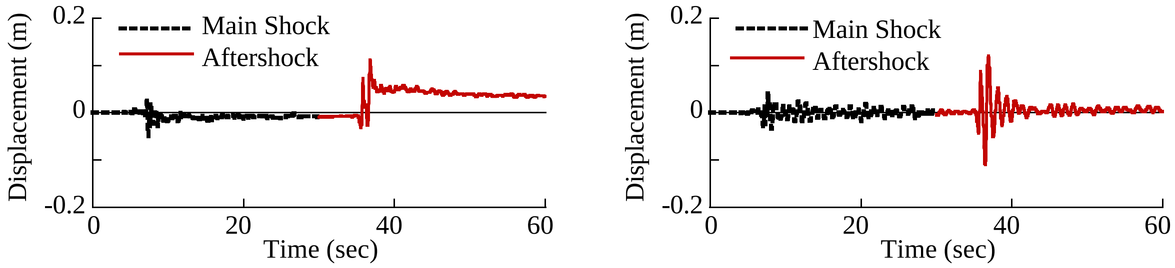


Fig. 8 Acceleration time histories of combined ground motions

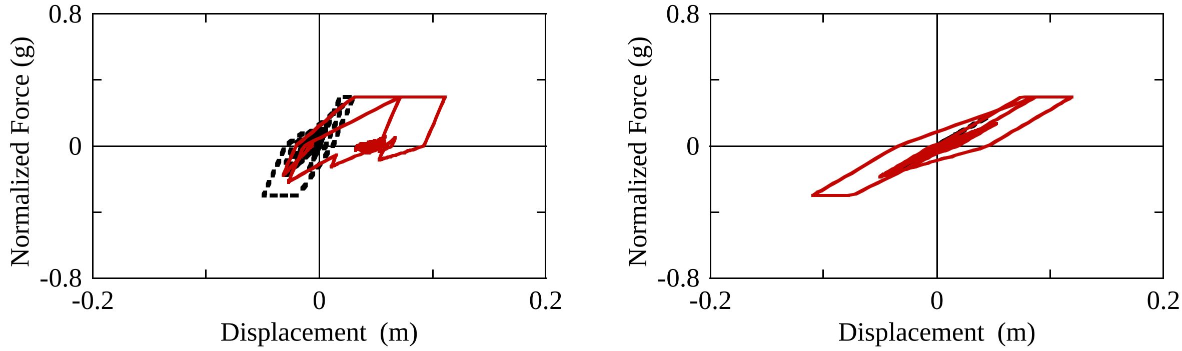


(a) Ojiya (NIG019) record (EW component) (b) Tohkamachi (NIG021) record (NS component)

Fig. 9 Effect of aftershocks on elastic response spectra



(a) Response displacement



(b) Force-displacement hystereses

(1) T = 0.5 sec and a_y = 0.3 g (2) T = 1.0 sec and a_y = 0.3 g

Fig.10 Nonlinear dynamic response for combination of main shock and aftershock of NS component of Tohkamachi (NIG021) records

Figure 10 shows nonlinear response of structures with 0.5 and 1 second of natural periods and 0.3 of normalized yield strength a_y for the Tohkamachi (NIG021) NS records. The stiffness degrading models with zero post-yield tangent stiffness and 5% viscous damping are considered. The aftershock produces even larger nonlinear response for the structure with 0.5 seconds. When the natural period is 1 second, the structure yields during the aftershock even though it remains elastic during the main shock.

Extending the results shown in Fig. 10 for various periods, another series of nonlinear response spectra were generated. The spectra were generated with constant normalized yield strength of structures a_y = 0.3 g to evaluate the effect of aftershocks because the yield displacements can be different between the main shock ground motion and the combined ground motion of the main and aftershocks if constant R is assumed. The stiffness degrading models with zero post-yield tangent stiffness and 5% viscous damping are considered for these analyses. Figure 11 shows the effect of aftershocks on the nonlinear response spectra for a_y = 0.3 g when subjected to the Tohkamachi (NIG021) NS records. When the aftershock strikes structures with natural period range of 0.5-1.5 seconds, the response increases up to 2 times of that occurs during the main shock, which results in larger residual displacements as well.

CONCLUSIONS

During a sequence of destructive earthquakes that struck the Niigata Chuetsu region, Japan, October 2004, valuable strong ground motions were recorded. A series of linear and nonlinear analyses was conducted to investigate the characteristics of the ground motions obtained during the Niigata-Ken Chuetsu earthquakes. These studies suggest that:

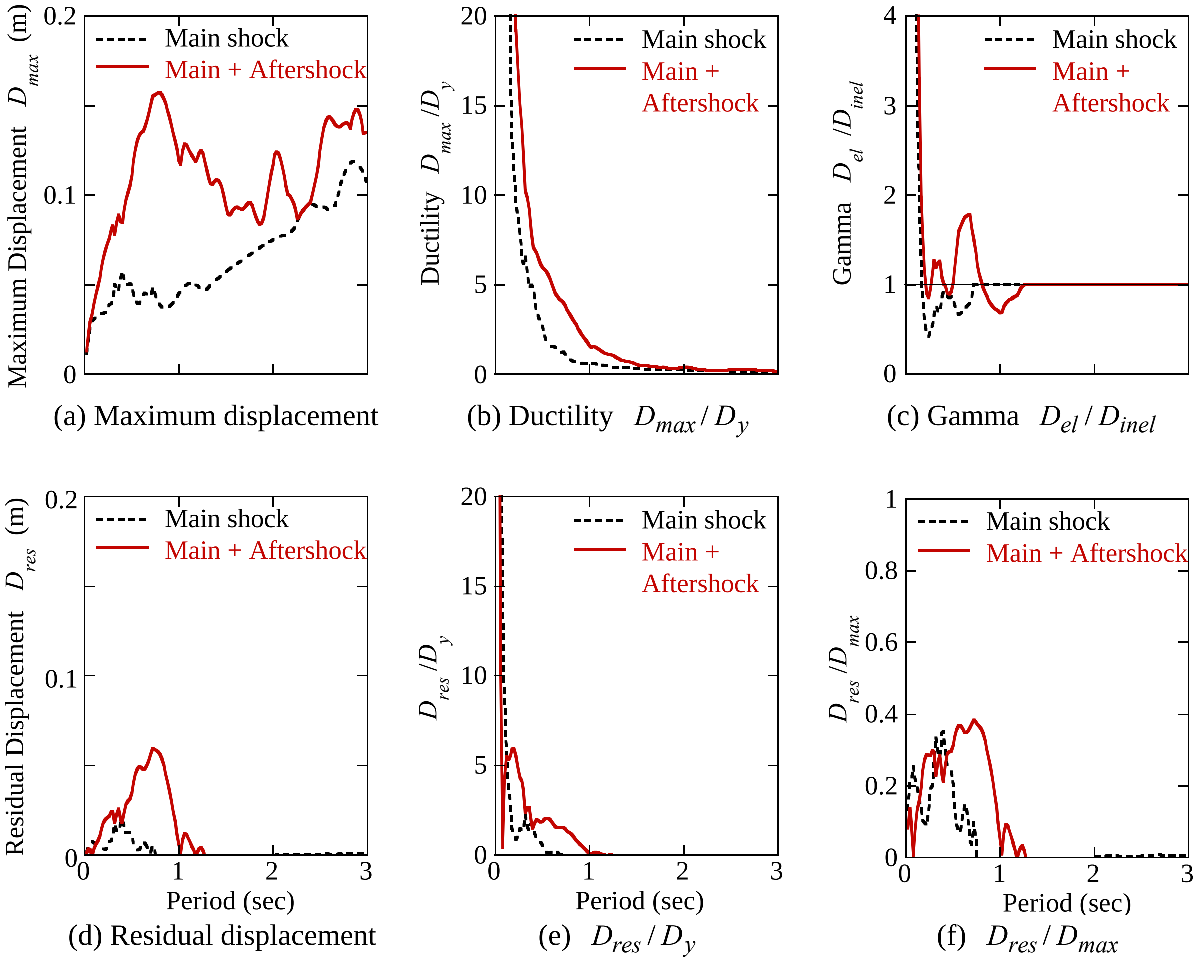


Fig. 11 Effect of aftershock on nonlinear response spectra with a_y = 0.3 g for NS component of Tohkamachi (NIG021) records

1) The records obtained close to the epicenter of the main shock (NIG019) produce larger response than those of the current design codes up to natural period of 2 seconds. The records have spectral amplitude up to about 1.5 seconds equivalent or larger than the Los Gatos record from the 1989 Loma Prieta earthquake and the JMA Kobe record from the 1995 Hyogo-Ken Nanbu earthquake.

2) The record with extremely large peak ground acceleration (= 17.2 m/sec^2) obtained at the Tohkamachi (NIG021) site produce large response only for relatively stiff structures. The response spectrum shows only 2 m/sec^2 around 1 second of natural period. Thus, damage caused by the ground motion could be limited only to especially weak structures or structures with short natural period range.

3) Nonlinear response spectra demonstrate that the EW component of Ojiya (NIG019) records could produce relatively large response displacement to structures with natural period of 0.7 to 1.25 seconds. However, the nonlinear response is smaller than the elastic response when the natural period of structures are larger than 0.5 seconds, which implies the equal displacement rule may be conservative in this range for this ground motion.

4) The NS component of Tohkamachi (NIG021) records does not produce large response compared to the Ojiya record. However, if yielding occurs, this record tends to produce larger nonlinear response displacements than those predicted based on the equal displacement rule.

5) The ground motions recorded at the Tohkamachi (NIG021) site during the aftershock that occurred 38 minutes after the main shock could produce larger response than those during the main shock. When the aftershock strikes structures with natural period range of 0.5-1.5 seconds, the response increases up to 2 times of that occurs during the main shock, which results in larger residual displacement as well.

6) Additional studies of these records are warranted to correlate observed damage with that predicted on the basis of numerical analyses, and to extend the scope of simple analyses such as those presented herein to include the effects of multiple components of excitation on nonlinear response.

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