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INFLUENCE OF STATIC DISPLACEMENT ON PEAK GROUND VELOCITY AT SITES THAT EXPERIENCED FORWARD-RUPTURE DIRECTIVITY

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This paper examines the contribution of the static displacement to the value of peak ground velocity at sites, where forward-rupture directivity took place. Time-history of the permanent displacement is approximated with a normal probability density function. A simple superposition of the static and dynamic displacement fields is considered and a procedure for removal of the permanent displacement is applied to several strong motion records with large final offset. Compared are the elastic SDOF-system demands due to ground motion with and without permanent displacement.

Key Words : *static displacement, peak ground velocity, forward-rupture directivity*

1. INTRODUCTION

Large-magnitude earthquakes are capable of producing extensive permanent ground displacements in the near-fault region. Maximum permanent displacement along the fault was measured about 10 m for the 1999 Chi-chi, Taiwan earthquake (JSCE 1999). Permanent ground displacements that accompany a seismic event are a consequence of the fault slip and are referred as the static displacement field of that event or as coseismic displacements (Hall et al. 1995, Tatcher 1986). They differ from the ground displacements induced by the seismic waves, which are generated during earthquake rupture propagation and referred as dynamic displacement field.

Despite their name, near-fault static displacements are developed rapidly, within a short period of time that is related to the slip rise time. Since they are likely to be non-reversal and continuous, their time history will appear as a pulse of motion with a ramp-type shape. Pulse-like dynamic ground displacements are observed near the fault due to the forward-rupture directivity effect. This effect occurs when the fault rupture propagates toward a site at a velocity nearly the S-wave velocity and causes S-waves to arrive simultaneously in a single pulse at the beginning of the seismic record (Somerville et al. 1997). Following the S-wave radiation pattern, the dynamic displacement pulse is oriented in normal to the fault direction and its amplitude can attain values as high as several meters. The high values of peak ground velocity (*PGV*) at many near-fault sites are often associated with similar pulses.

The objective of this paper is to examine the contribution of the permanent displacement to the value of *PGV* at sites, where forward-rupture directivity took place. A simple superposition of the static and dynamic displacement fields is considered and a procedure for removing of permanent displacement is applied to several strong motion records with large final offset.

2. NEAR-FIELD SEISMIC RECORDS WITH LARGE PERMANENT DISPLACEMENT

A set of five near-field ground motion records with large permanent displacement is utilized throughout

Table 1. Basic properties of strong motion records.

Recording Station	Earthquake	Magnitude M_w	Directivity	Shortest Distance (km)
Lucerne Valley	Landers, 1992	7.3	forward	1.1
Rinaldi Receiving Station	Northridge, 1994	6.7	forward	7.5
Shihkan (TCU068)	Chi-chi, Taiwan, 1999	7.6	forward	5.2
Tanstu (TCU052)	Chi-chi, Taiwan, 1999	7.6	forward	4.0
Tsaotun (TCU075)	Chi-chi, Taiwan, 1999	7.6	forward	1.0

the study. The basic properties of these records are listed in Table 1. The original waveforms are rotated to direction normal to the seismic fault, except for the record at Rinaldi Receiving Station. Detailed information about the strong motion records is given hereafter.

The record at Lucerne Valley was obtained during the strike-slip 1992 Landers earthquake. The station was located within a distance of 2 km from the fault trace and 42 km from the epicenter. Due to the forward-rupture directivity, the ground motion resulted in a large brief pulse. Iwan & Chen (1995) have tested the response of the recording accelerometer and developed a new data processing procedure in order to preserve the permanent displacement. The procedure revealed a recorded horizontal static displacement of nearly 2 meters.

Ground motion at Rinaldi Receiving Station was recorded in the 1994 Northridge earthquake that occurred on a previously unknown blind thrust fault. The station was sited within the Van Norman Complex, Los Angeles Department of Water and Power. The instrument was located above the fault plane, at its northern boundary (the buried fault rupture) and 9 km from the epicenter. Static displacements of amplitude several tens of centimeters were observed elsewhere in the Van Norman Complex using GPS and leveling data (Bardet & Davis 1996). The accelerogram at Rinaldi Receiving Station provided the largest ground velocity instrumentally recorded in the USA, 178 cm/s. The record used in this study is corrected without band-pass filtering and shows a final offset.

Large permanent ground displacements took palce near the Chelungpu fault during the 1999 Chi-chi, Taiwan earthquake. Maximum displacement amplitudes reached 6 to 10 meters on the hanging wall site, north from the epicenter. Central Weather Bureau, Taiwan released a CD-ROM with the uncorrected ground motion at 422 stations. Three near-fault records are used in this study - Shihkan (TCU068), Tanstu (TCU052) and Tsaotun (TCU075). All the records exhibit forward-rupture directivity effect. A ground velocity of 281 cm/s was recorded at Shihkan (TCU068) on the northern end of the fault. In fault-normal direction, the velocity of the ground reaches 383 cm/s. A similar procedure to that of Iwan & Chen (1995) was applied to account the acceleration baseline shifts. The shift amplitude is determined from a least-mean-square linear fit of the latter portion of the velocity and applied starting from the cross-section point of the fitting line with the original baseline. The permanent displacements obtained are consistent with the GPS-measured surface displacements.

3 CLOSED-FORM APPROXIMATION OF STATIC DISPLACEMENT

Consider a forward pulse-like displacement time history that represents the ground motion due to the static displacement field of an earthquake. As an approximation of the corresponding velocity pulse $v_{sp}(t)$ can be used a Gaussian-type function

$$v_{sp}(t) = V_{sp} \exp\left\{ -\frac{1}{2}\left[\frac{(t-t_c)}{T_p/n}\right]^2 \right\} \tag{1}$$

where V_{sp} is the amplitude of static velocity pulse, T_p - velocity pulse duration (period), t_c - time instant, at which the pulse is centered, n - constant equal to 6 and t is the time. The term T_p/n has the meaning of standard deviation and controls the actual spread of the pulse with respect to the given pulse duration T_p. Integration of Eq. (1) yields the static displacement pulse $d_{sp}(t)$

$$d_{sp}(t) = \frac{\sqrt{2\pi}}{n} V_{sp} T_p \Phi\left[\frac{(t-t_c)}{T_p/n}\right] \tag{2}$$

where Φ is the normal probability density function. Taking the derivative of Eq. (1) yields the acceleration pulse $a_{sp}(t)$

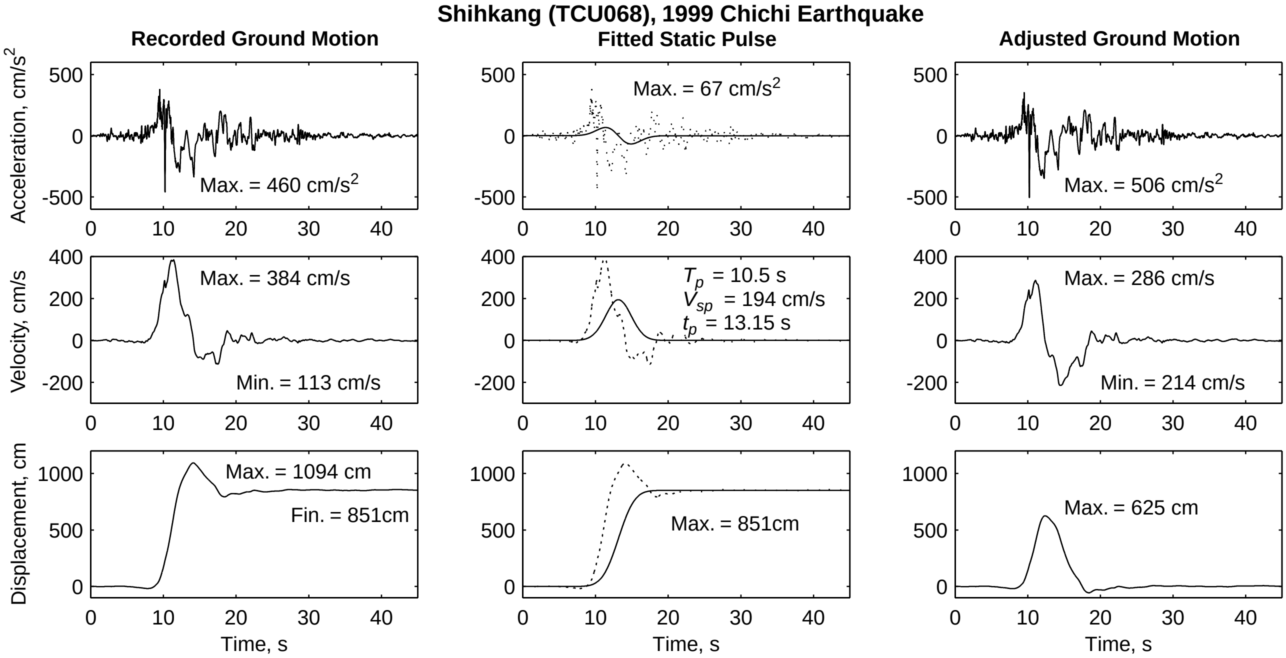

Figure 1. Time histories of original and adjusted motion at Shihkan (TCU068) from the 1999 Chi-chi, Taiwan earthquake.

$$a_{sp}(t) = \frac{-n^2 V_{sp}}{T_p^2}(t - t_c)\exp\left\{-\frac{1}{2}\left[\frac{(t-t_c)}{T_p / n}\right]^2\right\} \qquad (3)$$

Above time-histories have two advantages over the other shapes: 1) acceleration pulses are continuous functions that causes the SDOF-system acceleration response spectrum to approach peak ground acceleration at periods near zero and 2) relative time of pulse occurrence is explicitly implemented, which is useful for its parameterization.

4 REMOVAL OF STATIC DISPLACEMENT IN NEAR-FIELD SEISMIC RECORDS

In order to grasp the influence of the static displacement to the *PGV* values, a procedure for its removing is applied to the original ground motion and adjusted motion without static displacement is obtained. The procedure includes two steps. First step is to construct acceleration, velocity and displacement pulses using Eqs. (1) to (3) and second step is to extract these pulses from the original ground motion. In the superposition of the static- and dynamic-displacement pulse, it is assumed that they take place simultaneously and their duration is equal. The period of the static displacement is taken as the two time-intervals, within which maximum and minimum velocity occurs. Duration of the pulse T_p is determined as the sum of the corresponding zero-crossing periods and the center of the pulse t_c is the middle of that interval. Velocity pulse amplitude V_{sp} is determined from the displacement at the end of the ground motion.

The procedure for removing the static displacement is applied for the seismic records described in Section 2. The time-histories of the ground motion with and without permanent displacement at Shihkan are depicted in Figure 1. The values of *PGV* for the recorded and adjusted ground motions as well as the period of the fitted static pulse and recorded final displacement are listed in Table 2. The ratio of the two peak

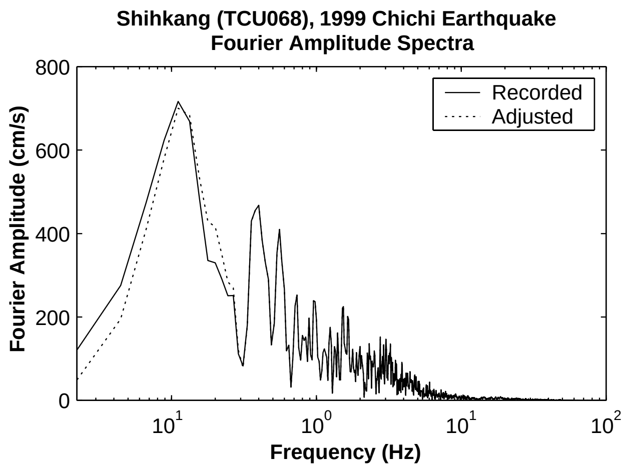

Figure 2. Fourier spectrum of original and adjusted motion at Shihkan, 1999 Chi-chi, Taiwan earthquake.

Table 2. Values of recorded and adjusted peak ground velocity.

Seismic Record	*PGV* Recorded (cm/s)	T_p (s)	*PGV* Adjusted (cm/s)	Ratio of Recorded to Adjusted *PGV*	Static Displacement (cm)
Lucerne Valley	132	8.5	103	1.28	137
Rinaldi Receiving Station	178	1.26	99	1.80	49
Shihkan (TCU068)	384	10.5	286	1.34	851
Tanstu (TCU052)	266	8.7	146	1.82	767
Tsaotun (TCU075)	116	5.85	71	1.63	113

velocities varies from 1.28 to 1.82. This result implies that the static displacement can contribute considerably to the value of *PGV* at near-field sites. However, forward-rupture directivity is the main reason for the high peak velocity amplitudes at these sites.

Figure 2 plots the Fourier spectra for the recorded and adjusted motion at Shihkan. It can be seen that the applied procedure has an effect of decreasing the Fourier spectrum amplitudes in the range below the static-pulse frequency, but not cutting them.

5 COMPARISON OF ELASTIC SDOF-SYSTEM DEMANDS DUE TO NEAR-FIELD MOTION WITH AND WITHOUT STATIC DISPLACEMENT

Effect of static displacement can be evaluated by comparing the demands of elastic SDOF systems with 5% critical damping subjected to the recorded and adjusted ground motions. The strength demand spectra due to the Rinaldi Receiving Station record pair are displayed in Figure 3. The difference between the spectral values of the adjusted and original accelerations becomes significant after the static pulse period i.e. around 1.0 seconds.

Figure 4 shows the SDOF-system displacement demands due to same motions. In the short period range, the two spectral ordinates are very close. The difference in the displacement demands starts to appear after the static-pulse period and increases with the growth of the period, reaching more than 50 per cent of the spectral ordinate of recorded motion at periods around 4.0 seconds.

Since the static-pulse period is short enough in the case of Rinaldi Receiving Station record, the difference between displacement demands due to original and adjusted motion can affect range of urban structures. Somerville (2000) emphasized that the near-fault ground motions from smaller earthquakes of magnitude M_w 6.7 to 7.0 (as the 1994 Northridge earthquake) are stronger in the period range 0.5 to 2.5 s than these from larger events of magnitude M_w 7.2 to 7.6 (as the 1999 Chi-chi,

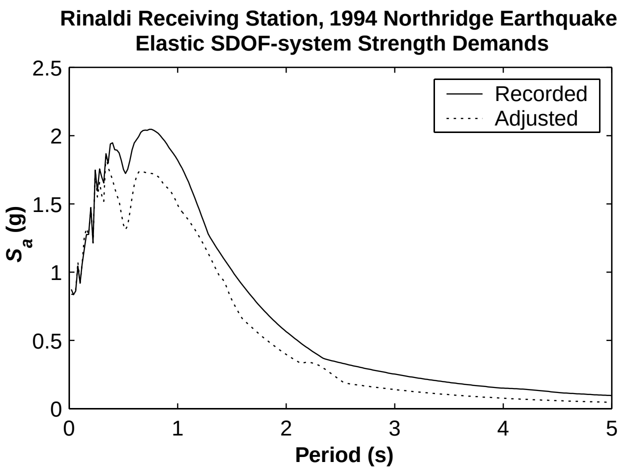

Figure 3. Elastic SDOF strength demands of original and adjusted motion at Rinaldi Receiving Station from the 1994 Northridge earthquake.

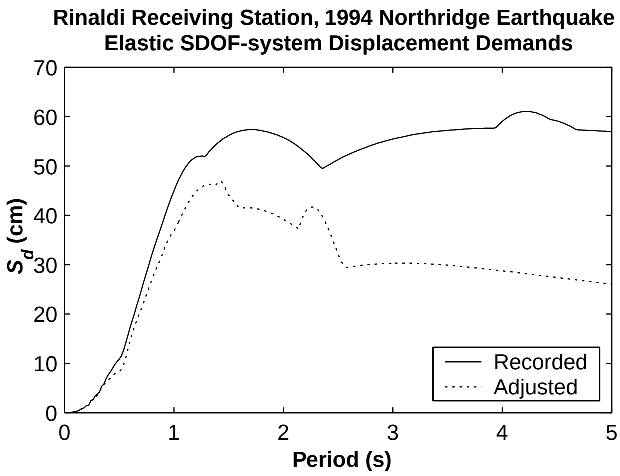

Figure 4. Elastic SDOF displacement demands of original and adjusted motion at Rinaldi Receiving Station from the 1994 Northridge earthquake.

Taiwan earthquake) and that the period of the near-field pulse is magnitude dependent.

6 CONCLUSIONS

The influence of the large static displacement on the *PGV* amplitude in near-field pulse-type ground motion is investigated. Permanent displacement is approximated with a normal probability density function. A procedure for its removing is applied to a number of near-field records with large final offset. Compared is the response of SDOF system due to recorded motion with and without static displacement.

Large static displacement can increase considerably the value of the peak velocity. Within the assumptions made, the growth is estimated from 30 to 80 per cent of the *PGV* amplitude due to the dynamic displacement field.

Comparison of demands of elastic SDOF systems, subjected to ground motion with and without static displacement, shows that their difference becomes significant after the period of the static pulse. At longer periods, elastic displacement demands due to the motion with permanent displacement can reach twice the demands due to the motion without it.

REFERENCES

Bardet, J. P. and Davis, C. [1996] "Engineering Observations on Ground Motion at the Van Norman Complex after the 1994 Northridge Earthquake," *Bulletin of Seismological Society of America*, **86**(1B), Special Edition, S333-S349.

Hall, J. F., Heaton, T. H., Halling, M. W. and Wald, D. J. [1995] "Near-Source Ground Motion and Its Effects on Flexible Buildings," *Earthquake Spectra*, **11**(4), 569-605.

Iwan, W. D. and Chen, X. [1995] "Important Near-Field *Proceedings from the 10th European Conference on* Ground Motion Data from the Landers Earthquake," in *Earthquake Engineering*, 229-234, A. A. Balkema, Rotterdam.

JSCE [1999] *The 1999 Ji-ji Earthquake, Taiwan - Investigation into the Damage to Civil Engineering Structures*, Japan Society of Civil Engineers.

Somerville, P. G., Smith, N. F., Graves, R. W. and Abrahamson, N. A. [1997] "Modification of Strong Ground Motion Attenuation Relations to Include the Amplitude and Duration Effects of Rupture Directivity," *Seismological Research Letters*, **68**(1), 199-222.

Somerville, P. G. [2000] "Characterization of Near Fault Ground Motion," in *Proceedings of US-Japan Workshop: Effects of Near-Field Earthquake Shaking, 20-21 March, 2000, San-Francisco,* 5-3 - 5-8, PEER, Richmond, CA.

Tatcher, W. [1986] "Geodetic Measurement of Active-Tectonic Processes," in *Active Tectonics (Studies in Geophysics)*, 155-163, National Academy Press.

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