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Sliding and overturning potential of Christchurch 2011 earthquake records

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SUMMARY

The 22 February 2011 M_w 6.3 earthquake produced a number of unique accelerograms in the city of Christchurch and the port of Lyttelton. Four of these records are analyzed in this paper. The two are from the Christchurch Catholic Cathedral College and Christchurch Hospital stations in the center of the city, which were placed on top of loose sandy soils that suffered softening due to liquefaction; one is from the Lyttelton station, Lyttelton Port Company, on a rock outcrop; and one is from the station at the Heathcote Valley Primary School, on stiff colluvial silts and sands near the edge of a steep and stiff sedimentary basin. The (elastic) response spectra are discussed and related to some salient characteristics of the motions. Symmetric and asymmetric sliding of a block resting through Coulomb friction on horizontal or inclined planes and rocking–overturning of rigid blocks, when excited at their base by these records, offer a strong indication of their 'destructiveness potential'. The corresponding sliding and overturning spectra of the 2011 records are compared with those of some historic accelerograms to get an understanding of the severity of ground shaking that caused 170 deaths and heavy geotechnical and structural damage in the city of Christchurch. The possible role played by the unusually large vertical accelerations is also explored.

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KEY WORDS: New Zealand earthquakes; ground motions; response spectra; sliding spectra; rocking spectra; vertical acceleration; liquefaction

1. INTRODUCTION: THE CHRISTCHURCH EARTHQUAKE RECORDS

Two earthquakes (Darfield, 4 September 2010, and Christchurch, 22 February 2011) with M_w 7.1 and M_w 6.3, respectively, shook the area of Canterbury in New Zealand. They were generated on hitherto completely unknown and unsuspected faults, surprising an earthquake-conscious nation. Several accelerograph stations, well distributed in the city and the surrounding communities, recorded the two events, offering invaluable ground motions. Only records from the second event, the Christchurch M_w 6.3 earthquake, are examined here. Table I lists all those records along with their peak values of acceleration (in all three directions). Figure 1 depicts the locations of the stations on the map (see also [1] for some additional information).

The records used for this study were taken from the GNS (Institute of Geological and Nuclear Sciences) strong-motion database and had their origins in the set of processed accelerograms available from the New Zealand national strong-motion network, GeoNet (ftp://ftp.geonet.org.nz/strong/processed/Proc/2011/). The processing generally follows the Caltech/US Geological Survey 'Volume II' procedures and includes band pass filtering between 0.1 and 25 Hz. For the particular records utilized herein, the band pass filter transition bands are 0.10–0.25 and 24.50–25.50 Hz. These four accelerograms studied in detail were

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Table I. Earthquake records of the 24 February 2011 $M_W = 6.3$ Christchurch seismic event at 14 selected stations in and near the city.

Record name	PGA_{H1} (g)	PGA_{H2} (g)	PGA_V (g)	Soil site
Christchurch Catholic Cathedral College (CCCC)	0.47	0.36	0.68	Estuarine deposits
Christchurch Hospital (CHHC)	0.33	0.35	0.50	Estuarine deposits
Christchurch Botanic Gardens (CBGS)	0.53	0.43	0.27	Estuarine deposits
Christchurch Resthaven (REHS)	0.71	0.37	0.53	Estuarine deposits
Shirley Library (SHLC)	0.31	0.34	0.50	Estuarine deposits
Pages Road Pumping Station (PRPC)	0.66	0.59	1.63	Estuarine deposits
Hulverstone Drive Pumping Station (HPSC)	0.22	0.29	1.07	Estuarine deposits
Christchurch Cashmere High School (CMHS)	0.35	0.40	0.79	Estuarine deposits
Christchurch Canterbury Aero Club (CACS)	0.19	0.22	0.19	Older gravelly deposits
Christchurch Papanui High School (PPHS)	0.21	0.20	0.20	Older gravelly deposits
Riccarton High School (RHSC)	0.29	0.25	0.19	Older gravelly deposits
Styx Mill Transfer Station (SMTC)	0.18	0.14	0.18	Older gravelly deposits
Heathcote Valley Primary School (HVSC)	1.43	1.16	1.44	Very stiff deposit/rock
Lyttelton Port Company (LPCC)	0.77	0.86	0.41	Volcanic rock

PGA, peak ground acceleration.

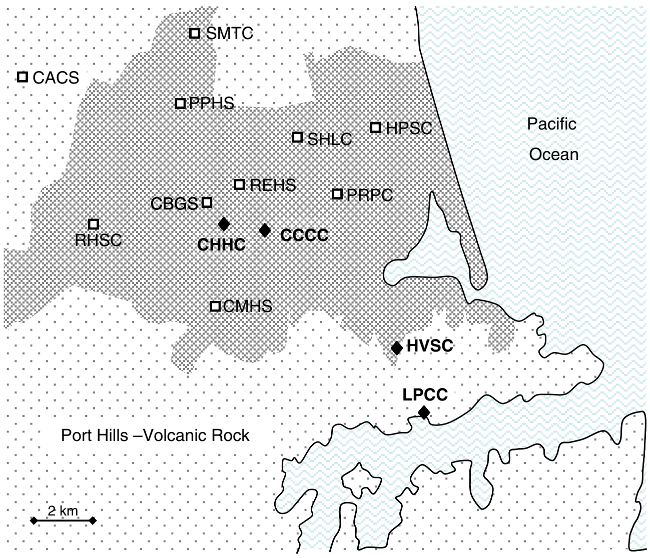

Figure 1. Map of Christchurch area with the location of seismograph stations indicated with open squares and four solid diamonds—the latter for the four stations whose records are studied here. CACS, Christchurch Canterbury Aero Club; CBGS, Christchurch Botanic Gardens; CCCC, Christchurch Catholic Cathedral College; CHCC, Christchurch Hospital; CMHS, Christchurch Cashmere High School; HPSC, Hulverstone Drive Pumping Station; HVSC, Heathcote Valley Primary School; LPCC, Lyttelton Port Company; PPHS, Christchurch Papanui High School; PRPC, Pages Road Pumping Station; REHS, Christchurch Resthaven; RHSC, Riccarton High School; SHLC, Shirley Library; SMTC, Styx Mill Transfer Station.

recorded on the CanNet component of the GeoNet, comprised of Canterbury University Seismograph Project digital accelerographs developed at the University of Canterbury [2, 3] and which employ micro-electro-mechanical system accelerometers with a flat response to well above the Nyquist frequency of 100 Hz. Therefore, such a low high-frequency cut-off is unnecessary.

Furthermore, for near-field records, rich in high-frequency components, the 25-Hz cut-off markedly affects the peak acceleration value. For example, for the Heathcote Valley Primary School (HVSC) record, baseline corrected and filtered with an 80-Hz low-pass filter only, peak acceleration values are 1.68, 1.265, and 2.20 g for the N26E, S64E, and UP components, respectively, compared with 1.43, 1.16, and 1.44 g of the band-pass-filtered, vol. II, accelerograms. Only two of these stations, near the

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Christchurch Hospital (CHHC) and on the grounds of the Christchurch Catholic Cathedral College (CCCC), are the focus of our study.

Christchurch sits on the eastern edge of the 80-km-wide fluvial Quaternary Canterbury Plains. The city is bounded to the east by the Pacific Ocean and to the south by the Port Hills, the northern extremity of the extinct Miocene volcanoes of Banks Peninsula. Beneath Christchurch, the sands and gravels of the Plains sediments are about 700 m deep and are underlain by a further 300 m of weathered volcanics, over greywacke basement. The eastern edge of the Plains sediments is overlain by a thin wedge of very loose fluvial and estuarine sands, silts, and peat, which has a depth of about 30 m at the coast and tapers out unevenly to zero near the western edge of the city [4, 5]. The central city and eastern suburbs are built on this loose layer, and although the former swamps and lagoons are now drained, the water table remains shallow.

The profile has three dominant resonators: (i) the overall profile including the volcanics, (ii) the 700 m of sediment; and (iii) the upper 30 m or less of loose post-glacial soils. With an average shear wave velocity of about 1100 m/s [6] in the overall profile, the effect of the first two comes in at around 3.5 and 2.5 s, respectively [e.g., for the sediments: $T_0 = (4 \times 700\,\text{m})/(1100\,\text{m/s}) = 2.55\,\text{s}$]. The thickness and the stratigraphy of the post-glacial sediments are quite variable, and their effects on surface motion are both variable and complex, as discussed by Berrill *et al*. [7], but in general, they affect components with periods of less than 1 s. We will see all three influences in the two city center records studied in the following.

The loose post-glacial soils generally do not extend far into the western part of the city, where the geologically much older Plains deposits, with a predominance of gravelly layers, extend to the ground surface [7]. Recorded accelerograms in that area (e.g., at the Riccarton High School accelerograph station) have smaller peak ground acceleration (PGA) values (about 0.20 g) and not a trace of ‘signature’ of liquefaction, in accord with the lack of structural and geotechnical damage in that area, hence our decision that no record from this area be examined here.

The third record, Lyttelton Port Company (LPCC), is from a station in the port of Lyttelton, placed directly on a volcanic rock outcrop—the only truly rock motion of the event. The fourth record, HVSC, is a motion on very stiff and shallow soil: the accelerograph is housed in a school kiosk at the edge of what appears to be a triangular (in two senses) valley, in the mountainous southernmost end of the city—at a distance of about 3 km from the LPCC station.

The three components of each of the four recorded acceleration time histories are plotted in Figure 2 and the corresponding velocity time histories in Figure 3.

Evidently, the selected four records offer a representative sample of the intensity and nature of shaking in the broader Christchurch area. Specifically, the two records in the city center, CHHC and CCCC, bear the effects of soft-soil conditions, including long-period amplification, as well as the acceleration de-amplification and period lengthening upon the occurrence of liquefaction. The remaining records in the city (center and east) are of similar intensity and nature, with more or less the same manifestation of liquefaction. Most of the records have very high vertical acceleration components—both in relative and absolute terms.

The other two motions are unique among the records: they have the highest amplitudes in almost all their three components and the highest dominant frequencies of all the records—as expected from motions on rock or very-stiff-soil deposit. It turns out that both of these stations lie on the ‘hanging wall’ of the seismogenic fault of the February 22 earthquake, not far from the intersection of ground surface and fault plane. The latter is a very steep thrust-and-strike slip fault, dipping $\approx 70°$ to the south (tentative estimate). In fact, Heathcote valley is almost crossed by this fault line, which implies that the HVSC station is barely 2 or 3 km from the fault rupture. Although all these seismological facts are undoubtedly critical in explaining the huge amplitudes of the two records (especially of HVSC), the scope of this paper is only to study *what is the* ***potential*** *of these motions to inflict damage to engineering systems—not* ***how*** *they were produced seismologically*. For a discussion on the latter, we make reference to the work of Bradley *et al*. [8, 9].

Each one of the four selected ground motions was obtained in areas with different types of geotechnical and/or structural damage. The LPCC accelerogram was recorded at the port of Lyttelton, where substantial structural damage occurred in buildings. Two noteworthy cases of structural failures are the partial destruction of the Timeball Station and the Lyttelton Museum.

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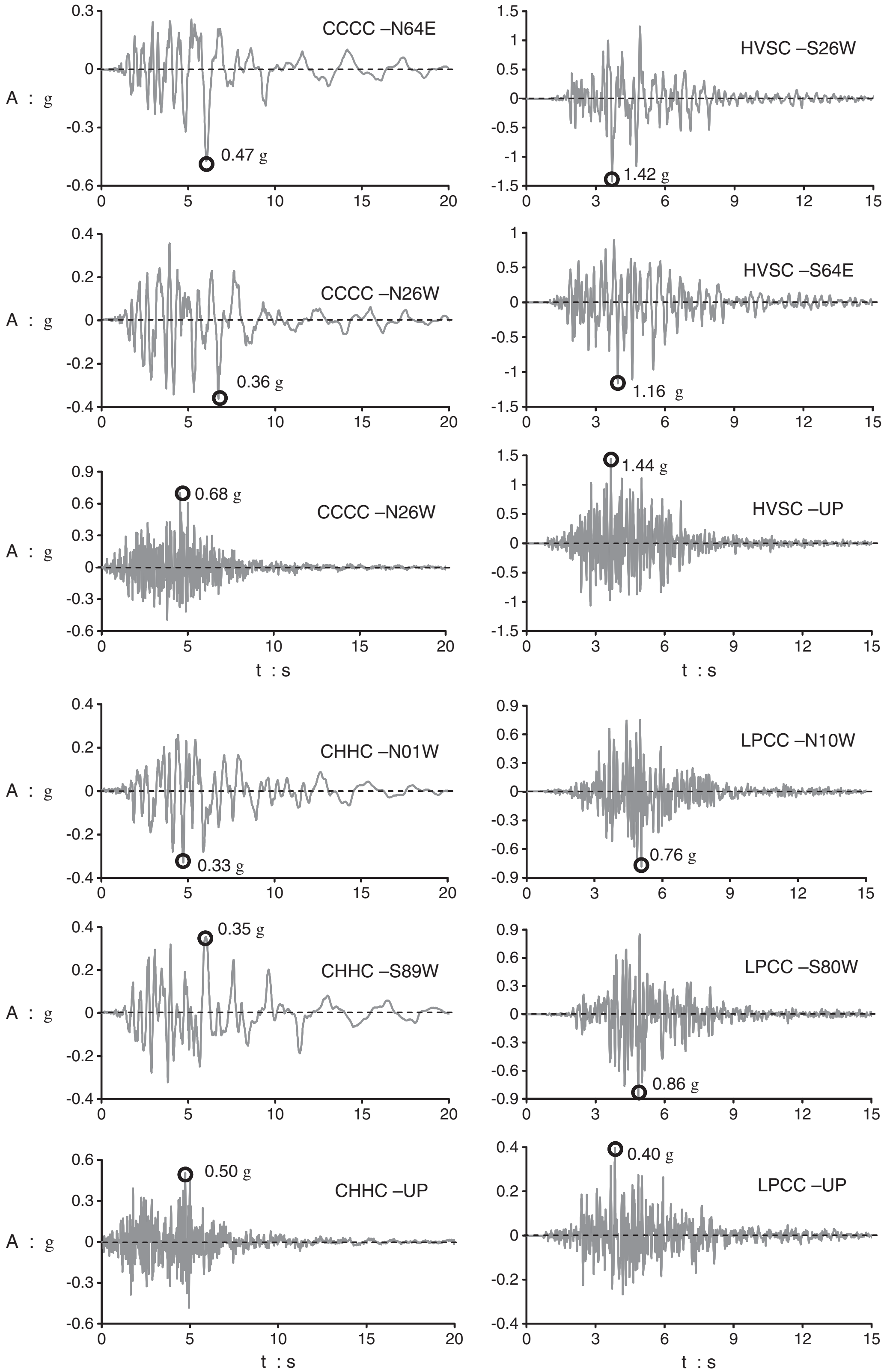

Figure 2. Acceleration time histories of the four records obtained from the GNS strong-motion database. (Note that these records have been band pass filtered, reducing high-frequency components and peak ground accelerations.) CCCC, Christchurch Catholic Cathedral College; CHCC, Christchurch Hospital; HVSC, Heathcote Valley Primary School; LPCC, Lyttelton Port Company.

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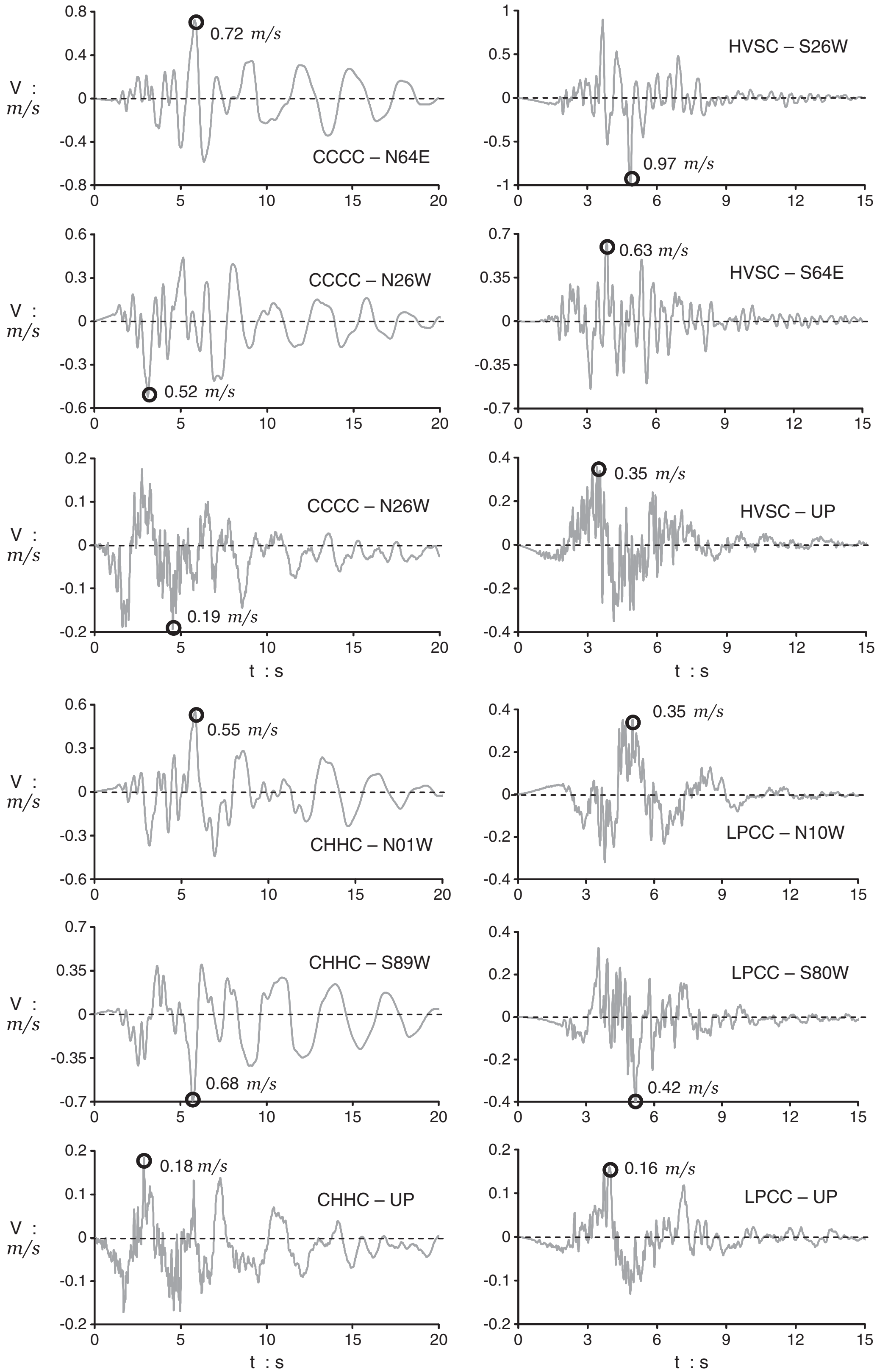

Figure 3. Velocity time histories of the four records from the GNS strong-motion database. CCCC, Christchurch Catholic Cathedral College; CHCC, Christchurch Hospital; HVSC, Heathcote Valley Primary School; LPCC, Lyttelton Port Company.

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Also, widespread damage of wharves and other infrastructure facilities took place in the Lyttelton port. The HVSC ground motion was recorded in a region with moderate structural damage despite the high levels of horizontal and vertical acceleration. The particular case of an obelisk overturning in Heathcote is illustrated in Figure 4. CCCC and CHHC stations are located in the center of Christchurch. Intense liquefaction was observed at the two sites as well as in many parts of the city, especially in those near the Avonside river. As already discussed, both records bear the characteristics of liquefaction.

2. CHARACTERISTICS OF THE SELECTED MOTIONS AND THEIR ELASTIC RESPONSE SPECTRA

The damped elastic response spectra, in terms of acceleration S_A, velocity S_V, and displacement S_D, offer a complete visual assessment of the potential of a ground motion to cause large response to (visco)elastic spring–mass systems. Figure 5 compares the 5% damped response spectra (hereafter called simply 'elastic response spectra') of the horizontal components of the four studied motions: the left column of the two soil records, CCCC and CHHC, and the right column of the two rock/stiff-soil records, LPCC and HVSC.

The following remarks are worthy of note:

a. Both components of the rock LPCC motion produce high spectral accelerations at very low periods (average $\max S_A \approx 3\,g$ at $T \approx 0.18$ s), but their 'elastic potential' drops very rapidly with increasing period—hardly a surprising behavior for rock motion having a PGA of $\approx 0.80\,g$ and many high–frequency cycles in excess of $0.60\,g$.
b. The very-stiff-soil motion, HVSC, with its huge values of PGA (both components exceeding $1\,g$) and low-period $\max S_A$ ($\approx 4\,g$), is richer in higher periods. A distinctive $S_A \approx 2\,g$ plateau in the period range $0.5 < T(\mathrm{s}) < 0.85$, approximately, with associated peaks of $S_V \approx 220$ cm/s and $S_D \approx 30$ cm, indicates a plausible 2D valley amplification soil effects on the S26W component of motion. As the recording station is near the edge of the 150-m-wide valley, a mere 10- to 20-m distance from the mountain slope, one could advance the hypothesis of 2D wave focusing effects rather than 1D soil amplification as the likely culprit of such significant relatively high-period components in the motion. This could perhaps be supported theoretically: in view of the very-high-frequency content of the nearest rock motion (LPCC) and the stiff and shallow subsoil, 1D soil amplification at $T \approx 0.80$ s could, at most, only partly account for the observed response. By contrast, ample theoretical evidence [10–12] suggests that, under high-frequency SV-wave (in-plane) excitation, significant amplification may take place at the edges of the valley, as a result of multiple

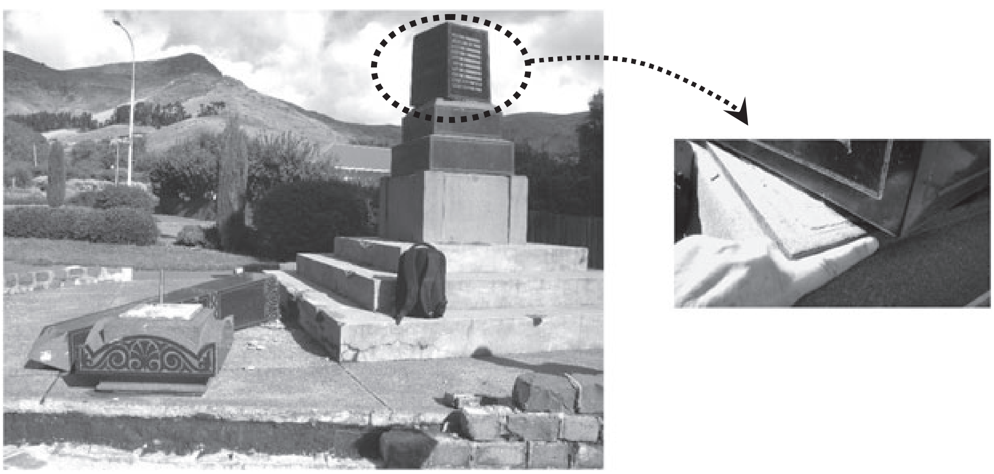

Figure 4. Overturned obelisk column at the Bridle Path Road and Martindales End, in Heathcote. Notice (in the detail) the sliding and the rotation of the remaining block over its base (photos by the authors).

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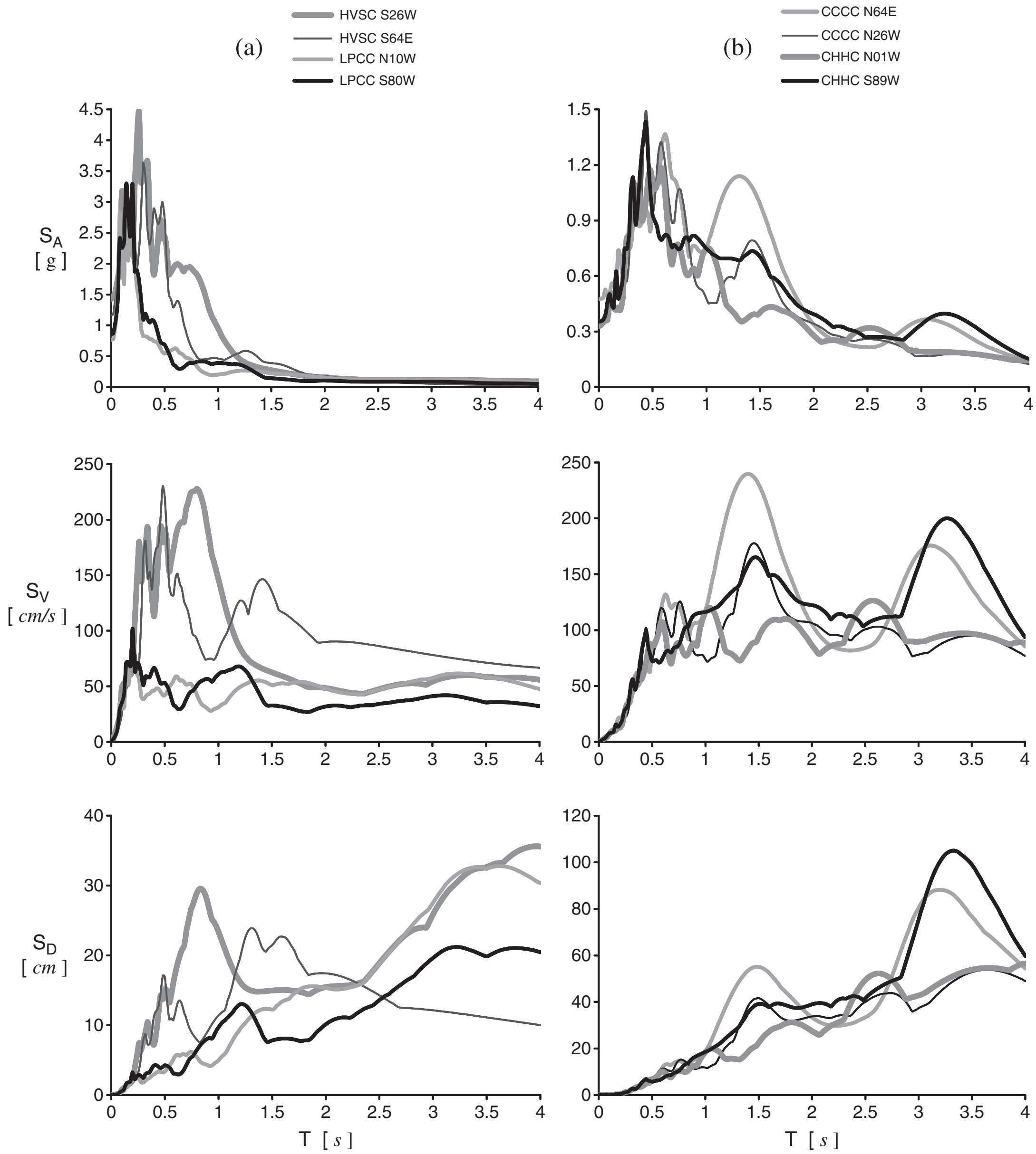

Figure 5. Elastic acceleration, velocity, and displacement spectra of the horizontal components of the recorded motions (5% damping). CCCC, Christchurch Catholic Cathedral College; CHCC, Christchurch Hospital; HVSC, Heathcote Valley Primary School; LPCC, Lyttelton Port Company.

wave reflections and interferences and that the response to SH-wave (out-of-plane) excitation may be quite different, offering a plausible explanation of the disparity between the two components (S26W, S64E). Another plausible cause of this high-amplitude plateau at $T \approx 0.50$–0.85 is forward rupture directivity. The fact that HVSC is located at the edge of the seismogenic steeply dipping rupture plane lends credence to this hypothesis. Perhaps all the aforementioned factors have contributed to some degree to generate such a strong motion, especially in the S26W component. A more eloquent explanation of the probable directivity-affected HVSC record is presented in Figure 6, in terms of displacement orbits of the records. Further examination of this point, however, is beyond the scope of this paper.

c. The two soil motions (CCCC and CHHC) produce response spectra with two broad peaks, which show probable effects of soil amplification (identified by Berrill *et al*. [7]): (i) in the period range

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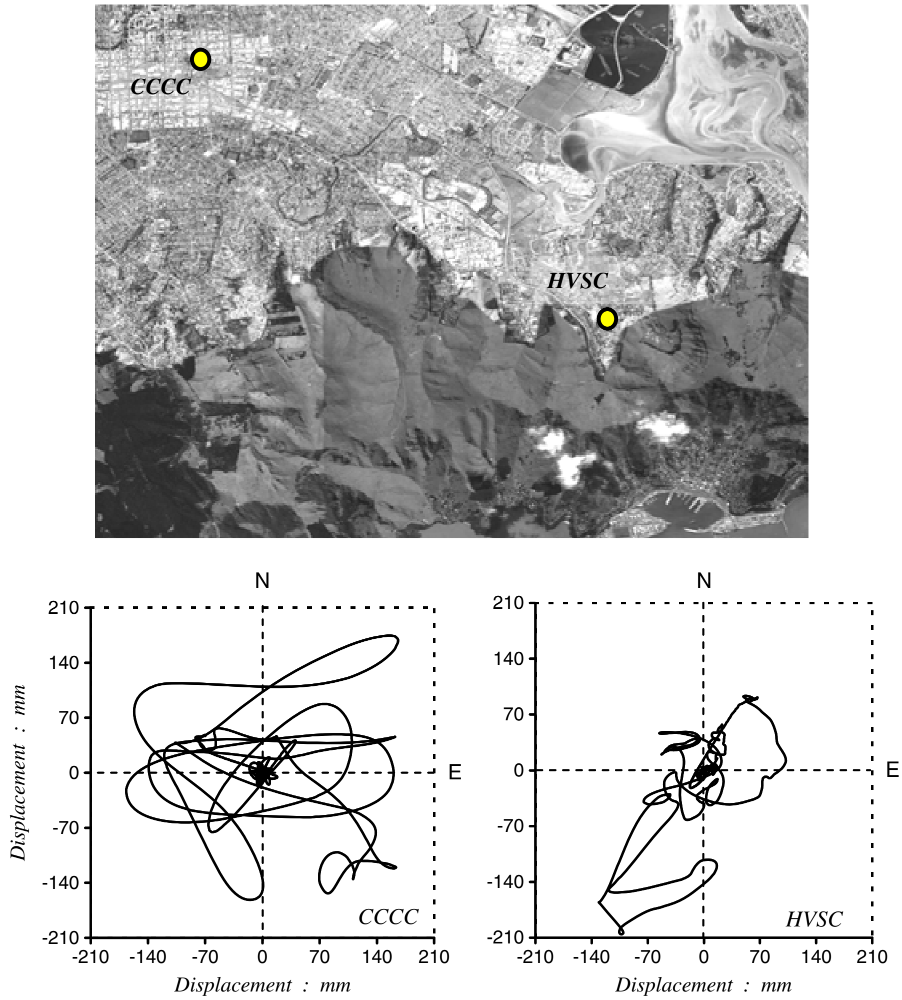

Figure 6. Location of the Christchurch Catholic Cathedral College (CCCC) and Heathcote Valley Primary School (HVSC) recording stations and displacement orbits of the two records. In the latter, notice the preferred west–south direction of the HVSC ground motion that may be the result of directivity and/or 2D valley amplification effects.

$1 < T(\mathrm{s}) < 1.7$ and (ii) in the range $2.8 < T(\mathrm{s}) < 3.5$, approximately. The latter may well be due to resonance of the 700-m-thick sedimentary layer; alternatively, it may also be the result of the oscillatory ground motion after liquefaction has occurred at depth. Such motion is clearly seen in all four acceleration time histories (as well as in their respective velocity histories) after about 6 s of motion. A supporting note is that Youd [13], using the then available (few) records on top of liquefied soil, had also noticed such a considerable enhancement of very-long-period response spectral values whenever the topmost ground layers continued to oscillate after liquefaction was triggered. This seems to have been the case with the two chosen records.

In addition to the elastic response spectrum, the so-called Arias Intensity of a particular ground motion has been often used as an 'index of potential destructiveness' of that motion. Defined as

$$I_A = \frac{\pi}{2g}\int_0^\infty A^2(t)\mathrm{d}t, \tag{1}$$

it has been correlated with several measures of 'damage' to engineering systems. Table II presents the values of I_A anticipated for each of the examined records. As expected, the HVSC motions have extremely high values of I_A, in excess of 11, compared with the city center motions, which have I_A

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Table II. Arias Intensity of the 24 February 2011 $M_W = 6.3$ Christchurch seismic event records at the stations presented in Table I.

Record name	$I_{A,H1}$ (m s)	$I_{A,H2}$ (m s)	$I_{A,V}$ (m s)	Soil site
Christchurch Catholic Cathedral College (CCCC)	2.3	2.6	3.1	Estuarine deposits
Christchurch Hospital (CHHC)	1.7	2.3	2.1	Estuarine deposits
Christchurch Botanic Gardens (CBGS)	2.6	1.3	0.8	Estuarine deposits
Christchurch Resthaven (REHS)	2.4	3.6	1.8	Estuarine deposits
Shirley Library (SHLC)	2.1	1.8	1.6	Estuarine deposits
Pages Road Pumping Station (PRPC)	2.0	2.2	20.5	Estuarine deposits
Hulverstone Drive Pumping Station (HPSC)	0.3	0.8	4.4	Estuarine deposits
Christchurch Cashmere High School (CMHS)	1.3	1.6	2.9	Estuarine deposits
Christchurch Canterbury Aero Club (CACS)	0.3	0.5	0.4	Older gravelly deposits
Christchurch Papanui High School (PPHS)	1.0	0.9	0.4	Older gravelly deposits
Riccarton High School (RHSC)	1.1	1.1	0.6	Older gravelly deposits
Styx Mill Transfer Station (SMTC)	0.4	0.4	0.3	Older gravelly deposits
Heathcote Valley Primary School (HVSC)	11.9	11.1	14.8	Very stiff deposit/rock
Lyttelton Port Company (LPCC)	4.6	5.5	0.9	Volcanic rock

values of about 2 to 3. (For easy reference, we mention here the I_A values of some notoriously destructive records: Kobe-JMA: 8.5, Northridge-Rinaldi: 7.5, Landers–Lucerne: 6.5, Chi-Chi–TCU068: 3.3.) Whether this index is a good predictor of (inelastic) damage in this particular case remains to be explored.

3. SLIDING AND OVERTURNING CAUSED BY GROUND MOTIONS: MOTIVATION AND DEFINITION

For systems whose deformation involves restoring mechanisms with a dominant linear component, the viscoelastic response spectra, S_A, S_V, S_D, of a particular accelerogram provide an excellent indication of its potential to cause unacceptable amplitudes of deformation in various structures (as a function of their elastic fundamental period). However, for systems with strongly nonlinear and/or inelastic restoring mechanisms, elastic response spectra are often inadequate descriptors of the damage potential. This is absolutely true in cases where no elastic component of restoring mechanism is present, such as with systems that rely solely on friction for lateral support. One can mention as an example (flat) friction-isolated structures. In geotechnical engineering, gravity-retaining walls and slopes rely primarily on frictional interfaces (rather than elastic restraint) for lateral seismic support. Ductile structures, designed to respond mainly in the inelastic region, have restoring force–displacement relationships that resemble the frictional mechanism.

An abstraction has been inspired by the preceding applications. To assess the potential of an accelerogram to inflict large irrecoverable deformation on highly inelastic systems, the seismic behavior of three idealized systems is explored. They are to be thought of as *analogs* of actual inelastic systems:

a. The sliding of a rigid block on a horizontal base
b. The sliding of a rigid block on an inclined (≥25°) base (called 'Newmark' sliding in the geotechnical literature after the introduction of such a sliding system in 1965 by Newmark [14])
c. The rocking–uplifting–overturning of a rigid slender block on a horizontal base

The former two systems are characterized by a rigid-plastic symmetric (a), or asymmetric (b), restoring force-versus-displacement relationships obeying Coulomb's friction law. The latter is characterized by a bilinear restoring moment-versus-rotation relationship, comprising an initial rigid branch and a subsequent branch descending to zero at the angle of imminent overturning. Figure 7 illustrates the three systems and their restoring force–displacement relation. The supporting base of each system is subjected to the particular ground motion under investigation, and the size of the resulting inelastic/nonlinear response serves as an index of the damage that this motion can inflict on the corresponding class of inelastic systems—the 'destructiveness' potential of the motion.

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The maximum resistance (‘strength’) of each system is controlled either by the coefficient of friction or by the slenderness ratio, for the sliding or rocking systems, respectively (Figure 7). By letting the ‘yield acceleration’ (defined as the maximum resistance divided by the mass of the block) vary parametrically for a given ground motion, we obtain ‘sliding’ and ‘overturning’ spectra. It could be argued that such spectra offer a more relevant picture of inelastic response (and damage) than the elastic response spectra or even the constant-ductility spectra (obtained by the well-known procedure of downscaling the elastic spectra as a function of the ductility) (see [15, 16] for an early recognition of the inadequacy of the latter). Also, a historical view of the importance of severe ground motion pulses in engineering is summarized in [17].

In the sequence, we present the sliding or rocking spectra of the four selected Christchurch motions to explore their damage potential and to compare it with that of other notable historic ground motions. We also investigate the significance of the vertical components of motion.

4. SYMMETRIC AND ASYMMETRIC SLIDING POTENTIAL OF THE SELECTED MOTIONS

The analysis of the behavior of a block on a horizontal or inclined base, which is subjected to motion $A(t)$ parallel to the plane, is obtained from elementary rigid body kinematics along with Newton’s second law of motion. The critical acceleration(s) that must be exceeded for slippage to be initiated are simply

$$A_c = \mu g, \tag{2}$$

$$A_{c1} = (\mu \cos\beta - \sin\beta) g, \tag{3a}$$

$$A_{c2} = (\mu \cos\beta + \sin\beta) g, \tag{3b}$$

in which A_c is the critical acceleration for sliding in either direction of the symmetric system, μ is the (constant) coefficient of friction, and A_{c1} and A_{c2} are the critical accelerations for downhill and uphill sliding for the asymmetric system of a plane inclined at an angle β, respectively. Usually, $A_{c1} << A_{c2}$, and as a result, sliding takes place only downhill.

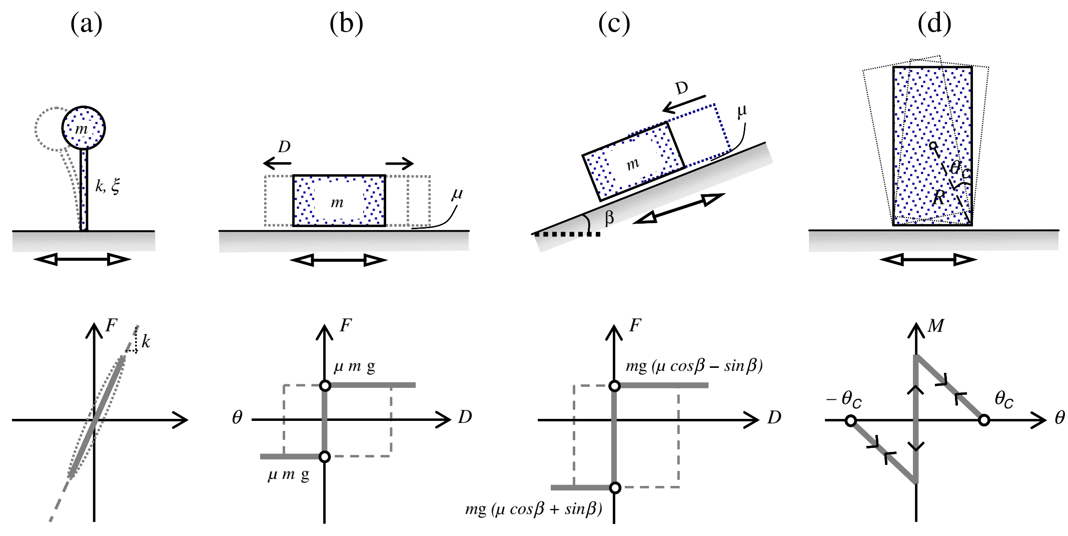

Figure 7. The fundamental systems (‘analogs’) studied in the paper with their restoring force–displacement or moment–rotation relations: (a) viscoelastic oscillation of a single-degree-of-freedom system, (b) ideally rigid-plastic sliding on a horizontal plane, (c) ideally rigid-plastic sliding on an inclined plane, and (d) rotational elastic oscillation of a rocking block on rigid base.

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Whenever the base acceleration exceeds A_c or A_{c1} (or, rarely, A_{c2}), slippage of the block takes place with respect to the base. This slippage lasts only momentarily, thanks to the transient nature of earthquake shaking; it terminates as soon as the velocities of the base and the block equalize. And the process continues until the motions of both the block *and* the base eventually terminate.

A graphical presentation of the solution procedure is given in Figures 8 and 9, for the strongest components of the CCCC and HVSC motions. Having selected a critical acceleration $A_c = 0.10\,g$ for both the horizontal and inclined base problems, we illustrate in these figures the acceleration and velocity time histories of the block and the base and the resulting relative displacement of the block with respect to the base. The size of the latter displacement is taken as an index of damage to the system. The following is evident:

- The HVSC motion, despite its huge peak amplitude, 14 times larger than the critical acceleration, produces a very modest peak value of symmetric slippage: 10 cm. As can be detected from the time histories, there are two main causes of such an 'underperformance' of the record: the relatively high-frequency content of the strongest part of the motion (which does not allow each slippage to

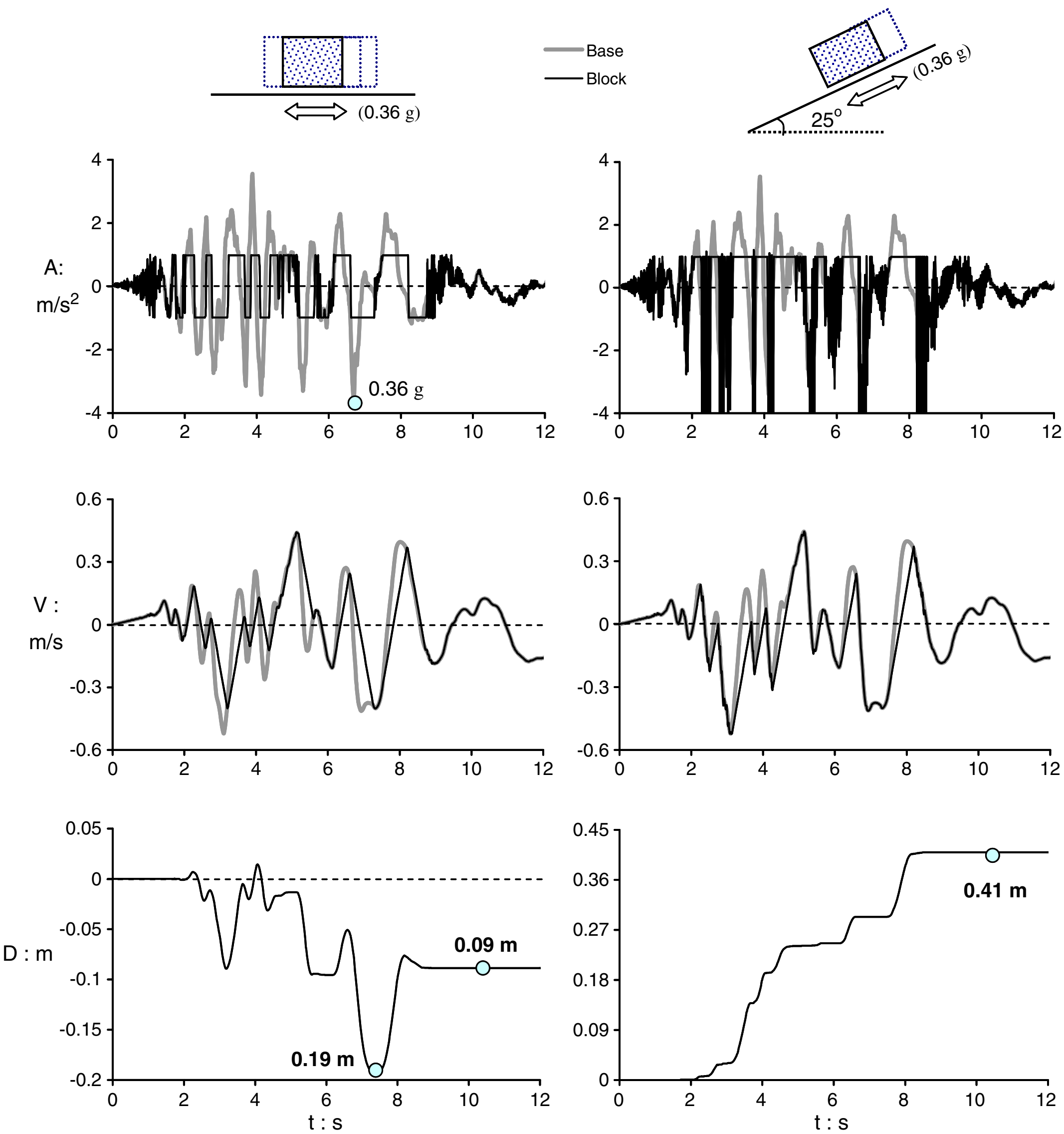

Figure 8. Influence of the symmetric (left) or asymmetric (right) nature of sliding on the response induced by the Christchurch Catholic Cathedral College-N26W ground motion for $A_c = 0.1\,g$.

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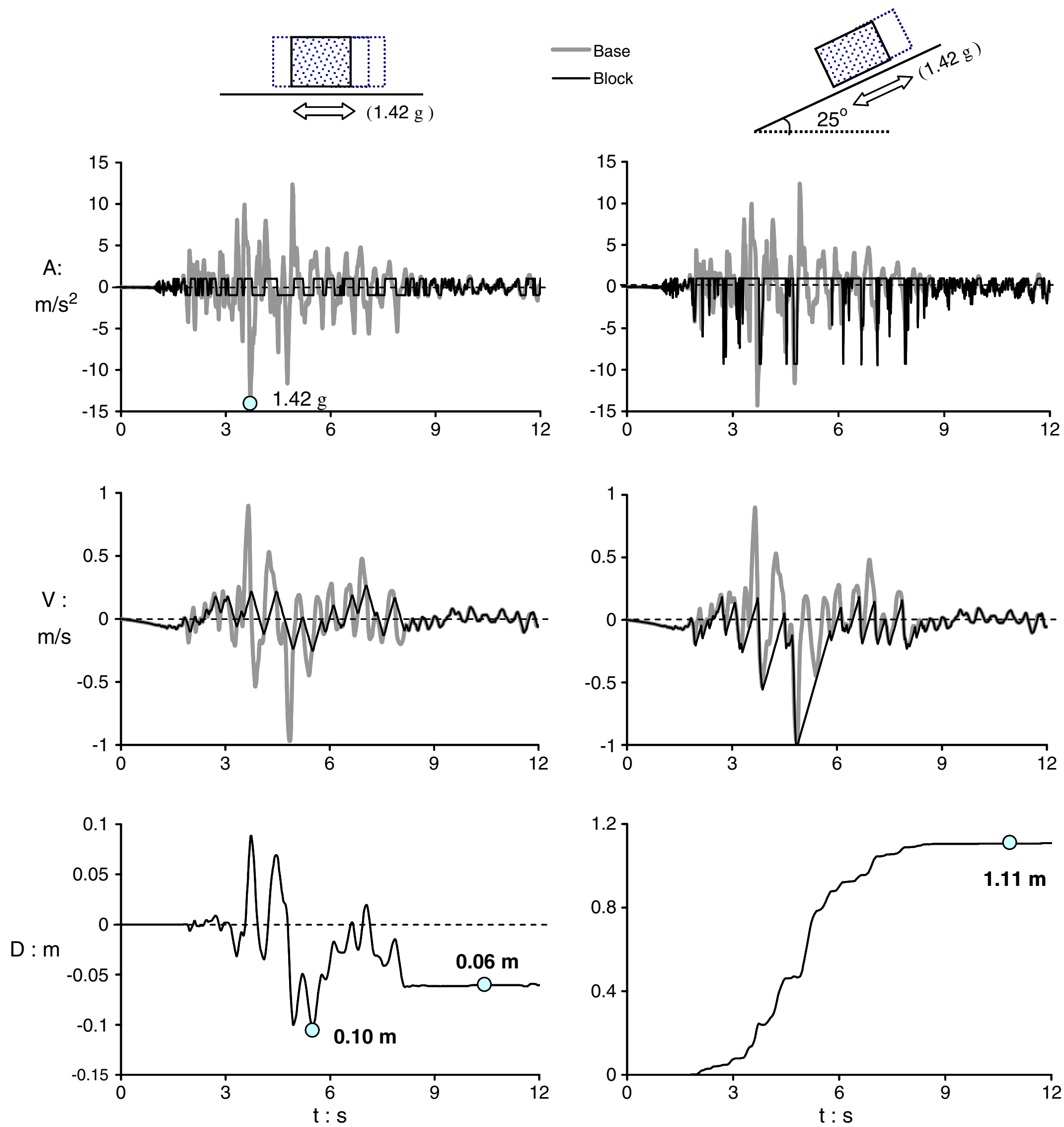

Figure 9. Influence of the symmetric (left) or asymmetric (right) nature of sliding to the response induced by the Heathcote Valley Primary School-S26W ground motion for $A_c = 0.1\,g$.

last long) and the quite symmetric nature of the motion (which produces positive and negative slippages of comparable amplitude—which thus cancel each other out).

- On the inclined plane, however, sliding displacements from the HVSC motion accumulate to a substantial permanent slippage of 111 cm. Apparently, the large number of significant cycles and the asymmetry of the system geometry outweigh the effects of the high frequency and the symmetric nature of the ground motion.
- The CCCC motion on the other hand with only one-third of the amplitude of the HVSC acceleration (0.47 g compared with 1.42 g) leads to a fairly substantial peak sliding displacement of 19 cm on a horizontal base—almost two times the peak of the HVSC-induced slippage. The main culprit is the relatively high period content of the motion, which allows each slippage to last long. The relatively asymmetric nature of the accelerogram also contributes somewhat, as the sliding reversals are now rather subdued.
- On the inclined base, the HVSC record is the more detrimental of the two: 111 cm compared with 41 cm of the CCCC record. Apparently, the larger number of strong cycles of the HVSC motion compensates to a large extent for the detrimental effect of the higher periods of the CCCC pulses;

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recall that this is an asymmetric problem in which accumulation of slippage (=damage) in one direction is a key mechanism.

By varying the critical acceleration from $A_c = 0.05\,g$ to $A_c = 0.30\,g$, we obtain the spectra of the symmetric and asymmetric sliding displacements for each component of all four studied motions. (For a given A_c, the effect of β is negligible as long as $\beta > 10°$, and therefore, uphill movement is unlikely. The effects of parameters such as the inclination angle, β, and the coefficient of friction, μ, among others on asymmetric sliding response are beyond the scope of this study and were presented by the authors in [18, 19].) Figures 10 and 11 compare these sliding spectra, for the horizontal and inclined bases, respectively. The most significant conclusions that are readily drawn from the two figures are as follows:

a. The symmetric sliding potential of the two motions recorded on top of the soil (CCCC and CHHC) is in general the highest, whereas that of the rock motion (LPCC) is the lowest—in spite of the far larger PGA and I_A values of this record (Table I). The potential of the HVSC motion is only about twice as large as the LPCC motion—but overall much smaller than the potential of the soil motions.
b. The preceding general picture is valid only for small values of the yield acceleration, say A_c 0.20–0.25 g, depending on the record. For larger A_c values, that is, for less inelastic response, whereas the sliding spectra of the soil motions (CCCC, CHHC) decrease rapidly with A_c, the spectra of HVSC and LPCC barely experience any drop and, in fact, may even increase with increasing A_c. The explanation of the former behavior is straightforward: as the A_c values approach 0.30 g, the PGA values of three of the soil motions (0.36, 0.30, 0.33 g) marginally exceed A_c; hence, sliding is negligibly small; the fourth soil motion (CCCC-N64E component) with PGA = 0.47 g gives a somewhat larger slippage of 7 cm compared with the HVSC's 9 cm

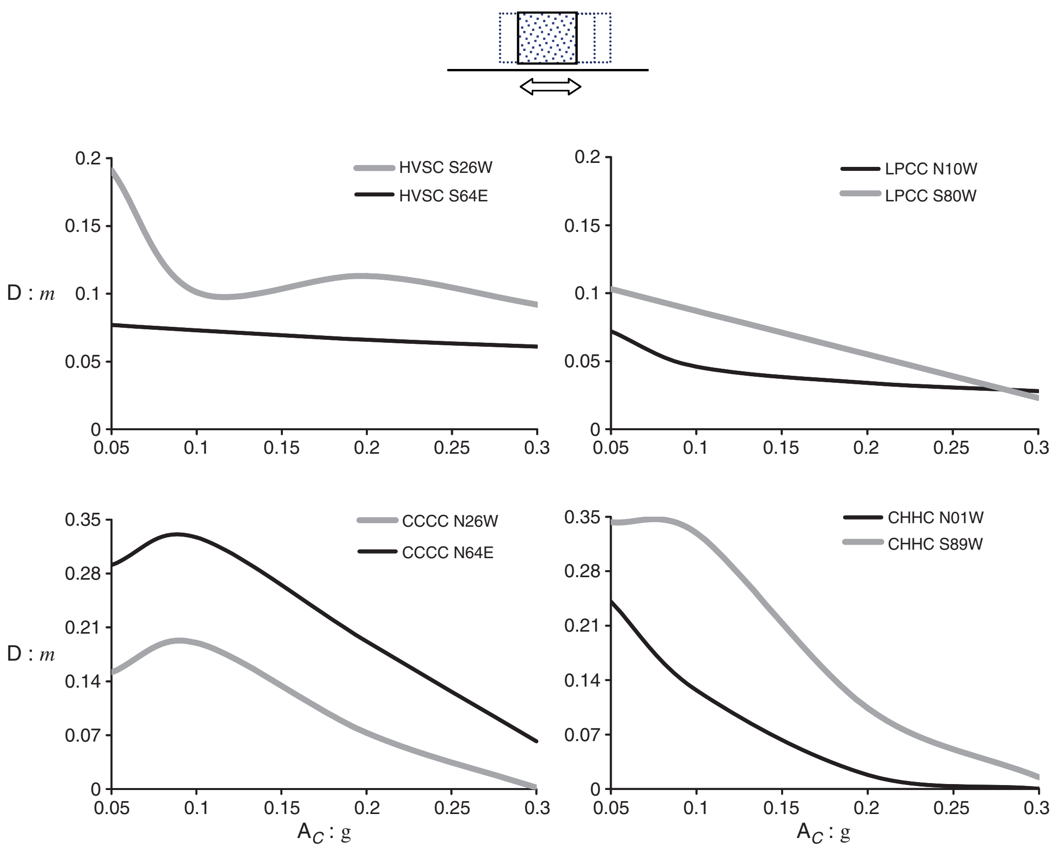

Figure 10. Sliding spectra of a block resting on a horizontal plane, subjected to horizontal excitation, in terms of maximum slippage D versus yielding acceleration $A_c \equiv \mu g$. The excitations are the four selected accelerograms. CCCC, Christchurch Catholic Cathedral College; CHCC, Christchurch Hospital; HVSC, Heathcote Valley Primary School; LPCC, Lyttelton Port Company.

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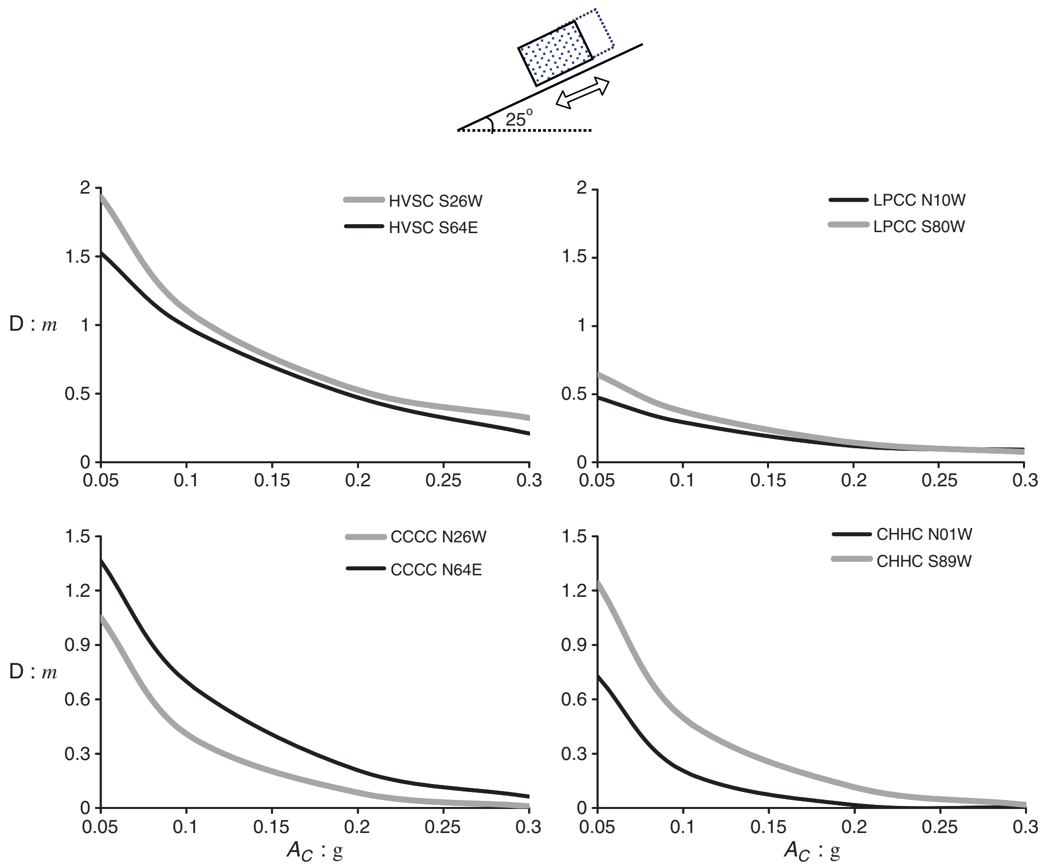

Figure 11. Asymmetric sliding spectra of a block resting on an inclined plane, subjected to horizontal excitation, in terms of (maximum = residual) slippage D versus yielding acceleration $A_c \equiv \mu g$. CCCC, Christchurch Catholic Cathedral College; CHCC, Christchurch Hospital; HVSC, Heathcote Valley Primary School; LPCC, Lyttelton Port Company.

(maximum). As for the paradoxical increase of slippage with increasing critical acceleration A_c (i.e., increasing resistance to sliding), the reader is referred to Gazetas *et al*. [18] for a detailed convincing explanation of what was named the 'Safe Gulf Paradox': it stems from the fact that when A_c increases some of the smaller peaks of motion, which would have produced substantial (beneficial) slippage in the opposite direction from the dominant direction of slippage when A_c was still small, now lose their 'power' faster than the larger peaks in the pernicious direction. In other words, the sliding in the 'weak' direction (which undermines the dominant sliding in the opposite direction) with increasing A_c decreases faster than the dominant sliding; hence, the detrimental direction is somewhat freed from the 'opponent', thereby producing larger slippage.

c. With asymmetric (downhill) sliding, the damage potential of the motions is not vastly different: HVSC and CCCC have in general the highest and similar potential; the LPCC has about 40% and CHHC about 70% of their potential. Again, the spectra of the soil records drop much faster with increasing A_c, approaching zero soon after 0.25 g. There is no paradoxical behavior with increasing A_c, however, as slippage now occurs only in one direction—downhill.

5. OVERTURNING POTENTIAL OF THE SELECTED MOTIONS

The rocking response of a slender solid block of mass m in nonsliding but tensionless contact with a rigid base, which is subjected to motion $A(t)$, is obtained numerically. The critical acceleration, which must be exceeded for uplifting of the block from its base to be initiated, is simply

$$A_c = \frac{b}{h} g \tag{4}$$

in which b is the width and h is the height of the solid block. Under a constant one-directional acceleration even barely exceeding A_c (i.e., under the action of a pseudostatic inertia force mA_c), the block will overturn, not so under seismic base excitation as numerous studies have shown [20–24]. The response and overturning of a given block depend on the amplitude, the frequency content, and the sequence of pulses of the ground motion. And for a given ground motion, the overturning is a function of the slenderness h/b and the absolute size of the block. The latter is measured, for instance, through the distance R of the block's center of gravity from the edge of the foundation.

It turns out that acceleration levels higher than A_c may be necessary to cause overturning of a block—in fact, *much* higher if the motion were dominated by high-frequency components [25–27].

Just as an elastic response spectrum $S = S$ (T, ξ) and a sliding spectrum $D = D$ (A_c, $\beta°$, where β is the base inclination angle) portray respectively the potential of a specific ground motion to cause large oscillatory viscoelastic response or to inflict large and irrecoverable slippage, a rocking–overturning spectrum $\theta = \theta$ $(R, h/B)$ can form yet another index of the potential destructiveness of a motion. As proposed by Makris and Konstantinidis [28], 'the rocking spectrum reflects "kinematic" characteristics of the ground motion that are not identifiable by the elastic response spectrum' and are only partially reproduced by the (symmetric and asymmetric) sliding spectra.

The results presented here are for a single value of the slenderness ratio

$$\frac{h}{b} = 5, \tag{5}$$

a value that implies a critical acceleration of $0.20\,g$ and a critical angle of rotation of $\vartheta_c = \arctan(b/h) \approx 11.3° \approx 0.197$ rad. Figure 12(a, b) refers to excitation with the CCCC and HVSC records (which were used in Figures 8 and 9). The absolute size of the block is variable, with parameter R taking values from a maximum of 12 m (a heavy block of the rotation that is invariably very small) to the minimum stable value R_{min} (a light block that topples under the particular base motion). R_{min} depends solely on the *nature* of the base motion, for a particular aspect ratio.

Figure 12(a, b), for each of the aforementioned two ground motions as excitation, illustrates the time histories $\vartheta = \vartheta$ (t) of rotation for five different values of R, starting from $R \approx 10.2$ m (a large block) and decreasing down to $R \approx 0.77$ m. (Note that the former value corresponds to a 4-m-wide × 20-m-high block whereas the latter to a 0.3-m × 1.5-m block. It must also be realized that development of nonzero angles of rotation is the result of uplifting from, and the subsequent impact on, the base.)

It is evident from this figure that, for all sizes of the block, the (soil-amplified) high-period CCCC motion leads to greater angles of rotation than the HVSC motion—despite the huge PGA of the latter. For one of the smaller sizes considered in Figure 12, $R \approx 1.28$ m, the CCCC motion leads to the brink of overturning ($\vartheta \approx \vartheta_c \approx 0.20$ rad) whereas HVSC produces an angle of 0.1 rad, that is, only half of ϑ_c.

The aforementioned differences arise mainly from the differences in the frequency content of the two motions. The large acceleration amplitudes of HVSC are high-frequency pulses, whereas those of the CCCC record are of low frequency. The more asymmetric nature of CCCC is also an additional aggravating factor.

By varying the size of R and computing numerically the peak values of the resulting angle of rotation, we determine the *rocking spectrum* of each ground motion ϑ_{max} $(R;\ h/b)$. Figure 13 plots these spectra for $h/b = 5$, for four of the selected components of motion. The following are noteworthy:

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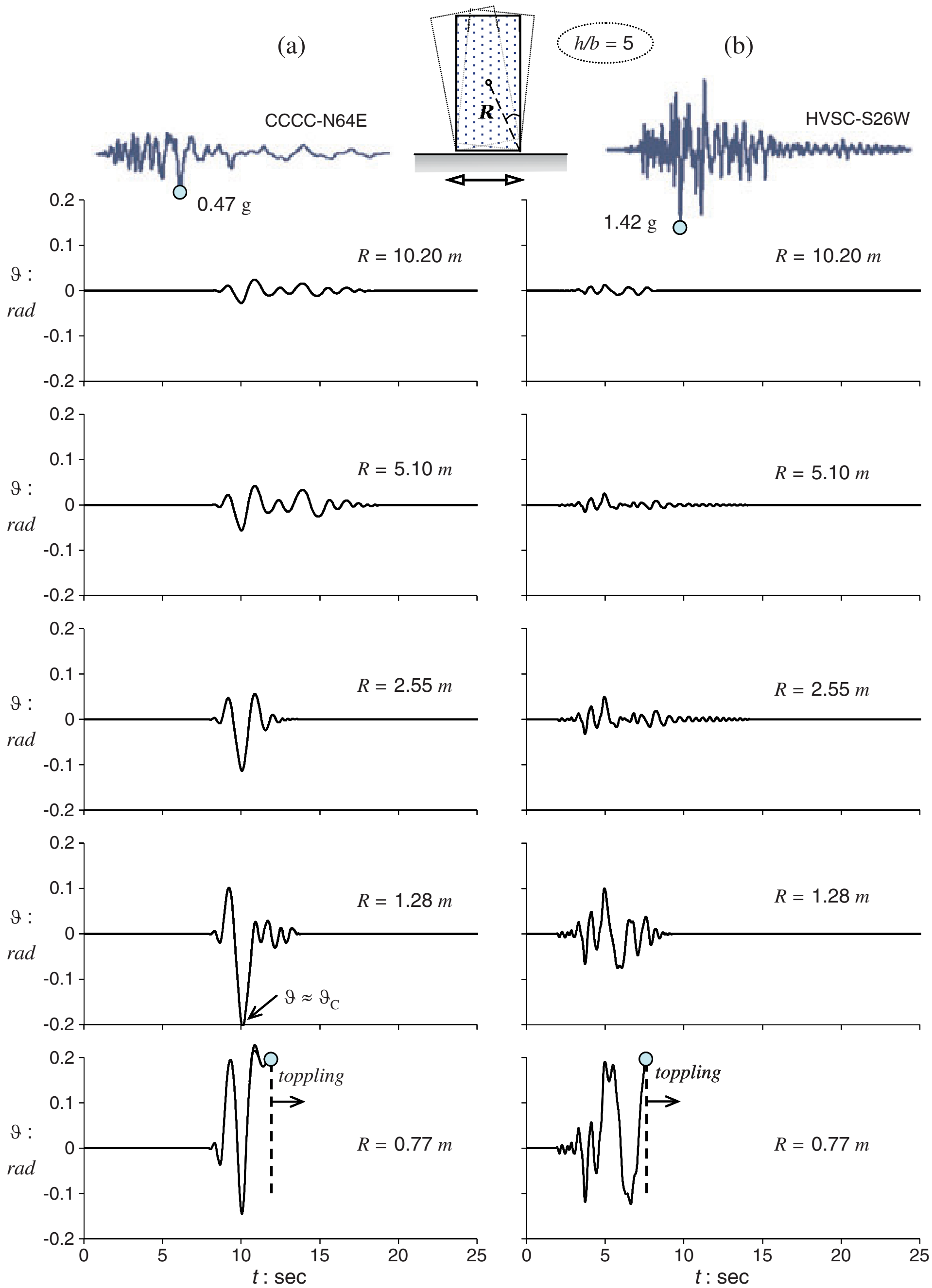

Figure 12. Rocking displacements of a slender block triggered by the horizontal component of the Christchurch Catholic Cathedral College (CCCC)-N64E and Heathcote Valley Primary School (HVSC)-S26W records, for values of the size parameter R varying from 10.20 m (large block) to 0.77 m (small block).

- The value of $R_{\min}$ decreases from CHHC to HVSC to CCCC to LPCC. This implies that the overturning potential decreases in the same order, thus CHHC has the highest potential and LPCC the lowest.
- At large R values, however, CCCC produces larger $\vartheta_{\max}$ values than HVSC (always) and CHHC (for some R values).

In conclusion, the rocking spectra of the four motions being explored reveal both differences *and* similarities in their potential for large rotation and overturning compared with their potential for large (symmetric or asymmetric) slippage.

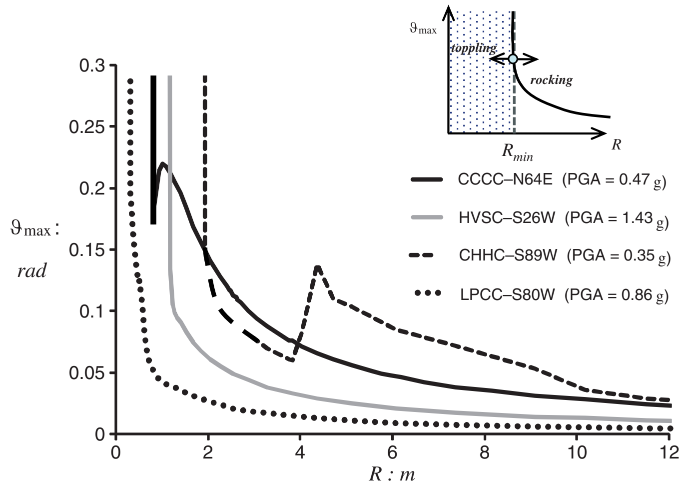

Figure 13. Rocking spectra of a slender block ($h/b = 5$) triggered by the horizontal component of four accelerograms recorded in the Christchurch 2011 Earthquake. The coefficient of restitution is $r = 0.6$. CCCC, Christchurch Catholic Cathedral College; CHCC, Christchurch Hospital; HVSC, Heathcote Valley Primary School; LPCC, Lyttelton Port Company; PGA, peak ground acceleration.

6. THE SIGNIFICANCE OF THE VERTICAL COMPONENT OF MOTION FOR SLIDING AND OVERTURNING

High vertical accelerations were recorded in many accelerograph stations (Table I). Especially in stations HVSC, Pages Road Pumping Station, Hulverstone Drive Pumping Station, Christchurch Cashmere High School, CCCC, Christchurch Resthaven, and CHHC, the peak values of vertical acceleration were higher than the largest peak horizontal acceleration of the record—indeed, in a few cases, by a factor of 2 or more. The causes of these high-frequency and high-amplitude accelerations must be sought in the source mechanics—the steep dipping of the thrust rupture is one of the plausible culprits, along with the orientation and proximity of the stations with respect to the fault. Our scope however is not to explain the origin of the motions but only to assess their consequences for sliding and rocking systems.

For the symmetric sliding system, Figures 14 and 15 illustrate the influence of the vertical component, A_V, of the CHHC and LPCC records on the time history of sliding for a critical acceleration $A_C = 0.1\,g$ (i.e., for a coefficient of friction of $\mu = 0.1$). We observe that the effect of $A_V(t)$ is rather negligible if not beneficial, as in some cases of LPCC. The main cause is that the increments and decrements of the frictional force at the interface caused by $A_V(t)$ are of a much higher frequency and therefore last only momentarily, compared with the 'plateaus' of the constant-friction force that lead to slippage when only A_H is applied. Reference is made to [18] for additional insight into the nature of the problem and to [29] for a statistical verification of this finding.

For the asymmetric system, Figure 16 plots the sliding spectrum, $D = D$ (A_c, $\beta = 25°$), for the CCCC-N64E component applied with and without the vertical component of this record. All possible polarities of the two components are examined as indicated by the arrows. It turns out that, although the polarity of the horizontal base motion is of great importance (as already found in [19]), the presence of the simultaneous vertical component does not lead to any larger slippage.

Therefore, for sliding systems, some of the high-vertical-acceleration histories recorded in Christchurch are of truly minor importance—not worthy of consideration. However, we will not generalize this finding to other systems and structures: there were many instances of compressional failures observed after February 22, both in columns and shear walls (Priestley, personal communication), suggesting that the vertical component may have played a significant role for them.

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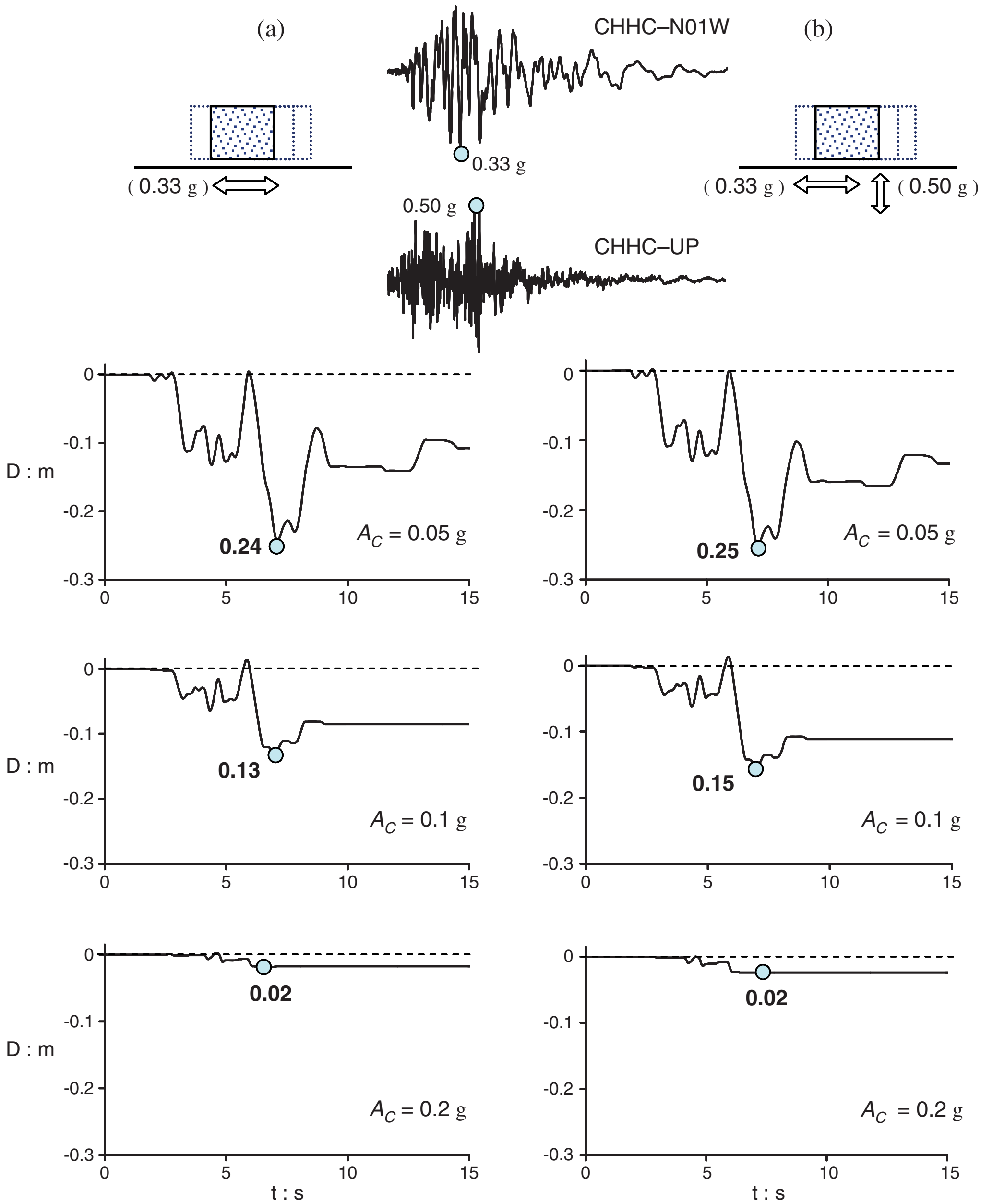

Figure 14. Sliding displacement triggered by (a) the horizontal component (left column) of the Christchurch Hospital (CHHC)-N01W record and (b) the simultaneously acting vertical and horizontal components (right column), for three values of A_c ($=\mu g$): 0.05, 0.10, and 0.20 g.

In rocking and overturning, however, the role of $A_V(t)$ is more interesting. For the five blocks with $h/b = 5$ and different sizes, decreasing from $R = 10.2$ m down to $R = 0.77$ m, Figure 17 compares the rotation time histories, $\vartheta(t)$, induced by the CCCC and HVSC horizontal motions, *with* and *without* their (simultaneous) vertical components. We notice that for the relatively heavy blocks ($R > 3$ m) the influence of the vertical component is negligible. It appears that the influence would be substantial only if the horizontal excitation acting alone would have brought the system on the verge of failure—toppling. This happens for the blocks with $R \approx 1.28$ and 0.77 m.

Specifically, for R ≈ 1.28 m, the horizontal CCCC excitation acting alone produces a peak rotation of $\vartheta_{max} \approx 0.195$ rad at $t \approx 10$ s—just short of the critical angle of overturning $\vartheta_c = \arctan$

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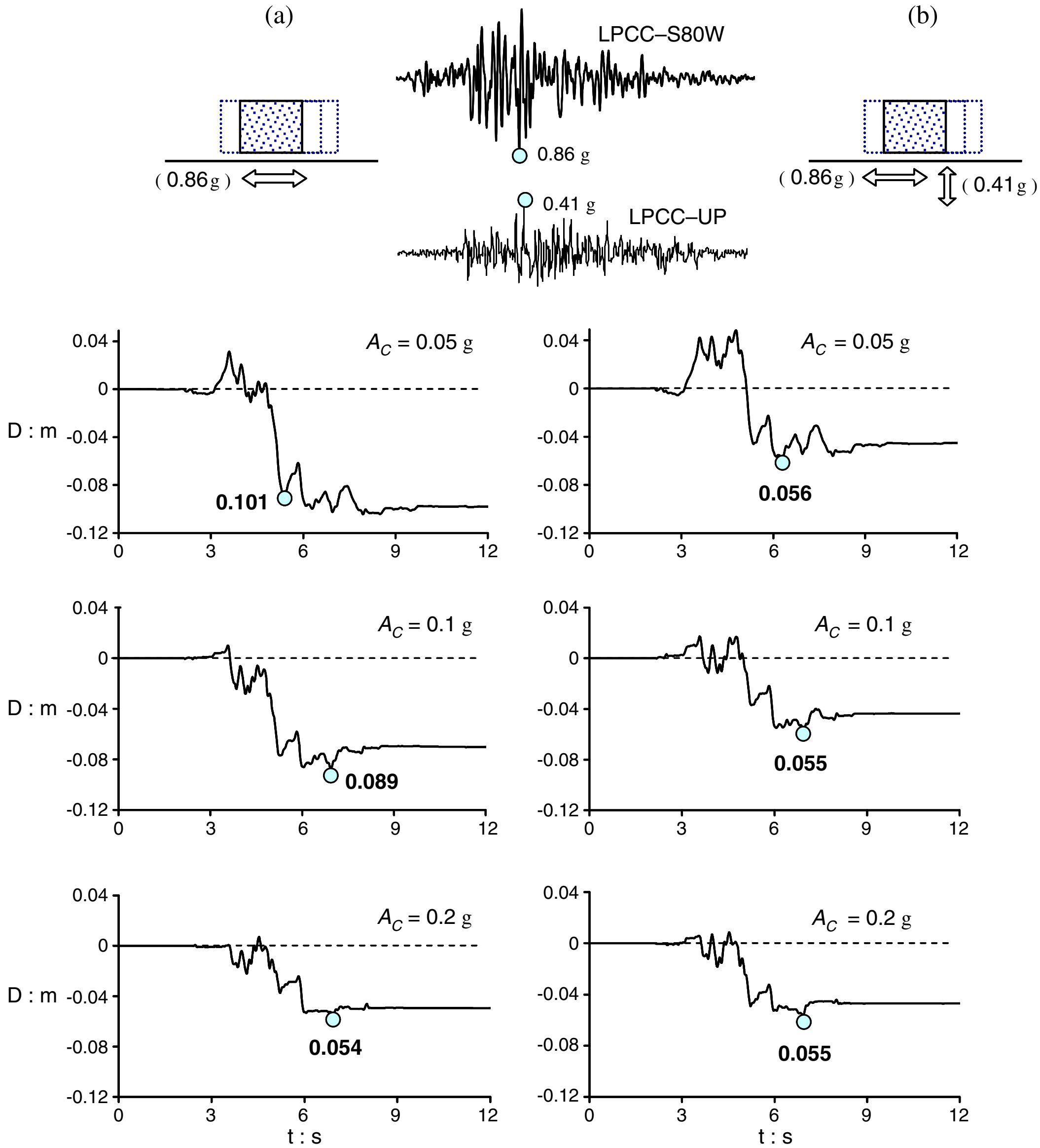

Figure 15. Sliding displacement triggered by (a) the horizontal component (left column) of the Lyttelton Port Company (LPCC)-S80W record and (b) the simultaneously acting vertical and horizontal components (right column), for three values of A_c ($=\mu g$): 0.05, 0.10, and 0.20 g.

(0.20) ≈ 0.197 rad. Accompanied by the vertical component of the record, this ground motion leads to failure at $t \approx 14$ s. For $R \approx 0.77$ m, however, toppling occurs at $t \approx 12$ s when only the horizontal motion acts. With both components acting, horizontal and vertical, the block survives after almost 'touching' ϑ_C at $t \approx 10$ s.

7. COMPARISON WITH THE POTENTIAL OF SOME OTHER WELL-KNOWN GROUND MOTIONS

Finally, for a broader picture of the sliding and overturning potential of the Christchurch ground motions, Figures 18 and 19 compare the respective spectra with those of some *very strong motions*

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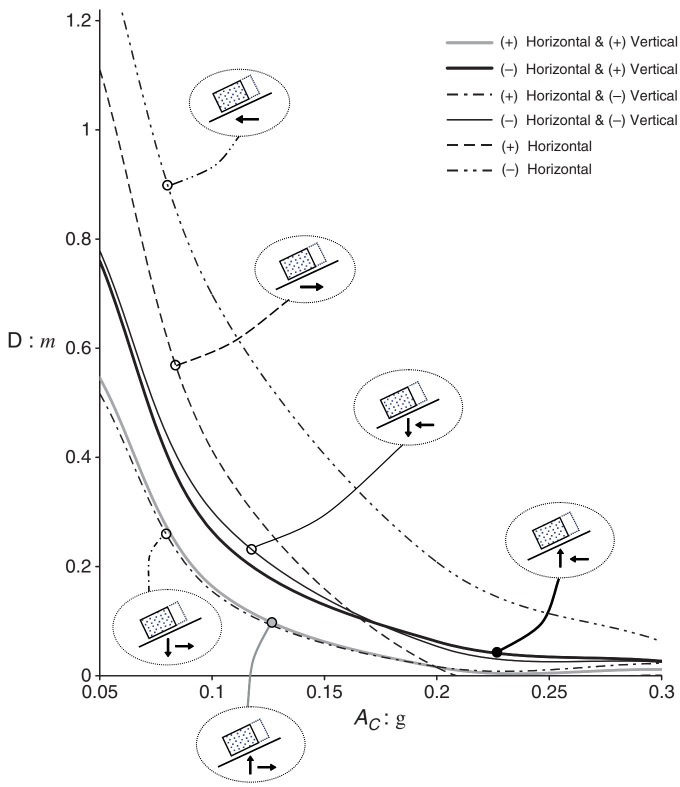

Figure 16. Sliding displacement, D, for several values of yielding acceleration, A_c. The triggering motion can be only the horizontal component, Christchurch Catholic Cathedral College-N64E (imposed with its normal and reverted polarity), or the simultaneously acting vertical and horizontal component (also with both polarities). Notice that it is the polarity of the horizontal acceleration that significantly affects the response. However, the vertical component effect is quite small.

from the Northridge 1994, Imperial Valley 1979, and Lefkada 2003 earthquakes. Most of these motions have the mark of forward rupture directivity, containing very severe pulses. Table III outlines the salient characteristics of these records.

It is evident that the studied motions have overall a high damage potential in asymmetric sliding, moderate-to-low potential in symmetric sliding, and moderate potential for overturning, as they compare with such formidable motions as Rinaldi (Northridge), El Centro Station No6 (Imperial Valley), and Lefkada (Lefkada).This general comparison sheds some light into the significant extent of geotechnical and structural damage in the Christchurch area during the 22 February 2011 earthquake.

8. CONCLUSION

The potential of four ground motions recorded in Christchurch to inflict damage to a variety of engineering systems is explored. Damped elastic response spectra S (T,ξ) (in terms of acceleration, velocity, and displacement) provide useful indirect information for the potential of a motion to damage systems with a dominating elastic force mechanism. For strongly inelastic systems, this paper introduced three new spectra to serve as indices of the 'destructiveness' potential of a motion: two sliding spectra $D=D$ (A_c) and $D=D$ $(A_c,\ \beta°)$ for symmetric and asymmetric slippage of a rigid block supported solely through Coulomb friction and a rocking–overturning spectrum ϑ_{max} $(R,\ h/b)$ for rotational 'stepping' oscillations of a rigid slender block.

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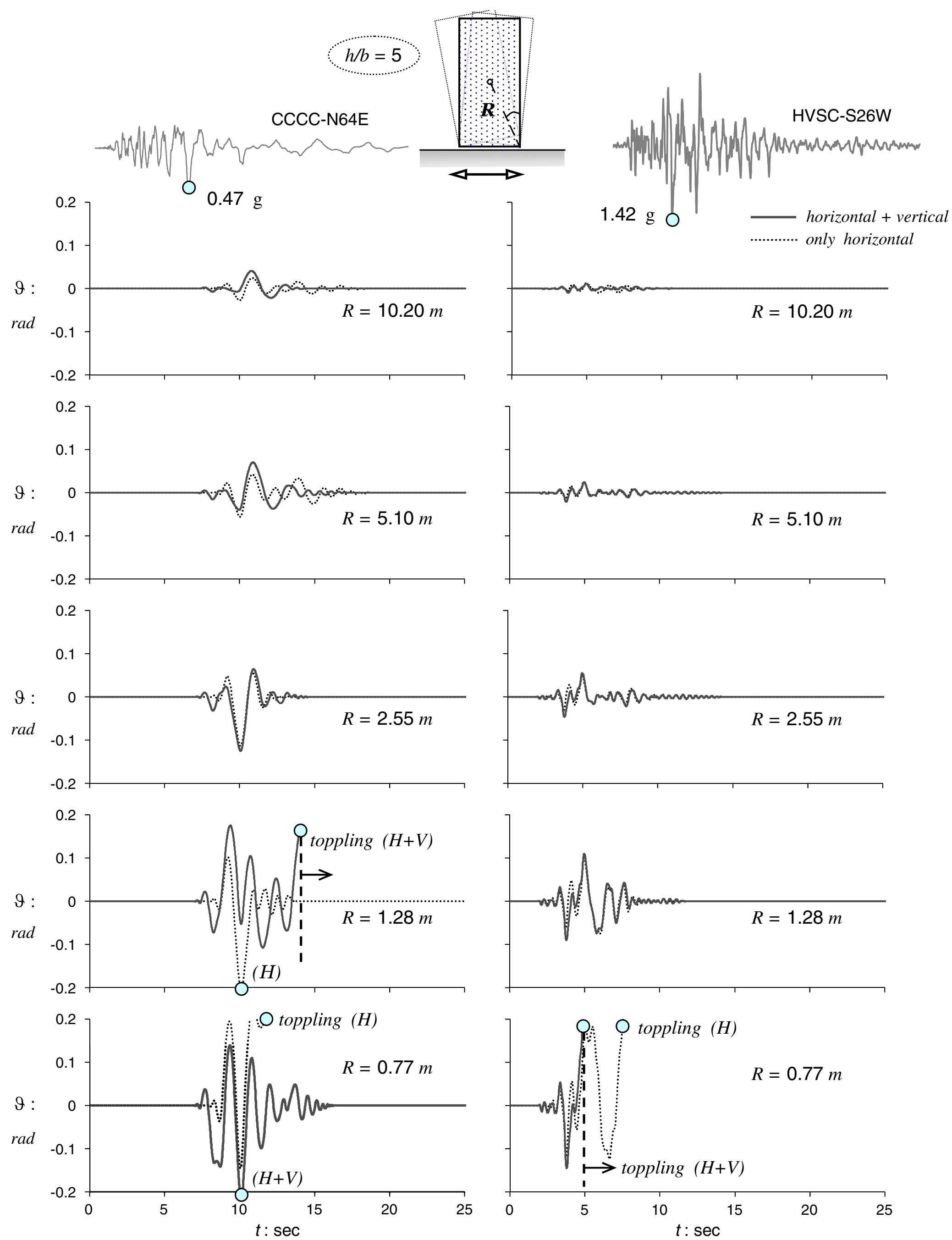

Figure 17. Rocking displacements of a slender block triggered by the horizontal and vertical components of the Christchurch Catholic Cathedral College (CCCC) and Heathcote Valley Primary School (HVSC) records, for values of the size parameter R varying from 10.20 m (large block) to 0.77 m (small block).

The aforementioned types of spectra for each of the four studied records gave a more complete picture than the elastic response spectra alone. Moreover, it was shown that the Christchurch motions were of sufficient damaging potential to explain the overall damage in the city. For sliding systems and, to a lesser extent, for rocking systems, the large vertical acceleration components of some of these records were found to have only a negligible effect. This conclusion should not be unduly generalized to other systems. For instance, the structural engineers find evidence of compressional failure in walls and columns.

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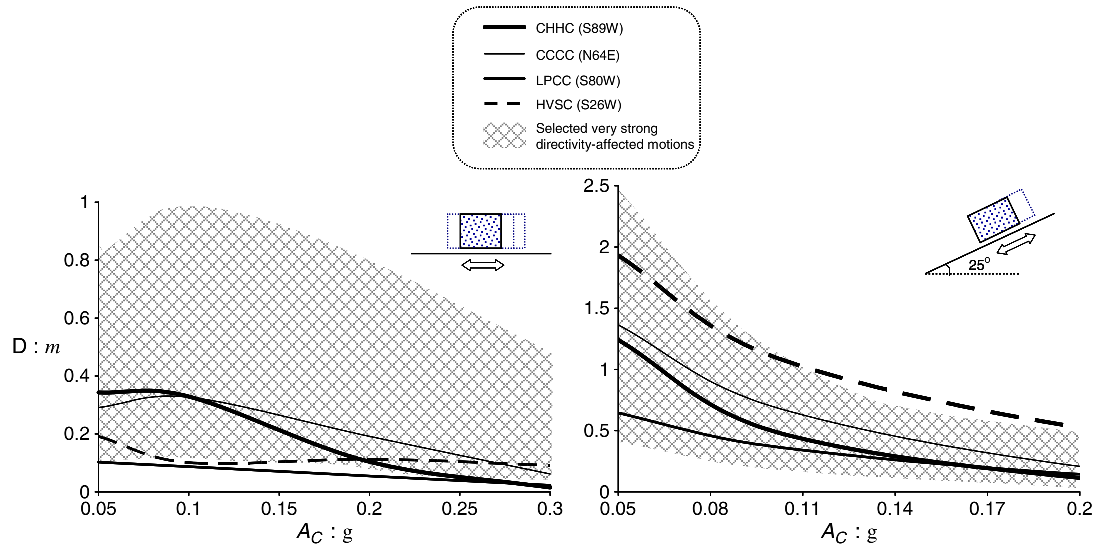

Figure 18. Yielding displacement on a horizontal and an inclined plane induced by the 2011 Christchurch earthquake compared with sliding results (gray-shaded area) of selected directivity-affected strong motions from the similar-magnitude 1994 Northridge, 1979 Imperial Valley, and 2003 Lefkada earthquakes. CCCC, Christchurch Catholic Cathedral College; CHCC, Christchurch Hospital; HVSC, Heathcote Valley Primary School; LPCC, Lyttelton Port Company.

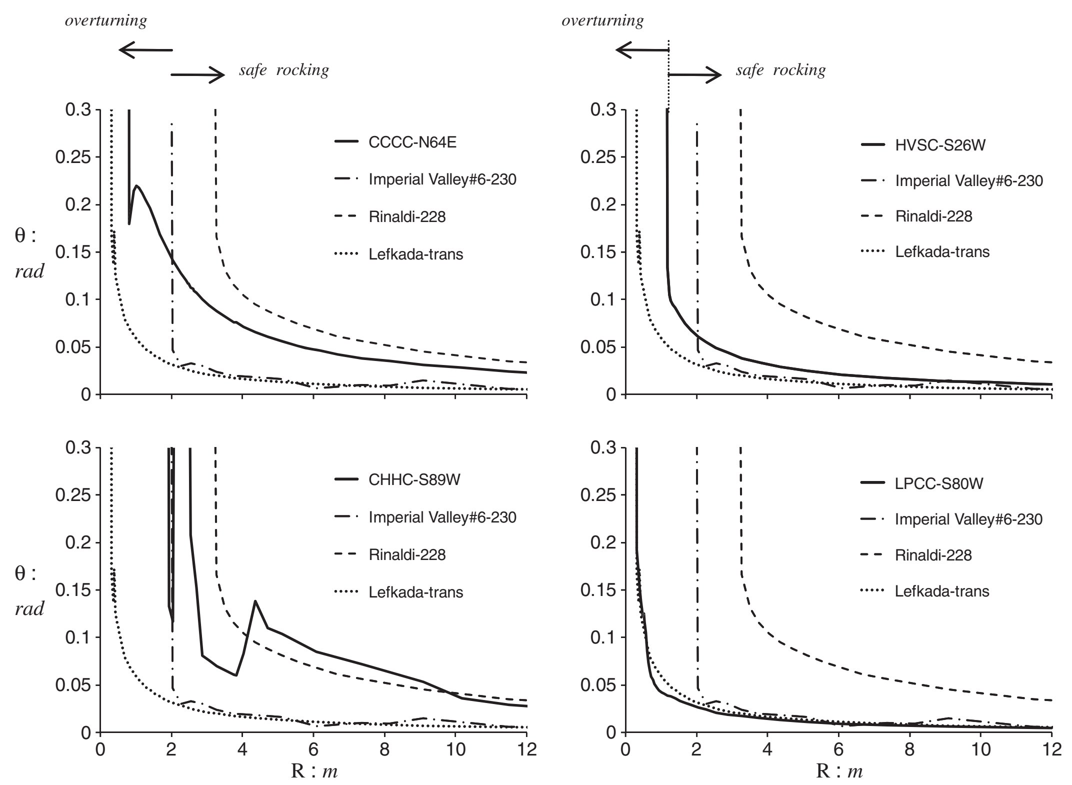

Figure 19. Rocking spectra of a slender block with respect to the size parameter R, calculated with four records of the 2011 earthquake. Comparison with three records from the aforementioned earthquakes. The coefficient of restitution is $r=0.7$. CCCC, Christchurch Catholic Cathedral College; CHCC, Christchurch Hospital; HVSC, Heathcote Valley Primary School; LPCC, Lyttelton Port Company.

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Table III. List of the near-fault earthquake records of similar magnitude to the 24 February Christchurch earthquake, utilized as excitations in this study.

Earthquake, magnitude	Record name	PGA (*g*)	PGV (m/s)	PGD (m)
Lefkada, Greece (14 August 2003), $M_W = 6.4$	Lefkada-Long	0.34	0.28	0.07
	Lefkada-Trans	0.42	0.35	0.40
Northridge 1994, California (17 January 1994), $M_w = 6.8$	Jensen Filtration Plant-22°	0.42	0.87	0.27
	Newhall Firestation-360°	0.59	0.75	0.18
	Rinaldi-228°	0.84	1.48	0.26
Imperial Valley, California (15 October 1979), $M_W = 6.8$	No 4-140°	0.49	0.37	0.20
	No 4-230°	0.36	0.77	0.59
	No 6-230°	0.44	1.09	0.66
San Fernando, California (9 February 1971), $M_W = 6.7$	Pacoima Dam-164°	1.23	1.15	0.32

PGA, peak ground acceleration; PGV, peak ground velocity; PGD, peak ground displacement.

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