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THE CHRISTCHURCH 2011 EARTHQUAKE: ELASTIC AND PERFECTLY-PLASTIC RESPONSE POTENTIAL OF SELECTED GROUND MOTIONS

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ABSTRACT

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. Their elastic response spectra are discussed and associated with some salient characteristics of the motions. Also, symmetric and asymmetric sliding of a block resting through Coulomb friction on horizontal or inclined planes, when excited at their base by these records, offer a strong indication of their "destructiveness potential" in terms of perfectly-plastic response. For strongly inelastic systems the paper introduced two new spectra to serve as indices of the "destructiveness" potential of a motion: the sliding spectra for symmetric and asymmetric slippage of a rigid block.

Keywords: sliding, Newmark's model, elastic spectrum, perfectly-plastic, yielding displacement

INTRODUCTION: THE CHRISTCHURCH EARTHQUAKE

Three earthquakes (Darfield, 4 September 2010, Christchurch, 22 February 2011, and 10 km east of Christchurch, 13 June 2011) with M_w 7.1, M_w 6.3 and M_w 6.0, respectively, shook the area of Canterbury in New Zealand. Several accelerograph stations, well-distributed in the city and the surrounding communities, recorded the events, offering invaluable ground motions. Only records from the second event, the Christchurch M_w = 6.3 earthquake, are examined in this paper.

Table 1 lists all those records along with their peak values of acceleration and their Arias Intensity in all three directions. Figure 1 depicts the locations of the stations on the map. Two city stations, CHHC near the city hospital and CCCC on the grounds of the Catholic Community College, are discussed. The third record, LPCC, is from a station in the port of Lyttelton, placed directly on volcanic rock outcrop. The fourth record, HVSC, is a motion on very-stiff-and-shallow soil at the edge of what appears to be a triangular valley, in the mountainous southernmost end of the city.

GROUND MOTIONS

Characteristics of the selected motions

The four records offer a representative sample of the intensity and nature of shaking in the broader Christchurch area. In particular, 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 other two motions, LPCC and HVSC, are unique

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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.

The three components of each of the four recorded acceleration time-histories are plotted in Figure 2; the corresponding velocity time-histories in Figure 3. The scope of this paper is to study what is the potential of these motions to inflict damage to engineering systems.

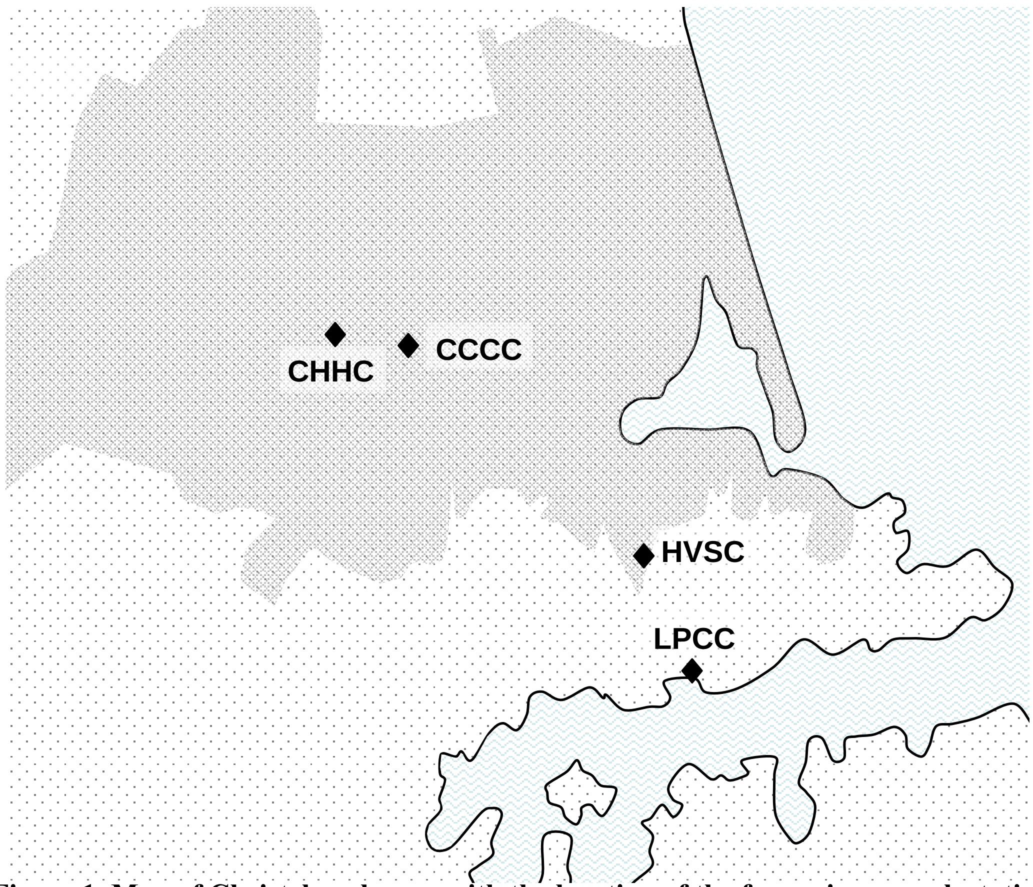

Figure 1. Map of Christchurch area with the location of the four seismograph stations whose records are utilized in our study

Table 1. The selected records of the 24 February 2011, M_W = 6.3 Christchurch EQ studied herein

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
Heathcote Valley Primary School [HVSC]	1.43	1.16	1.44	Very Stiff Deposit
Lyttelton Port Company [LPCC]	0.77	0.86	0.41	Volcanic Rock

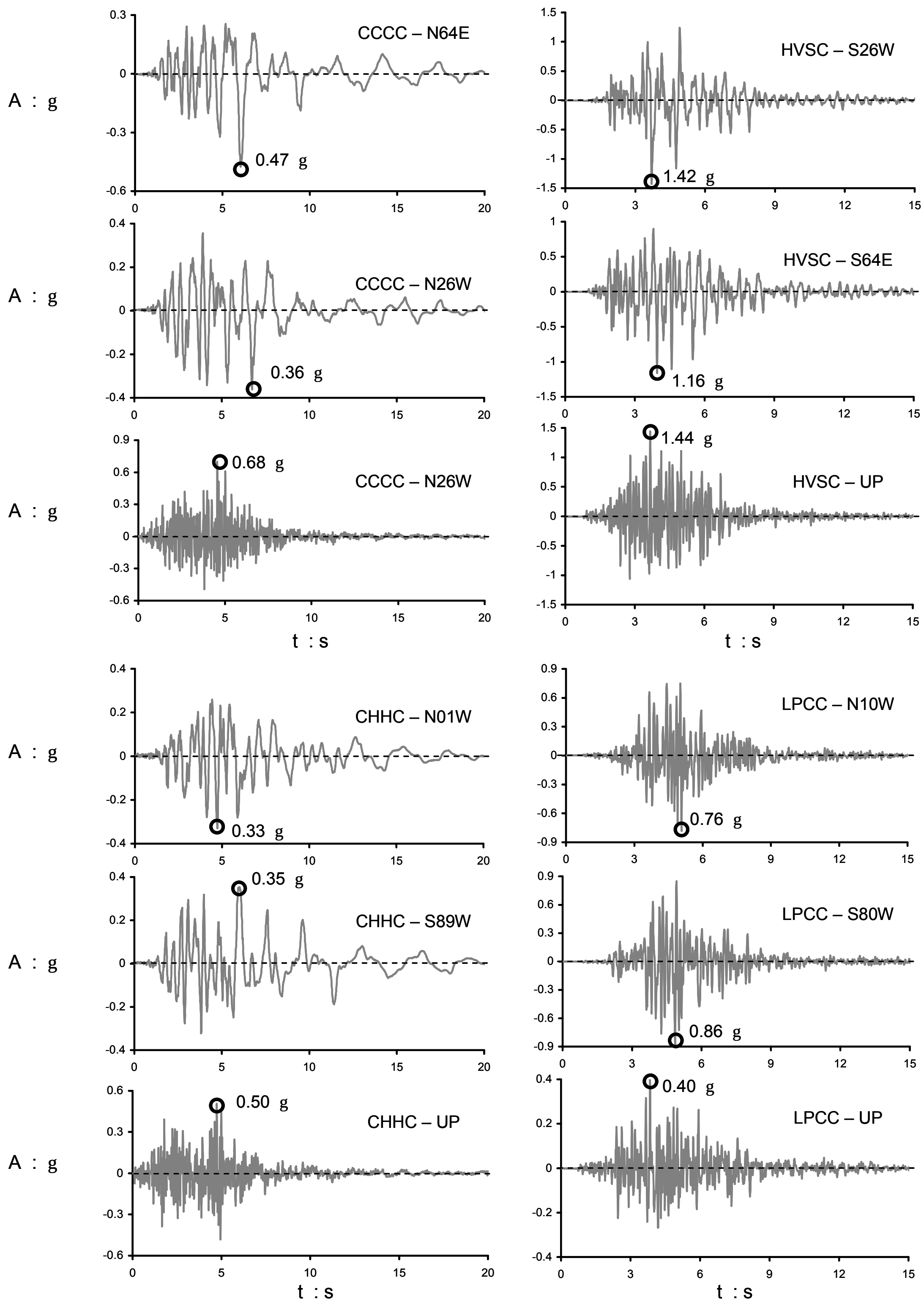

Figure 2. Acceleration time histories of the four records that we obtain from the NGS strong motion database

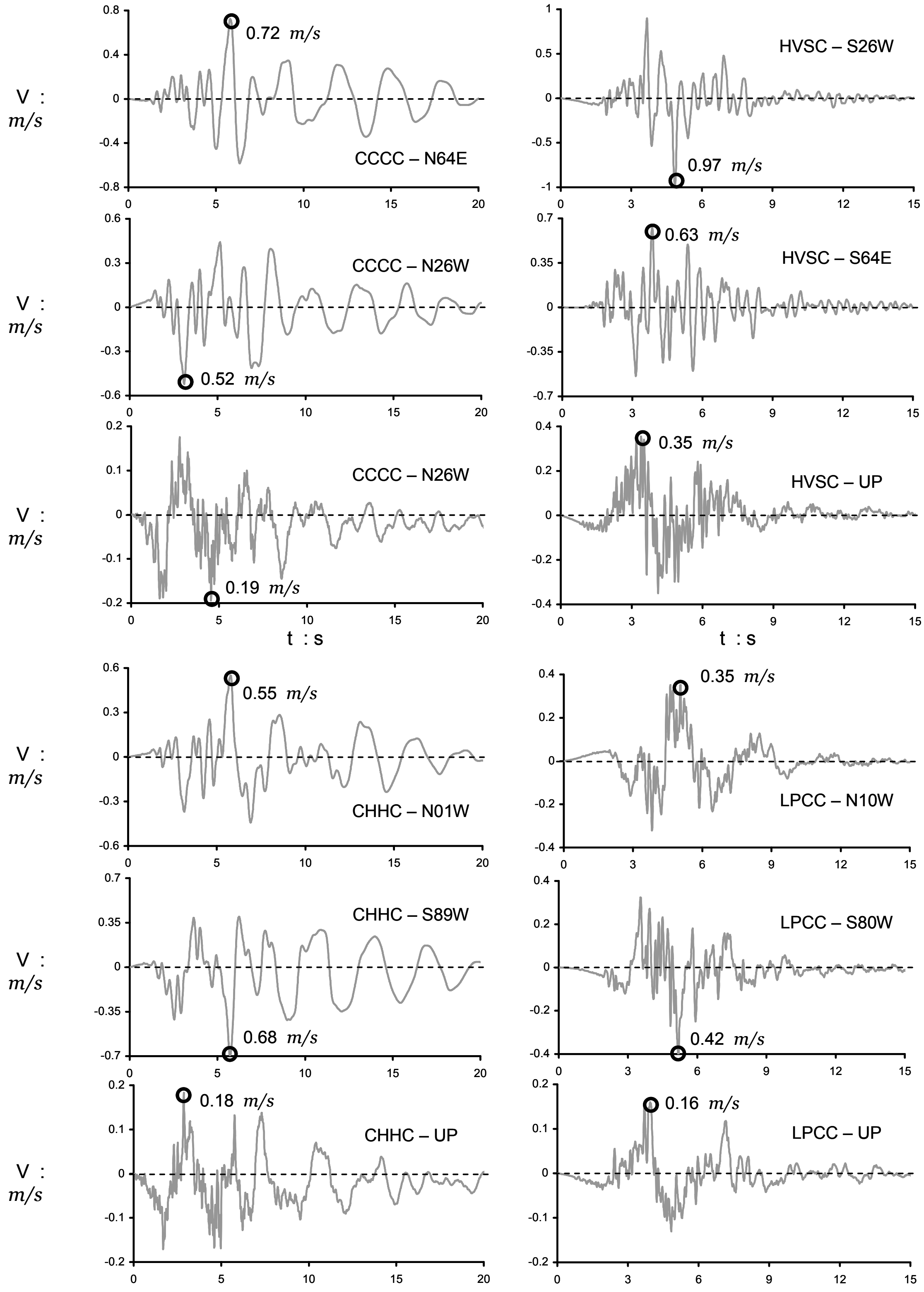

Figure 3. Velocity time histories of the four records that we obtain from the NGS strong motion database

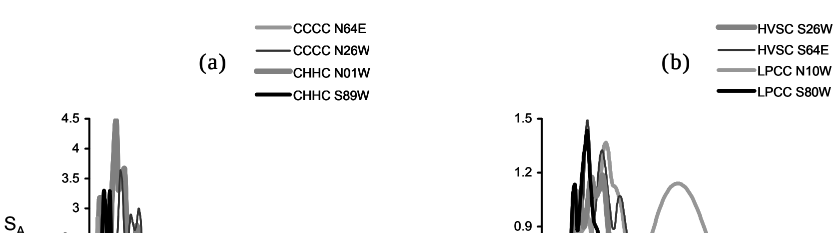

Figure 4. Elastic acceleration, velocity and displacement spectra of horizontal components of the recorded shaking motions (5% damping)

Elastic Response

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 viscous–elastic spring–mass systems. Figure 4 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 two soil motions, CCCC and CHHC, produce response spectra with two broad peaks which hint at probable effects of soil amplification: (i) in the period range $1 < T(s) < 1.7$; and (ii) in the range $2.8 < T(s) < 3.5$, approximately. The latter is most likely 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 seconds of motion.

The very–stiff–soil motion, HVSC, with its huge values of PGA (both components exceeding 1 g) and low-period max $S_A \approx 4g$, is richer in higher periods. A distinctive $S_A \approx 2$ g plateau in the period range 0.5 < T (s) < 0.85, approximately, with associated peaks of $S_V \approx 220$ cm/s and $S_D \approx 30$ cm, indicates plausible 2D valley–amplification soil effects on the S26W component of motion. A plausible cause of this high-amplitude plateau at T ≈ 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.

Rock motion LPCC produces high spectral accelerations at very low periods (average max $S_A \approx 3g$ at T ≈ 0.18 s), but their "elastic potential" drops very rapidly with increasing period. This is not a surprising behavior for rock motion having PGA ≈ 0.80 g and many high–frequency cycles in excess of 0.60 g.

Symmetric and asymmetric sliding response

For systems whose deformation involves restoring mechanisms with a dominant linear component, the viscous-elastic response spectra provide an effective indication of its potential to cause unacceptable amplitudes of deformation. However, for systems with strongly nonlinear and/or inelastic restoring mechanisms, elastic response spectra are often inadequate descriptors of the damage potential.

To assess the potential of an accelerogram to inflict large irrecoverable deformation on highly inelastic systems, the seismic behavior of two idealized systems is examined: the sliding of a rigid block on a horizontal base, and the sliding on an inclined plane. These sliding systems are characterized by a rigid-plastic symmetric or asymmetric restoring force versus displacement relationship obeying Coulomb's friction law, as illustrated in Figure 5. The maximum resistance of sliding systems is controlled by the coefficient of friction. By letting the "yield acceleration" (defined as the maximum resistance divided by the mass of the block) to vary parametrically for a given ground motion, we obtain "sliding" spectra.

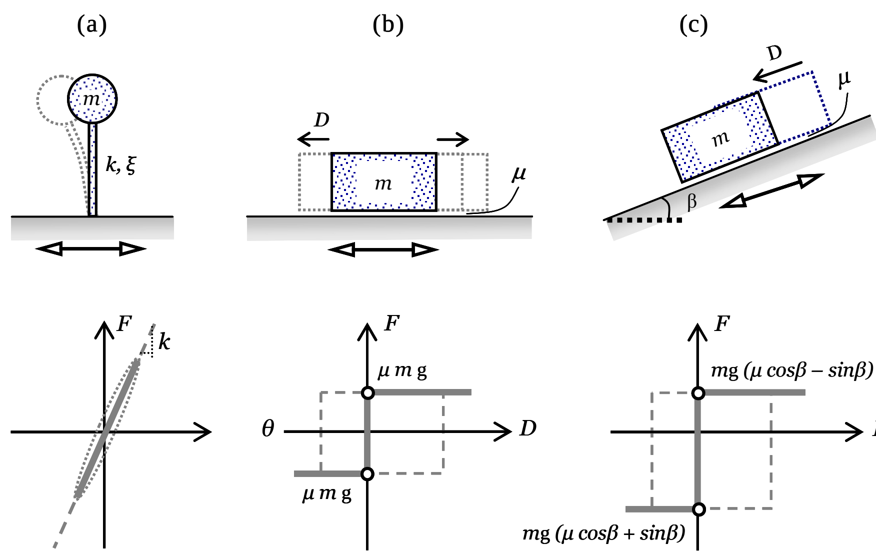

Figure 5. The fundamental systems ("analogues") studied in the paper with their restoring force-displacement relations: (a) visco-elastic oscillation of a single-degree-of-freedom system, (b) ideally rigid-plastic sliding on a horizontal plane, and (c) ideally rigid-plastic sliding on an inclined plane

Response of a block on 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) which must be exceeded for slippage to be initiated are simply:

$$A_C = \mu\, g \quad (1)$$

$$A_{C1} = (\mu \cos\beta - \sin\beta)\, g \quad (2a)$$

$$A_{C2} = (\mu \cos\beta + \sin\beta)\, g \quad (2b)$$

in which A_C = the critical acceleration for sliding in either direction of the symmetric system; μ = the (constant) coefficient of friction; A_{C1} and A_{C2} = the critical accelerations for downhill and uphill sliding for the asymmetric system of a plane inclined at an angle β. Usually $A_{C1} << A_{C2}$ and as a result sliding takes place only downhill. 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.

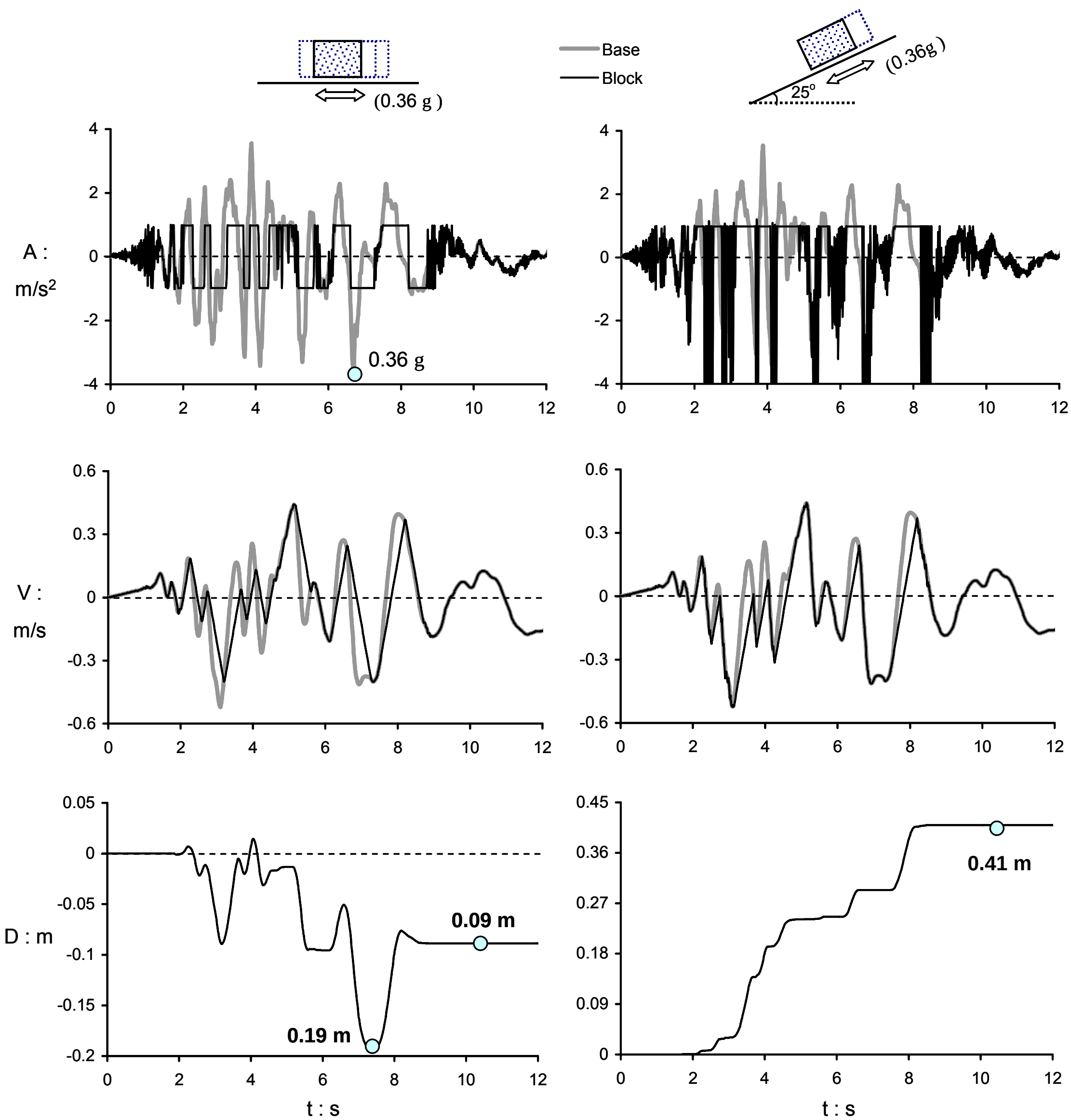

Figure 6. Influence of the symmetric (left) or asymmetric (right) nature of sliding to the response induced by the CCCC-N26W ground motion for A_C = 0.1 g

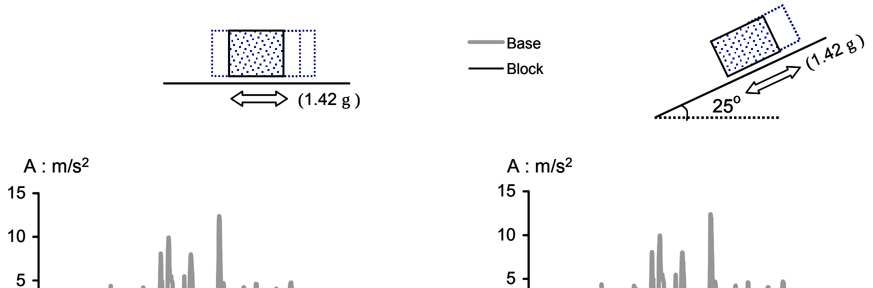

Figure 7. Influence of the symmetric (left) or asymmetric (right) nature of sliding to the response induced by the HVSC-S26W ground motion for A_C = 0.1 g

A graphical presentation of the solution procedure is given in Figures 6 and 7, for the strongest components of the CCCC and the HVSC motions. Having selected a critical acceleration A_C = 0.10 g for both the horizontal and inclined base problems, these figures illustrate 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.

By varying the critical acceleration from A_C = 0.05 g to A_C = 0.30 g the spectra of the sym-metric and asymmetric sliding displacements are obtained for each component of all four studied motions. Figures 8 and 9 compare these sliding spectra, for the horizontal and inclined base, respectively. The symmetric sliding potential of the two motions recorded on top of soil (CCCC and CHHC) is in general the highest, while that of the rock motion (LPCC) is the lowest — in spite of the far larger PGA values of this record (see Table 1). 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.

The above general picture is valid only for small values of the yield acceleration, say $A_C < 0.20$ g – 0.25 g, depending on the record. For larger A_C values, i.e. 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 in-creasing 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 g, 0.30 g, 0.33 g) marginally exceed A_C — hence sliding is negligibly small; the fourth soil motion, with PGA = 0.47 g, gives a somewhat larger slippage of 7 cm compared with the HVSC's 9 cm (maximum). As for the paradoxical increase of slippage with increasing critical acceleration A_C (i.e. increasing re-sistance to sliding), the reader is referred to Gazetas et al (2009) for a detailed convincing explanation of what was named the "Safe Gulf Paradox".

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.

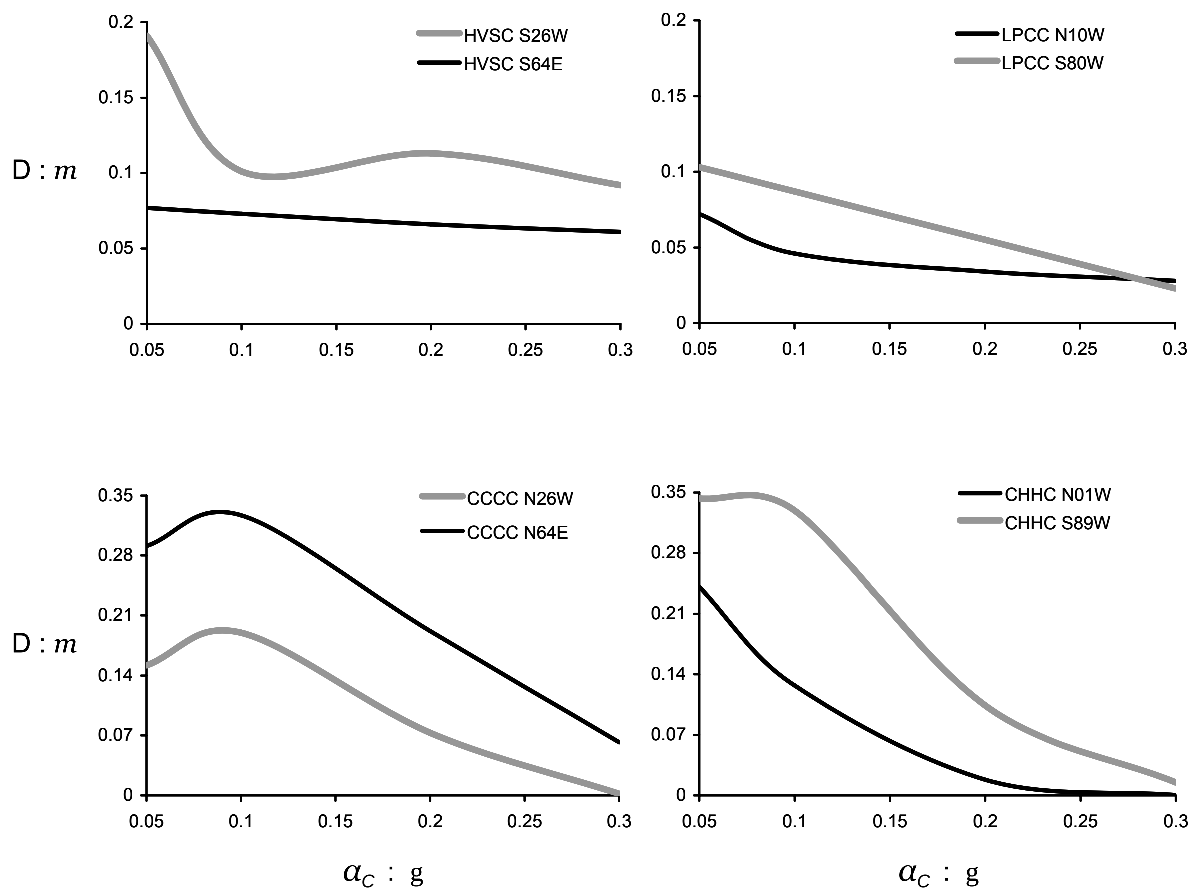

Figure 8. Sliding response of a block resting on a horizontal plane, also subjected to horizontal motion. The excitations are the four selected accelerograms. Results are presented in terms of slippage, D, versus yielding acceleration, A_C =μg

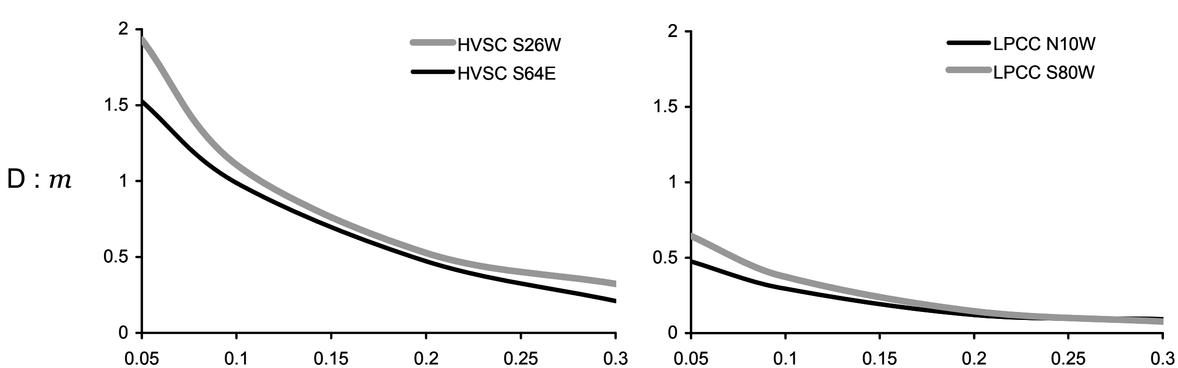

Figure 9. Asymmetric slippage of a block on top of an inclined plane subjected to horizontal motion. The excitations are the four selected accelerograms. Results are presented in terms of slippage, D, versus the downhill yielding acceleration, $A_{C1} = (\mu \cos \beta - \sin \beta)\, g$

CONCLUSIONS

For strongly inelastic systems the paper introduced two new spectra to serve as indices of the "destructiveness" potential of a motion: the sliding spectra $D = D(A_C)$ and $D = D(A_C, \beta)$ for symmetric and asymmetric slippage of a rigid block, respectively. It was shown that the Christchurch motions were of sufficient damaging potential to explain the overall damage in the city.

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