4th International Conference on
Earthquake Geotechnical Engineering
June 25-28, 2007
Paper No. 1563

RUPTURE−DIRECTIVITY AND FLING−STEP EFFECTS ON NEWMARK BLOCK SLIDING

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ABSTRACT

We study the effects of ground motions influenced by forward rupture directivity and fling step pulses on the sliding response of a block on an inclined plane. Recent earthquake records with prominent near fault characteristics are utilized. Attention is paid on the role of excitation polarity on the induced slippage; it is shown that reversing the polarity of a specific excitation may lead to substantially different response (much larger or much smaller). High frequency spiked accelerograms, such as the Sakarya (Kocaeli 1999) or Lucerne (Landers 1992) records, proved to be of substantial slippage potential as a consequence of hidden long-period acceleration pulses. The results reveal the potential of much higher sliding displacements than those predicted by the established charts of Makdisi and Seed (1978), Ambraseys & Sarma (1967), and Yegian et al (1988), who utilized records hardly affected by the aforementioned near-fault effects.

Keywords: sliding, inclined plane, forward directivity, fling step, near fault triggering

INTRODUCTION

Following Newmark (1965), the one-directional dynamic sliding of a rigid block on an inclined plane has been used to estimate the seismic response of earth dams, embankments, and retaining walls during earthquakes. In this study we propose that the slippage computed in such an analysis be used as an indicator of the destructiveness of ground motions on strongly-inelastic systems.

The "rigid block-inclined plane" analog was further utilized by Seed and Martin (1966), Ambraseys and Sarma (1967), Makdisi and Seed (1978), who developed procedures for predicting the permanent displacements of dams. Additional studies of slip in relation to the intensity of ground shaking have been made by Richards and Elms (1979) for evaluating the response of shallow foundations and gravity retaining walls, and by Whitman and Lin (1983), Yegian et al (1988), Gazetas and Uddin (1994), Kramer and Smith (1997) for analyzing the behavior of dams and embankments.

A rigid block of mass m, resting on an inclined plane (at an angle β with the horizontal) is subjected to seismic excitation parallel to the base with peak ground acceleration a_H (in g units). The interface obeys Coulomb's friction law, with a constant coefficient of friction μ (Figure 1a).

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Dynamic equilibrium of the block at any instant (Figure 1b) leads to the following expressions for the block's acceleration when it slides downhill or uphill, respectively:

$$a_{C\,1} = \mu \cos\beta - \sin\beta \qquad (1)$$
$$a_{C\,2} = \mu \cos\beta + \sin\beta \qquad (2)$$

Since always $a_{C1} \ll a_{C2}$ the acceleration a_{C1} for downhill movement is called critical sliding acceleration. Base acceleration, $a_H(t)$, at a particular moment in time has a different value which can be greater of lower than a_{C1}. As long as $a_H(t)$ does not exceed $a_{C\,1}$ the block does not slip. As soon as $a_H(t)$ exceeds $a_{C\,1}$ sliding initiates, which will stop when the block and the base acquire the same velocity (vectorially). Knowing the critical acceleration and the time history of base excitation, permanent displacements in every sliding stage can be calculated. Thanks to the transient nature of the earthquake loading, the block may be subjected to a number of acceleration pulses higher than this critical acceleration, which simply produce (accumulating) permanent deformation rather than complete failure. Theoretically, sliding on an inclined plane can happen in both directions: uphill or downhill. However in practice, for planes with inclination angle greater than 5^o, sliding occurs only downhill: hence the term asymmetric sliding.

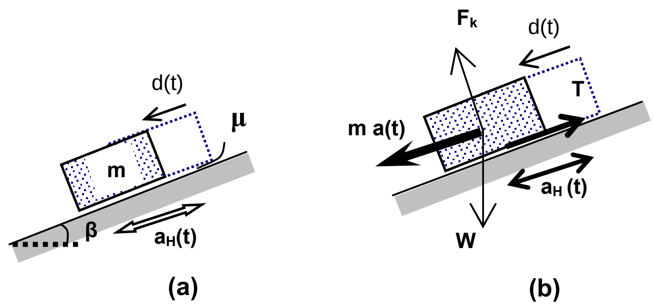

Figure 1. Schematic representation of Newmark's model used in the parametric study. (a) A rigid block resting on an inclined sliding interface governed by Coulomb's friction law, (b) Forces acting on the block that tends to slide downwards subjected to upward excitation.

ASYMMETRIC SLIDING BY NEAR FAULT GROUND MOTIONS

In the last two decades, several strong earthquakes have occurred providing a great number of near-fault records bearing the influence of forward rupture directivity and fling-step effects (Somerville 2000, Abrahamson 2003). In our sliding study 15 horizontal components of records are used as input shaking parallel to the base. However, only 5 of these are discussed in this paper (Table 1). A grouping of all the 15 records according to some salient characteristics is as follows:

- *High–frequency records*: Santa Monica (Northridge 1994), UCLA (Northridge 1994), Lucerne (Landers 1992), Sakarya (Kocaeli 1999).
- *Records with a single dominant velocity pulse*: Imperial Valley No 4 & 6 (Imperial Valley 1979), Yarimca (Kocaeli 1999), Sakarya (Kocaeli 1999), TCU 068 (Chi-chi 1999), Lucerne (Landers 1992), Rinaldi (Northridge 1994), Pacoima Dam (Northridge 1994).
- *Records with multiple dominant velocity pulses*: JMA (Kobe 1995), Takatori (Kobe 1995), Imperial Valley No 4, TCU 102 (Chi-chi 1999), Jensen (Northridge 1994).
- *Records with fling-steps*: Yarimca (Kocaeli 1999), Sakarya (Kocaeli 1999), TCU 068 (Chi-chi 1999), Lucerne (Landers 1992)

- *Records affected by forward or backward directivity*: Fukiai (Kobe 1995), JMA (Kobe 1995), Takatori (Kobe 1995), Takarazuka (Kobe 1995), TCU 068 & 102 (Chi-chi 1999), Imperial Valley No 4 & 6 (Imperial Valley 1979), Newhall (Northridge 1994), Rinaldi (Northridge 1994), Jensen (Northridge 1994).

Table 1. Ground motion records discussed in this paper

Earthquake	Magnitude M	Record	Distance from Fault [km]	PGA [g]	PGV [cm/s]
Northridge (1994)	6.8	Jensen (22^o component)	4	0.42	87
Northridge (1994)	6.8	Rinaldi (228^o component)	3	0.83	148
Landers (1992)	7.3	Lucerne (275^o component)	1.1	0.72	116
Kocaeli (1999)	7.4	Sakarya (EW component)	25	0.41	82
Kocaeli (1999)	7.4	Yarimca (60^o component)	25	0.23	94

Directivity Effect

Record severity is usually measured with its peak ground acceleration (PGA). However, this is not the rule for elastoplastic systems, especially those involving asymmetric sliding. Objective factors of the damage potential of a motion can be: the frequency, the effective acceleration magnitude, the detailed sequence of acceleration pulses. In case of directivity affected ground motions, the acceleration time-histories carry the signs of rupture process in a series of successive long period acceleration pulses.

Figure 2 portrays the sliding response of a rigid block triggered by the Jensen record. Notice that the acceleration time-history contains a series of long period pulses (T ≈ 1 sec) with magnitude of acceleration of about 0.30 g, starting at t ≈ 3.7 sec until t ≈ 12 sec. For a ratio $a_{CI} / a_H = 0.05$, Jensen excitation induces a sliding displacement of 4.55 m as the result of three major slides, which are clearly shown in the velocity time-histories of Figure 2. The long duration two-sided (not predominantly on the positive or negative side) acceleration cycles when integrated, reveal this triplet of two-sided velocity pulses (the first starts at 3.8 sec containing a velocity step of almost 1.8 m /s, the next one starts at 6.4 sec with a velocity step 1.2 m /s, and the last one starts at 10.4 sec with a velocity step 0.5 m /s) which lead to the aforementioned slides.

Fling-Step Effect

Generally, the term fling refers to permanent dislocation: (a) parallel to the fault rupture vicinity in case of a strike-slip fault, (b) perpendicular to the rupture in case of a normal fault. Therefore, flinged records exhibit permanent displacement at the end of shaking. For instance, Figure 3 illustrates the acceleration, velocity, and displacement time-histories of the Lucerne record. Observe the maximum and permanent displacements of 1.2 m and 0.4 m respectively. The substantial displacement of 1.2 m and the resultant dislocation of 0.4 m are mainly attributed to a single velocity pulse presented by the dotted areas in Figure 3. Records affected only by directivity have zero permanent displacement as a result of equally balanced velocity pulses. In other words, the area of positive velocity pulses is equal with the area of the negative velocity pulses. However, this is not the case with flinged records. In near fault regions the rupture dislocation seems to be transferred to the records through one-sided velocity time-histories. Either one, the positive or the negative, of velocity areas overshadows the other, leading to permanent displacement (offset).

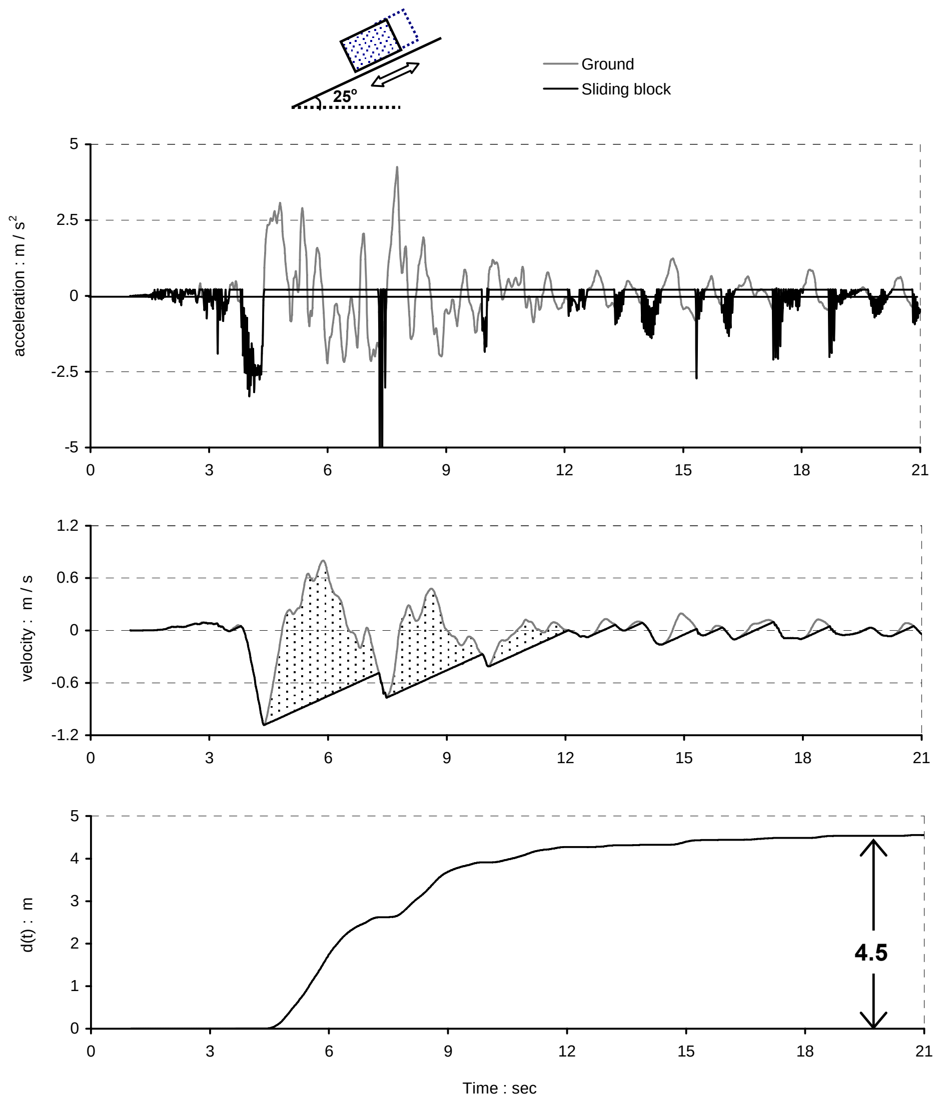

Figure 2. Acceleration and velocity time-histories of the rigid block and the input base excitation, as well as slippage time-history of the sliding block triggered by the Jensen record (22° component) for a slope of inclination *β=25°* and critical acceleration ratio $a_{C1}/a_H = 0.05$. The slippage of 4.55 m is the outcome of three major sliding episodes (dotted areas) induced by three successive velocity pulses resulting from the forward-rupture directivity related acceleration pulses (starting at about 4 sec and ending at 12 sec).

Ground motions affected by fling step usually give the impression of "harmless" high frequency spiked accelerograms. Nevertheless, they contain long period pulses that induce considerable "damage". In case of asymmetric sliding systems, the results of such a record are portrayed in Fig. 4. A total slippage of 2.31 m is triggered almost exclusively by the velocity pulse with step of nearly 2 m/s and duration of 4 sec (starting at t ≈ 12 sec, until t ≈ 16.5 sec). Therefore, in sliding systems neither the peak acceleration nor the peak velocity matter, as much as the velocity step and pulse duration. For example, in left hand-side of Figure 5 is presented the sliding response induced by the Sakarya record. Sakarya ground motion is a well known fling affected record with a permanent dislocation of 2 m. It can be easily observed the velocity pulse of 0.8 m /s peak value and 4.5 sec duration, a feature attributed to fling. Despite of that, the induced slippage is just 1 m because the particular velocity pulse is one-sided (positive). On the contrary, for the Yarimca excitation (right in Figure 5) the sliding response climbs up to 4.3 m owning to the large velocity step of 1.4 m /s. The slippage starts when the velocity takes the value: - 0.5 m/s. This negative part triggers the slippage; if there were no negative part, keeping everything else the same, the result could be much smaller slippage (dotted line on velocity time-history).

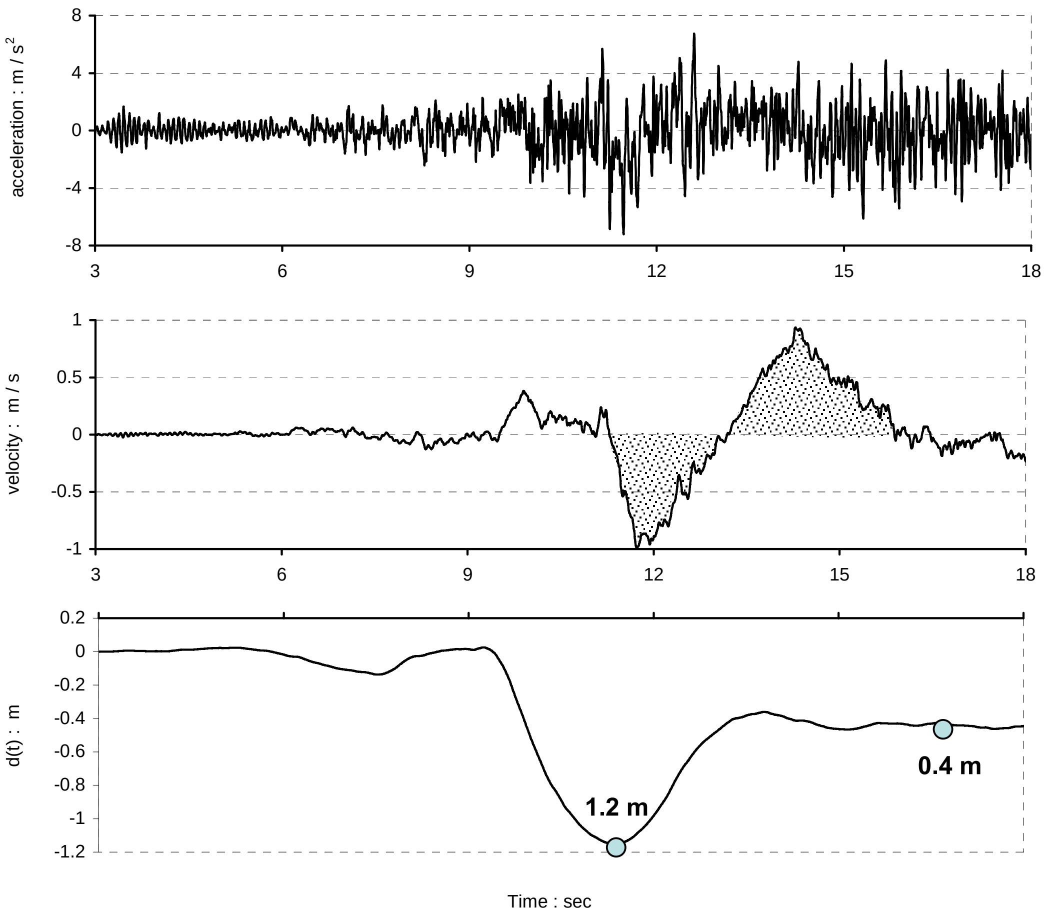

Figure 3. Acceleration, velocity and displacement time-histories of the Lucerne record. Note the maximum and permanent dislocation of 1.2 m and 0.4 m respectively; results of the fling rupture effect.

Influence of excitation polarity

Reversal of excitation may lead to significantly different sliding displacement. Figure 6 illustrates the response of a block on a plane of $\beta = 25^o$, subjected to the Rinaldi record applied in the +x (left) or in the –x (right) direction. For every acceleration ratio, the slippage of the block differs by a factor of at least 2. For instance, for a_{C1} / a_H = 0.05, the +x excitation induces 1.73 m sliding deformation while inverted (-x) triggers 4 m of slippage. The culprit: the well-shaped acceleration pulse of 0.84 g magnitude and 2 sec duration (starts at t = 3 sec until t = 5 sec), which acts either as a barrier to sliding (left plots of Fig. 6) or as the major contributor (right).

One can imagine two identical steep banks of a channel; they have opposite slope directions and in case of an earthquake they are subjected to the same input motion. This is similar to the case of two identical slopes with the same direction, which are excited by the same motion in opposite directions. Even if the slopes were identical, their damage during Northridge earthquake would be significantly different.

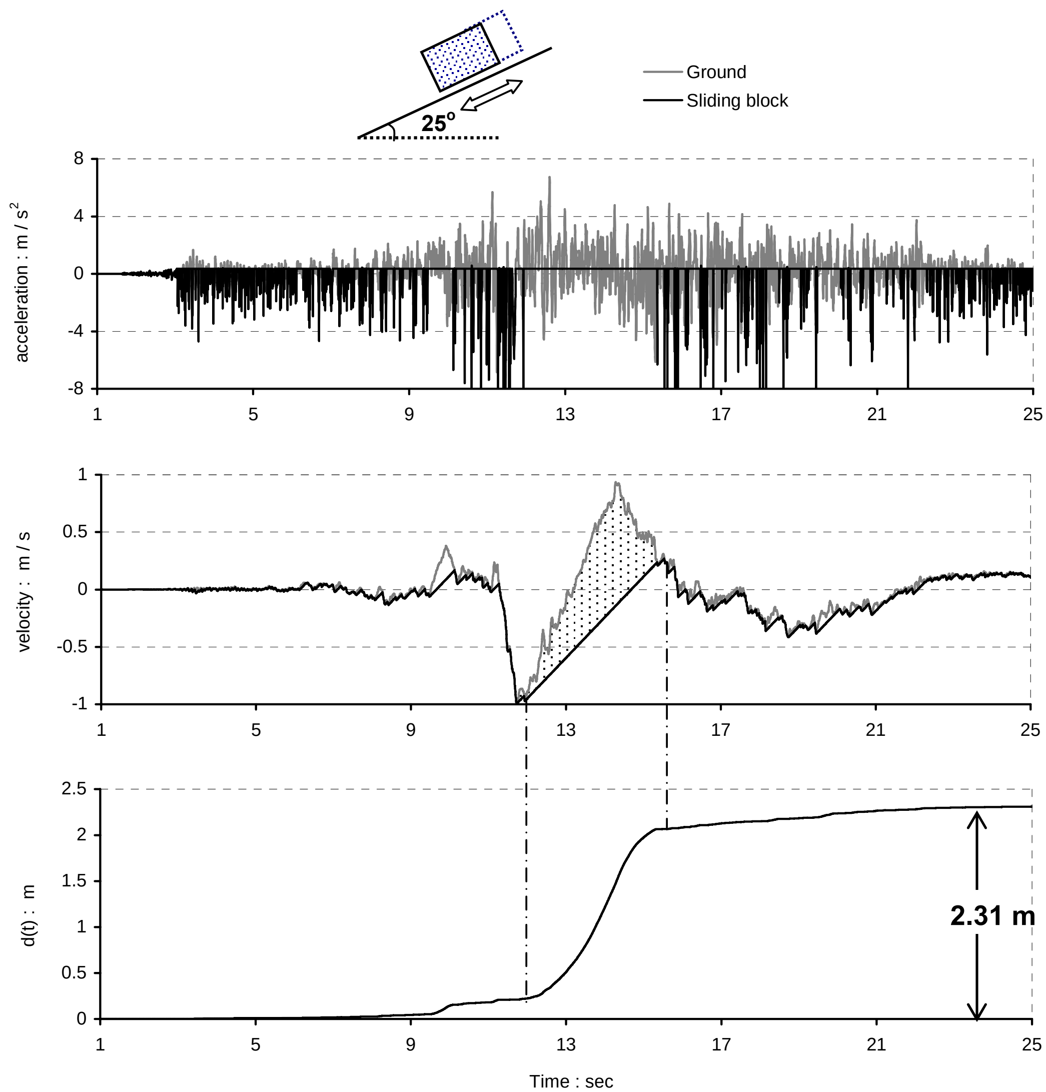

Figure 4. Acceleration, velocity, and slippage time-histories for the Lucerne (275° component) ground motion for a slope with inclination *β=25°* and critical acceleration ratio $a_{C1}/a_H = 0.05$. That particular record is representative of high-frequency flinged ground motions. Notice the well shaped pulse in velocity induced not by the numerous spikes of acceleration but by the "hidden" long period acceleration pulses.

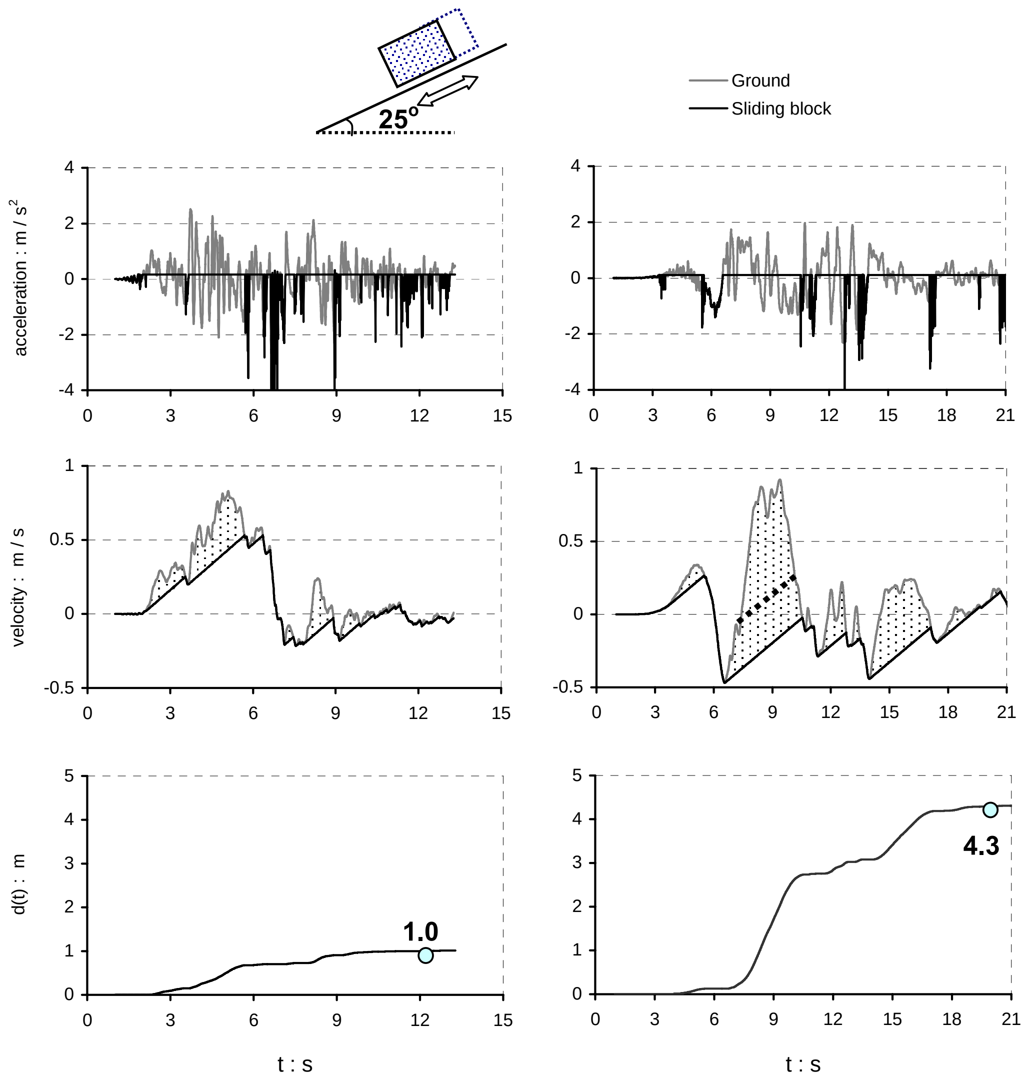

Figure 5. Acceleration, velocity and slippage time-histories for the Sakarya d (left) and the Yarimca (right) records of a block on an inclined plane with $\beta = 25^o$ and acceleration ratio $a_{C1}/a_H = 0.05$.

COMPARISON WITH AVAILABLE CHARTS

As a useful epilogue, a comparison is performed of the results of our study with the relevant chart for sliding displacement published by Makdisi & Seed (1978). The comparison is portrayed in Fig. 7. The computed data points for the studied records of Kobe, Northridge, and Imperial Valley earthquakes are displayed on the top plot, while the bottom figure contains the slippage due to the flinged records. For most of the records (particularly the strong near fault ground motions such as TCU 068 NS) the curves of Makdisi & Seed, understandably, fail to predict even the order of magnitude of sliding.

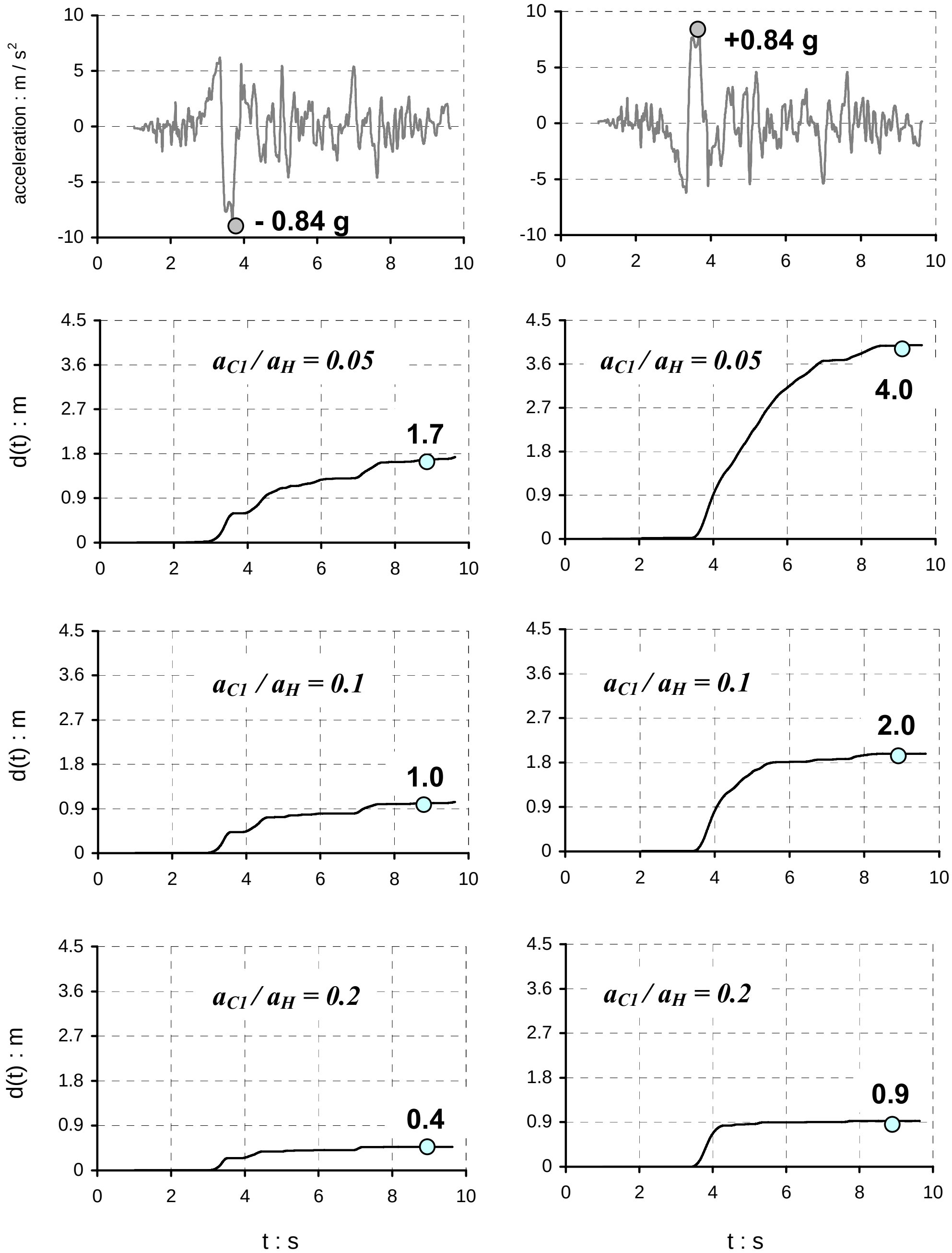

Figure 6. Effect of the polarity of accelerogram on asymmetric sliding. Shown on the top line is the Rinaldi record in +x direction (left) and –x direction (right) form. The next three lines compare the slippage histories for three different acceleration ratios.

CONCLUSIONS

The paper has studied the effect of near-fault phenomena such as forward directivity and fling step on asymmetric sliding. Near fault characteristics (such as long duration pulses, their sequence, large velocity steps) play a significant role on sliding response. The main conclusions of the study are:

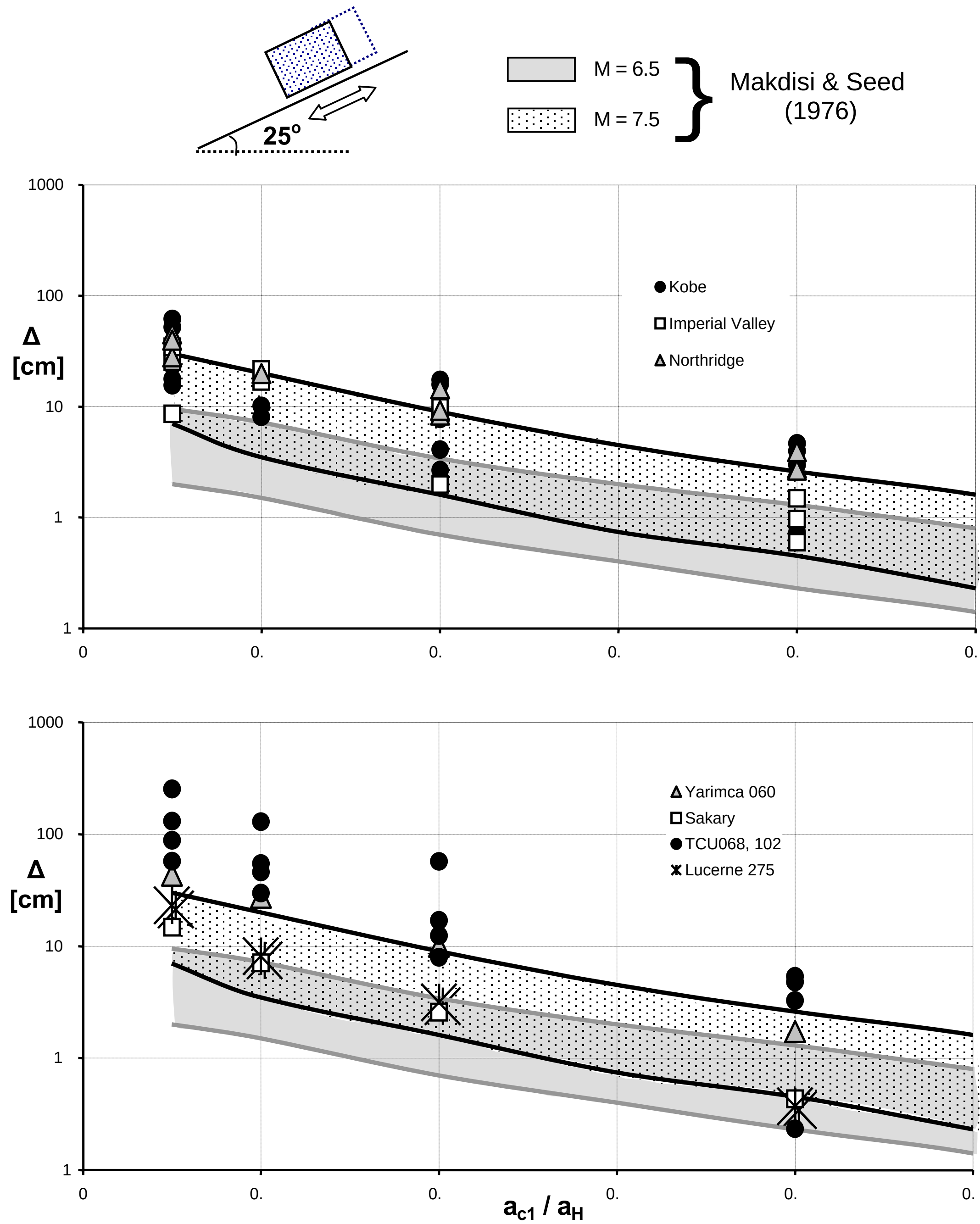

Figure 7. Comparison of the computed data points with the published ranges of Makdisi & Seed (1976).

- Peak ground acceleration is of small importance in asymmetric sliding, in contrast with the frequency content and polarity of the excitation. Records with moderate to small peak ground acceleration but with long duration velocity pulses (i.e. TCU 068, Yarimca, Sakarya) induce greater slippage than high peak acceleration ground motions with small duration velocity pulses (i.e. Santa Monica, UCLA).

- By inverting the polarity of an excitation the induced slippage can be significantly different. Isolated pulses which trigger substantial sliding when imposed in one direction, may inhibit slippage when their direction is reversed.
- Inclined sliding appears to be of strongly non-linear nature; the largely unpredictable detailed pulse sequence and the form of the ground shaking have a dominant influence on sliding response.

AKNOWLEDGEMENTS

The authors wish to acknowledge partial financial support of this work by the Lessloss Research Program of the European Union (Contract No. GOCE-CT-2003- 505488).

REFERENCES

Ambraseys, N.N., & Sarma, S.K. (1967). The response of earth dams to strong earthquakes. Géotechnique 17, 181 - 213.

Bertero, V.V., Mahin, S.A., & Herrera, R.A. (1978). Aseismic design implications of near-fault San Fernando earthquake records. Earthquake Engineering and Structural Dynamics, Vol. 6, 31 – 42.

Elms, D.G. (2000). Refinements to the Newmark sliding block model. Proceedings of 12th World Conference in Earthquake Engineering, 2132.

Gazetas, G. & Uddin, N. (1994). Permanent deformation on pre-existing sliding surfaces in dams. Journal of Geotechnical Engineering, Vol.120, No.11, 2041 – 2061.

Gazetas, G. (1981). Vertical oscillation of earth and rockfill dams: analysis and field observation. Soils and Foundations, Vol. 21(4), 265 - 277.

Kramer, S. L. & Smith, M. (1997). Modified Newmark model for seismic displacements of compliant slopes. Journal of Geotechnical and Geoenvironmental Engineering, Vol. 123, 635 – 644.

Lin, J.S., & Whitman, R.V. (1986). Earthquake induced displacements of sliding block. Journal of Geotechnical Engineering, Vol. 105(12), 1427 - 1434.

Makdisi, F.I. & Seed, H.B. (1978). Simplified procedure for estimating dam and embankment earthquake induced deformations. Journal of Geotechnical Engineering Division, ASCE, Vol. 104, 849 – 867.

Newmark, N.M. (1965). Effect of earthquakes on dams and embankments. Géotechnique 15, 139 – 160.

Richards, R., Elms, D.G. & Budhu, M. (1982). Seismic bearing capacity and settlement of foundations. Journal of Geotechnical Engineering Division.

Richards, R. & Elms, D.G. (1979). Seismic behaviour of gravity retaining walls. Journal of Geotechnical Engineering Division.

Sarma, S.K. (1975). Seismic stability of earth dams and embankments. Géotechnique 25, No 4, 743 – 761.

Seed, H.B., & Martin, G.R. (1966). The seismic coefficient in earth dam design. Journal of the Soil Mechanics and Foundation Division, ASCE, Vol. 92, 25 - 58.

Yegian, M.K., Marciano E.A., & Ghahraman, V.G. (1991). Earthquake induced permanent deformations: a probabilistic approach. Journal of Geotechnical Engineering, Vol. 117(1), 35 - 50.

Yegian, M.K., Marciano E.A., & Ghahraman, V.G. (1988). Integrated seismic risk analysis for earth dams. Report No CE-88-15.