SECOND EUROPEAN CONFERENCE ON EARTHQUAKE ENGINEERING
AND SEISMOLOGY, ISTANBUL AUG. 25-29, 2014

"ELASTIC", "CONSTANT–DUCTILITY" AND "SLIDING" SPECTRA AS BASIS OF INELASTIC RESPONSE PREDICTION

Evangelia GARINI[1] and George GAZETAS[2]

ABSTRACT

It is universally accepted in earthquake engineering that elastic Design Response Spectra (consisting of a horizontal constant-acceleration branch from very low to medium periods and a descending branch at higher periods) adequately describe the seismic threat at a site; hence they must be closely respected from the selected accelerograms–excitations, even for highly inelastic systems. In fact, Inelastic Design Response Spectra were derived for a specified constant ductility μ, to be used directly for elastic response analysis of inelastic multi-dof systems. However, the validity of this presumption (employing elastic spectrum to produce inelastic spectrum) was seriously questioned by the engineering community decades ago. The weakness of the above use of elastic design response spectra for strongly inelastic systems is shown in this paper, using the "sliding" spectra.

In case of sliding systems governed by the Coulomb's friction law, we introduce the idea of equivalent sliding motions for a given displacement level, and present particular shortcomings of elastic response spectra for such anelastic systems. The concept of equivalent sliding motions is as follows: for a given predetermined level of sliding displacement and yielding acceleration A_C, we obtain the appropriate scaled ground motions that induce this predetermined slippage. The studied sliding systems herein consists of a rigid block on top of: (a) a horizontal plane or (b) a sloping plane of inclination angle β. The yielding interface between the block and its base has a coefficient of friction, μ. Both systems are excited with 90 near-fault strong ground motions bearing the effects of forward directivity and fling step.

INTRODUCTION

Intensity is a non-instrumental perceptibility measure of damage to structures, ground surface effects, e.g. fractures, cracks, floor drifts, and sometimes even human reactions to earthquake shaking. It is a descriptive method which has been traditionally used to establish earthquake size and potential destructiveness, especially for pre-instrumental events. Hence, it is a subjective damage evaluation because of its qualitative nature, related to population density, familiarity with earthquake and type of constructions.

The need for an objective quantitative index of seismic destructiveness led to the concept of elastic spectrum that widely used as a measure of earthquake destructiveness on structural engineering. The next step was to extent the notion of elastic response of any single degree of freedom system from elastic to inelastic spectrum. However, parameters such as the near-fault characteristics of ground motions, the level of system's inelasticity had not been considered. Therefore, in case of sliding systems governed by the Coulomb's friction law, we introduce the idea of equivalent sliding motions

[1] Post-doctoral Researcher, NTUA, Athens, Greece, geocvemp@yahoo.gr
[2] Professor, NTUA, Athens, Greece, gazetas@ath.forthnet.gr

for a given displacement level, and present particular shortcomings of elastic response spectra for such anelastic systems.

In following sections, we revise the fundamental points of elastic spectrum of a ground motion and we proceed with the explanation of equivalent sliding motions.

ELASTIC AND INELASTIC RESPONSE SPECTRA

A response spectrum is a plot of the maxima of the acceleration, velocity and displacement response of single-degree-of-freedom systems with various natural periods when subjected to an earthquake ground motion. A family of curves is usually calculated for a given excitation, for different values of structural damping. For many practical structural applications, it is sufficient to employ the spectral values of the acceleration, velocity, or displacement rather than their values at each instant during the time history.

The shape of earthquake spectrum is influenced by a number of factors, which are similar to those affecting earthquake ground-motion characteristics, such as the fault mechanism and source rupture characteristics, the earthquake magnitude, the distance from the seismic source, the wave travel path. Some of these factors are more influential than others. The three fundamental parameters influencing spectra are: magnitude, distance and site conditions. However, in engineering practice when designing a new structure or studying the retrofit of an existing one, the knowledge of all these parameters is almost impossible. Therefore, seismic codes recommend spectra that are dependent on peak ground parameters and the soil conditions only.

A common practice is that for different earthquake magnitudes and distances the design spectra are just scaled up or down, whereas the actual spectrum shape remains the same. However, this might not be the case of inelastic and degrading systems, where the shaking duration will have an effect. Hence, it is not possible to compensate for magnitude effects by scaling only since the spectral shape changes and the scaling may not be of a linear form.The need for an objective quantitative index of the intensity of seismic response has prompted the development of the elastic spectrum, which was latter extended to elastic Design Response Spectra [EDRS] and Inelastic Design Response Spectra [IDRS]. For elastic–ideally-plastic force–displacement behaviour of a system, the following expressions have been particularly popular for the reduction factor Ry which divides the EDRS to obtain IDRS:

$$Ry = 1 \quad \text{for} \quad T_{elastic} < Ta \tag{1a}$$

$$Ry = (2\mu - 1)1/2 \quad \text{for} \quad Tb < T_{elastic} < Tc \tag{1b}$$

$$Ry = \mu \quad \text{for} \quad T_{elastic} > Td \tag{1c}$$

in which $Ta < Tb < Tc < Td$ depend on soil and seismicity characteristics of the particular site. Linear interpolation is assumed between Ta and Tb as well as between Tc and Td (e.g., Chopra 2000).

Thirty-five years ago in his seminal work to explain the failures of the Olive View Hospital in the San Fernando 1971 earthquake, Professor Vitelmo Bertero seriously questioned the validity of the above presumption. The shortcomings of EDRS and IDRS for strongly inelastic systems are shown herein by employing the consepts of "sliding" spectra and equivalent sliding motions.

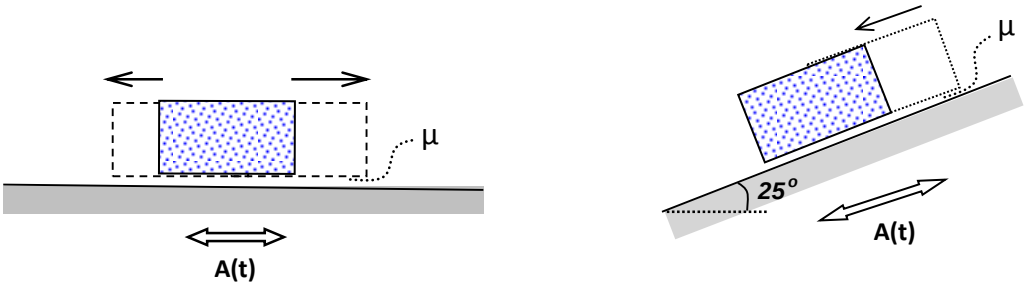

Figure 1. The inelastic systems utilised: a rigid block standing on a horizontal plane (left) and a block on top of a sloping plane (right).

THE CONCEPT OF EQUIVALENT SLIDING MOTIONS

The inelastic systems that we employ in this study consist of a rigid block resting on a plane (horizontal or inclined) triggered by an earthquake recorded ground motion (Figure 1). The interface between the base and the block obeys the Coulomb friction law, thus characterized by one parameter: the friction coefficient, μ. The block remains in full contact with its base, moving with the same acceleration and velocity, until the triggering acceleration exceeds the critical yielding acceleration of:

(i) $A_C = \mu\, g$, in case of horizontal plane, and

(ii) $A_C = (\mu \cos\beta - \sin\beta)g$, in case of the inclined plane.

The response of the block is fully inelastic since sliding starts. For the inclined system, the relative block—base displacement prevails in the downward direction therefore slippage accumulates in every sliding period and the block cannot end up in its initial position. Whereas in the horizontal plane, sliding occurs in both directions and the block can return to its origin. The seismic records utilized as excitations in our study are listed in Table 1.

Table 1. List of significant earthquake records bearing the effects of 'directivity' and 'fling', utilized as excitations in this study

Earthquake, Magnitude	**Record Name**
Kobe - Japan, (16 January 1995) $M_W = 7.0$ $M_{JMA} = 7.2$	Fukiai, JMA-0°, JMA-90°, Nishi Akashi -0°,Nishi Akashi -90°, Shin Kobe –NS, Takarazuka-0°, Takarazuka-90°, Takatori-0°, Takatori-90°
Imperial Valley – California, (15 October 1979) $M_W = 6.8$	No 4-140°, No 4-230°, No 5-140°, No 5-230°, No 6-140°, No 6-230°, No 7-140°, No 7-230°, No 9 Differential Array-270°, No 9 Dif. Array-360°
Landers - California, (28 June 1992) $M_W = 7.3$	Lucerne-0°, Lucerne-275° Joshua Tree-0°, Joshua Tree-90°
San Fernando - California, (9 February 1971) $M_S = 6.7$	Pacoima Dam-164° Pacoima Dam-254°
Erzincan - Turkey, (13 March 1992) $M_S = 6.9$	Erzincan (Station 95)-EW Erzincan (Station 95)-NS
Loma Prieta - California, (17 October 1989) $M_S = 7.1$ $M_W = 6.8$	Los Gatos Presentation Center-0° Los Gatos Presentation Center-90° Saratoga Aloha Avenue-0°, Saratoga Aloha Av.-90°
Gazli - USSR, (17 May 1946) $M_S = 7.0$	Karakyr-0° Karakyr -90°
Northridge 1994 - California, (17 January 1994) $M_W = 6.8$	Jensen Filtration Plant-22° & 292°,L.A. Dam-64° & 334°, Newhall Firestation-90° & 360°, Pacoima Dam (downstream)-175° & 265°, Pacoima Kagel Canyon-90° & 360°, Rinaldi-228° & 318°, Santa Monica City Hall-90° & 360°, Sepulveda VA-270° & 360°, Simi Valley Katherine Rd-0° & 90°, Sylmar Hospital-90° & 360°
Chi-Chi Taiwan, (20 September 1999) $M_W = 7.5$	TCU 052-EW & NS, TCU 065-EW & NS, TCU 067-EW & NS, TCU 068-EW & NS, TCU 075-EW & NS, TCU 076-EW & NS, TCU 080-EW & NS, TCU 084-EW & NS, TCU 102-EW&NS
Kocaeli - Turkey, (17 August 1999) $M_W = 7.4$ $M_S = 7.8$	Duzce-180°, Duzce-270°, Sakarya-EW, Yarimca-60° Yarimca-330°
Tabas - Iran, (16 September 1978) $M_S = 7.4$	Tabas-LN Tabas-TR
San Salvador – El Salvador, (10 October 1986) $M_S = 5.4$ $M_W = 5.6$	National Geographical Institute-180° & 270°, Geotechnical Investigation Center-90° & 180°, Institute of Urban Construction-90° & 180°
Duzce - Turkey, (12 November 1999) $M_S = 7.5$ $M_W = 7.2$	Bolu-0° & -90°, Duzce-180° & -270°

For a given predetermined level of sliding displacement and yielding acceleration A_C, we define as equivalent sliding motions the appropriate scaled ground records that induce this predetermined slippage. For instance, Figure 2 illustrates all the records that for an inclined system ($\beta = 25^o$) with A_C = 0.05 g induce a sliding of 20 cm. So, the JMA record (90° component) must be down-scaled to a PGA = 0.13 g to lead to a sliding of 20 cm; while for the same slippage, the Simi Valley record (component 0°) must be doubled from 0.13 g to 0.26 and the Institute of Urban Construction record (IUC 90°) to 0.27 g. As a consequence of Figure 2, in Figure 3 are presented all the elastic response spectra that result in the same sliding potential of 20 cm.

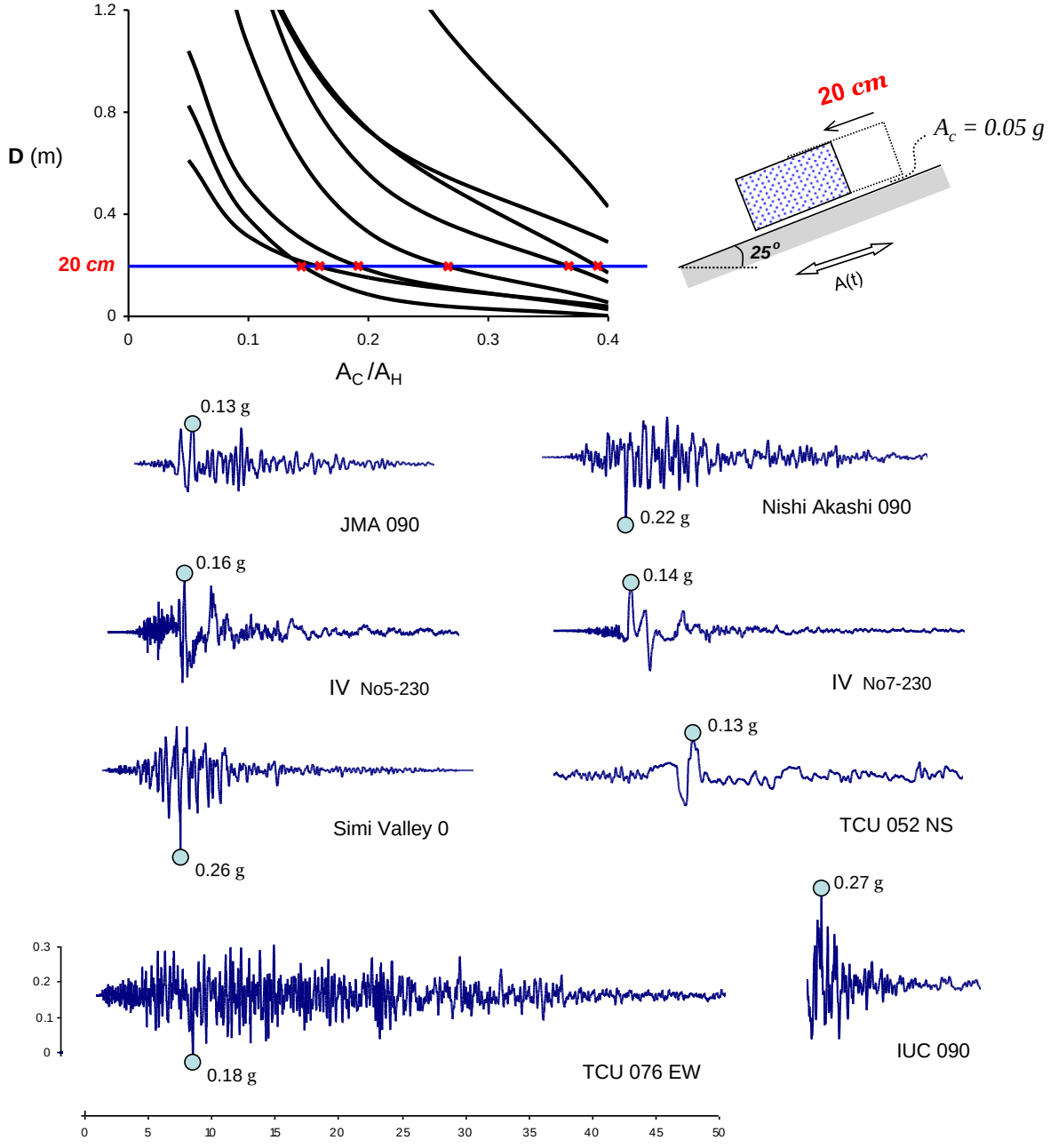

Figure 2. Equivalent acceleration records (with their peak values marked with circle) that induce a slippage of 20 cm to a rigid block with critical yielding acceleration A_C = 0.05 g, on an inclined base of $\beta = 25^o$.

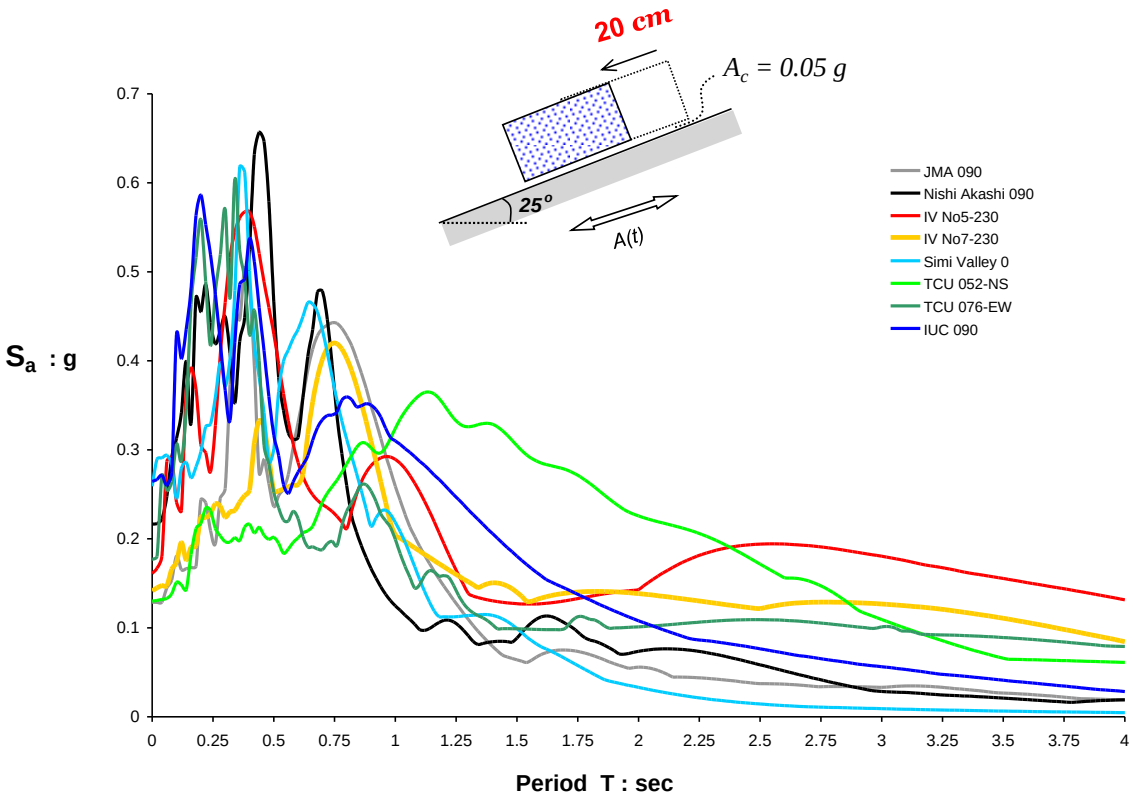

Figure 3. Elastic response spectra of the equivalent acceleration time histories triggering 20 cm of sliding on the block on a 25° inclined base (A_C = 0.05g).

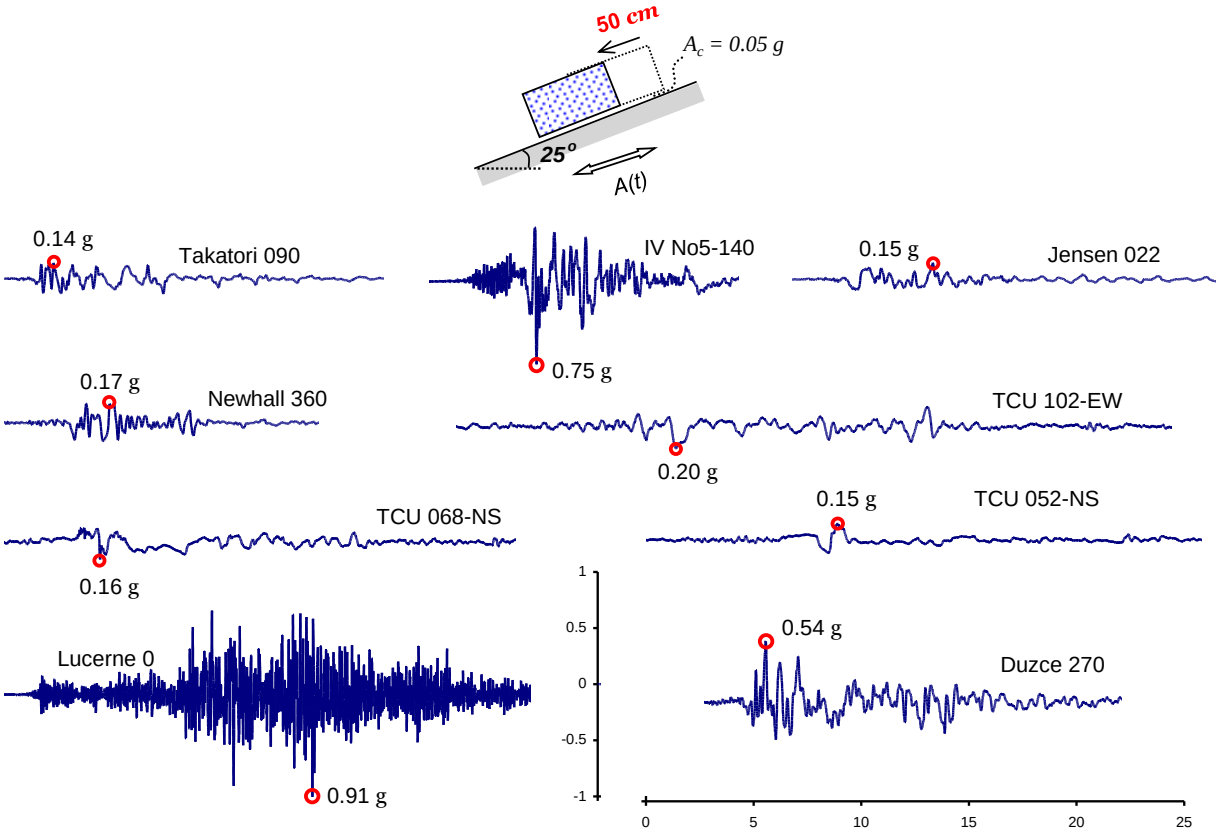

Figure 4. Equivalent acceleration that induce a slippage of 50 cm to a rigid block with critical yielding acceleration A_C = 0.05 g, on an inclined base of β = 25°.

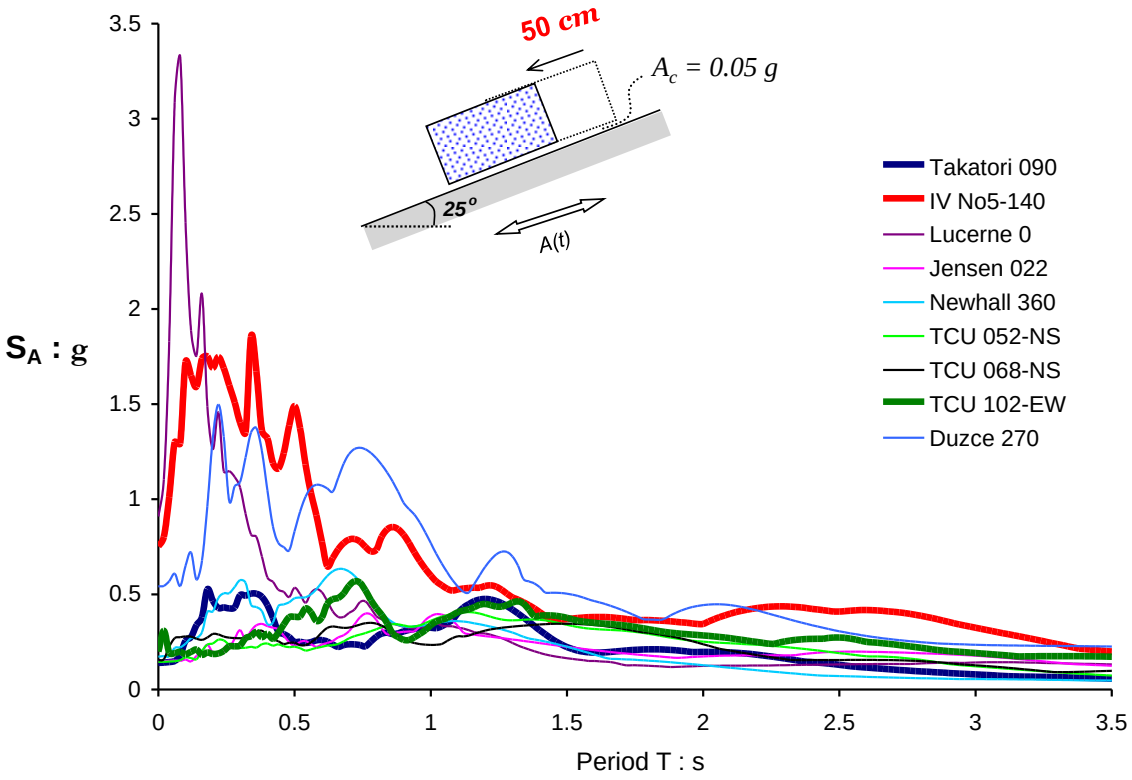

Figure 5. Elastic response spectra of the equivalent acceleration time histories triggering 50 cm of sliding on the block on a 25° inclined base (A_C = 0.05g).

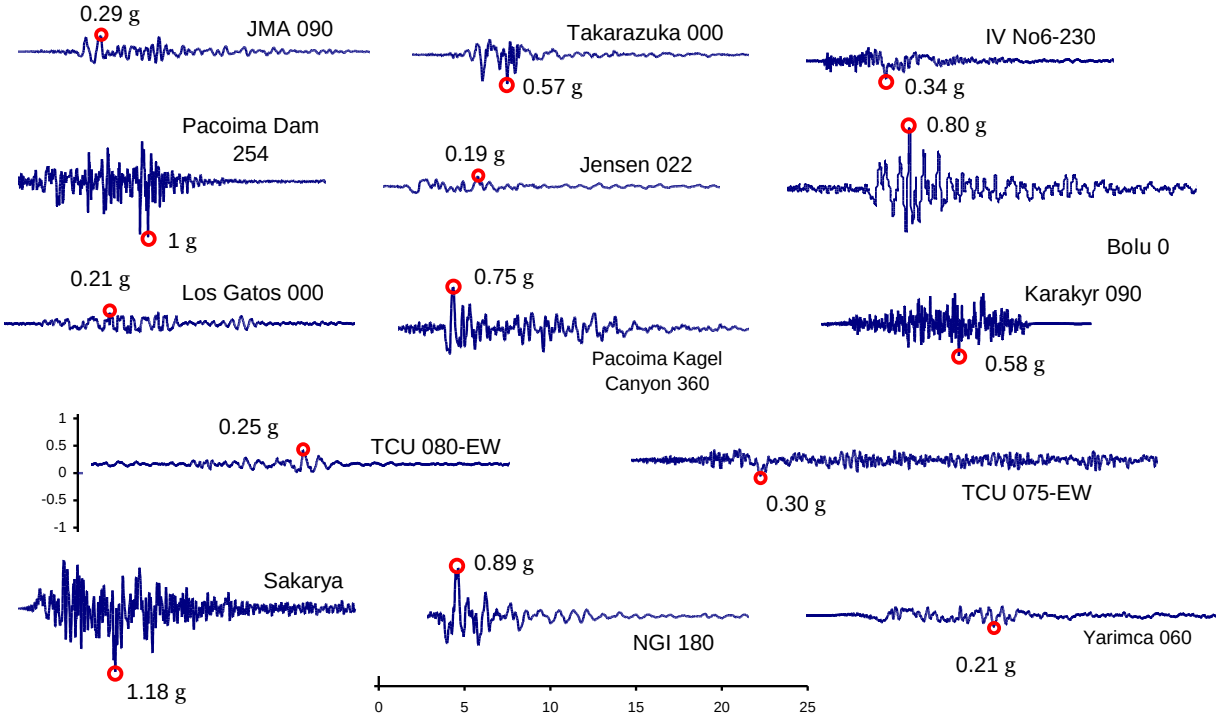

Figure 6. Equivalent acceleration that induce a slippage of 1 m to a rigid block with critical yielding acceleration A_C = 0.05 g, on an inclined base of β = 25°.

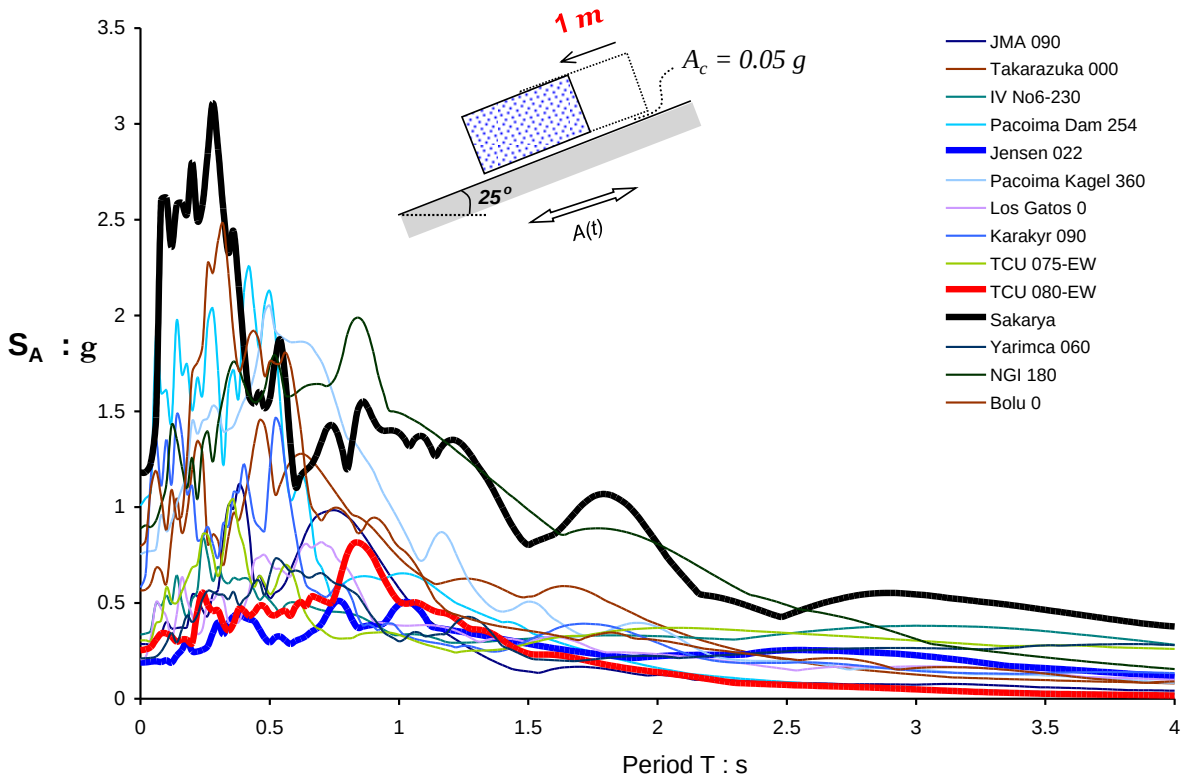

Figure 7. Elastic response spectra of the equivalent acceleration time histories triggering 1 m of sliding on the block on a 25° inclined base (A_C = 0.05g).

Figures (4, 5) and (6, 7) present the equivalent sliding motions and their elastic response spectra for sliding displacements of: 0.5 m, and 1 m respectively. Notice that as the common level of sliding increases (A_C decreases), the acceleration discrepancy among the records becomes starking. For example, in Figure 7 the elastic spectrum of the Sakarya record scaled to induce sliding of 1 m, is almost three times larger than the elastic spectrum of the down-scaled Jensen Filtration Plant record (component 22°) that triggers the same slippage. In other words, these two elastic spectra have the same inelastic response for our system! In case of yielding on a horizontal base ($\beta = 0^o$) with A_C = 0.15 g, the equivalent ground motions that induce maximum sliding of 3 cm are shown in Figure 8. The potential of the block to slide either left of right with the same critical acceleration, result in smaller maximum and residual yielding displacements comparing to slippage induced on an inclined base. However, the differences between the equivalent accelerograms remain substantial. What is more, the corresponding response spectra (see bottom plot in Fig.8) exhibit considerable difference: the Rinaldi 228° spectrum and the TCU 068-NS spectrum (which is three times larger in all period range) inflict the same slippage of 3 cm.

Furthermore, an elastic response spectrum does not always reflect the importance of the detailed sequence of acceleration pulses. Figures 9 and 10 illustrate the acceleration time histories and the corresponding elastic spectra of the Erzincan-EW and Rinaldi 228° records respectively, that induce a sliding displacement of 1 m. The excitations are applied with their recorded and reversed polarity. The elastic response spectrum is of course independent of the polarity of motion: normal and reversed records have identical spectra. However, in asymmetric sliding the polarity has significant effect on the resulting slippage. Figure 10 pictures the equivalent normal and reversed polarity Rinaldi 228° acceleration time histories and their elastic spectra. The Rinaldi record scaled to 0.41 g triggers 1 m sliding displacement when applied in one direction, while when reversed it must be reduced to half, 0.22 g. So, two elastic spectra of identical shape but different magnitude (one half the other) result in almost exactly the same slippage !

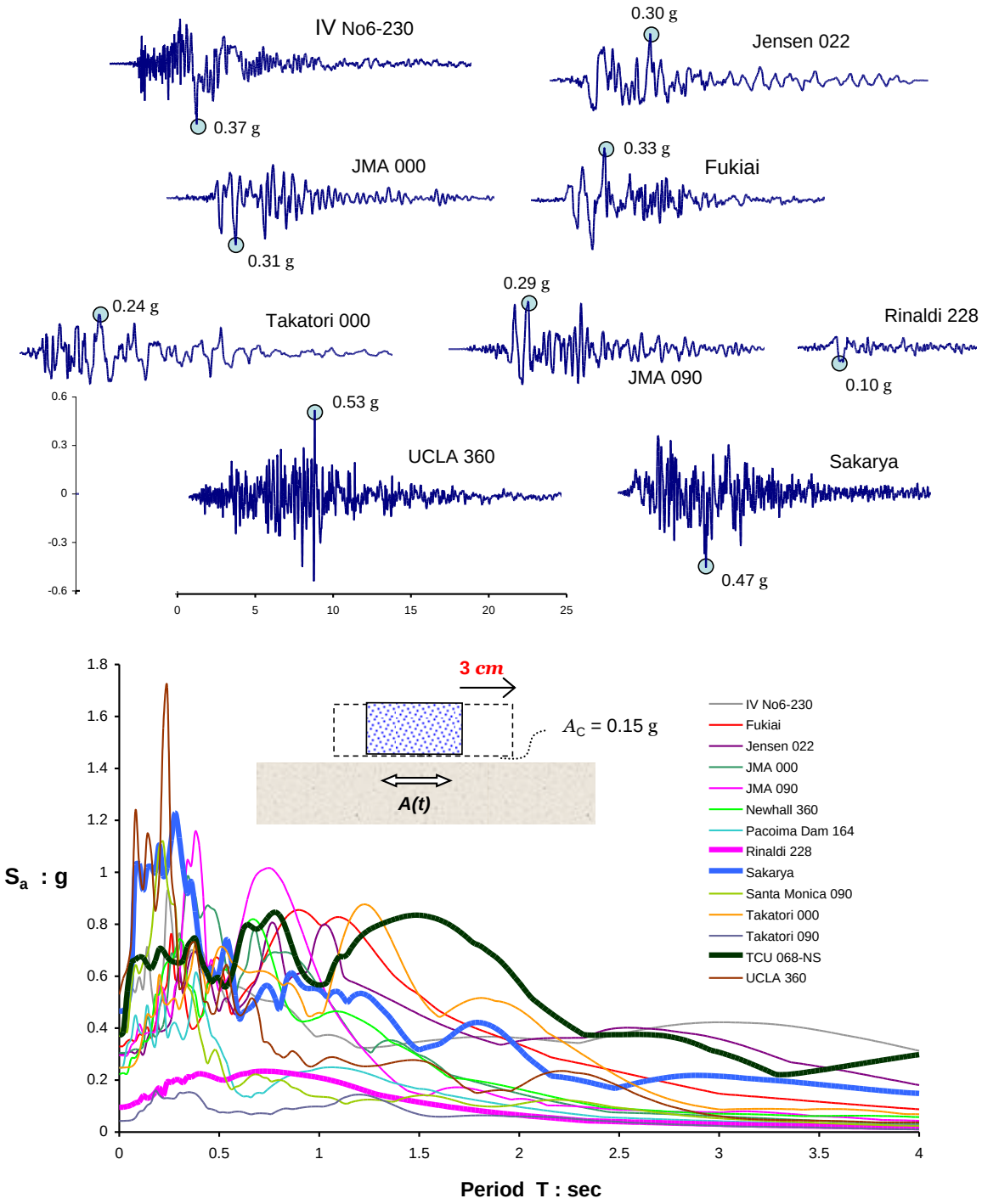

Figure 8. Equivalent acceleration motions and their elastic response spectra, that induce a slippage of 3 cm to a rigid block with critical yielding acceleration A_C = 0.05 g, on a horizontal plane.

CONCLUSIONS

The paper studied the yielding response of a sliding block resting on top of a horizontal and on inclined plane when subjected to 90 strong near-fault ground motions. For each level of slippage, the equivalent acceleration time histories were derived as well as their response spectra. Discussion about the ability of elastic spectra to capture the essential characteristics of ground severity especially for inelastic systems elucidate several troublesome aspects of utilising EDRS and IDRS in design of strongly anelastic systems. As a conclusion, the use of elastic spectrum as a representative index of the

destructiveness of a motion is limited. The need of more resilient indicators emerges for inelastic systems.

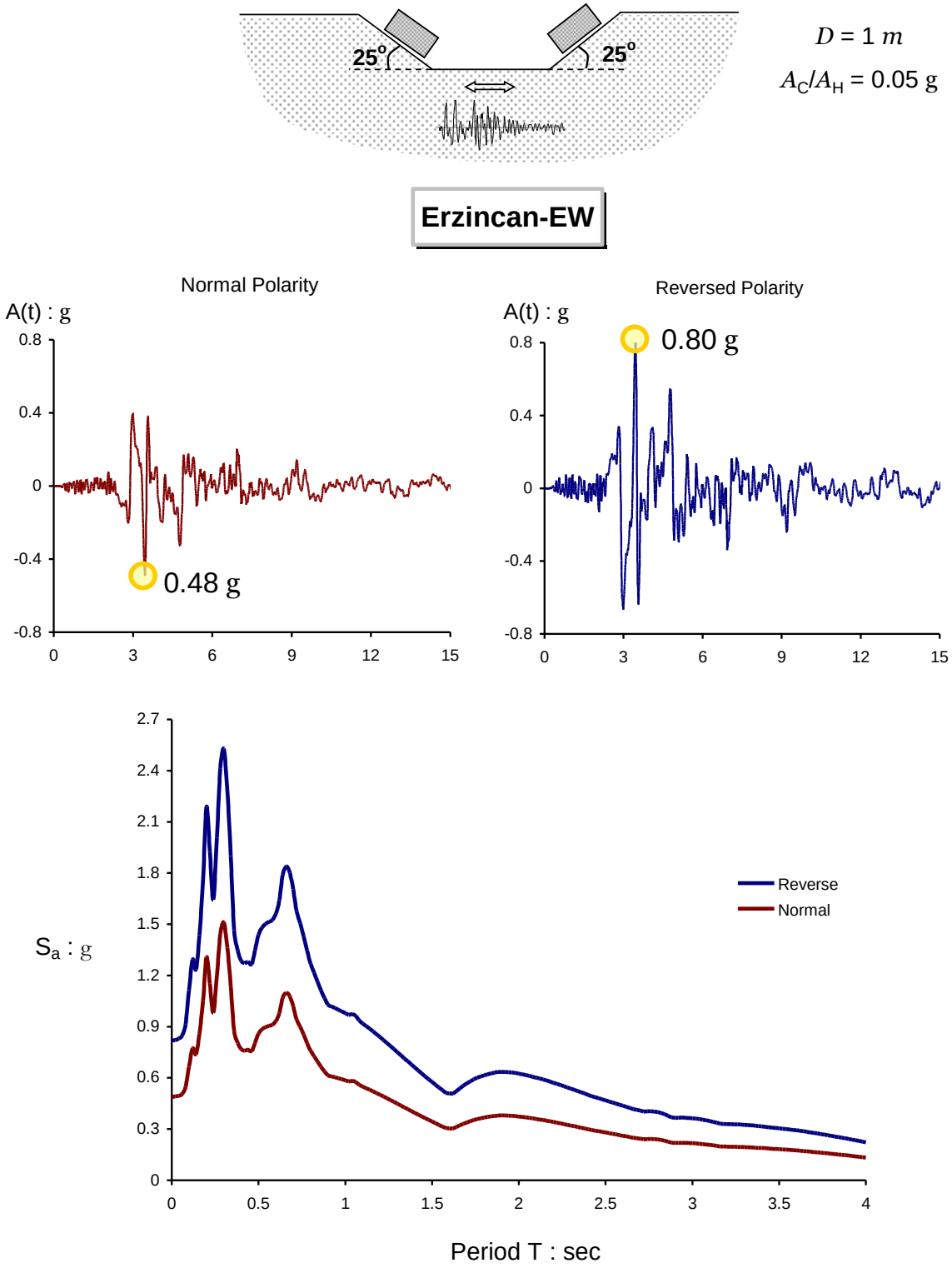

Figure 9. The Erzincan-EW record applied with its normal polarity induces 1 m of slippage (A_C = 0.05 g, $\beta = 25^o$). The equivalent reversed polarity accelerogram has to be increased up to a peak value of 0.80 g to result in the same displacement. Also the elastic response spectra of the motion are illustrated.

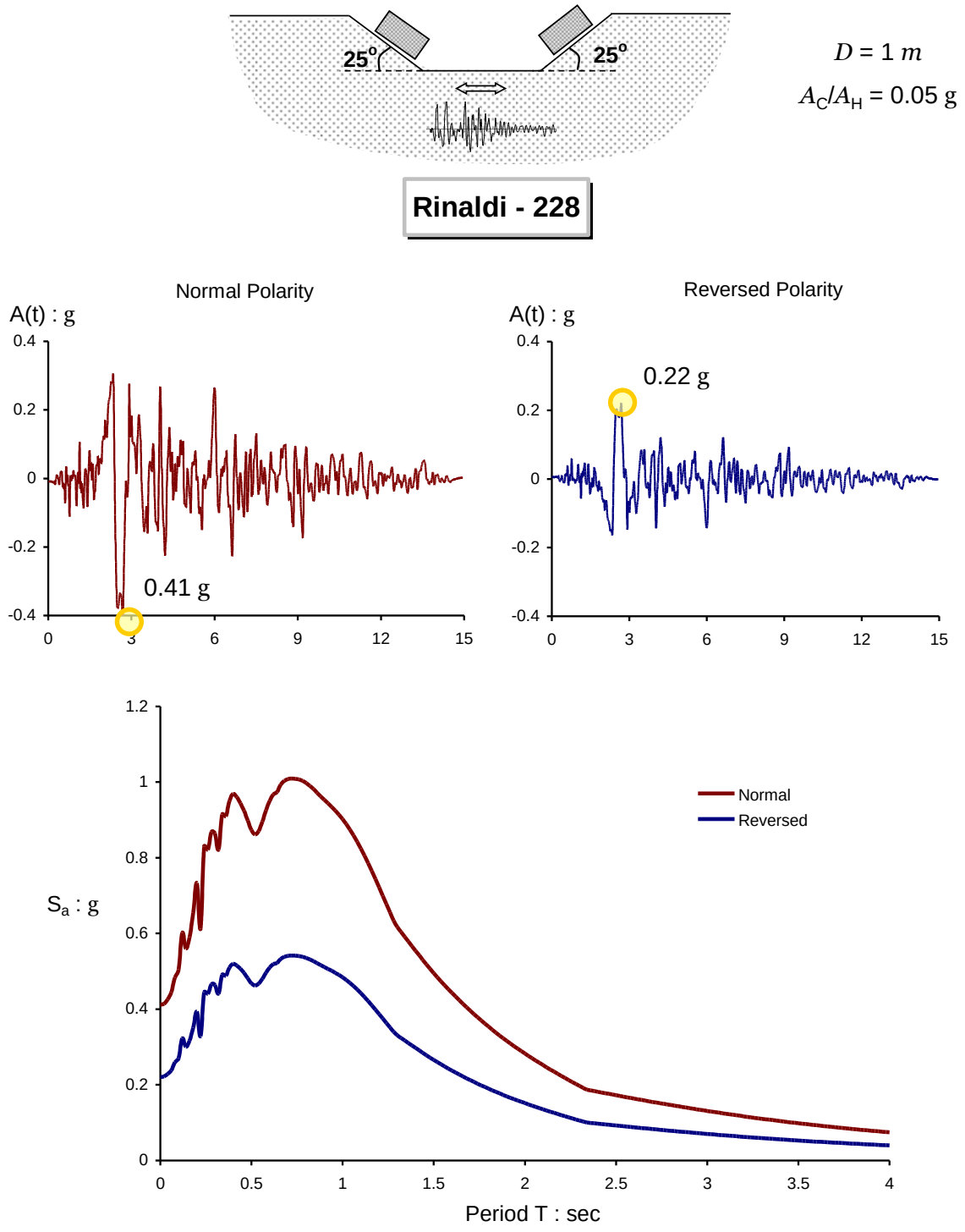

Figure 10. The Rinaldi 228° record applied with its normal polarity induces 1 m of slippage (A_C = 0.05 g, β = 25°). The equivalent reversed polarity accelerogram has to be reduced down to 0.22 g to result in the same displacement. Also the elastic response spectra of the motion are illustrated.

REFERENCES

Abrahamson, N. A. (2001). Incorporating Effects of Near Fault Tectonic Deformation into Design Ground Motions, University at Buffalo MCEER: Friedman F. V. Professional Program, webcast: http://mceer:buffalo.edu/outreach/pr/Abrahamson.asp

Alavi, B., and Krawinkler, H. (2000). Consideration of Near-Fault Ground Motion Effects in Seismic Design,

Proceedings of the 12th World Earthquake Conference on Earthquake Engineering, New Zealand.
Bertero, V.V. (1976). Establishment of design earthquakes : evaluation of present methods, Proceedings, International Symposium of Earthquake Structural Engineering, St. Louis, University of Missouri-Rolla, Vol. 1, 551-580.
Bertero, V.V., Mahin, S.A., and Herrera, R.A. (1978). Aseismic Design Implications of Near-Fault San Fernando Earthquake Records, Earthquake Engineering and Structural Dynamics, Vol. 6, 31-42.
Bray, J.D., and Rodriguez-Marek, A. (2004). Characterization of Forward–Directivity Ground Motions in the Near-Fault Region, Soil Dynamics Earthquake Engineering, Vol. 24, 815-828.
Constantinou, M.C., Gazetas, G., and Tadjbakhsh, I. (1984). Stochastic Seismic Sliding of Rigid Mass Against Asymmetric Coulomb Friction, Earthquake Engineering and Structural Dynamics, Vol. 12, 777-793.
Garini E., Gazetas G. and Anastasopoulos I (2011). Asymmetric 'Newmark' Sliding Caused by Motions Containing Severe 'Directivity' and 'Fling' Pulses, Geotechnique, 61(9), 733-756.
Gazetas G., Garini E., Anastasopoulos I., & Georgarakos T. (2009). Effects of Near–Fault Ground Shaking on Sliding Systems, Journal of Geotechnical and Geoenvironmental Engineering, ASCE, Vol. 135, No. 12, 1906-1921.
Hancock, J. & Bommer, J. J. (2005). The effective number of cycles of earthquake ground motion, Earthquake Engineering & Structural Dynamics, 34, 637-664.
Housner G.V. (1952). Spectrum intensities of strong motion earthquakes. In Proceedings of the Symposium on Earthquake and Blast Effects on Structures, EERI, Oakland California, 20–36.
Iwan, W.D., Huang, C.T., and Guyader, A.C. (2000). Important Features of the Response of Inelastic Structures to Near-Fault Ground Motion, Paper No. 1740, Proceedings of the 12th World Earthquake Conference on Earthquake Engineering, New Zealand.
Jibson, R. (1994). Predicting earthquake-induced landslide displacements using Newmark's sliding block analysis, Transportation Research Record, No. 1411, Transportation Research Board, Washington, D.C., 9-17.
Kramer, S. L., and Lindwall, N. W. (2002). Dimensionality and Directionality Effects of Newmark Stability Analysis, Journal of Geotechnical and Geoenvironmental Engineering, ASCE, Vol. 130, 303-315.
Makris, N., and Psychogios, T. (2006). Dimensional response analysis of yielding structures with first mode dominated response, Earthquake Engineering Structural Dynamics, Vol.35, 1203-1224.
Mavroeidis, P.G., and Papageorgiou, S. A. (2010). Effect of Fault Rupture Characteristics on Near-Fault Strong Ground Motions, Bulleting of the Seismological Society of America, Vol. 100, No. 1, 37-58.
Newmark, N. M. (1965). Effects of Earthquakes on Dams and Embankments, Géotechnique, Vol. 15, No. 2,139-160.
Sasani, M., and Bertero, V.V. (2000). Importance of Severe Pulse-Type Ground Motions in Performance-Based Engineering: Historical and Critical Review, Proceedings of the 12th World Conference on Earthquake Engineering, New Zealand, Paper No 1302.
Somerville, P. (2003). Characterization of Near Fault Ground Motions for Design, ACI Specialty Conference, U.C. San Diego, American Concrete Institute
Wartman, J., Bray, J. D., and Seed, R. B. (2003). Inclined Plane Studies of the Newmark Sliding Block Procedure, Journal of Geotechnical and Geo-environmental Engineering, ASCE, Vol. 129 (8), 673-684.