



2-DIMENSIONAL NON-LINEAR VALLEY EFFECTS AT HEATHCOTE VALLEY DURING THE 2011 CANTERBURY EARTHQUAKE: A CASE STUDY

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ABSTRACT

Scope of this paper is to investigate the amplification pattern that could be held responsible for the unprecedented levels of acceleration recorded at the Heathcote Valley School station (HVSC) in the Christchurch City of New Zealand during the 22nd February 2011 M_w 6.3 earthquake. Emphasis is given on the investigation of the role of basin effects on the intensity of shaking. Fully non-linear 2-dimensional time-history FE analyses are performed on a number of possible valley configurations compatible with the area topography. Among others, the study parametrically assesses the role of valley depth, its possible non-symmetric shape and the amount of induced soil non-linearity. It is concluded that the strongly inelastic soil behavior alone, may sufficiently explain the high amplitude of shaking at long periods. However, it is shown that only when considering the 2 or 3 dimensional bedrock shape is it possible to reproduce the observed phenomena such as the intensity of the PGA, the spectral peak at $T = 0.35$ s, and the details of the recorded time-history.

INTRODUCTION AND PROBLEM DEFINITION

The role of sedimentary valleys on modifying the seismic motion at the ground surface has been thoroughly investigated in international literature. Their 2D (or 3D) geometry may induce complex wave propagation phenomena. Incoming waves are subjected to multiple refractions within the valley boundaries, while at the same time surface waves are generated at the valley edges and propagate along its surface. The focusing of these refracted waveforms as well as the constructive interference of the surface and incoming waves may be regarded as the most important amplification mechanisms associated with non-level bedrock geometry, and are considered to be responsible for intensified ground motions both in terms of acceleration level and duration [Sanchez-Sesma & Esquivel, 1979; Bard & Bouchon, 1980; Chávez-García & Bard, 1988; Kawase, 1996; Pitarka et al., 1998; Zhang & Papageorgiou, 1996; Archuleta et al., 2003; Hartzell et al., 2003; Olsen et al., 2006]. Scope of this study is through building upon this knowledge to:

interpret and if possible reproduce the extremely strong ground motion recorded during the 22nd February 2011 (M_w 6.3) earthquake at the Heathcote Valley School station (HVSC) in the Christchurch City of New Zealand. The event was the second and the most destructive [Bradley et al., 2011] from a sequence of four seismic shocks known as the Canterbury earthquakes; the first event

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took place on September 4th 2010 (M_w 7.1) and was followed by the 22nd February shaking, the 13th June (2011) (M_w 6.1) and the December 23rd 2011 event (M_w 5.9).

The HVSC Record

The Heathcote Valley Primary School station (HVSC) lies on the edge of the homonymous Heathcote Valley on a narrow triangular canyon in the vicinity of the Port Hills, as shown on the map of Figure 1. During the February event, the recorded motion enclosed some very distinctive features that are worth studying. The EW component of the HVSC record exhibited a peak ground acceleration of 1.2g, while multiple times throughout the 12 sec duration of the strong motion the measured acceleration exceeded 0.8g. This is also clearly manifested in the elastic response spectrum of the record; astonishing high spectral accelerations of 4.2g and 3.7g at $T = 0.3$ s and $T=0.48$ s respectively, while for all periods between 0.55 and 0.7s the spectrum exhibits a well-defined plateau at almost 2g (Fig.2a and b). Scope of this study is to investigate the connection between that basin geometry and this systematically amplified motion at the HVSC station.



Figure 1. Aerial View of the Heathcote Valley highlighting the location of the HVSC strong motion recording station.

THE HEATHCOTE VALLEY CASE STUDY: MISSING DATA AND ASSUMPTIONS

Attempting to reproduce the response at the HVSC station is a quite challenging task, owing to the fact that there are too many uncertainties and very few undisputable data. A brief list of the missing data would include:

(a) *The exact valley geometry*: although the soil profile at the HVSC station [Wood et al, 2011] (Figure 2c) is known up to the depth of 49 m, there are no available data for the subsoil geometry of the bedrock. To this end a number of possible configurations are studied (from purely 1d formations) to shallow trapezoidal valleys and deeper (symmetrical or not) triangular formations, all of them compatible with the measured soil profile at the HVSC station.

(b) *The exact rock outcropping motion in the vicinity of the HVSC station*: the only rock motion obtained after the February earthquake is the one recorded at the LPCC station which –unfortunately– lies much further from the fault than HVSC (Smyrou et. al., 2011). Due to the lack of a more appropriate motion, the outcropping acceleration time history of the EW component of the LPCC motion, will be used as an input motion for our set of analysis (Fig. 2a).

(c) *The strength and the dynamic properties of the soil materials*: given the high intensity of the excitation motion (PGA at 0.6g), a pronounced non-linear hysteretic behavior of the valley materials should be expected. Since there are no data regarding their strength and their dynamic properties reasonable assumptions based on engineering judgment have been made.

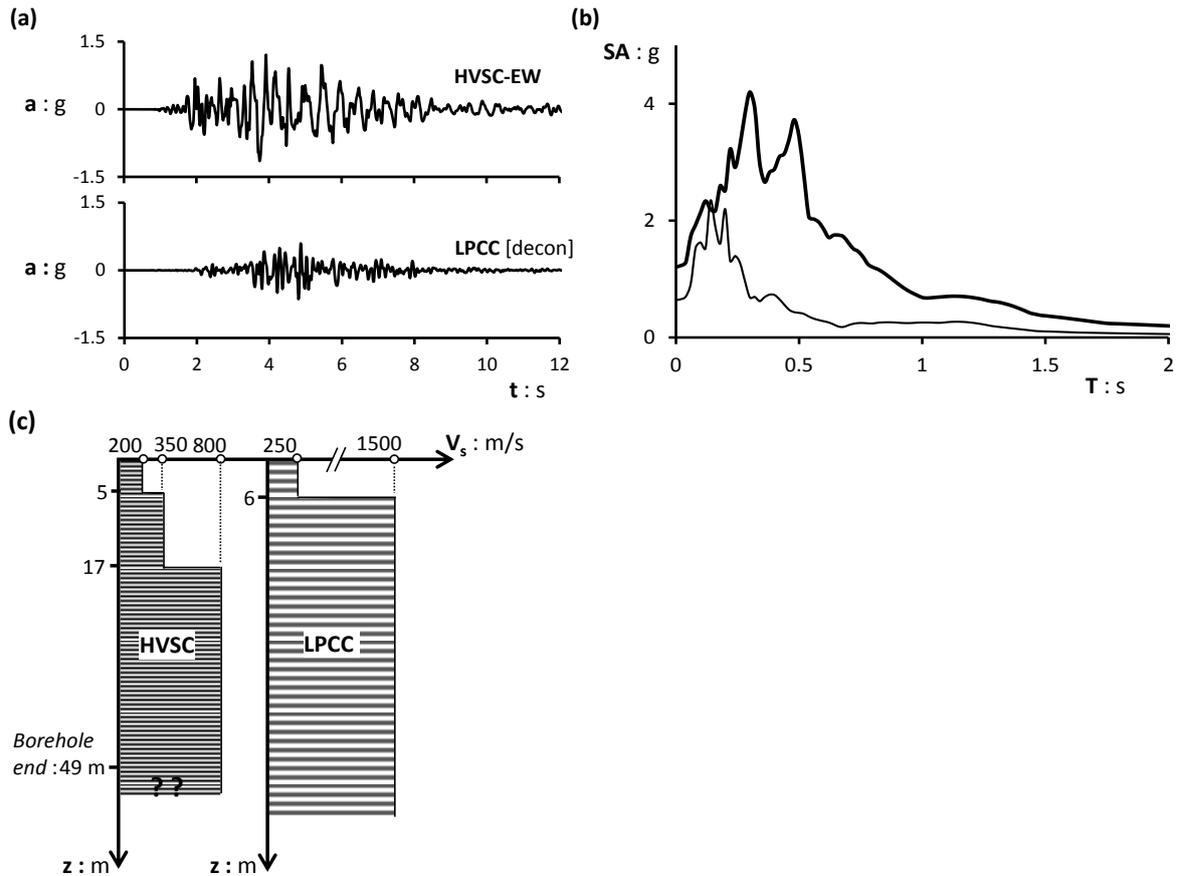


Figure 2. (a) The recorded acceleration time history (HVSC-EW) and the calculated outcropping motion at the LPCC station (to be used as excitation in the ensuing FE analyses). (b) The respective elastic response spectra ($\xi=5\%$) and (c) the measured soil profiles (according to Wood, *et al.* 2011), at the two locations.

THE VALLEY GEOMETRY

The Heathcote Valley forms a quite narrow canyon in the EW direction while in the NS axis it develops quite smoothly extending throughout the city of Christchurch. Based on this observation, it is reasonable to assume that in the NS direction the soil response is nearly 1-dimensional, and valley effects (if any) are expected to take place mainly at the EW orientation. Following this reasoning, only 2D modes of the EW valley section are assumed. These are:

(i) *A family of shallow, trapezoidal, and completely symmetric valleys.* In all of them the bedrock (soft rock) is located at depth of $z=-17$ m, while the inclination of the valley boundary is being varied parametrically $\theta=12^\circ, 24^\circ, 30^\circ$

(ii) *A deep symmetric triangular valley* which may be produced by the aforementioned shallow valley of $\theta=24^\circ$ assuming that the bedrock boundary continues dipping towards the valley center at a constant inclination until reaching a maximum depth of $d=150$ m. In this scenario the bedrock is a very stiff (volcanic) rock of $V_s = 1500$ m/s, while a layer of non-constant depth (soft Rock) and $V_s = 800$ m/s covers the area between the soft valley soil and the stiff boundary.

(iii) *A non-symmetric deep valley*, where the inclination of the west soil-soft rock boundary is slightly increased from 24° to 30° .

All models are excited by vertical incident waves; a reasonable assumption considering the proximity of the valley to the fault projection.

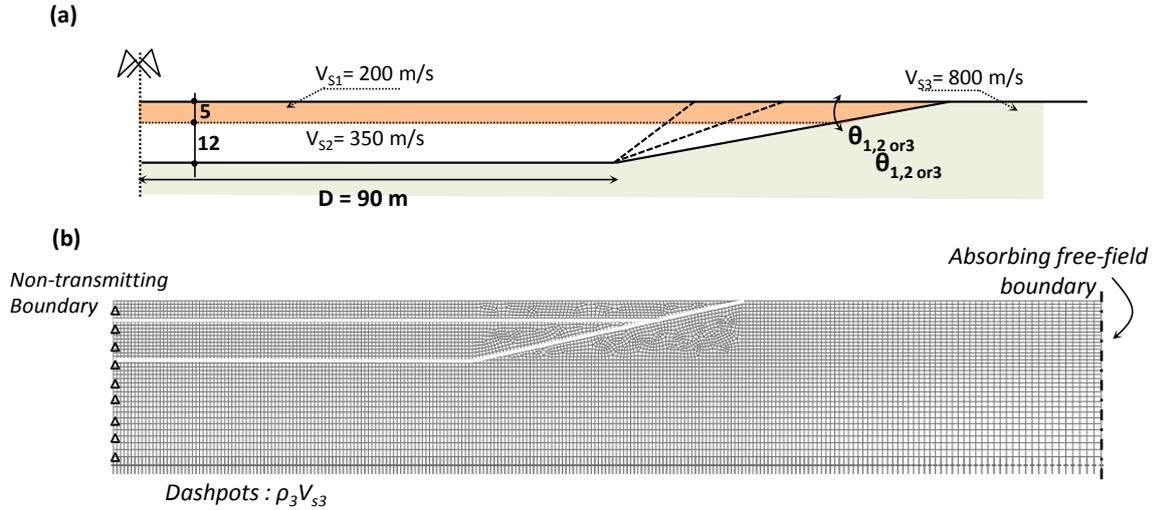


Figure 3. (a) The three shallow valley configurations in which the inclination of the bedrock is varied parametrically $\theta_{1,2 \text{ or } 3} = 12^\circ, 24^\circ$ or 30° . (b) View of the finite element mesh (for the case of $\theta_2 = 24^\circ$).

ANALYSIS METHODOLOGY

A schematic view of the shallow valley configuration is illustrated in Figure 3(a). The valley consists of two soil layers, a surface soft soil layer of $V_s = 200$ m/s and 5 m depth and an underlying 12 m stiffer soil layer with $V_s = 350$ m/s. These two layers are enclosed within a soft rock formation (bedrock) with shear wave velocity of 800 m/s.

Plane-strain time history analyses are performed in time domain with the finite element (FE) code ABAQUS. A view of the FE mesh is displayed in Figure 3b. Following the validated analysis methodology described in Gelagoti et al (2010), very finely discretized quadrilateral continuum elements have been used in soil modeling (element size less than 1m) so as to ensure realistic representation of the propagating wavelengths at the frequency range of interest. Radiation damping is taken into account by introducing appropriate absorbing boundaries at the base of the numerical model. Free-field boundaries responding as shear beams are placed at the two lateral boundaries, to appropriately capture simulate the free-field 1D motion produced by in-plane vertically incident SV waves.

To simulate the visco-elastic soil response a Rayleigh damping component is introduced at each soil layer to account for some limited material damping, while the nonlinear hysteretic soil behavior is modeled by employing a kinematic hardening constitutive model, incorporating the Von Mises failure criterion and an associative plastic flow rule. The model has been validated against centrifuge experiments, and shown to effectively capture the undrained cyclic soil response of clayey materials [Anastasopoulos et. al., 2011].

TESTING THE VALIDITY OF THE SHALLOW VALLEY SCENARIO

The assumption of visco-elastic soil

Although hardly justifiable (considering the intensity of the earthquake shaking), an initial set of analyses is performed in which all soil materials are assumed to behave visco-elastically. To this end, the damping coefficient ξ is set to 7% for the top soil layer, while a $\xi = 5\%$ and $\xi = 1.5\%$, have been selected for the stiffer soil layer and the bedrock respectively.

Figure 4a illustrates the spatial distribution of the aggravation factor (AG) along the surface for all three valley geometries. [It is reminded that aggravation factor is defined herein as the ratio of maximum predicted acceleration at each valley point when the 2-D geometry is simulated, over the maximum computed acceleration at the same location following the 1-D amplification theory

(i.e. $AG = \max(a_{2D})/\max(a_{1D})$). It is evident that in all cases (regardless of the inclination angle of the sloping boundary) the AG values consistently are very close to 1 along the whole valley surface; a fact that implies no evidence of valley-effects, as if the valley is very shallow to be captured by the incoming waves.

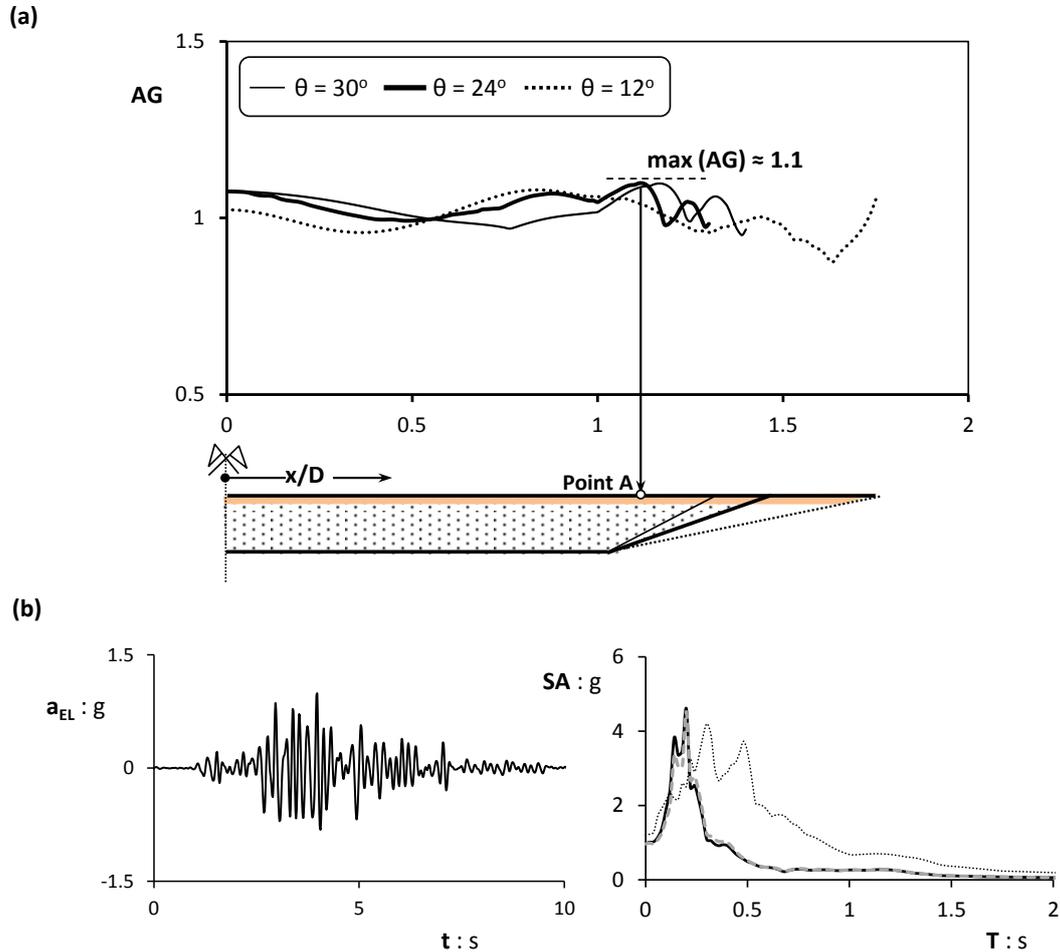


Figure 4. The ‘shallow Valley’ Scenario (assuming viscoelastic soil response) : (a) spatial distribution of the aggravation factor (AG) along all three valley configurations; (b) the calculated acceleration time history at the location of maximum Aggravation (Point A) and the respective elastic response spectrum. For comparison purposes the 1d analysis (grey dashed line) and the ‘target’ spectrum of the recorded motion are also plotted (black dotted line).

This is further supported by the plots of Figure 4b where the elastic response spectrum at Location A (i.e. point where the maximum AG is recorded) is compared to the spectrum derived by 1-D analysis (at the exact same location). Observe that that the two lines practically coincide, a fact that affirms the aforementioned suggestion that for the particular valley scenario the importance of 2d valley effects is only trivial. Moreover, although the PGA Value is accurately reproduced, the time history of the computed motion has a much higher frequency content and smaller duration than the recorded motion. As such the spectral amplitudes of our simulation practically vanish after 0.4 s, contrary to the recorded response, where the spectral values are magnified at a period range of $T = 0.4 - 0.6$ s. Similar trends are observed for all positions along the valleys for all three inclination angles.

THE DEEP VALLEY SCENARIO

The investigation of the previous paragraph has shown that the shallow valley model could not sufficiently explain the experienced ground motion at the HVSC station, and therefore it couldn't be regarded as representative of the bedrock geometry in the area of study. In this paragraph another candidate profile is examined which will be referred herein as the “deep valley” configuration. The justification of this assumption is based on the following evidence:

a. The documented profile at the location of the station shows no evidence of bedrock up to its termination depth of 50m, thus rendering it likely that the bedrock lies further deeper.

b. The station lies adjacent to the Port Hills, which are known to consist of volcanic bedrock which may reasonably be assumed to be extending underneath the Heathcote Valley. Following measured values by Wood et al (2011) in adjacent areas the shear wave velocity of the volcanic rock is assumed equal to 1500 m/s.

The finite element mesh of the deep Valley is depicted in Figure 5. The top 17m are identical to the shallow case scenario, but here the soft rock layer doesn't develop horizontally but forms a deep triangular formation of maximum depth 150 m. The response of the valley has been studied assuming both visco-elastic and fully non-linear soil behavior, while in both cases the soft rock and the volcanic bedrock are considered to perform linearly elastically ($\xi_{\text{rock}}=1.5\%$, $\xi_{\text{soft-rock}}=3\%$). For the non-linear analyses, the soft soil ($V_s=200$ m/s) is modeled as a material of $S_u = 60$ kPa with a rigidity ratio of $G/S_u = 2000$, while for the underlying soil ($V_s=350$ m/s) an undrained shear strength of $S_u = 125$ kPa ($G/S_u = 1400$) is assumed. The hysteretic behavior of both materials is calibrated against measured data (i.e. $G-\gamma$ and $\xi-\gamma$ curves) by Raptakis et al. (2000)

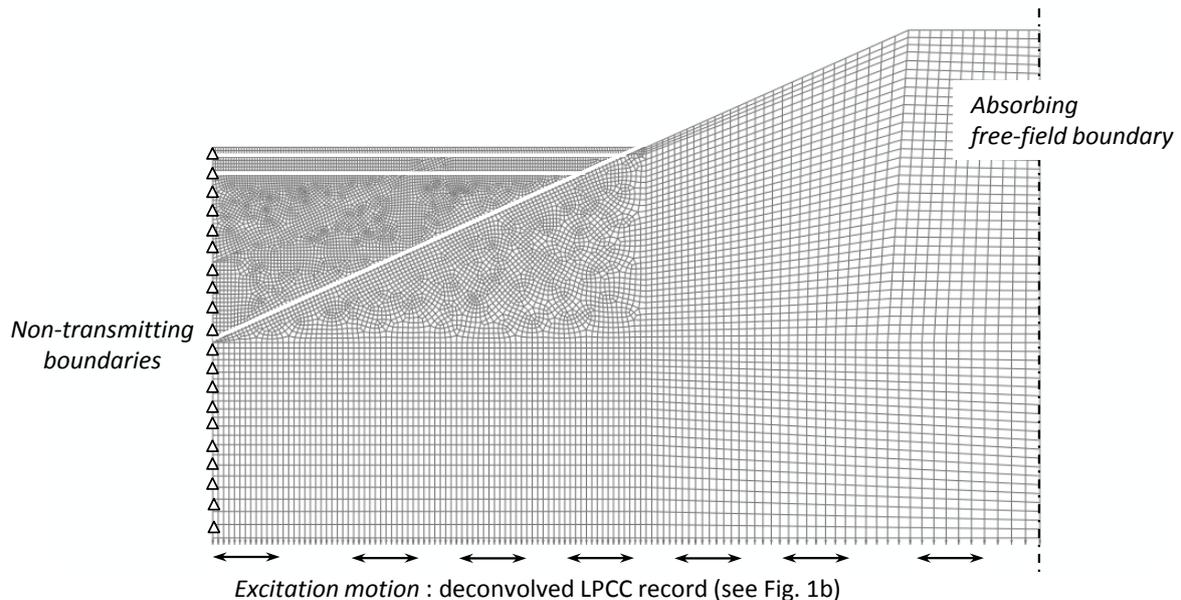


Figure 5. The deep and symmetric Valley : FE model and assumption of soil properties.

The seismic response of the deep valley formation is presented in Figure 6. It is clear that irrespectively of the performance of the top soil layers, the presence of the deep valley significantly enhances the 2d basin effects. For the visco-elastic assumption (gray line), at several locations across the valley surface AG values as high as 1.25 may be observed. Still though, as demonstrated by the left plot of Fig.6b, the computed response (at point B) may hardly describe the recorded motion. Although the first spectral peak at $T= 0.3$ s is somehow captured, the computed motion is lacking the long period components of the recorded acceleration time history.

By allowing the top layers to perform nonlinearly, the aggravation pattern is substantially modified. Although the AG remains lower than 1.2 in the greatest part of the valley, it tends to increase to 1.3 as we move towards the valley edge. The first encouraging results come from the spectra of Figure 6b (middle and right plot) where the computed response at two characteristics

locations [namely, at point C (local maximum at the AG plot) and at point D (corresponding to the valley center) are depicted. The spectral shape closely resembles the target response at periods 0.15s to 0.4s. Yet, SA values continue to drop rapidly for periods greater than 0.4 s. Similar conclusions are drawn when comparing the computed acceleration time history against the recorded one (Fig. 6c); although the PGA value is under-predicted, the duration of the record and the frequency content (in a lesser extend) are more correctly captured.

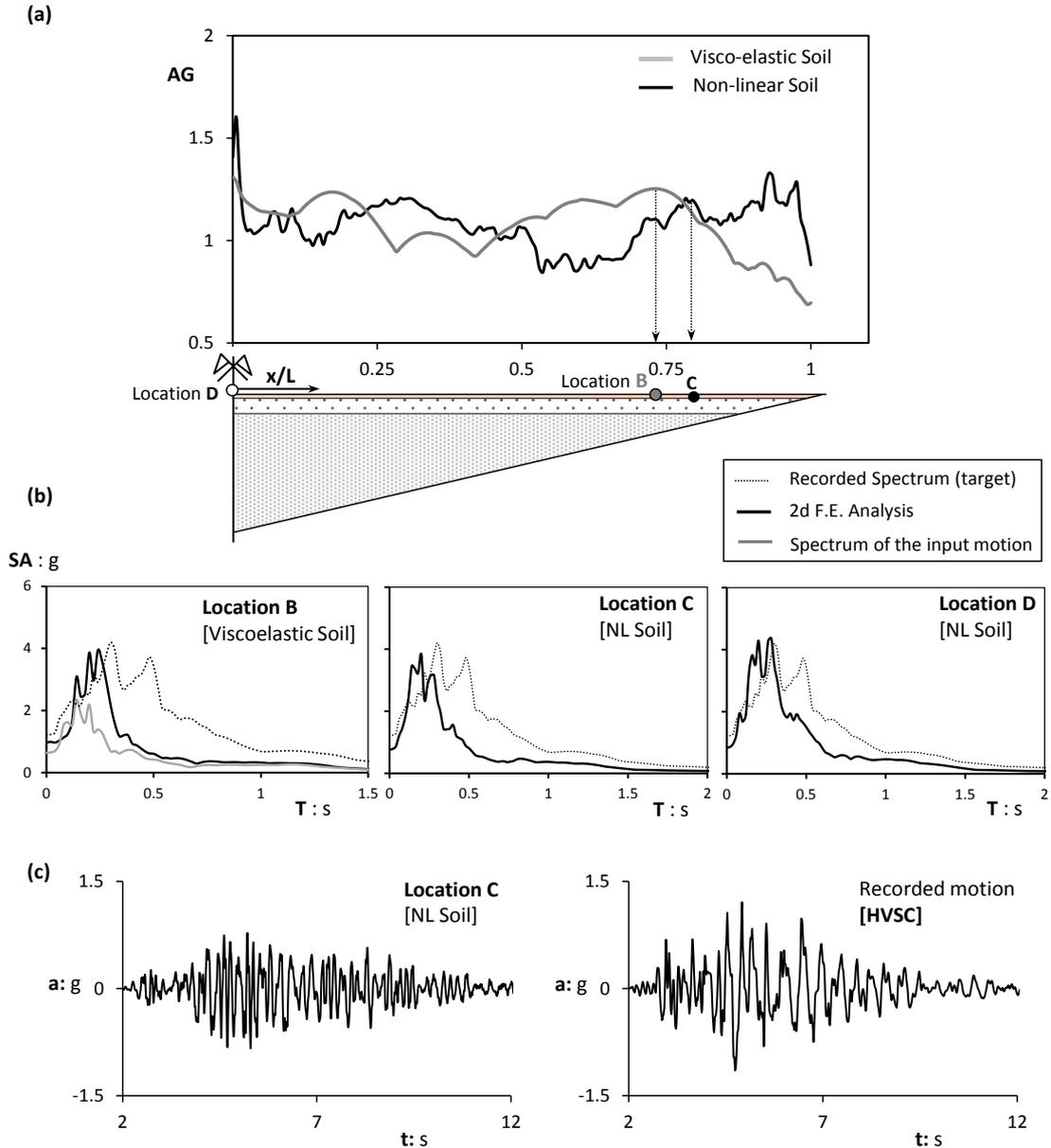


Figure 6. The ‘deep Valley’ scenario: (a) Spatial distribution of the aggravation factor (AG) assuming elastic and fully-nonlinear soil response; (b) elastic response spectra at the locations of maximized Aggravation (for comparison purposes the ‘target’ spectrum of the recorded motion is also plotted (black dotted line)); (c) the computed time history at Location C is compared to the recorded motion.

INVESTIGATING THE EFFECT OF A SLIGHT ASYMMETRY

In the preceding, a perfectly symmetrical valley has been assumed; a simplifying assumption which is very likely to contradict reality. However, asymmetry has been repeatedly reported to significantly modifying the valley response (e.g. Papageorgiou & Kim, 1991). Due to lack of data as to the exact valley geometry, the present study investigates the effects of a hypothetical slightly asymmetric variation of the deep Valley. To this end, while the east boundary of the Valley is preserved, at the

west valley edge the stiff-soil soft-rock interface is assumed to exhibit a steeper inclination angle, equal to 30° (instead of 24°).

The comparison of the response of the symmetric and the non-symmetric valleys in terms of aggravation factor is portrayed in Figure 7a. Note that the presence of a steeper reflecting boundary at one edge may produce additional amplification at certain locations along the eastern part of the valley, while at the same time a significant portion of the valley surface (lying closer to the west boundary) is experiencing considerably de-amplified motions. This ambivalence is clearly demonstrated in terms of acceleration time history and spectral response in the plots of Figure 7(b) and (c). Quite surprisingly, the computed motion at location E is greatly affected by the presence of this asymmetry: peak acceleration values are enhanced, the spectral response is somehow shifted to larger periods, while an impressive spectral aggravation is observed at $T \approx 0.3$ sec.

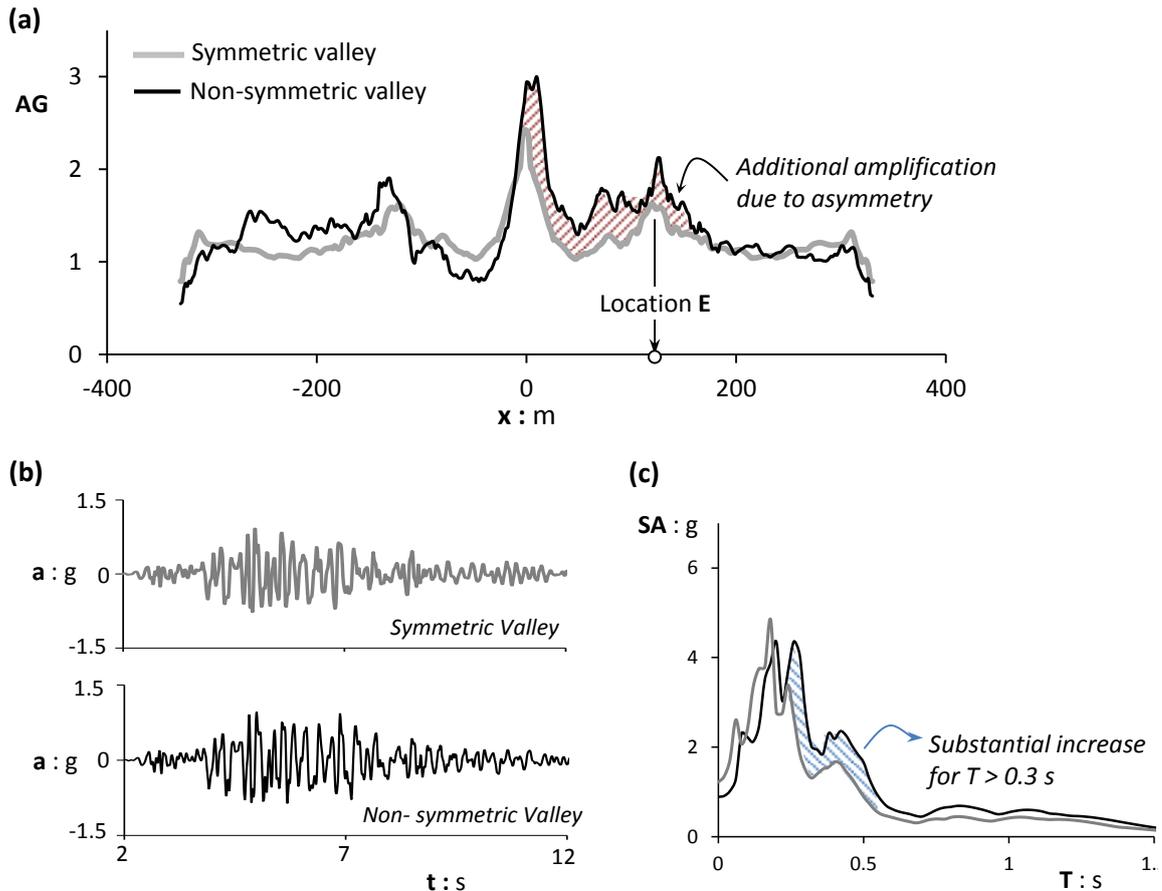


Figure 7. Effect of the asymmetry on: (a) the spatial distribution of the Aggravation Factor; (b) the computed time history at the same Location (Location E); (c) the elastic response spectrum. In all plots the black line corresponds to the non-symmetric valley and the gray line to the symmetric case.

EFFECT OF SOIL INELASTICITY

Up to this point, consideration of 2D wave scattering phenomena in non-linear valleys, has allowed the reproduction of high acceleration spikes, the duration of the strong motion and the large spectral values for ($T < 0.4$ sec). Yet, none of the aforementioned assumptions has been proven appropriate for the simulation of the extremely long-period pulses that do prevail throughout the original record. To this end, a final assumption is made: *the undrained shear strength of the stiff soil ($V_s=350$ m/s) is further reduced (from 125 kPa to 85 KPa) to allow for a more intensive inelastic 'activity' also within the deeper soil layers.*

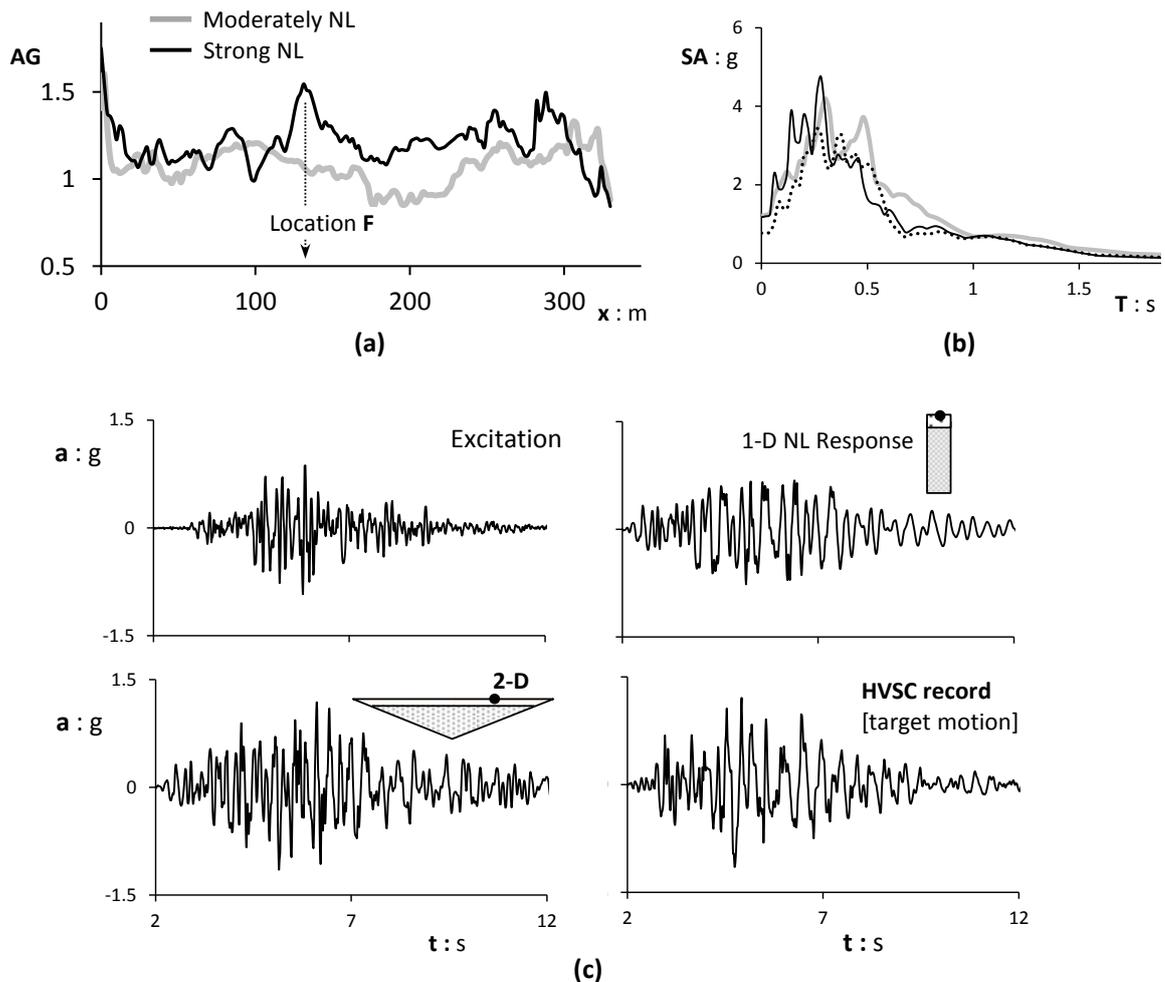


Figure 8. (a) Effect of strong soil non-linearity on the spatial distribution of the AG factor valley. (b) Comparison of the computed against the recorded response in terms of: (b) spectral accelerations and (c) acceleration time histories: (top left plot) excitation motion, (top right plot) result of 1D, (bottom left) the computed ground motion at location F, (bottom right) the recorded HVSC accelerograph.

The results of this set of analysis are portrayed in Fig. 8. Interestingly, as evidenced by the AG pattern, this increased inelasticity not only does not alleviate the 2-d valley effects, but rather amplifies them further. The AG factor (Fig. 8a) presents a substantial local peak around $x=150$ m (where $AG > 1.5$), while apparently large AG values are experienced at all locations between $x=150-300$ m. Similar trends have been reported by *Gelagoti et al (2012)*, who concluded that as soil plastification increases, the effective shear modulus of the soil, and thereby the produced wavelengths are shrinking; the shorter the wavelengths, the stronger the wave scattering within the valley and the higher the computed aggravation.

In complete accord with the previous statement, the calculated acceleration time history at point F is impressively amplified (compared to both the input motion and the respective 1d response). But most importantly, the high acceleration peaks (which could be mainly attributed to the 2d valley geometry) are now coupled with a substantial long-period component of motion (due to strong inelastic soil behavior), resulting in a time history that closely resembles the recorded HVSC motion (Fig. 8b and c).

CONCLUSIONS

This study has provided preliminary evidence that the extraordinary acceleration systematically recorded at the HVSC station during the Canterbury earthquake events of 2010-2011 could be a result

of the existence of a deep valley combined with strongly non-linear soil response: the low-frequency component of the motion may only be reproduced when accounting for a strongly inelastic ‘activity’ within the top soil layers, but it only when assuming the presence of a non-level substructure, that the exact details of the time history may be adequately explained.

Yet, the actual record presents high spectral values at $T = 0.6 - 1$ sec, that were not persuasively reproduced in the simulated time history. The authors believe that these values may be associated with near-source effects or, as Bradley and Cubrinovski (2011) suggest, with wave focusing due to the presence of a very deep sedimentary valley.

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