Seismic Response of Systems founded on Isolated Footings on top of Alluvial Basins

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SUMMARY:
Scope of this paper is the preliminary quantification of the role of 2D wave scattering effects on the seismic response of simple structures. To this end, the paper explores the response of an 1-dof system and a frame founded on the surface of alluvial valleys employing fully non-linear numerical analyses with due account of Soil-Structure Interaction effects. By properly modeling the soil-foundation interface, analyses are able to capture phenomena associated with soil yielding and foundation detachment. It is shown that valley effects may provoke unexpected response of the foundation due mainly to the generation of a geometry-induced synchronous parasitic acceleration. The latter may under circumstances cause uplifting of the foundation which may provisionally either impose severe stressing on the superstructure or reduce the amount of inertia transmitted to structural members thus being beneficial under even extreme shaking conditions.

Keywords: 1-dof system, valley effects, wave propagation, vertical acceleration, SSI

1. INTRODUCTION - SCOPE OF STUDY

Although wave scattering phenomena within alluvial valley formations have been extensively studied in the literature **(***Bard & Bouchon, 1980; Sanchez-Sesma and Luzón, 1995; Chavez-Garcia, et al 1999; Olsen et al., 2006*), relatively scarce research data exists as to the response of structural systems subjected to valley-affected ground motion. Motivated by such findings, this paper attempts to interpret and quantify the role of 2D valley effects on the seismic vulnerability of structures on the basis of the performance of idealized elastic or non-linear SDOF oscillators and Realistic Structural systems such as nonlinear Frame structures. These systems could be sensitive to specific ground motion features that may be particularly intensified in valley formations such as "parasitic" vertical component (*Gelagoti et. al. 2010, 2012*). By varying the Factor of Safety against vertical Loading, it is attempted to demonstrate the different response of some representative engineering structures. Fully nonlinear foundation behavior is incorporated in the analyses by properly modeling the soil-foundation interface to account for phenomena associated with soil yielding and foundation detachment.

2. ANALYSIS METHOD

The parametric investigations to be conducted in the sequel refer to a quite mild trapezoidal valley of maximum depth of 24 m with its geometry portrayed in Figure 1. The shear wave velocity V_S of the soil within the valley has been set to V_S = 100 m/s, so as to model a quite soft clayey material with undrained shear strength of S_u = 42 kPa. The shear velocity of the substratum is equal to V_R = 400 m/s, yielding an impedance contrast ratio ($\rho_R V_R / \rho_S V_S$) between the soil and underlying bedrock of 5. The model is excited by a Ricker 1 pulse of amplitude 1 g (Figure 1b) which corresponds to a quite long period input motion. Due to its narrow–band nature the pulse is considered as particularly appropriate for bringing the governing trends to light.

The problem is analyzed in the time domain employing the finite element (FE) method, assuming plane-strain conditions. Soil is modeled with very finely discretized quadrilateral continuum elements, so as to ensure realistic representation of the propagating wavelengths. Radiation damping is taken into account through appropriate absorbing boundaries at the base of the numerical model. "Free-field" conditions are ensured at the two lateral boundaries of the model through appropriate kinematic constraints, thus reproducing the “shear beam” type of motion produced by in–plane vertically incident SV waves.

The numerical analysis methodology employed herein has been extensively validated against recorded seismic response in *Gelagoti et al. (2010)*. Rayleigh Damping has been introduced in order to effectively reproduce the visco-elastic soil response, while the fully non-linear soil behavior has been modeled employing a kinematic hardening constitutive law obeying the Von Mises failure criterion and an associated flow rule (*Anastasopoulos et. al., 2011*).

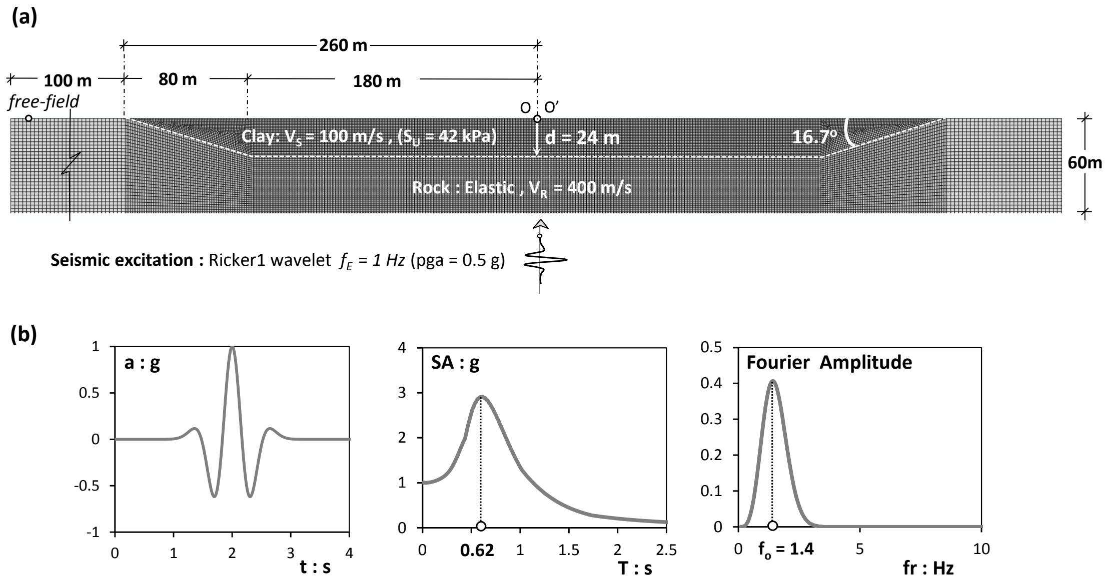

Figure 1. (a) Finite element mesh and problem parameters (the values in the brackets are assumed in the non-linear analyses). **(b)** Acceleration time history and specta (response and fourier) of the excitation motion (Ricker wavelet with f_E = *1 Hz).*

3. 2D WAVE PROPAGATION PHENOMENA ON SIMPLE STRUCTURES: ASSUMPTION OF ELASTIC SOIL RESPONSE

This scenario corresponds to the response of the example valley to a low-amplitude earthquake and serves as the “base case” which illustrates the various mechanisms composing the 2-d amplification pattern. Results are presented in Figure 2 in the form of :

(a) Spatial distribution of Aggravation Factor (defined as the ratio of the peak value of horizontal acceleration taking account of 2 dimensional phenomena over the peak acceleration value produced on top of the corresponding 1-d soil column)

(b) Seismogram synthetics; a graphic diagnostic tool that provides the evolution of generated waveforms as they appear on the surface of the valley. As such, the vertical axis of the diagram represents the longitudinal section along the valley while the acceleration time histories are plotted along the horizontal axis.

The shape of the Aggravation Factor distribution plotted in Fig. 2a reveals intense 2-dimensional phenomena leading to amplification of ground motion of as high as 40% compared to the 1d soil response. As explained in *Gelagoti et al (2010)*, the produced aggravation pattern may be attributed to the interference of oppositely propagating Rayleigh waves or the interference of Rayleigh waves with vertically propagating SV waves.

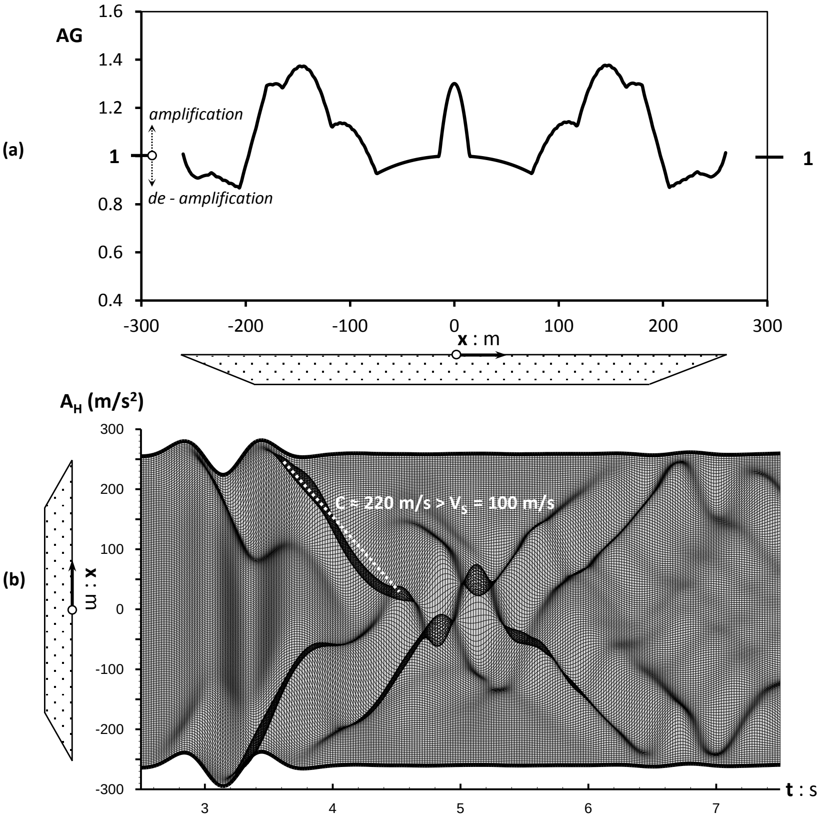

Figure 2. **(a)** Spatial distribution of aggravation factor (AG) when the study-valley is excited by a Ricker 1 wavelet assuming elastic soil response within the valley. **(b)** View of the quite complex wave-field pattern.

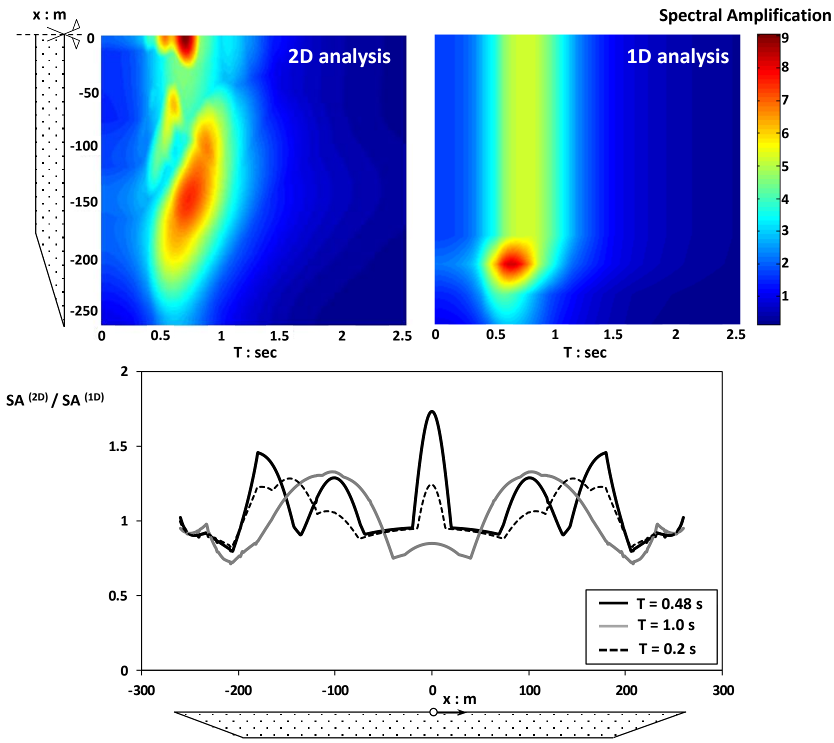

Figure 3. **(a)** Elastic Response Spectrum as simultaneous function of position along the valley surface and Period (Left: 2D Simulation; Right: 1D Simulation). **(b)** Spatial Distribution of Spectral Aggravation Factor for a relatively rigid (T = 0.2 s); for a medium (T = 0.48 s) and a quite flexible (T = 1 s) system.

This behavior may be better explained by the spatial distribution of ground motion on the surface of the valley which is plotted in Figure 2b: the initial arrivals of SV waves are followed by some later arrivals of Rayleigh waves generated at the valley edges.

It is expected that such a significant amplification of the ground motion will be reflected on the response of 1-dof structures founded on top of the formation. Evidently, the spectral amplification (Fig. 3a) calculated when considering 2-dimensional phenomena tends to remarkably exceed that of the 1-dimensional scenario along practically most part of the valley surface within a period range of 0.1<T<1, following a quite inhomogeneous pattern. This effect is better manifested in Figure 3b which plots the spatial distribution of the Spectral Aggravation Factor (defined as S_A^{2D} / S_A^{1D}) for three characteristic 1-dof systems, namely a relatively rigid one (of T = 0.2 s) a medium (T = 0.48s) and a flexible system of T = 1s. Although the three curves do display some disparities among them, it is obvious that the positions of the peaks are related with the positions of Rayleigh waves interferences discussed about previously. In terms of amplitude, 2D effects are more tangible for the case of the T = 0.48s oscillator whose spectral aggravation in the very center of the valley reaches AG = 1.8; this however is trailed by a steep trough in the plot dropping the AG value to a mere AG = 1 until the peak is repeated but at a lower amplitude. On the other hand, the long-period (T = 1 s) system is naturally less able to follow a similarly volatile aggravation pattern. Yet, although it remains practically insensitive to the valley when founded close to its center, it is prone to a substantial aggravation ranging from 1.2 to 1.4 along an important part of the valley length (roughly 80 < x < 180).

4. THE ROLE OF INDUCED SOIL NON-LINEARITY

The effect of non-linear soil response on 2-d valley phenomena has been the subject of a number of studies by, among others, *Zhang and Papageorgiou (1996), Pergalani et al (2003), Lenti et al. (2009)*. Most of their research evidence suggests that the effect of soil nonlinearity is repealing for the induced valley phenomena: quite invariably they tend to diminish. AG values have been shown to remain significantly lower than those observed when neglecting soil inelasticity, while particularly susceptible are the late arrivals of surface waves that are essentially filtered out.

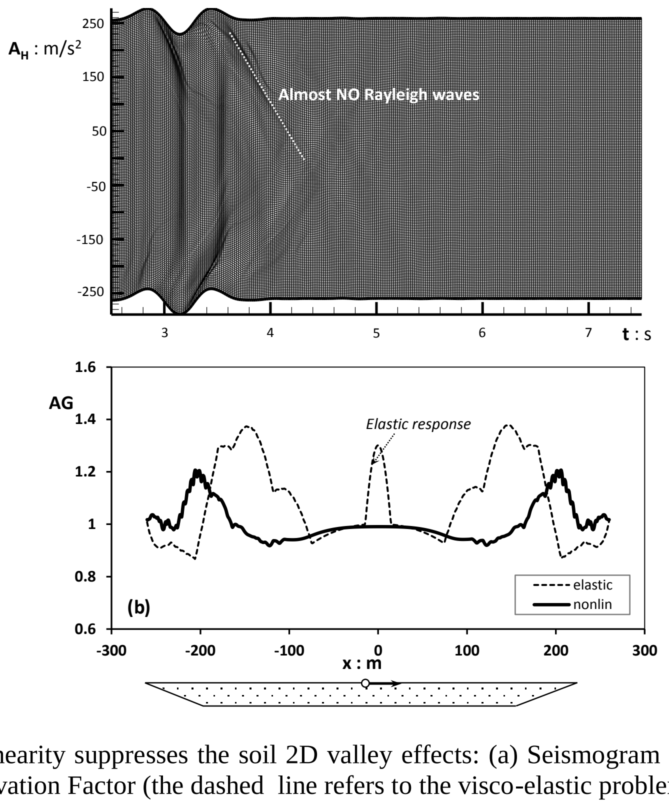

Figure 4. Soil non-linearity suppresses the soil 2D valley effects: (a) Seismogram synthetic and (b) Spatial Distribution of Aggravation Factor (the dashed line refers to the visco-elastic problem).

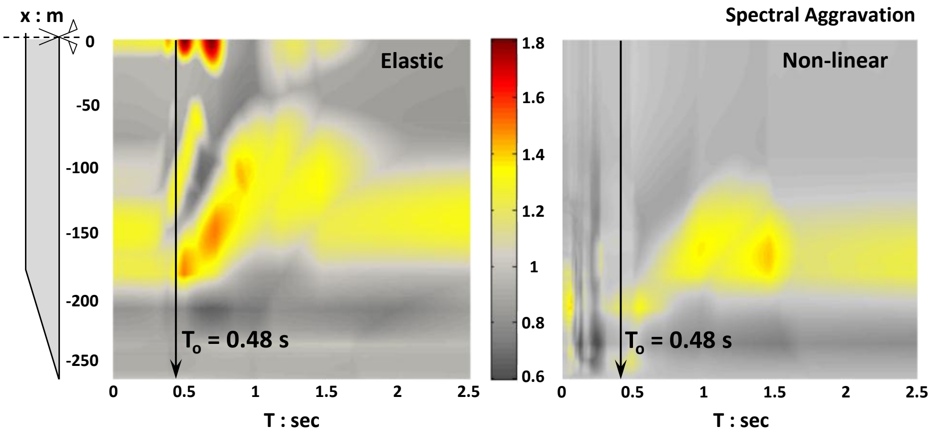

Figure 5. Spectral Aggravation Ratio plotted as simultaneous function of position along the valley surface and period (Left : Visco-elastic Soil Response ; Right: Nonlinear Soil Response).

This conclusion is generally confirmed when examining the produced wavefield pattern (Figure 4a) which now manifests itself through a smoothened shape reflecting a quite poor population of produced waveforms. Limited 2-dimensional phenomena are only localized close to the valley edges as indicated by the slight “crumpling” of the seismogram in that area. This is also mirrored on the spatial distribution of AG (Figure 4b): the induced non-linearity results in decreased amplifications along most part of the valley surface while the maximum value of AG drops from 1.4 to 1.2.

The previously observed pattern is similar in terms of structural response as reflected on the spectral aggravation plots of Figure 5. A de-amplification of maximum values is evident along the whole period range, while the steep peaks of values as high as 1.8 observed in the elastic problem have now vanished limiting the only noticeable amplification in the region around x = 175m, where the boundary slope increases. Recalling the aforementioned medium stiffness oscillator of T = 0.48s, it is worth noticing that its response tends to remain insensitive to the valley geometry independently of its position along it. Based on such results, it would be rational to conclude that, at least for systems with 0.1 < T < 0.5, consideration of valley effects as calculated by the prevailing elastic soil approach would be utterly over-conservative compared to conventional 1-dimensional amplification analysis.

Yet, as shown in the ensuing, 2-d effects are not only limited to amplification of horizontal ground motion but may well give rise to the generation of a parasitic vertical component which although often neglected by design could be crucial for the overlying structures.

5. THE ROLE OF PARASITIC VERTICAL ACCELERATION

5.1 Generation of the parasitic motion

As evidenced by *Harmsen & Harding (1981), Othuki & Harumi (1983), Fishman & Ahmad (1995), Gelagoti et al (2010)* the presence of a non-level subsurface geometry may (under circumstances) generate a vertical component due to the refraction of waves at the inclined interfaces of the bedrock (Fig. 6a). Moreover, contrary to the horizontal component, whose amplitude has been previously seen to deteriorate when accounting for soil non-linearity, the parasitically generated vertical component A_V may reach surprisingly high values. These are localized within the valley wedges rather than spread along the valley surface as in the case of elastic analysis (Fig. 6b).This shift of the peak location is, as explained earlier, attributable to the geometry of the valley relative to the wavelength of the seismic excitation. As the wavelength decreases due to the development of higher strain levels (and subsequent decrease of Vs), the geometry becomes more perceptible by the incoming waves, and wave refractions towards the convex borders of the valley wedges are intensified.

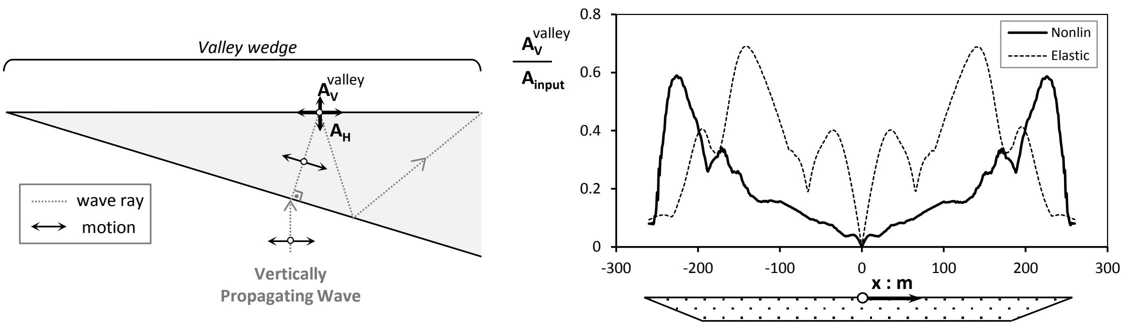

Figure 6. Generation of a parasitical vertical motion on the valley surface : schematic illustration of the generation mechanism and spatial distribution of the maximum vertical acceleration (normalized over the maximum horizontal input acceleration) assuming elastic (dashed line) and inelastic soil behavior (solid line)

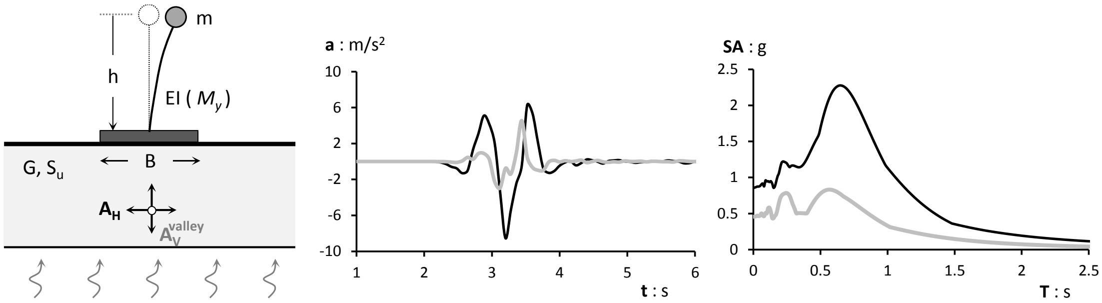

Figure 7. An idealized SDOF oscillator is excited by a pair of horizontal (black line) and valley-generated vertical acceleration (gray line).

In contrast to the natural vertical component of an earthquake, which is usually of very high frequency to pose a serious threat to structures, such "parasitic" valley-generated vertical component *can be detrimental for overlying structure* : being a direct result of geometry, it is fully correlated and of practically the same dominant period as the horizontal component (*Kourkoulis et al; 2012*). Proof of this statement is offered by Figure 7b which plots the horizontal and vertical acceleration time histories and their corresponding response spectra as calculated at the position under study when the valley is excited by purely horizontal Ricker-1 pulse (PGA=1g) at its base. In an attempt to preliminarily quantify the role of such parasitic vertical component on an overlying structure, this section investigates the response of the T = 0.48 s oscillator on top of the same valley geometry assuming a more competent strength of S_u = 85 kPa while maintaining the same Ricker-1 input motion on its base. The oscillator is then assumed to be founded on the location of maximum vertical acceleration amplitude i.e. near the valley edges, at x = 220m.

As shown on Fig. 7a, the structure under study consists of a 3m high 1-dof system supported on a surface foundation of width B = 3.3m. The mass and stiffness of the oscillator has been varied (Table 1) while maintaining the fundamental period constant, in order to achieve a safety factor against vertical loads of either FS_V = 6 or 3. In the former case, provided that the column is modeled as an elastic beam (*Types A and B*), the rocking response of the foundation is expected to materialize through uplifting while in the latter through soil yielding. To this end special interface elements have been used between the footing and the soil allowing sliding or detachment of the foundation. Finally, *Type-C* oscillator refers to a non-linear column whose strength in terms of maximum bending moment is M_y *=190 kNm*, According to conventional capacity design norms, the column strength is lower than that of its supporting footing (whose M_{ult} *=220 kNm*) and as such, it is expected to yield once the imposed ground motion exceeds its design acceleration of a_g *= 0.36 g* (common for all systems).

To isolate the effect of the parasitic (valley-generated) vertical component, two sets of analyses are conducted: (a) the soil-structure model is subjected solely to the *horizontal component* A_H of the ground motion produced on the valley surface; and (b) simultaneously subjected to the *horizontal and* *vertical components* (A_H and A_V) recorded at the valley model surface (at the location of maximum A_V). The presence of Av may either *increase* or *decrease* the axial load transmitted through the column onto the footing, thus affecting its response either detrimentally or even beneficially as discussed in detail in the sequel.

Table 1. Characteristics of the three oscillators used in the analyses

Superstructure							Foundation (S_U = 85 kPa)		
1-dof	Height (m)	mass (tn)	I_{yy} (m^2)	E (kPa)	T_o (sec)	M_y (kNm)	width : (m)	SF_V	M_{ult} (kNm)
Type A	3.0	24.0	1.25E-03	3.00E+07	0.48	∞	3.3	6.0	220
Type B	3.0	48.0	2.50E-03	3.00E+07	0.48	∞	3.3	3.0	220
Type C	3.0	24.0	1.25E-03	3.00E+07	0.48	190	3.3	6.0	220

5.2 1-dof system subjected to simultaneous horizontal and vertical component

The effect of a synchronous *positive* vertical acceleration pulse accompanying the strong horizontal pulse is schematically outlined in the deformed mesh of Figure 8a and is associated with a potential loss of contact between the footing and the ground, which may result in kinematically-induced increased rotation of the oscillator (Figure 8b). Indeed, the response of the two systems is identical up to the instant t=4.5s when, during the main horizontal acceleration pulse, the footing whose vertical load *N* is already reduced due to its rocking-deformation, is abruptly subjected to a simultaneous strong vertical acceleration pulse which momentarily leads to complete loss of contact (N=0) with the bearing soil (Fig 8b). At that instant, the horizontal displacement of the system top increases by about 35% from 22 to 30 cm (Fig. 8d). Similar results are obtained when investigating the response of the $FS_V = 3$ system.

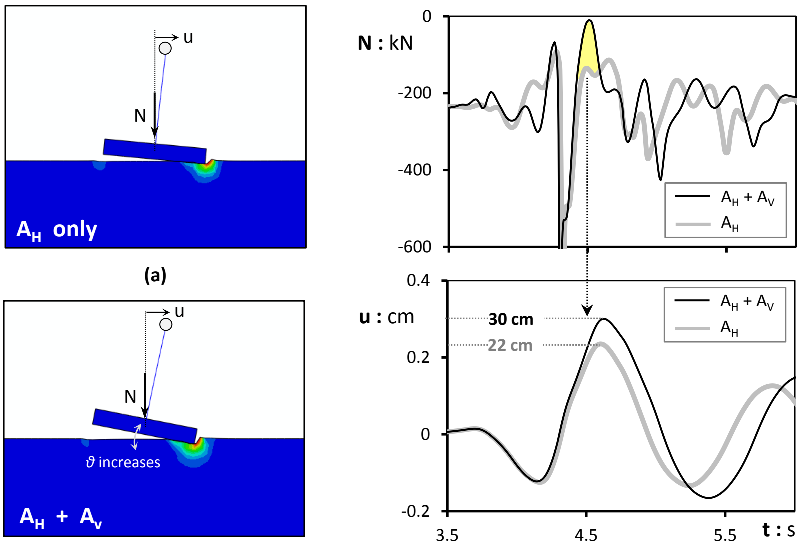

Figure 8. Illustration of the detrimental role of the valley-generated vertical acceleration on the response of an *elastic* SDOF oscillator (with T=0.48 s) founded on the valley surface through a square foundation of B=3.3 m: **(a)** deformed shape at the instant of maximum response, **(b)** time history of the axial load N and **(c)** displacement at the top of the oscillator with and without the simultaneous action of the A_V component.

Interestingly, the effect of the parasitic vertical acceleration is not necessarily detrimental and is proven to be a function of various parameters requiring further investigation. As such, of significant importance is definitely the nature and characteristics of the imposed strong motion. In this context, Figure 9 portrays the response of the same oscillator when subjected to the time histories calculated on the valley surface, when its depth increases from 24m (i.e. the original case examined so far) to 48 m.

Notice (Figure 9a) that the vertical acceleration in this deep valley scenario does again amplify the maximum rotation observed, but has also a tremendous effect on the free-vibration part of the response causing the oscillator rotation to fluctuate between 0.15 and -0.15 rad as opposed to only ±0.07 rad when ignoring the parasitic component. As could possibly be expected, this is accompanied by a notable increase of the period of the soil-structure system past the forced-vibration phase. Surprisingly though (Figure 9b), when the system is founded on the right edge of the valley (i.e. the polarity of the vertical acceleration component is reversed), the parasitic vertical component de-amplifies the experienced rotation during both the forced and the free vibration phase.

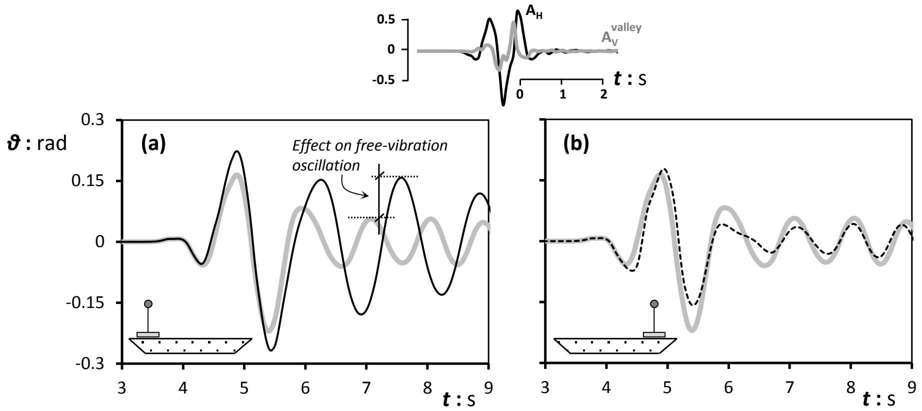

Figure 9. The polarity of the vertical acceleration may completely modify the response : (a) detrimental and (b) beneficial role

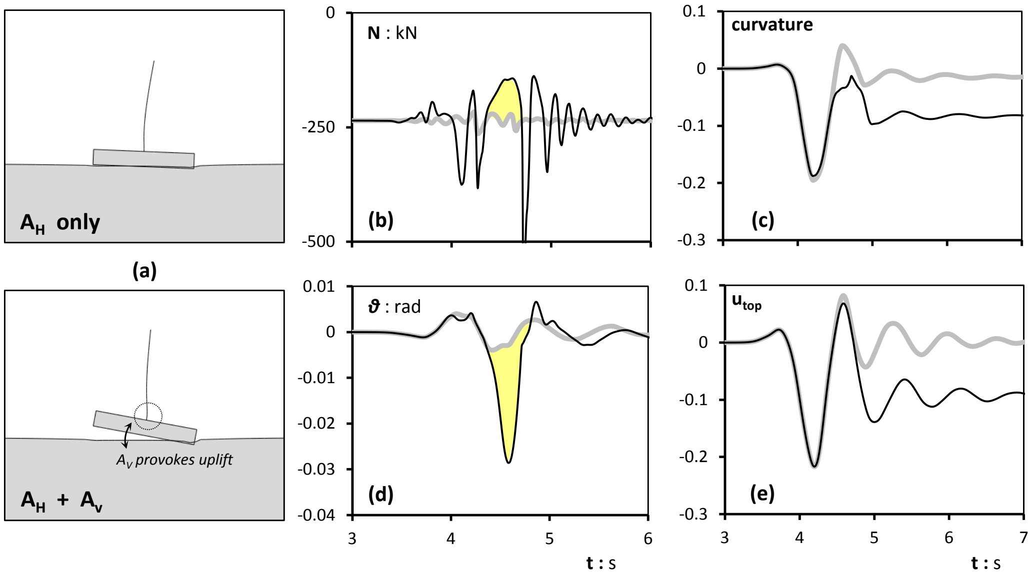

Figure 10. Illustration of the detrimental role of the valley-generated vertical acceleration on the response of a *nonlinear* SDOF oscillator (with T=0.48 s) founded on the valley surface through a square foundation of B=3.3 m with FS_V = 6: **(a)** deformed shape at the instant of maximum response and time history of **(b)** axial load N, **(c)** curvature, **(d)** footing rotation and **(e)** displacement at the top of the oscillator with (black line) and without (gray line) the simultaneous action of the A_V component.

Results may be even more dramatic when modeling the oscillator as an inelastic beam of specific strength defined as Type C in Table 1. As portrayed in Figure 10a, in the absence of vertical component the system responds through column bending (as would be conventionally expected) oscillating around an equilibrium position, while its axial load (Fig. 10b) displays a negligible fluctuation around its initial value (i.e. the weight of the mass). The column curvature reaches a quite high value during the main horizontal acceleration pulse (Fig 10c) which is however recovered afterwards thus resulting in minimal residual distortion both in terms of curvature and horizontal displacement (Figs. 10 c and e). The picture is however reversed when the vertical acceleration component is considered. The latter is materialized in the form of a salient upwards pulse (at about t = 4.5s) responsible for a drastic decrease of the vertical load (Fig. 10b) transmitted to the foundation which is forced to uplift as demonstrated by the footing rotation plot of Figure 10d. Throughout this phenomenon, the effective period of the oscillator-foundation system is shifted far beyond than the fixed system assumption of T = 0.48s, and consequently the inertial force of the oscillating mass is out of phase and therefore inadequate to retrieve the column back to its equilibrium position. This results to a residual curvature c ≈ 0.08 at the column base and displacement of around 10 cm on its top, corresponding to a quite significant residual drift of about 3.3%.

6. RESPONSE OF A SIMPLE FRAME STRUCTURE

Analyses are conducted using a non-linear, fairly simple symmetric 2-storey 1-bay frame (Fig. 11a). examined in detail by *Gelagoti et al. 2012*. The superstructure is designed conventionally, according to current seismic codes for a design acceleration A_d = 0.36 g and behavior factor q = 3.5, while its columns are founded on square B = 2 m footings, allowed to detach from the supporting ground. As input acceleration on the base of the valley, we have utilized the Tabas accelerogram recorded during the devastating Tabas earthquake in Iran 1981. Hence, the frame will be subjected to the resulting valley affected horizontal and vertical components of ground motion on the surface, which, as shown in Figure 11a, obtain a tremendous amplitude of 0.83 g peak horizontal and 0.62 g vertical acceleration. Following the same rationale as previously, the frame is assumed to be located close to the valley edges at the position of maximum parasitic vertical acceleration.

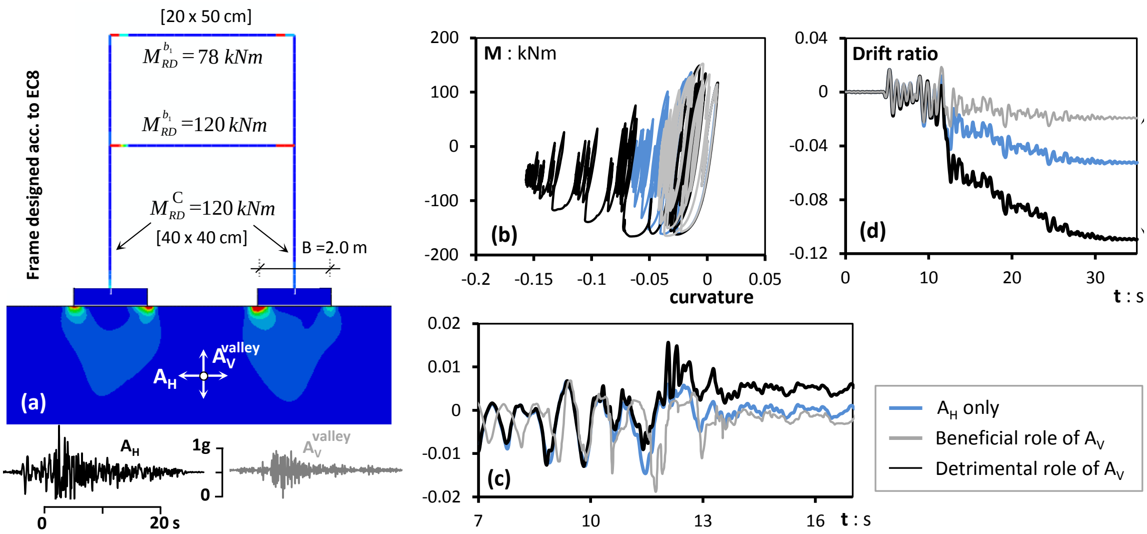

Figure 11. Effect of the valley-generated A_V component on the seismic performance of a 2-storey Frame (designed according to EC8) : **(a)** problem definition and schematic illustration of the frame response, **(b)** Moment-curvature loops at the base of the left column and time history of **(c)** footing rotation and **(d)** drift

Even in the absence of vertical acceleration, the severity of imposed shaking is such that a significant distress is produced on the column whose residual curvature obtains a value of c_{res} =0.08 accompanied by a drift ratio of almost 5% (Fig 11b). The presence of the parasitic component however produces an equivocal effect on the response: it may either improve or fatally deteriorate depending on the polarity of the imposed parasitic motion. In the beneficial scenario, the acceleration pulse at instant t = 12.5s, producing foundation rocking through uplifting thus impeding the transmission of higher inertial force (due to the horizontal motion) to the superstructure (Fig. 11c and d). On the other hand, in case of reversed polarity, the vertical acceleration pulses produce a very substantial rotation of the foundation which maintains a positive sign from 12s < t < 15s, therefore being insensitive to the reversal of the horizontal acceleration direction. Consequently, the column is forced to a kinematical- induced drift which is irrecoverable during subsequent cycles of motion.

7. CONCLUSIONS

This paper has explored the response of an 1-dof oscillator and a non-linear frame structure founded on the surface of alluvial valleys employing fully non-linear numerical analyses with due account of Soil-Structure Interaction effects. It has been shown that soil non-linearity may significantly reduce the intensity of 2-d wave scattering effects on structural response. However, the non-level valley geometry may well give rise to the generation of a parasitic vertical component of motion which although often neglected by design could be crucial for the overlying structures. Depending mainly on the polarity of the imposed time history, the parasitic acceleration may be either beneficial or detrimental. The effect of a synchronous vertical acceleration pulse accompanying the strong horizontal pulse is associated with a potential loss of contact between the footing and the ground, which may result in kinematically-induced increased rotation of the structural system. In the beneficial scenario however, acceleration pulses may produce footing uplifting thus impeding the transmission of higher inertial force (due to the horizontal motion) to the superstructure.

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