

## EFFECTS OF SOIL NONLINEARITY ON THE GEOMORPHIC AGGRAVATION OF GROUND MOTION IN ALLUVIAL VALLEYS

Prodromos N. PSARROPOULOS<sup>1</sup> and George GAZETAS<sup>2</sup>

### ABSTRACT

Records and analyses in the past have shown that the geomorphy of an alluvial valley may amplify the ground motion (apart from the amplification related to soil stratigraphy), elongate the duration of strong ground motion, and cause differential ground motions, phenomena that can adequately be described with the term “*geomorphic aggravation*”. However, as most of the cases in the literature are involved with small or moderate earthquakes (in which soil response remains quasi-elastic), the query is whether the unavoidable nonlinear soil behavior during a strong earthquake may affect this aggravation. The present study is involved with an alluvial valley in Japan, the seismic response of which has been monitored during small and moderate earthquakes with accelerometers located at the base and the surface of the valley. The seismic response of the valley has been simulated with linear and nonlinear two-dimensional numerical analyses. Soil non-linearity has been realistically taken into account via a commonly used equivalent-linear procedure. Results show that the valley geomorphy profoundly aggravates the seismic ground motion in the presence of small levels of damping, while on the other hand, the potential soil nonlinearity may lead to substantial decrease of geomorphic aggravation by diminishing the reflected body waves, and the horizontally propagating surface waves.

Keywords: valley effects, site effects, amplification, aggravation, soil nonlinearity

### INTRODUCTION

For many years, the term “*local soil effects*” was used to describe exclusively the influence of *soil stratigraphy* on the seismic ground motion. Such effects were taken into account by the well-known one-dimensional (1-D) analysis, assuming parallel soil layers of infinite extent excited by vertically incident waves. However, during numerous strong earthquakes in recent years (1988 Spitak, 1989 Loma Prieta, 1994 Northridge, 1995 Kobe, 1999 Athens) the reported variability of ground shaking or the non-uniform distribution of damage could not be sufficiently explained by the simple 1-D analyses. Thorough geophysical and geotechnical surveys, in combination with the utilization of small seismographic arrays and various analytical or numerical simulations have suggested that the aforementioned discrepancy may be attributed to the existence of subsurface irregularities, like alluvial valleys or sedimentary basins (Aki 1988 and 1993; Sánchez-Sesma & Esquivel 1979; Bard & Bouchon 1980; Sánchez-Sesma et al 1988; Graves 1996; Faccioli et al 1997; Bielak et al 1999, Paolucci 1999). It was realized that, apart from the soil-material conditions, the geomorphic features of a valley (in 2 dimensions) or a basin (in 3 dimensions) tend to alter and usually aggravate the amplitude, frequency content, duration, and spatial variability of ground shaking.

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<sup>1</sup>Lecturer, Department of Infrastructure Engineering, Hellenic Air-Force Academy, Athens, Greece,  
Email: [prod@central.ntua.gr](mailto:prod@central.ntua.gr)

<sup>2</sup>Professor, School of Civil Engineering, National Technical University of Athens, Greece,  
Email: [gazetas@ath.forthnet.gr](mailto:gazetas@ath.forthnet.gr)

The main phenomena that constitute the “*valley amplification*” effects on site response have been summarised for the geotechnical community by Aki (1988) and Finn (1991); some newer major seismic events have dramatically reinforced their main conclusions. A typical example of *valley effects* is the damage distribution observed during the 1988 Armenia earthquake (Yegian et al, 1994; Bielak et al, 1999). Numerical studies have also shown that the extent of damage reported in the Marina District, San Francisco, during the 1989 Loma Prieta earthquake, could be mainly attributed to the 2-D *site* conditions (Zhang & Papageorgiou 1996). Graves (1998), simulating the seismic response of the San Fernando basin in the 1994 Northridge earthquake, showed that the subsurface irregularities may have caused a large amplification, especially in the long period ground motions. Finally, during the 1995 Hyogoken-Nambu earthquake, most of the damage in the city of Kobe occurred within the so-called “disaster belt”, a narrow zone 1 km wide, nearly 20 km long, located between about 1 to 1.5 km from the Rokko mountain rock outcrop. Numerical analyses by various researchers have supported the idea that the 2-D valley geometry (in combination with the unquestionable forward-rupture directivity effects) had led to that particular concentration of damage.

The above phenomena have been documented either by observations, or multi-dimensional site-specific ground response analyses (in 2 or 3 dimensions). However, most of the available data of the recorded motions refer mainly to weak-motion excitation (small-magnitude earthquakes or microtremors), and most of the analyses are based on the assumption of linearly elastic, or at most, linearly visco-elastic soil behaviour. However, the stress-strain behaviour of soft soils is highly nonlinear. Therefore, it is reasonable to question the range of validity of conclusions drawn on the basis of linear analyses. Almost a decade ago, Aki (1993), referring to the research needs for improving seismic microzonation, pointed out that “*the most urgent requirement is a clear understanding of the nonlinear amplification effect at soil sites*”. Despite the seismological and geotechnical evidence of soil nonlinearity only a very small number of published nonlinear analyses have seriously questioned the substantial *aggravation* caused by *weak-motion valley effects*: Marsh et al (1995), comparing numerically the linear and nonlinear seismic response of simple 2-D alluvial valleys, were the first to demonstrate that soil nonlinearity results in lower peak accelerations and lower response spectra. Zhang & Papageorgiou (1996), simulating the seismic response of the Marina District Basin during the 1989 Loma Prieta Earthquake and utilising an equivalent-linear method (to account for soil nonlinearity), showed that in the case of strong-motion excitation “*three-dimensional (3-D) focusing and lateral interferences, while still present, are not as prominent as in the weak-motion excitation case*”. Additionally, the abovementioned study underlined the fact that the energy dissipation during strong-motion excitation dampens substantially the surface waves, and thus, the response of the valley is dominated by the nearly vertically propagating waves. More recently, Sincraian & Oliveira (1998) examined the nonlinear behaviour of Vovli valley in Greece (see Chavez-Garcia et al 2000), while Xu et al (2002) simulated a hypothetical 3-D basin assuming elastoplastic soil behaviour obeying Drucker-Prager’s model. They showed that the amplitude of ground accelerations is significantly reduced due to soil nonlinearity. On the other hand, Bielak et al (2000) pointed out that soil nonlinearity during strong-motion excitation reduces the amplitude of *surface waves* only, while the other valley related wave phenomena from the overall local geological structure remain present. Therefore, a key issue relating to “*valley amplification*” effects, and consequently to microzonation research, is to quantify the degree and extent of the reduction which is effected by soil nonlinearity of the rather huge 2-D or 3-D amplifications often computed, and especially recorded during small-strain excitations, where soil deposits behave linearly.

The present study, trying to shed some light on this important issue, analyses numerically the effects of the subsurface geomorphic conditions of an alluvial valley in Japan on its ground surface seismic motion. The valley, crossed by the Ohba Ohashi bridge, consists of shallow deposits of soft soil surrounded by a relatively-stiff base and quite steep lateral boundaries. As several seismic records have been obtained (at the base and the surface of the valley) during many earthquakes and ambient vibration tests in the past, the examined valley can be considered as a natural experiment (Tazoh et al 1984, 1988). The 2-D seismic behaviour of this valley has been examined in the past by various researchers. Ohtsuki et al in 1984, utilising a hybrid method based on the finite-difference and the finite-element method, calculated the acceleration and displacement waveforms on the ground surface, and the strain distribution over the inclined boundary. The 2-D numerical modelling showed clearly

the generation of surface waves from the irregular boundary. Fukuwa et al in 1985 examined the same valley under SH excitation and compared their results with the available records, utilising a hybrid 2-D method combining boundary-element and finite-element methodologies. On the other hand, the insufficiency of 1-D analyses to explain the recorded amplification and the subsequent level of shaking at the ground surface of the valley has been observed by other researchers. For example, Fan (1992) and Gazetas et al (1993), examining the seismic response of the foundation of the Ohba-Ohashi bridge, performed 1-D wave propagation analyses. They showed that 1-D theory could not adequately explain the recorded level of shaking at the ground surface, and concluded that 2-D analyses were necessary to capture the valley effects. As mentioned above, the “entrapment” of seismic waves in the valley and the generation of surface waves at the edges of the valley are phenomena expected to have the following “*valley amplification*” effects:

- The intensity of the ground shaking may be amplified at certain location more than 1-D wave theory predicts. We will use the term “*aggravation*” to describe the additional amplification, above the corresponding amplification computed with 1-D analysis. Such aggravation may be observed not only on the amplitude of the ground shaking (in terms of peak ground acceleration or velocity), but on its spectral content as well.
- The spatial variability of the ground surface motion may be substantial, even for closely-spaced locations characterized by the same soil profile. The ensuing differential motions are usually of great interest on the seismic response of long structures such as bridges and pipelines.

The goal of this paper is to capture numerically these effects.

## METHODOLOGY OF THIS STUDY

As all the available recorded motions of the Ohba Ohashi site were from weak and relatively weak excitations, linear 2-D ground response analyses were initially conducted, utilising two different numerical models, based on the Finite-Element (FE) method and the so-called Spectral-Element (SE) method, respectively. In both models an incident SV wave excitation was induced. The linear FE analysis was based on the “*effective seismic excitation*” technique proposed by Bielak & Christiano (1984), and developed by Loukakis (1988). With this approach, the problem of seismic response of a 2-D valley is transformed into an equivalent one, in which the seismic source is located in the interior of the domain of computation. The advantage of this technique is that, by introducing the seismic excitation directly within the region of interest (through equivalent dynamic point forces), the artificial boundary (at the vertical sides and the bottom of the model) is needed exclusively to absorb the scattered energy (radiation damping) of the system. Therefore, the artificial transmitting boundary (dashpots in this case) may be placed as close to the examined region as the accuracy of the absorbing boundary permits; no approximation is involved in the specification of the free field motion. This option permits the discretization of a limited area of the surrounding ‘bedrock’, minimising thus substantially the size of the model, and consequently the computational cost in memory and CPU time.

The SE modeling was performed by AHNSE (Advanced Hybrid Numerical Solver for Elastodynamics), developed in the framework of the TRISEE Joint European Research Project (Faccioli et al 1997). The excitation is implemented as an incident plane SV wave obtained by imposing the same acceleration to all nodal points belonging to a selected horizontal line, and, as in the FE model, absorbing boundaries were placed around the domain of interest.

The verification of the two numerical models has been performed by successfully reproducing some of the recorded time-histories of the ground surface motion, using as input the recorded ground base motions (Psarropoulos et al 1999). Additionally, the analyses showed that the spatial variability in ground surface motion was evident for certain excitations even for relatively short distances, despite the identical soil profile of these locations.

Then, to demonstrate the influence of potential nonlinear soil behaviour on the valley amplification of the specific site, nonlinear 2-D ground response analyses were performed, utilising the FE method. Soil nonlinearity was taken into account approximately by an iterative procedure referred to as the “equivalent-linear” method, according to which the values of soil stiffness and damping are consistent with the level of cyclic shear strain (Vucetic & Dobry 1991, Hudson et al 1994). In our parametric investigation, the nonlinear soil behaviour is provoked either by increasing the intensity of excitation or by decreasing the *plasticity index* (*PI*) of the soil layers.

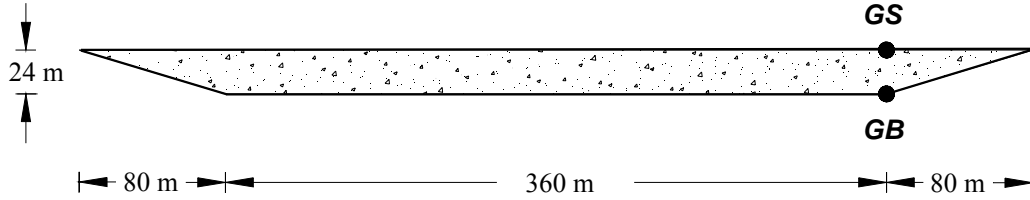
By comparing records and numerical results, it is shown that the 2-D features of the valley and the relatively sharp impedance contrast with the underlying soil may have a profound effect on the amplitude and the frequency content of the ground surface motion when soils behave linearly (either due to the weakness of excitation or their own high *PI*). Additionally, the duration of motion is elongated, while spatial variability of certain frequency components is substantial. The development of soil nonlinearity decreases the amplitude of the multiply-reflected and horizontally propagating waves, leading to substantially lower valley amplification effects. Laterally propagating Rayleigh waves and body waves (including their interferences) are particularly sensitive to the relatively-high material damping generated with nonlinear soil re-action. In that case, a better agreement between 1-D and 2-D site response analyses is expected. We have to mention that a limitation of our analysis (and of most published multi-dimensional nonlinear analyses in the literature) is the reliance on the equivalent-linear approximation. Clearly, this is hardly an ideal way to model soil response for strongly nonlinear behavior in 2 or 3 dimensions. The numerical example and the *state of the art* in the reviewed literature make clear that there exists a continued need for more research on nonlinear multi-dimensional analyses and observations.

## CHARACTERISTICS OF THE VALLEY AND RECORDED SEISMIC MOTIONS

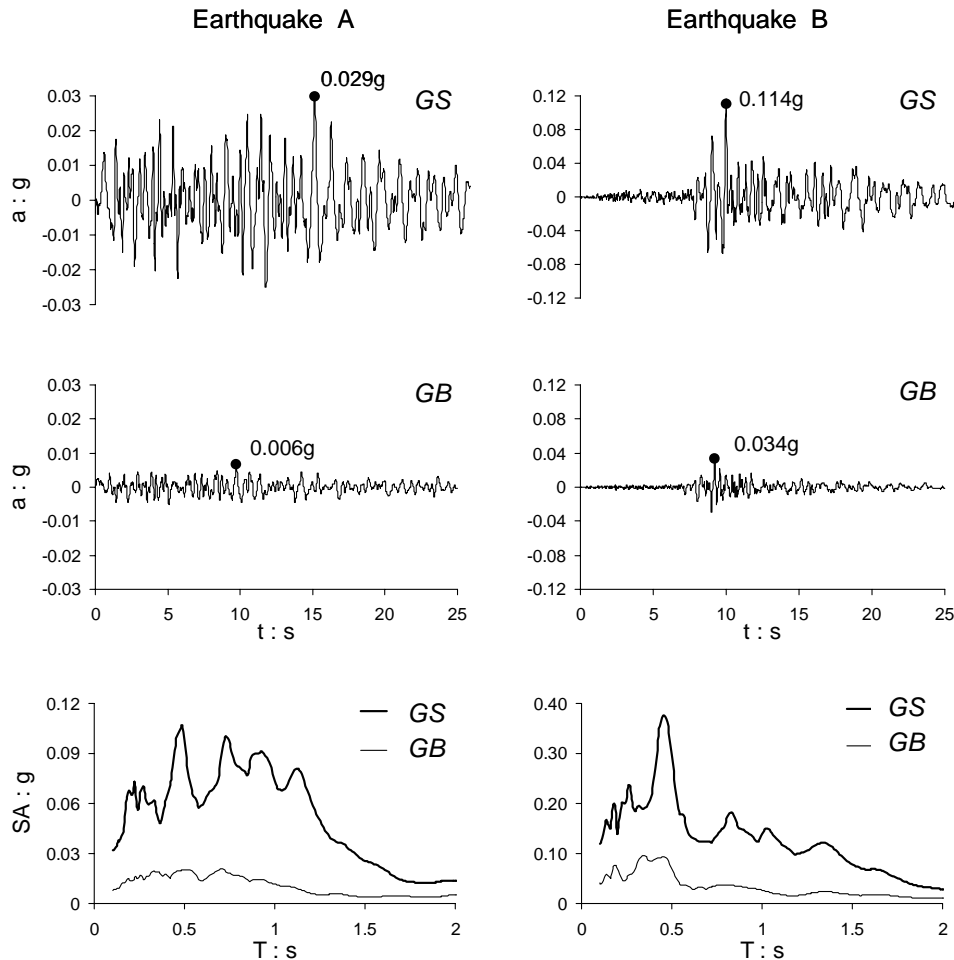
The valley, the seismic behaviour of which is examined in our study, constitutes a soft alluvial valley near Fujisawa City, Japan. It is crossed by the Ohba-Ohashi bridge, which is a 600-meters-long road bridge built across Hikichi river. The specific site constitutes a natural experiment, as the valley is characterized by substantial 2-D features, while on the other hand, both valley and bridge have been instrumentally monitored during numerous earthquakes and ambient vibrations in the past (Tazoh et al 1984 and 1988). However, as this study focuses solely on the seismic response of the valley, the seismic motions recorded at the ground base and the ground surface are of significant importance. Figure 1 sketches the arrangement of two of the accelerographs (one at the ground base (*GB*) and another at the ground surface (*GS*)), and the simplified geometry of the valley, based on which the numerical models were developed. The geologic profile consists of a maximum of 20-25 meters of soft alluvium, underlain by relatively-stiff diluvial deposits. The top soil layers consist of extremely soft clayey strata, containing humus and silt. Despite the soil improvement that had been performed before the bridge construction, the standard penetration test values *N* remained almost zero, while the shear-wave velocity, *V<sub>s</sub>* was ranging between 40 to 65 m/s. The underlying substratum consists of layers of stiff clay and sand characterized by *N* values over 50 and *V<sub>s</sub>* around 400 m/s. Ground water table is almost at the ground surface, while the water content of the top soil layers exceeds 100 %, reaching at points 250 %, with correspondingly small soil densities. It is important to note that the top soil layers of the valley are characterized by large to extremely large *PI* (in excess of 150), thereby likely to behave almost linearly even at large strain levels (Vucetic & Dobry 1991). More details on the soil-profile characteristics can be found in the original publications (Tazoh et al 1984, and 1988).

The earthquake observations had been carried out by the Institute of Technology of Shimizu Corporation (Tazoh et al 1988). The free-field motion of the valley had been adequately recorded with accelerographs installed almost at the ground surface and at the interface with the underlain relatively-stiff soil that is regarded as the bedrock. From 1981 till 1985, 14 earthquakes had been recorded. Two of them (with *M<sub>JMA</sub>* = 6) were used in our numerical study, hereafter referred to as Earthquakes A and B). The latter was the major local earthquake reported for the area during that period (Kanagawa-Yamanashi-Kenzakai earthquake), registering the maximum acceleration levels at the ground surface

(0.114g). As the in-plane seismic motion (SV wave excitation) is examined, the recorded acceleration time-histories in the longitudinal direction (i.e. parallel to the bridge axis) at the ground base of the profile (*GB*) and at the ground surface (*GS*) are given in Figure 2, along with their response spectra. It is evident that the peak accelerations are amplified by almost 4 times, while the spectral amplification seems even higher.



**Figure 1. Simplified geometry of the valley and location of two of the accelerographs, at ground base (*GB*) and at ground surface (*GS*).**



**Figure 2. Acceleration time-histories  $a(t)$  and acceleration response spectra  $SA(T)$  of the two earthquakes (A and B) recorded at the ground base (*GB*) and the ground surface (*GS*) of the valley, in the longitudinal bridge direction.**

## LINEAR SITE RESPONSE ANALYSES

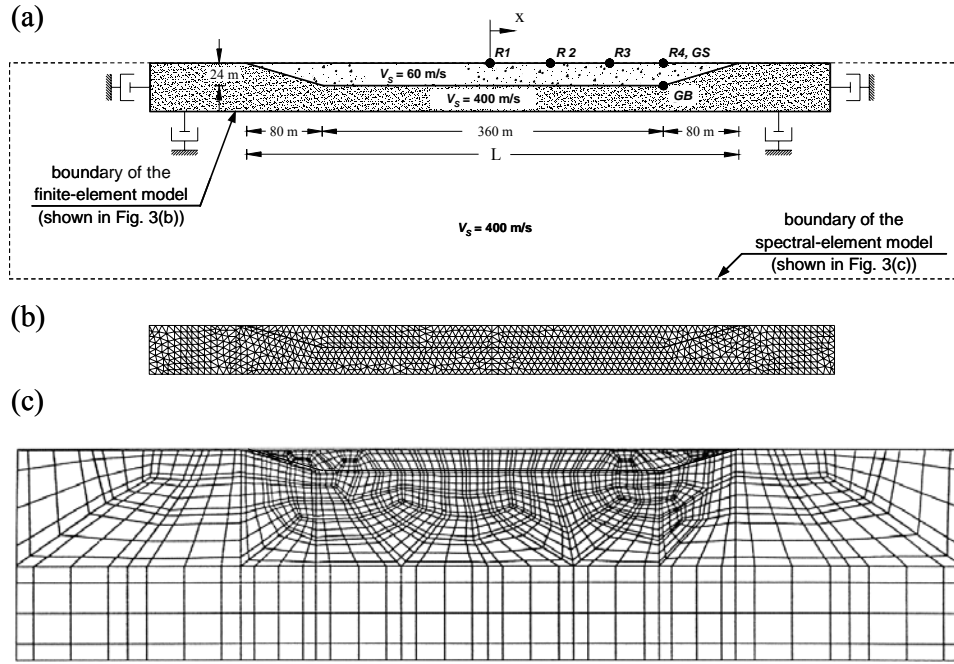
Initially, it was attempted to capture the “*valley amplification*” effects on the ground surface motion of the valley when soil behaves linearly. In that case it is possible to compare directly the numerical results with the available records, as there had been two reasons for the soft soil layer to behave linearly. The first reason was that even the strongest earthquake is characterized by low acceleration levels, while the second one was that the soft soil layer is characterized by large  $PI$ , behaving almost linearly even at large strain levels. To verify both linear models each of the recorded ground base ( $GB$ ) acceleration time histories of the two earthquakes was applied as SV wave excitation. The aim was to obtain the recorded acceleration time histories at the ground surface ( $GS$ ).

The geometry and the soil properties of the valley were idealized, assuming a trapezoidal shape and assigning a constant low-strain  $V_s$  to the soil stratum equal to 60 m/s (see Figure 3(a)). The figure also shows the four points of interest on the surface ( $R1$ ,  $R2$ ,  $R3$ ,  $R4$ ). Point  $R1$  is at the middle of the valley surface, while point  $R4$  is located at the right-hand-side edge of the valley, coinciding with the location of accelerograph  $GS$ . The FE analyses were performed utilising the commercial code ABAQUS (HKS, 1998), while the SE analyses were performed with the code AHNSE (Faccioli et al 1997). All the analyses are based on the assumption of linear visco-elastic soil behaviour, which is quite acceptable for earthquakes with relatively-low acceleration levels and for clayey deposits with very high  $PI$ , as is the case here. By trial-and-error it was discovered that a material critical damping ratio of about 3% (a very reasonable value for a soft soil) led to the most satisfactory results in both recorded earthquakes examined. Note that in both numerical codes utilized material damping is of Rayleigh type. The spectral-element mesh consists of *macro* elements split into 16 *micro* elements. The size of the elements has been tailored to the local wavelength of the propagating waves, while the material damping was kept at 3%. The excitation is implemented as an incident plane SV wave obtained by imposing the same acceleration to all nodal points belonging to a selected horizontal line, and, as in the FE model, absorbing boundaries were placed around the domain.

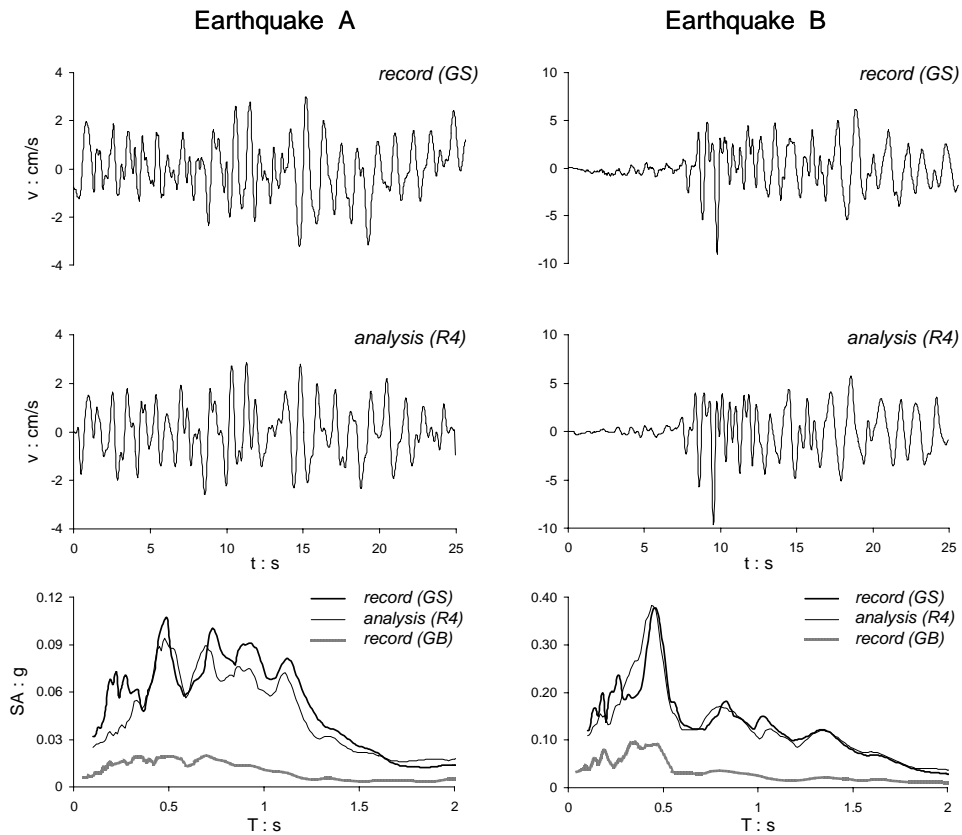
Figure 4 depicts a comparison between the recorded and the calculated ground motion for the two seismic events, in terms of velocity and spectral acceleration. As there were no additional records (other than  $GS$ ) available on the valley surface, the satisfactory comparison between records and analyses at this location ( $GS$  versus  $R4$ ) offers a first validation for the linear FE model and the applied method of analysis. Figure 5 depicts the results obtained for the edge of the valley ( $GS$ ,  $R4$ ) in the case of the strongest event. It shows the comparison between the recorded and the computed *aggravation factor* ( $AG$ ), which is defined as the ratio between the amplification factor predicted by the 2-D analysis ( $AF_{2-D}$ ) and the corresponding predicted by the 1-D theory ( $AF_{1-D}$ ). *Aggravation* is of the order of 3 for a wide frequency range, implying thus substantial “*valley amplification*” effects. The available records are in accord with the numerical results, while the inadequacy of 1-D theory to reproduce the recorded motion is evident.

## NONLINEAR SITE RESPONSE ANALYSES

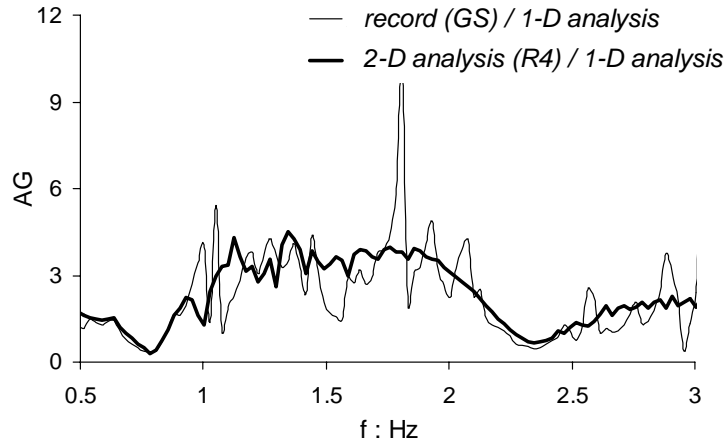
The previous linear analyses were verified by the recorded *aggravation factors*. However, there were suspicions that the rather huge *valley amplification* of the ground motion was merely the outcome of linear soil behaviour, and that the soil nonlinearity could have a profound influence on “*valley amplification*” effects. Although the nonlinear behaviour of soil deposits is strongly depended on the intensity of the excitation, many clayey deposits are characterized by high  $PI$ , exhibiting nonlinear behaviour only at higher shear-strain levels (Vucetic & Dobry 1991). A typical example of this behaviour is the Mexico City clay, which during the 1985 earthquake behaved far more linearly than expected, with disastrous consequences for the structures in a central part of the city. This means that, even when the ground shaking of a valley is strong, the aforementioned “*valley amplification*” effects may be kept vivid in the case of soft clayey materials.



**Figure 3. Numerical models used in the linear analyses: (a) Idealized geometry and  $V_s$  values of the two models. (b) & (c) Finite-element and Spectral-element discretization of the valley and the surrounding ground, respectively. Note that SV wave excitation is used in both cases and that all figures are in the same scale (without any exaggeration).**



**Figure 4. Comparison (in terms of velocity time histories  $v(t)$ ) between the recorded ground motions (GB and GS), and the ground surface motion calculated by the linear finite-element (FE) analyses (R4). Acceleration response spectra  $SA(T)$  of the two earthquakes are also shown.**



**Figure 5. Earthquake B: Recorded versus computed aggravation factor (AG), defined as the ratio of the recorded (or the computed with 2-D analysis) amplification factor divided by the corresponding amplification factor predicted with the 1-D analysis ( $AG = AF_{2-D} / AF_{1-D}$ ).**

In the current study, in order to account for a hypothetically nonlinear soil behaviour, an extensive investigation was conducted. Two-dimensional equivalent-linear analyses were performed utilising the FE code QUAD4M (Hudson et al 1994). Soil nonlinearity was taken into account by an iterative procedure according to which the values of soil stiffness and material damping are consistent with the level of maximum shear strain. The results of Vucetic & Dobry (1991) demonstrate that the degree of soil nonlinearity increases with decreasing  $PI$ . Therefore, increased soil nonlinearity may be achieved either by increasing the intensity of the excitation, or by reducing the  $PI$  of the soil.

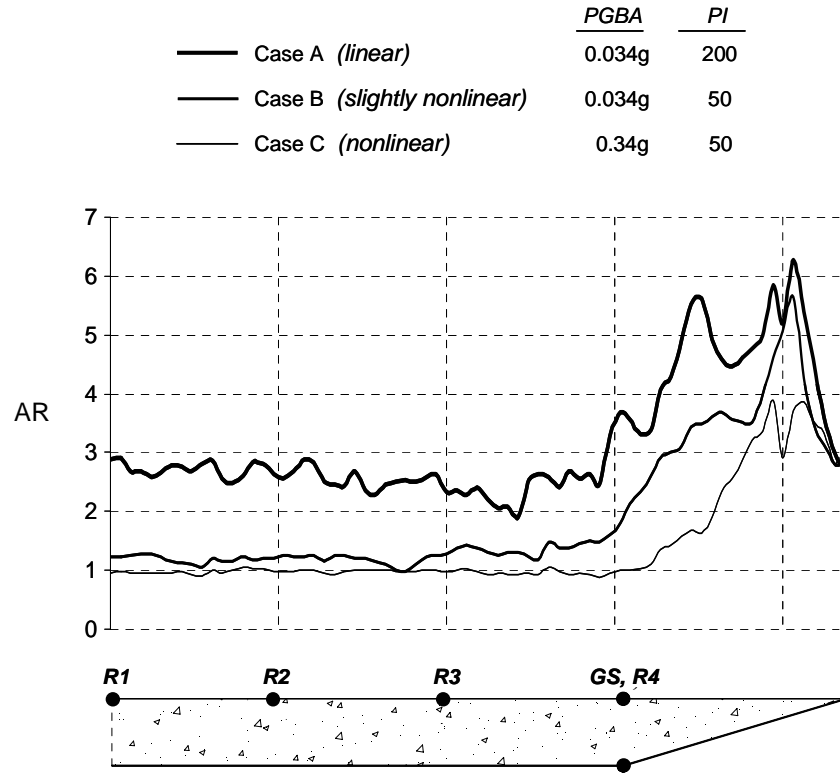
Thus, a parametric study was conducted to examine the influence of (a) the peak ground base acceleration ( $PGBA$ ), and (b)  $PI$  on the seismic response of the examined valley. Initially, the  $PGBA$  of Earthquake B is scaled from 0.034 g up to 0.34 g, while  $PI$  ranges parametrically from 200 to 50. Three cases are thus examined. The first of them coincides with the linear case already examined, while the other two are hypothetical:

- Case A: Linear ( $PGBA = 0.034g$  and  $PI = 200$ )
- Case B: Slightly non-linear ( $PGBA = 0.034g$  and  $PI = 50$ )
- Case C: Non-linear ( $PGBA = 0.34g$  and  $PI = 50$ )

Figure 6 shows for each case the distribution along the valley surface of the *Amplification Ratio AR*, defined as the ratio between the peak ground surface acceleration ( $PGSA$ ) and the peak ground base acceleration ( $PGBA$ ). Comparisons between cases A and B (where the  $PGBA$  is the same) reveal the influence of  $PI$  on the seismic response. On the other hand, the comparison between cases B and C shows clearly the influence of the ground shaking intensity. Note that, while moving from case A to case C,  $AR$  is being substantially reduced, reaching values even lower than unity, implying de-amplification effect. The main conclusion is that for a soil deposit with a moderately high  $PI$ , increasing the intensity of base excitation reduces the amplification almost everywhere on the surface. Apparently the increased nonlinearity, with the occurrence of large hysteretic damping, leads to reduced accelerations on the surface. In addition, waves generated at the edges and propagating laterally across the valley attenuate substantially; thus the undulatory (in space) nature of surface acceleration is diminished. On the other hand, with decreasing  $PI$  the soil becomes less (*not more*) linear, and the trends are essentially the same as with increasing intensity of motion.

Finally, we notice that the spatial variability of ground shaking may be significant even for relatively short distances. The phenomenon may be of extreme importance for long structures, and could be evaluated with 1-D analysis only in the cases where strongly nonlinear response prevails.

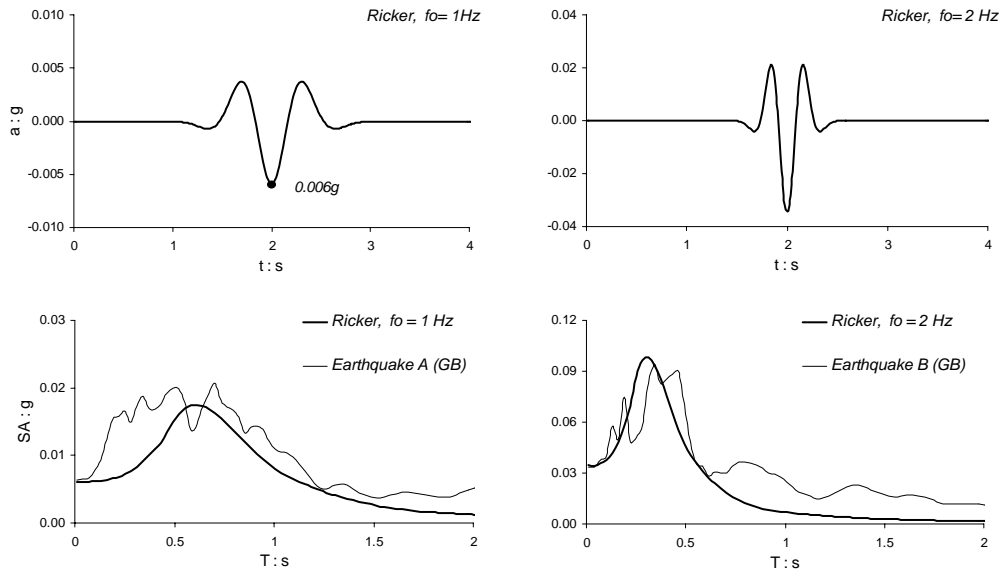




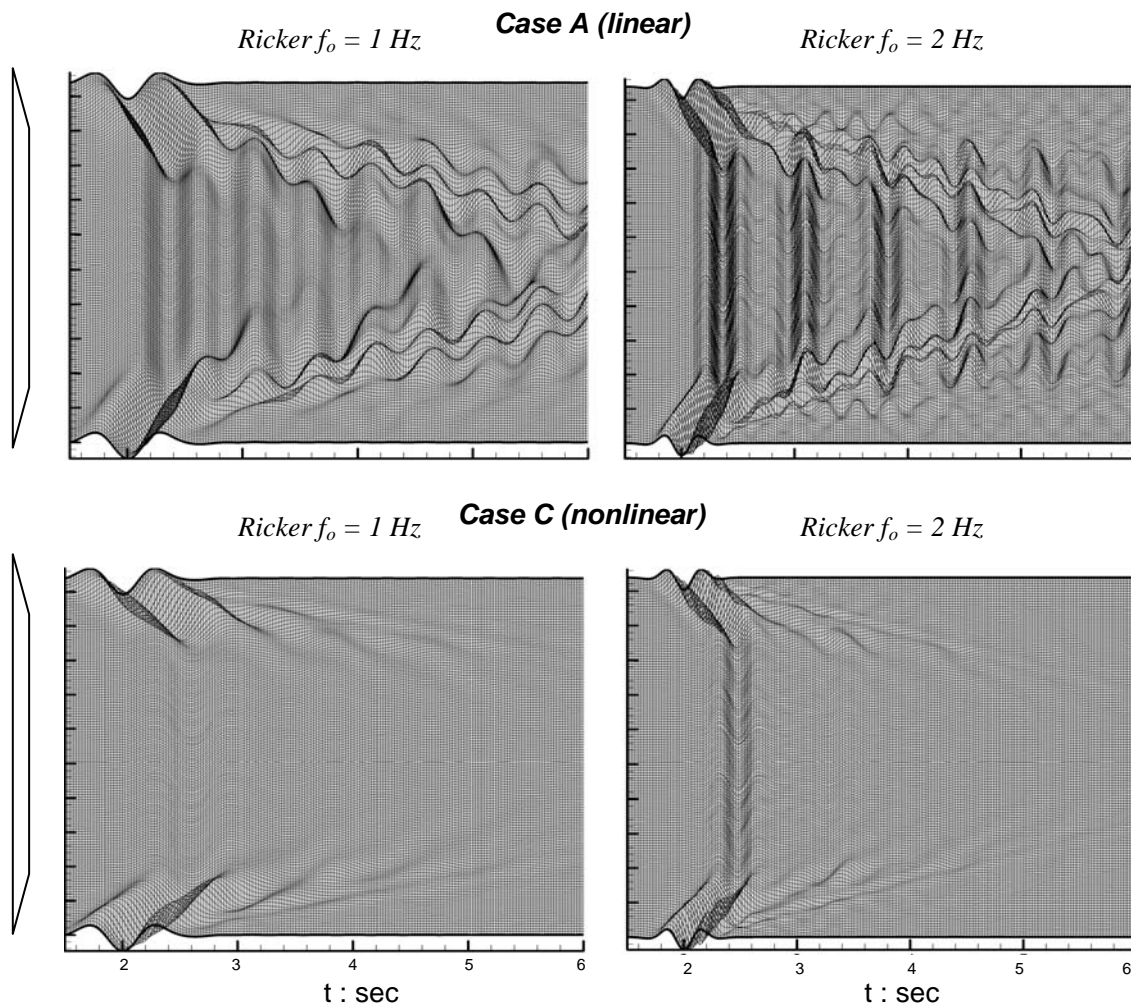
**Figure 6. Equivalent linear analysis for Earthquake B: Distribution along the right half of the valley surface of the *Amplification Ratio*, defined as the ratio between  $PGBA$  and  $PGBA$ , for two different values of  $PGBA$  ( $= 0.034g$  and  $0.34 g$ ), and two different values of  $PI$  ( $PI = 200$  and  $50$ ).**

To investigate the influence of soil nonlinearity on the wavefield of the valley, the aforementioned parametric study (three cases of soil nonlinearity) was repeated using as base excitation two Ricker pulses of characteristic frequencies  $f_0 = 1$  Hz and  $f_0 = 2$  Hz, respectively (Ricker, 1960). Their acceleration time-histories  $a(t)$  and the corresponding acceleration response spectra  $SA(T)$  are shown in Figure 7. It is evident that the first Ricker pulse is relatively rich in a wide range of periods, up to 1 sec, while the second covers a range of periods up to 0.5 sec. Note that, despite the simplicity of the waveforms, their response spectra are quite similar with the ground base motion of Earthquake A and Earthquake B, respectively.

An illuminating way of visualizing the various types of waves (body and surface), as they propagate in the valley, is the plot of the horizontal acceleration time histories of numerous closely-spaced points that constitute the ground surface. The resulting shapes reveal various wave phases that can be identified through their respective wave velocities. For instance, in Figure 8 the seismogram synthetics calculated along the surface of the valley subjected to the Ricker pulses for the two extreme cases of nonlinearity examined are shown. Especially in the linear case (Case A) the observed waveforms are clearly depicted: (a) vertically propagating incoming SV waves, (b) refracted inclined waves by the wedge-shaped boundary of the valley, and (c) surface Rayleigh waves generated at the edges, and propagating back and forth. The velocity of the surface Rayleigh waves, graphically estimated, is around 120 m/s, while the apparent velocity of the refracted inclined waves is 200 m/s (as theoretically expected).



**Figure 7. Acceleration time-histories  $a(t)$  and the corresponding acceleration response spectra  $SA(T)$  of the two Ricker wavelets used as excitation in our study. The response spectra of the ground base acceleration of Earthquakes A and B are also included.**



**Figure 8. Wavefields of horizontal acceleration calculated along the surface of the valley for the two extreme cases of nonlinearity examined for the two Ricker pulses ( $f_o = 1$  Hz, and  $f_o = 2$  Hz).**

While shifting progressively from Case A (linear case) to Case C (nonlinear case), both energy dissipation (due to the hysteretic nature of soil behavior) and soil stiffness degradation take place. It is obvious that energy dissipation dampens all the waveforms. In this way the interferences of vertical or inclined body waves from multiple reflections at the soil–base interface and the free surface are substantially affected, while on the other hand, the laterally propagating surface Rayleigh waves are so strongly attenuated that cannot even be distinguished in the nonlinear case (Case C) at distances beyond the first point from the edge. Nevertheless, the stiffness degradation is responsible for the notable decrease of the Rayleigh wave velocity observed particularly in the slightly nonlinear case.

## CONCLUSIONS AND DISCUSSION

In the present study an attempt has been conducted to capture the significant 2-D valley effects on the amplitude and the variability of ground shaking of a soft alluvial valley in Japan, the response of which has been recorded during many earthquakes. Utilising linear 2-D numerical models under SV excitation, it was showed that the observed high amplification was the outcome of low acceleration levels of the recorded excitations and high *PI* of the soft soil layers. Equivalent-linear 2-D analyses with hypothetical strong input motions reveal that the increased intensity of base shaking, and/or the decreased soil *PI* may both lead to increased nonlinearity of soil response. The significant energy dissipation that takes place in such a case dampens substantially the laterally propagating Rayleigh waves generated at the valley edges, while the decreased soil modulus renders any wave resonance of vertically propagating body waves less important of vertical or inclined body waves from multiple reflections at the interfaces. As a result, the response is dominated by vertical S wave propagation, and thus 1-D soil amplification theory may reproduce the motion satisfactorily (even if somewhat conservatively), provided of course that soil nonlinearity is properly accounted for.

## ACKNOWLEDGEMENTS

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