EXPERIMENTAL AND NUMERICAL STUDY ON EARTHQUAKE-INDUCED GROUND STRAINS

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ABSTRACT :

Seismic design of buried structures is mainly based on the evaluation of the ground-motion induced strain field, and of the related seismic action effects on the structure. The main drawback of this approach is that it cannot rely upon a direct measure of the design parameter, strain meters being not generally available in seismic networks. For an indirect measure, simplified formulas relating peak ground strain to peak ground velocity are generally used, based on 1D wave propagation theory in homogeneous media. These formulas, dating back to Newmark's studies, suffer from several major limitations: i) they should not be applied when the structure crosses strong lateral discontinuities in soil properties; ii) even for homogeneous media they strongly depend on the wave type and on the incidence angle, a kind of information that is not generally available to the designer; iii) they do not account for spatial incoherency of ground motion.
Starting from some meaningful results obtained through an experimental procedure for evaluating transient ground strains from dense seismic networks, a summary of the results of a parametric numerical study of wave propagation inside a real basin, the one of the Turkish town of Düzce, hit by two major earthquakes in 1999 that badly affected the buried pipeline network, will be shown. This allows us to give insights into the relative contribution to earthquake induced ground strains of different effects, such as frequency content of input motion, basin-edge induced seismic waves, soil-nonlinearity.

KEYWORDS: Transient Ground Strains, Buried Pipelines, Domain Reduction Method, Spectral Elements

1 INTRODUCTION

It is widely recognized that, in the absence of earthquake induced permanent displacements, seismic design of long, flexible buried structures is predominantly affected by the deformation of the surrounding soil, while inertial and kinematic soil-structure interaction effects are generally negligible (St John & Zarah, 1987; Hashash et al., 2001). Transient strains and curvatures are a result of incoherent or out of phase ground motion along their length and longitudinal deformations may dominate under seismic action rather than shear strains. Focusing on the longitudinal ground strain, which is the largest component close to the surface, it is common practice to indirectly estimate Peak Ground Strain (PGS) as the ratio of Peak Ground Velocity (PGV) and a suitable measure of the apparent propagation velocity ($C_{ap.}$), i.e.:

$$PGS = PGV/ C_{ap.} \tag{1.1}$$

Eq. 1.1, dating back to the pioneering studies of Newmark (1967), is based on 1D wave propagation theory in homogeneous unbounded media, so that it should in principle be applied when the propagation of seismic waves approaches the previous theoretical assumption. In spite of its simplicity, the practical application of Eq. 1.1 may lead to large differences in the PGS estimations, partly due to the variability of apparent wave propagation velocity, typically ranging from 2 km/s to 4-5 km/s (see. e.g. Abrahamson, 2003; O'Rourke and Deyoe, 2004), and to the unknown prevailing wave type, longitudinal or surface waves. Furthermore, site effects, near-field conditions and spatial incoherency of ground motion may play an important role, as amply discussed in Zerva (2003). The uncertainty in the PGS evaluation is also reflected in some technical guidelines for seismic design of underground

structures (e.g., Eurocode 8, 2006; ALA, 2001; AFPS/AFTES, 2001), that may yield differences of at least a factor of two, as underlined by Paolucci and Pitilakis (2007).
To provide an experimental basis, Paolucci and Smerzini (2008) proposed an observationally-based procedure. Earthquake-induced ground strains were evaluated from displacement records obtained by two dense seismic networks (Parkway Valley, New Zealand and UPSAR, California) using a suitable spatial interpolation technique (Biharmonic Spline algorithm). The close spacing of the stations, of the order of few tens of m for the Parkway Valley temporary network and of about 100 m on average for the UPSAR one, allowed to reconstruct with satisfactory accuracy the three-component displacement field at ground surface, from which the components of the strain tensor were evaluated by a classical centered finite difference scheme. We limit herein to recall some of the most meaningful results obtained through this method: i) a variability of about a factor of two of the scaling factor C between PGV and PGS (see Eq.1.1) can be attributed to the dependence on azimuth; ii) a linear trend of observed PGS as a function of PGV is found with a remarkably low dispersion. Namely, the least squares best-fitting line turns out to be:

$$PGS = PGV/\psi \tag{1.2}$$

where ψ = 963 m/s is the median value, while ψ_{16} =71 m/s and ψ_{84} = 1382 m/s correspond to the 16° and 84° percentile, respectively.
Starting from this observational evidence, we will illustrate a numerical procedure to estimate ground strains, involving the simultaneous effects of a 3D seismic source, the propagation path, complex geological site conditions, such as strong lateral variations of soil properties, and topographic amplification. This approach, named Domain Reduction Method (DRM) has been applied to analyze the wave propagation inside the Düzce basin, Turkey, struck by two major earthquakes on August 17 and November 12, 1999, that badly affected the buried pipeline network. Although the Düzce basin seems to be characterized by a 1D seismic response, ground strains depend mainly on 2D/3D features of wave propagation and are sensitive to near field effects, surface wave generation and oblique incidence. As a consequence, 2D/3D numerical analyses are necessary for an accurate estimate of ground strains. In this framework, a parametric study has been carried out to asses the relative contribution to earthquake induced ground strains of different effects, such as the frequency content of the seismic source, basin-edge induced seismic waves and soil-nonlinearity. Finally, numerical PGS, have been related to PGV and compared to the available experimentally-based relationships.

2 THE NUMERICAL COUPLED METHOD APPLIED TO THE CASE OF DÜZCE

Ground strains have been estimated in the city of Düzce referring to the November 12, 1999 event. In particular, the NS cross-section shown in Figure 1, aligned with one of the main water distribution pipelines of the town, has been analysed. Being at some 10 km fault distance, the town of Düzce was in the near field. Due to the nature of the numerical models involving 2D in plane wave propagation, we have focused on the longitudinal ground strain PGS_a along the direction *a* of the NS cross-section, which is the largest strain component close to the surface.
To reduce the computational effort required by such a large scale numerical problem, which extends for more than 15 km, the Domain Reduction Method (Hisada & Bielak., 2003; Faccioli et al., 2005) has been applied. This is a powerful sub structuring method, where the analysis of the source and the wave propagation in the Earth crust, modelled as a layered half-space, is separated from that of the localized irregular region, including site effects or structure interaction. The main feature of this approach is the possibility of coupling solutions typically obtained by different methods in two different domains. Figure 1 shows the adopted scheme.
The original problem has been subdivided into two simpler ones solved in two successive steps: i) an auxiliary problem (Step I) from which the Düzce basin has been removed and replaced by the same material as the surrounding domain; ii) a reduced model (Step II) which contains the Düzce basin, the geological feature of interest, but not the causative fault. Two different methods have been coupled: I) the semi-analytical approach of Hisada & Bielak (2003), which simulates the wave propagation field induced by an extended seismic source, has been used to solve the 3D auxiliary problem, including the source and the wave propagation in the half-space; II) the Spectral Element Method (SEM) has been used to simulate the wave propagation along the 2D cross-section.
The excitation applied to the reduced model is a set of equivalent localized forces derived from the first step.

These forces are equivalent to and replace the original seismic forces applied in the first step to reproduce the seismic source. In Figure 1 the dark boundary of elements represents the effective boundary where the free field displacements are evaluated in the first step and the equivalent forces are applied in the second step.

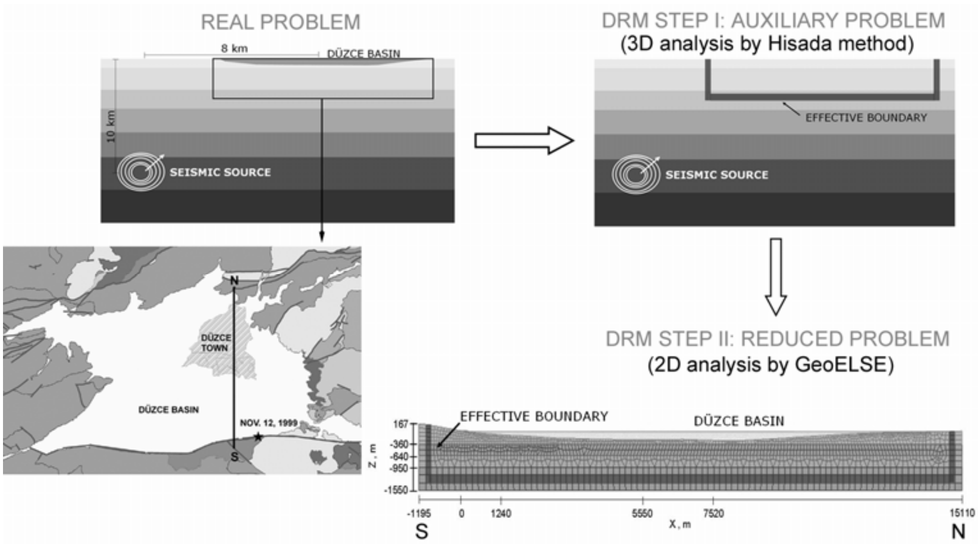


Figure 1 Scheme of the DRM procedure applied to the case of the Düzce urban area. The real problem is subdivided into two simpler ones analyzed in different steps. Step I: 3D analysis of the source and the wave propagation in a layered half-space using the semi-analytical method of Hisada & Bielak (2003). Step II: 2D wave propagation in the Düzce basin, along a NS cross-section, by means of the Spectral Element Method

2.1 Domain Reduction Method: step I

A 3D analysis of the source and the wave propagation in a layered Earth crust profile has been carried out using the semi-analytical method of Hisada and Bielak (2003).
A proper definition of the seismic source model and of the soil profile, especially at depth, was not straightforward, due to the numerous uncertainties in the available recorded data and to different interpretations and assumptions.

2.1.1 Source model of the November 12, 1999 earthquake

Several studies were performed to reproduce the rupture process of the November, 1999 Düzce earthquake (see e.g. Yagi and Kikuchi, 1999; Bürgmann et al., 2002), showing some discrepancies among the different proposed source models. In this study an extended seismic source with the hypocenter located at 10 km depth (40.77°N, 31.20°E), a spatially uniform slip distribution and a slip time-dependence given by a smoothed ramp function, as proposed by Yagi and Kikuchi (1999), has been adopted and named in the following as model I. The source parameters are listed in Table 2.1.

Table 2.1 Model I: source parameters of the rupture model for the November 12, 1999 earthquake

Depth [km]	M_0 [N m]	M_W	Δu_m [m]	W [km]	L [km]	V_R [km/s]	Rise time [s]	Strike [°]	Dip [°]	Rake [°]
10	4.9×10^{19}	7.1	5.6	16.5	16.5	2.8	2.8	265	65	-168

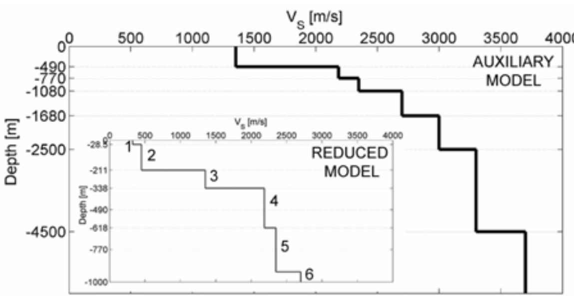
Since model I has been found to be rather poor at high frequency, propagating frequencies up to about 0.5 Hz, significant effort has been dedicated to reproduce higher frequency contributions by constructing a multi-event source process, denoted as model II in the following. Four "secondary" events (labelled from 2 to 5 in Table 2.2), with significantly smaller M_o and different source parameters, such as hypocenter depth, slip distribution, rupture velocity and rake angle, have been added up to the "primary" event (denoted as 1 in Table 2.2), which has been chosen to be as close as possible to the source model of Table 2.1. Note that, the "secondary" sources do not affect significantly neither the overall seismic moment nor the dominant waveform, rather they enrich the frequency spectrum up to around 3 Hz, at least. A detailed comparison between results obtained at the end of the DRM procedure using both the source models I and II will be illustrated later on in Figure 3.

Table 2.2 Model II: list of seismic events used to simulate a multi-event source model for the November 12, 1999 earthquake. For all events length L and width W of the fault are the same as in model I (see Table 2.1)

Event #	Depth [km]	M_0 [N m]	Δu_{max} [m]	V_R [km/s]	Rise time [s]	Strike [deg]	Dip [deg]	Rake [deg]
1	10	$4.6\ 10^{19}$	5.6	2.8	2.8	265	65	-168
2	10	$8.3\ 10^{18}$	4.3	2.9	0.5	265	65	-120
3	10	$7.9\ 10^{18}$	4.0	3.0	1.0	265	65	-168
4	25	$1.4\ 10^{18}$	1.5	2.9	0.8	265	65	-90
5	25	$6.3\ 10^{17}$	0.7	3.6	0.6	230	45	-130

2.1.2 Layered soil model

Düzce is located in a flat basin of quaternary deposits, at about 200 m on the sea level and surrounded by mountains of older rocks. The Düzce basin mainly consists of silty clay, originated by lake deposits and sands and gravel, with alluvial origin (Aydan et al., 2000). At the first step of the DRM procedure, the Düzce basin is excluded, so that the shallow soft layers which characterize the basin, shown in Figure 1, are not considered. Instead, the seismic response of a simplified layered soil configuration has been evaluated by the Hisada & Bielak (2003) method. In particular the Boore & Joyner (1977) model for a generic rock site, whose shear velocity profile at depth is shown in Figure 2, has been assumed. This model, although not derived ad hoc for the region under study, yields a good agreement with the recorded data (a detailed comparison will be illustrated in Figure 3).



Layer No	ρ [t/m³]	V_P [m/s]	V_S [m/s]	Q_S	Depth [m]	Thickness [m]
1	1.80	796	325	30	from -21.8 to -50.4	28
2	2.00	937	450	50	from -50.4 to -233	183
3	2.20	2300	1350	100	from -233 to -360	126.5
4	2.25	3750	2180	150	from -360 to -640	280
5	2.30	4000	2350	200	from -640 to -950	310
6	2.30	4600	2700	200	from -640 to ∞	-

Figure 2 Left:V_S profile adopted for the first step analyses (bold line): Boore and Joyner, (1997) model for generic rock site (an average value for the uppermost 490 m has been assumed). The profile at the Düzce accelerograph station on the 2D cross-section used in the second step is inserted (thin line). Dynamic soil properties for the reduced model, referring to the Düzce accelerograph station are reported (right).

2.2 Domain Reduction Method: step II

In the second step the Spectral Element Method, implemented in the GeoELSE numerical code (http://geoelse.stru.polimi.it) has been used to simulate the 2D wave propagation along the NS cross-section.
Since the reduced problem is two-dimensional, the effective forces that exactly reproduce at the boundary of the reduced model the wave propagating from the seismic source have been evaluated taking into account only the vertical and horizontal displacements in the SN cross-section plane, as referred in Figure 1. The cross-section has been discretised by quadrilateral Spectral Elements in order to propagate frequencies up to 5 Hz.

2.2.1 Soil model

The S-wave profile adopted for the reduced model, referring to the Düzce accelerograph station (Meteorological

Station, located x = 5500 m from the S end on the NS cross-section in Figure 1), is shown in Figure 2. The profile in the uppermost 500 m has been refined with respect to the previous numerical simulation based on the Hisada method, including the soft layers of the basin.
The materials are assumed linear visco-elastic. Internal soil dissipation has been introduced by a frequency dependent quality factor $Q=Q_o f/f_o$, where Q_o is the quality factor at frequency f_o. We have been refer Q_o to f_o =0.5 Hz.
Both linear and non-linear simulations have been performed. In particular a non-linear behaviour has been simulated for the surface layer of the Düzce basin. From a computational point of view, at each time step of the numerical simulation the maximum shear strain, averaged on each spectral element, defines the updated shear modulus and damping ratio, following the shear modulus reduction and damping curves proposed Ishibashi & Zhang (1993) for plasticity index equal to 20 and stress equal to 200 kN/m^2.

3 COMPARISON BETWEEN NUMERICAL RESULTS AND AVAILABLE RECORDS IN DÜZCE

The results of the two-step simulation procedure, both in liner and non-linear behaviour, have been compared with the instrumental observations at the Düzce accelerograph station. Velocity and displacement wave forms have been obtained from single and double integration of recorded accelerations. Figure 3 shows that the surface soil response is generally well reproduced in terms of displacement and velocities time histories, approaching reasonably the peak recorded values. In the frequency domain, it is apparent that source model I can not excite frequencies above ~0.5 Hz, while observed motion is much richer at high frequency. Indeed such a source description limits energy radiation in the low-frequency range due to its simplicity. Rather, source model II, obtained from different rupture segments, adds a more realistic complexity to the ground motion, with reasonable accuracy over frequencies up to 3 Hz at least, achieving a satisfactory agreement of the simulated seismic ground response with the observations.
The non-linearity, not shown for brevity, slightly influences the response in terms of displacement amplitudes and frequency content.

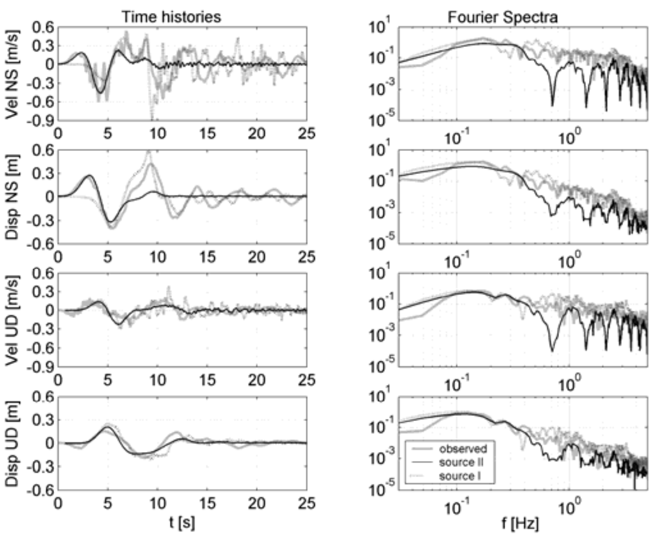


Figure 3 Comparison between NS components of observed (bold line) and simulated velocities and displacements time histories (left) and respective Fourier spectra (right) at the Düzce station. Results obtained in linear behaviour with both the source model I (dotted line) and II (thin line) are shown

4 GROUND RESPONSE OBTAINED BY THE DRM AND 2D IN PLANE WAVE PROPAGATION

Surface soil response evaluated by the DRM procedure has been compared with that obtained by a 2D Spectral Element (SE) analysis along the NS cross-section using a vertical plane wave as input motion, to assess the influence of the rupture directivity of the near fault and to test the validity of the two approaches.
The assumed vertically propagating shear wave has been obtained by a deconvolution of the instrumental records at

the Düzce accelerograph station, using the soil model with properties listed in Figure 2.
It is interesting to analyze the surface spatial variation of horizontal peak ground displacement PGD, velocity PGV, acceleration PGA and longitudinal PGS_a strain (Figure 4) evaluated along the NS cross-section with both the DRM and the 2D analysis in plane wave condition. Note that the origin of the x-axis denotes the Southern basin edge.

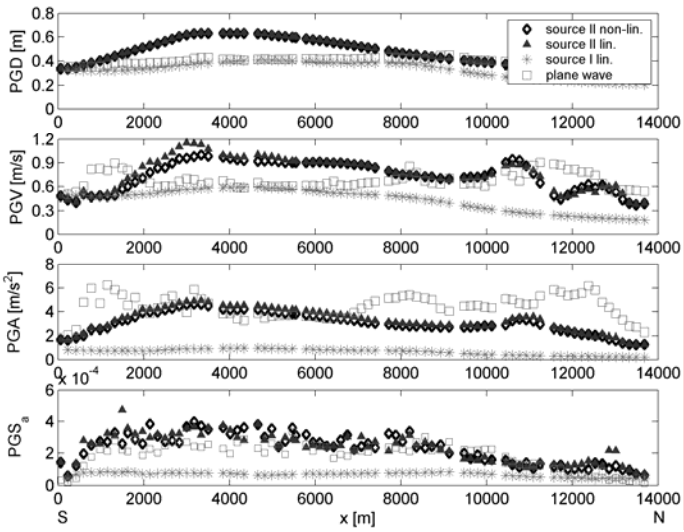


Figure 4 Comparison of surface ground response along the NS cross-section in terms of horizontal peak ground displacement (PGD), velocity (PGV), acceleration (PGA) and longitudinal strain (PGS_a). The results have been obtained with the DRM procedure using both the source model I and II, and with a 2D SE analysis using a plane wave as input motion. The origin of the x-axis denotes the Southern basin edge

While applying the DRM procedure there is a smooth variation with horizontal distance of PGD and PGV, PGA and PGS_a are strongly influenced by the lateral discontinuities, which imply a significant increase of values between around 1 km and 4 km from the South edge. Note that the town of Düzce lies between around x = 4500 m and x = 11500 m at the surface of the numerical model. As expected, the damping at the North side of the cross-section, due to the decreasing of the spread source energy South to North along the propagation path, cannot be simulated assuming a vertical plane wave as input motion. In fact, in this case, the soil response amplification at the basin borders is evident at both the North and the South basin edges as shown in Figure 4. The numerical analysis, involving the seismic source by the DRM procedure, correctly simulates the attenuation of ground motion from S to N, in agreement with the geometrical spreading of energy. The DRM analysis with source model I yield very low and unrealistic values for such a kind of earthquake (M_w 7.1), due to the lack of contribution of frequencies higher than 0.5 Hz. It is worth highlighting that a strong contribution in terms of strain is carried by the complexity of seismic source: passing from source model I to II PGS increase of a factor of 3-4.
In Figure 5 the horizontal displacement time histories simulated at the surface of the Düzce basin are plotted, together with the corresponding horizontal (in-plane) components of ground strain. It is clear that, corresponding to the lateral (South) edge of the basin, surface waves are generated and that the largest horizontal (in plane) strain components are carried by such waves, while strains induced by the nearly in-phase S arrivals are much smaller. Furthermore, since PGS_a is carried in this case by Rayleigh waves, while PGV by S-waves, a straightforward correlation between PGS_a and PGV such as eqs. (1.1) or (1.2) should be considered with care. In fact, as shown in Figure 6, the best correlation between PGS_a and PGV can be obtained by a value of $C_{ap.}$ equals to about 3000-3500 m/s, while the apparent propagation velocity of S waves $V_{Sap.}$(~ 6000 m/s) leads to unrealistically values of strains, and the Rayleigh velocity V_R (~ 1800-2200 m/s) in equation 1.1 is not proper since PGV is carried by S-waves, but V_R refers to R-waves.
The numerical PGS_a values are in agreement with the range suggested for the seismic design of underground structures (PGS_a = PGV/2000 ÷ PGV/4000) as described in the introduction. Nevertheless the numerical PGS_a turn out to be significantly smaller than those predicted by Eqn. (1.2), based on observational evidences. This may be reasonably due, as carefully discussed by Zerva (2003), to small-scale heterogeneities, spatial incoherence of ground motion and 3D effects which are disregarded in this analysis.

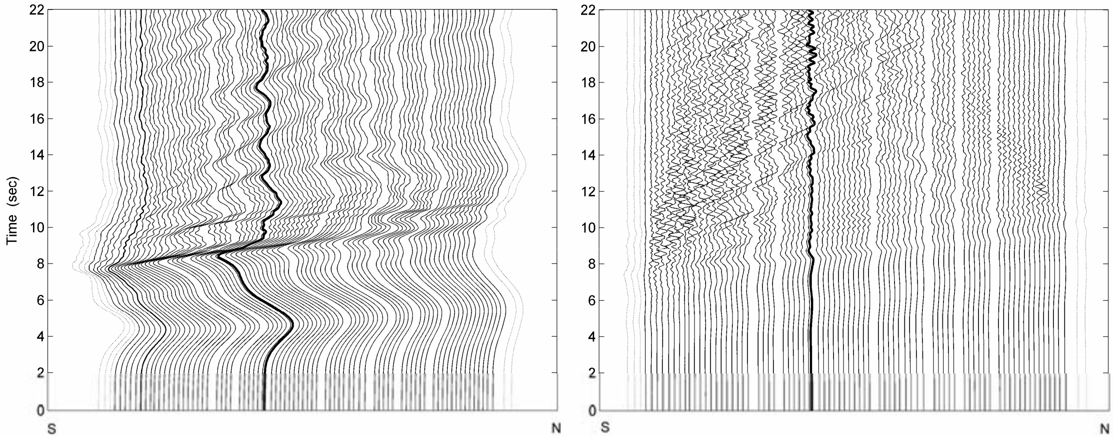


Figure 5 Horizontal displacement (left) and strain (right) time histories at receivers located along the NS cross-section in the Düzce basin. Dotted lines refer to points out of the basin, the thick one refers to the site of the Düzce station. In the figure time histories are spaced with reference to the relative distance between not equispaced receivers; white strips indicate large distance

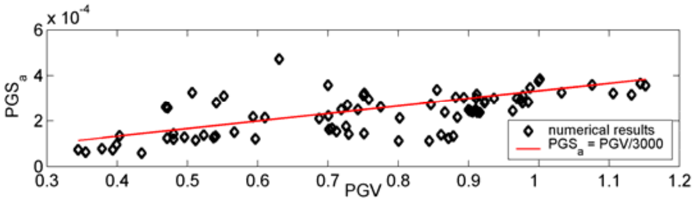


Figure 6 Horizontal PGS_a vs. PGV obtained by numerical simulations (open symbols) along the NS cross-section and estimated by equation 1.1 (PGV / $C_{ap.}$) with $C_{ap.}$=3000 (thin line)

5 CONCLUSIONS

We have explored in this paper the problem of the evaluation of transient ground strains in a large urban area, such as the town of Düzce in near field condition during the November 12, 1999 earthquake. The problem has been tackled by the Domain Reduction Method developed by Bielak et al. (2003), involving seismic wave propagation including the source, the propagation path, and the amplification effects induced by the Düzce basin.

The definition of a numerical model in near field condition is a very difficult task since it requires a detailed knowledge of the different elements under study, which involve a spatial extension of several kilometres. In spite of these difficulties a good agreement with observations up to about 3 Hz has been achieved simulating a multi-event source process (model II), while a single-event simple model (model I) yield very low and unrealistic values, exciting frequencies up to ~0.5 Hz only. The numerical results indicate that a straightforward linear correlation between PGS and PGV should be considered with care. Furthermore, the comparison with the available experimentally-based relationship for PGS points out that spatial incoherence of ground motion, small-scale heterogeneities and 3D effects, disregarded in this analysis, may play a relevant role in PGS evaluation.

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