

## NUMERICAL EVALUATION OF EARTHQUAKE INDUCED GROUND STRAINS: THE CASE OF DÜZCE

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### ABSTRACT

In the absence of earthquake induced permanent displacements and deformations, the seismic response of buried structures, as water pipelines, mainly depends on the amplitude of transient strains induced in the ground. Among the numerous cases of towns which suffered extensive damage to lifeline systems during a major earthquake, Düzce, Turkey, provides one of the best documented case histories, with a detailed damage assessment survey carried out after the earthquakes of August 17 and November 12, 1999. In this contribution, we will illustrate a procedure to estimate ground strains, involving the simultaneous effects of the seismic source, the propagation path, complex geological site conditions, such as strong lateral variations of soil properties, and topographic amplification. To reduce the computational effort required by such a large scale numerical problem, a powerful sub structuring method, termed Domain Reduction Method (DRM), was considered. This approach has been applied to the case of Düzce, referring to the November 1999 event. In particular, a cross-section aligned with the main water distribution pipe has been analyzed. We focused on the longitudinal ground strains, which are the largest component close to the surface. In particular peak ground strains have been related to peak ground velocity, to check the available relations used in the engineering practice and to verify the accuracy of a simplified analytical formula, which takes into account the effect of lateral heterogeneities on ground strains. Finally, the potential damage of water pipelines along the cross-section has been evaluated using different vulnerability relations.

Keywords: Buried Pipelines, Domain Reduction Method, Spectral Element Method, Ground Strains

### INTRODUCTION

Damage to gas transmission and water pipelines may cause catastrophic disruption of fundamental services for human needs. In the absence of earthquake induced permanent displacements and deformations, the seismic response of buried structures depends mainly on the amplitude of transient strains induced in the ground. 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. The near-field effects in the form of strong velocity pulses in the fault-

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normal direction pose a very crucial situation for this type of lifelines. Moreover, the intensity and duration of the near-field shaking depend on the location and orientation of the structure with respect to the direction of fault rupture.

Among the numerous cases of towns which suffered extensive damage to lifeline systems during a major earthquake, Düzce, Turkey, provides one of the best documented case histories, with a detailed damage assessment survey carried out after the earthquakes of August 17 and November 12, 1999. Being at some 10 km fault distance, the town of Düzce was in the near field of the 12 November 1999 event. 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 contribution, we will illustrate a procedure to estimate ground strains, involving the simultaneous effects of the seismic source, the propagation path, complex geological site conditions, such as strong lateral variations of soil properties, and topographic amplification. To reduce the computational effort required by such a large scale numerical problem, a powerful sub structuring method, termed Domain Reduction Method (DRM), has been applied. In the first step, a 3D analysis of the source and the wave propagation in the half-space has been carried out using a semi-analytical approach, which simulates the wave propagation field induced by an extended seismic source. In the second step, the Spectral Element Method (SEM) has been used to simulate the 2D wave propagation in the region of interest.

This approach has been applied to the case of Düzce, referring to the November 12, 1999 event. In particular, a cross-section aligned with the main water distribution pipes has been analyzed. Due to the nature of our numerical models involving 2D in plane wave propagation, we focused on the longitudinal ground strains, which are the largest component close to the surface. In particular peak ground strains (PGS) have been related to peak ground velocity (PGV), in order to check the available relations used in the engineering practice and to verify the accuracy of a simplified analytical formula, which takes into account the effect of lateral heterogeneities on ground strains.

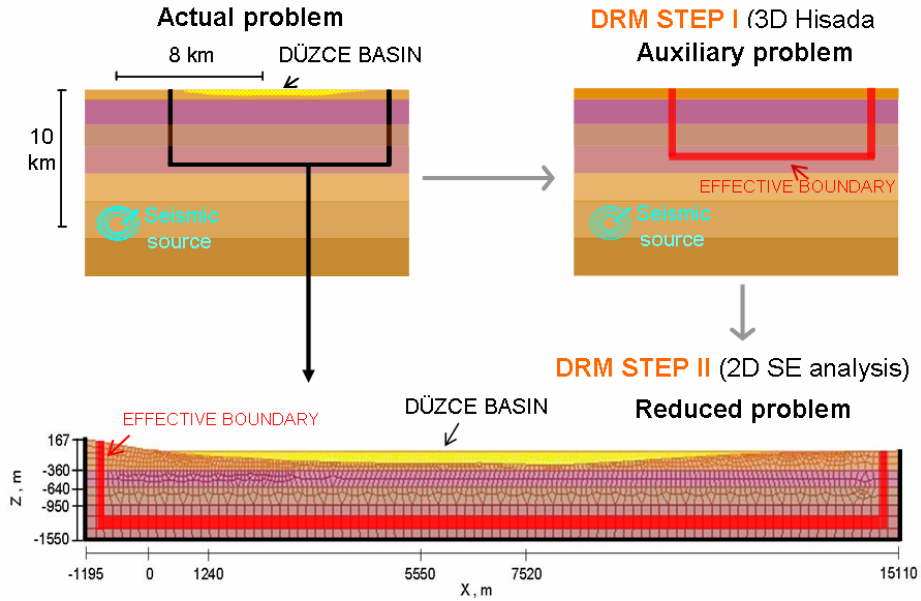
Finally we tried to evaluate the potential damage of water pipelines along the NS cross-section by means of vulnerability relations available in literature, to check the differences obtained using PGV or PGS as a measure of the hazard intensity.

## **COUPLED METHOD ADOPTED**

The Domain Reduction Method (Bielak et al., 2003, Faccioli et al., 2005) has been applied to study the seismic response of the Düzce basin during the November 12 earthquake. This is a powerful sub structuring method, where the analysis of the source and the wave propagation in the Earth crust, modeled 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 is 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. 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.

In this study the possibility of coupling solutions coming from different methods is fully exploited. In fact, a 3D analysis has been carried out using the semi-analytical method of Hisada and Bielak (2003) in the first step; a 2D numerical analysis has been computed by means of the Spectral Element Method 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. Step II: 2D wave propagation in the Düzce basin by means of the Spectral Element Method**

#### Domain Reduction Method: step I

Here 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). This relies on the computation of displacements and stress of static and dynamic Green's functions for viscoelastic horizontally layered half spaces. It uses an analytic form for the asymptotic solutions of the integrands of Green's functions, stemming from the generalized R/T (reflection and transmission) coefficient method and the stress discontinuity representations for boundary and source conditions respectively.

#### Source model of the November 12, 1999 earthquake

Several studies have been performed to reproduce the rupture process of the November, 1999 Düzce earthquake (i.e. Yagi and Kikuchi, 1999, Birgören et al., 2004). In this study an extended seismic source with the hypocenter located at 10 km of depth and a slip time-dependence given by a smoothed ramp function, as proposed by Yagi and Kikuchi (1999), has been adopted. The source parameters are listed in Table 1.

**Table 1. Source parameters of the rupture model for the November 12, 1999 earthquake**

Source coord.	Depth	$M_o$	$M_w$	$\Delta u_m$	W	L	$v_R$	Rise time	Strike	Dip	Rake
( $^{\circ}$ )	(km)	(Nm)	-	(m)	(km)	(km)	(km/s)	(s)	( $^{\circ}$ )	( $^{\circ}$ )	( $^{\circ}$ )
40.77°N 31.20°E	10.00	$4.9 \times 10^{19}$	7.1	5.60	16.50	16.50	2.80	2.80	265	65	-168

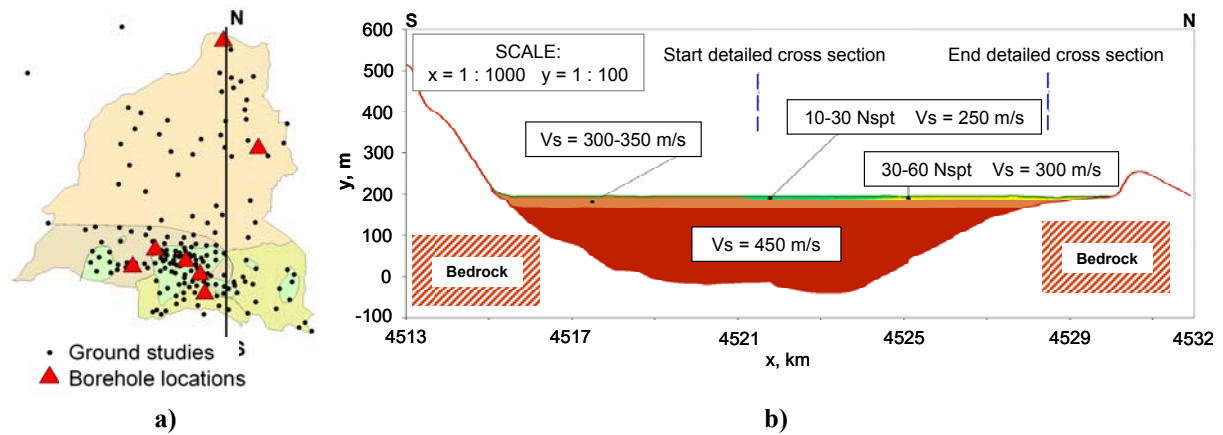
#### Available information to construct a numerical model of the Düzce basin

To construct the numerical model for the simulation of seismic response of Düzce basin, the following information was considered.

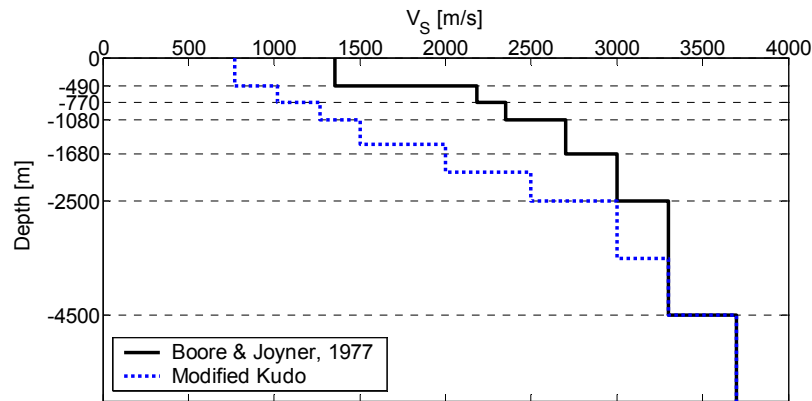
- The geological maps and borehole data provided by KOERI, together with several soil profiles from deep borings provided by AUTH (courtesy of Prof. K. Pitilakis). The NS cross-section has been obtained from these data as shown in Figure 2, together with the available NSPT data.

- b) The velocity profile provided by Kudo et al. (2002), based on array observations of microtremors at Düzce city, 1 km east from the strong-motion observation site. The SPAC method was used to determine the phase velocity of Rayleigh waves from which the shear wave velocity profile was obtained by an inversion procedure. Since this is only an indirect measure of the  $V_S$  profile, the previous information based on cross-hole surveys was preferred. Note also that the Kudo profile stops at nearly 1 km depth where a relatively low shear wave velocity of 1500 m/s is proposed.
- c) A standard rock model proposed by Boore and Joyner (1997) successfully used by Faccioli et al. (2002) to reproduce the seismic response recorded at Düzce and neighboring cities during the November 1999 earthquake.

To highlight the problems arising from the merging of the information at points b) and c) the Boore and Joyner rock velocity model is superimposed to the Kudo model in Figure 3. For the latter case we regularly increased  $V_S$  to reach realistic values at about 3 km depth. Note that the shallow layers adopted for the local response of the Düzce basin are not considered.

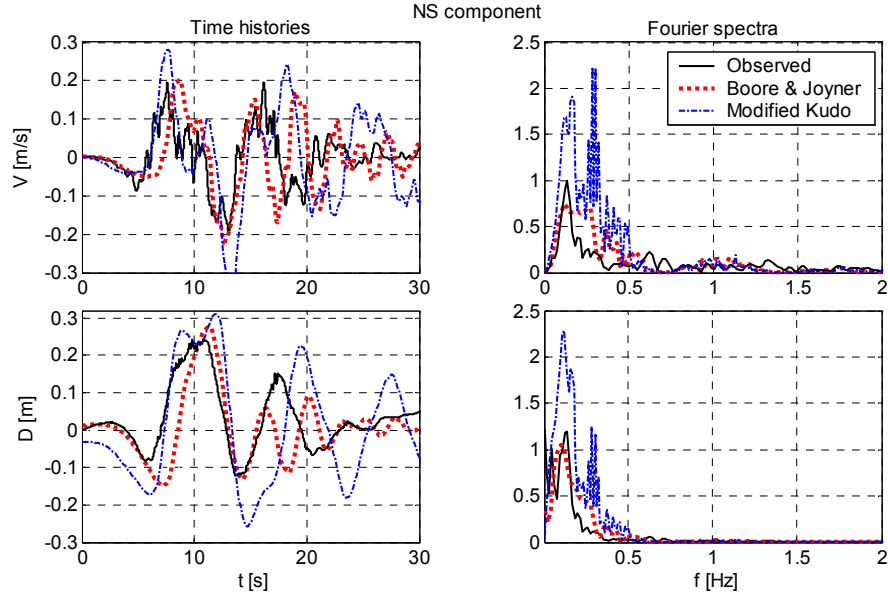


**Figure 2. a) Location of available Borehole and shallow ground studies in the town of Düzce (courtesy of Prof. K. Pitilakis); b) Soil profile of the SN cross-section determined at Studio Geotecnico Italiano**

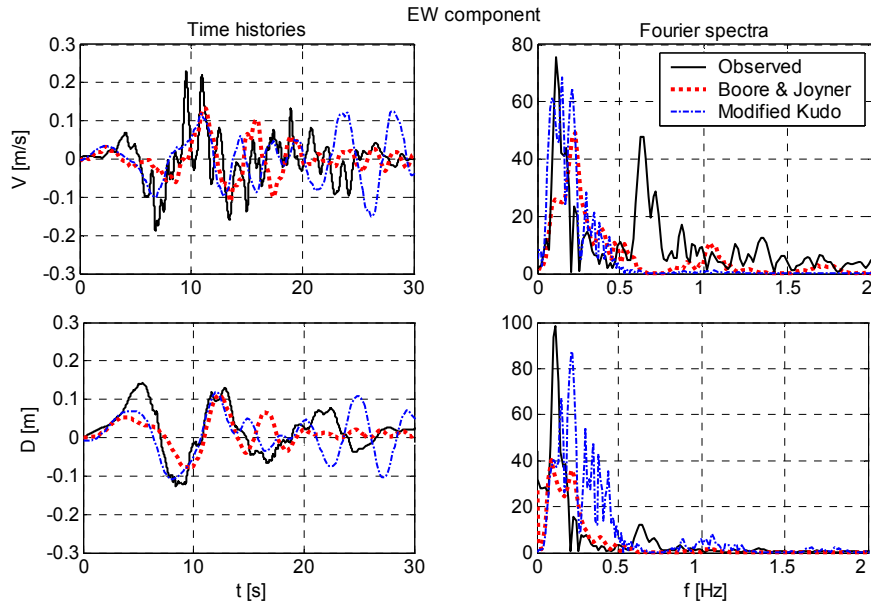


**Figure 3.  $V_S$  profile proposed for the first step analysis: modified Kudo (thin line), Boore and Joyner, 1997. Both profiles adopt average values for the uppermost 490 m.**

The problems in adopting the Kudo model are apparent, since it provides a relatively high and perhaps unrealistic velocity gradient that deeply affects the ground response at surface. To point out this effect, we show in Figure 4 and Figure 5 the comparison of numerical simulations with the ground motion recorded at Karadere (stiff soil) during the November 12, 1999 earthquake at about 26 km from the epicenter. The record at Bolu has been analyzed too, but not reported for brevity. The location of these sites is reported by Faccioli et al. (2002).



**Figure 4. Comparison of NS components of observed and simulated velocities and displacements time histories (left) and Fourier spectra (right) at Karadere station**



**Figure 5. Comparison of NS components of observed and simulated velocities and displacements time histories (left) and Fourier spectra (right) at Karadere station**

The numerical results have been obtained using the Hisada and Bielak method, i.e., the first step of the DRM where the Düzce basin is excluded. It is clear that using the Kudo model leads to an overestimation of observed ground response, so that in the following we preferred to consider the Boore and Joyner profile at least for the definition of the crustal profile. For the detailed model of the Düzce basin considered in the second step, we will make reference to the deep boring profiles. Note that we are not interested in a detailed simulation of the seismic response at Düzce, but rather in the evaluation of the most critical zones in the basin in terms of peak ground velocities and strains; therefore the agreement achieved in this first step can be considered satisfactory.

### **Domain Reduction Method: step II**

In the second step the Spectral Element Method, implemented in the GeoELSE numerical code (Stupazzini et al., 2006) has been used to simulate the 2D wave propagation in the Düzce basin.

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 Spectral Elements in order to propagate frequencies up to 5 Hz.

The materials are assumed linear visco-elastic. Internal soil dissipation has been introduced by a frequency dependent quality factor  $Q=q_0 f / f_0$  where  $q_0$  is the quality factor at frequency  $f_0$ ; in the following we will consider  $f_0 = 0.5 H\zeta$ .

#### Soil model

The S-wave profile adopted for the reduced model, referring to the Düzce accelerograph station (Meteorological Station, located 5500 m from the S end on the NS cross-section in Figure 1), is shown in Figure 6. 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 (Figure 2). The adopted dynamic soil properties are listed in Table 2. We have omitted in the numerical model a thin surface layer, about 5 m thick with  $V_s=250$  m/s, because its introduction would have induced an excessive reduction of the minimum grid size, with a corresponding reduction of the time step and a consequent increase of the computational time. Moreover, this layer would have influenced only the high frequency range of minor relevance for this study.

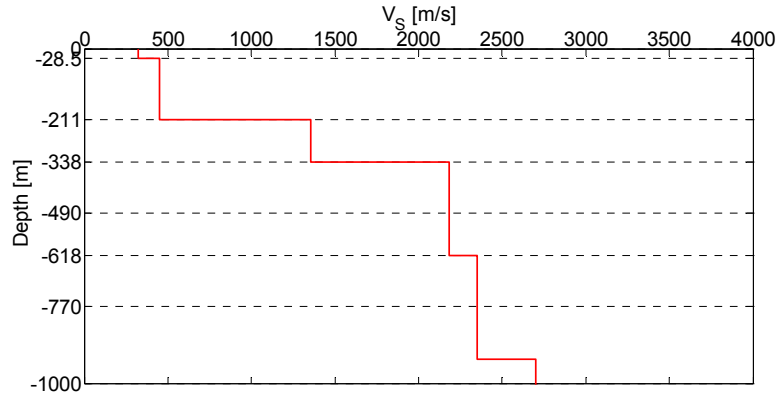


Figure 6. VS profile adopted for the reduced model at the Düzce accelerograph station

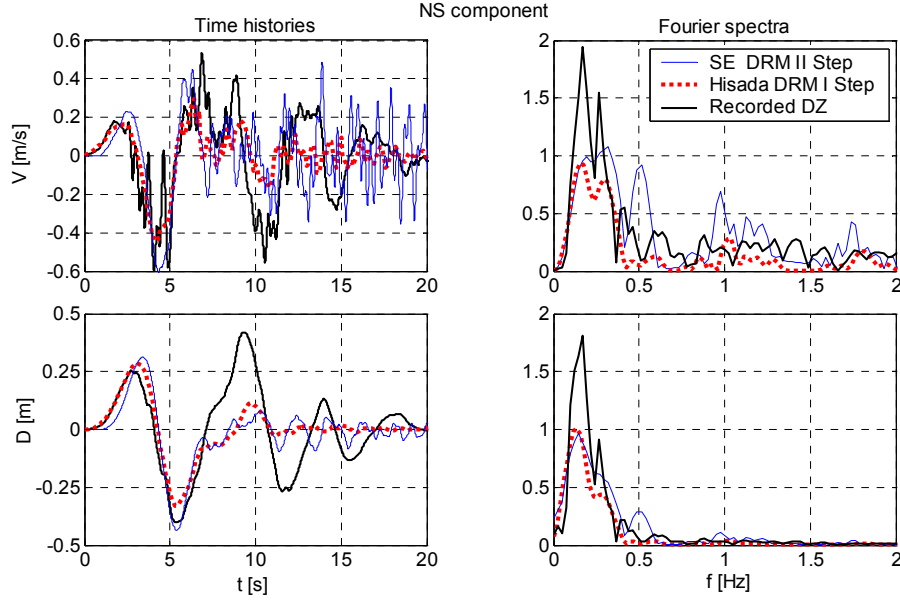
Table 2. Dynamic soil properties for the reduced model (see Figure 6). Layers are listed from top to bottom

Layer No	$\rho$ (t/m <sup>3</sup> )	$V_P$ (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 -950 to $\infty$	-

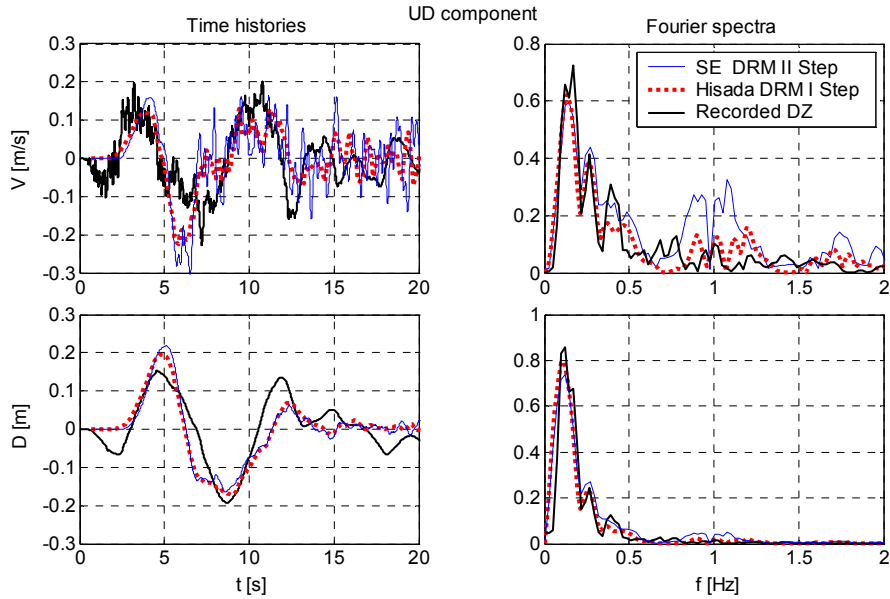
#### Comparison of simulated results with available observed data in Düzce

The final results of the two-step simulation procedure have been compared with the instrumental observations at the Düzce accelerograph station. Velocity and displacement wave forms obtained from single and double integration of recorded accelerations. Figure 7 and Figure 8 show that the soft basin slightly influences the response in terms of displacement amplitudes, introducing an amplification that tends to exceed the observed values especially at 0.5 Hz in the NS component. Probably a more regular increase of  $V_s$  with depth would have decreased such a sharp peak.

In spite of these discrepancies, the overall agreement with the observed response can be considered as satisfactory, at least for the purpose of this study.



**Figure 7. Comparison of NS components of observed and simulated velocities and displacements time histories (left) and Fourier spectra (right) at the Düzce station**

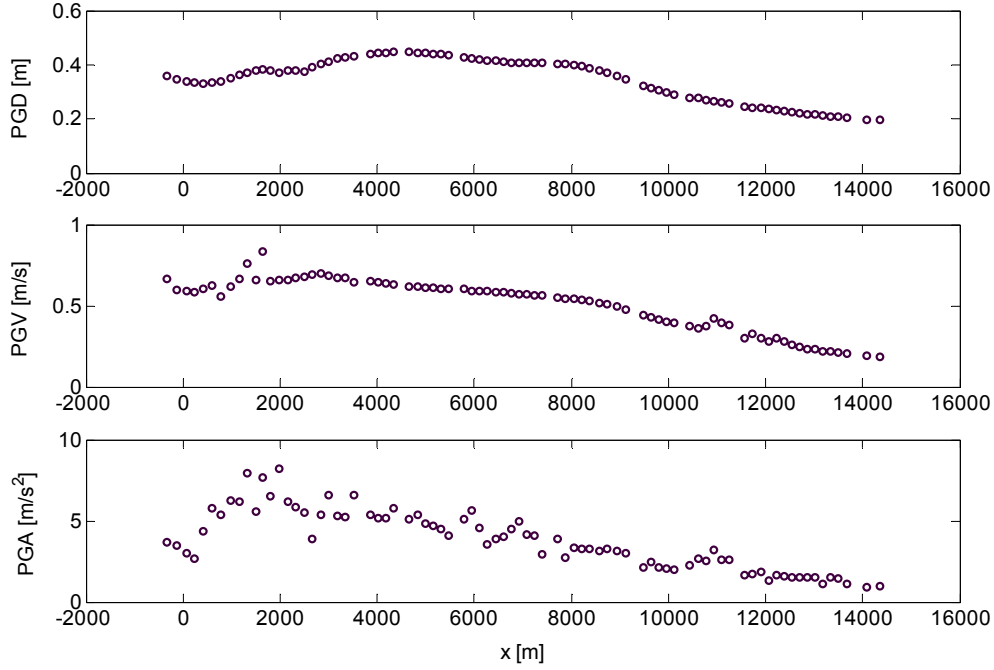


**Figure 8. Comparison of UD components of observed and simulated velocities and displacements time histories (left) and Fourier spectra (right) at the Düzce station**

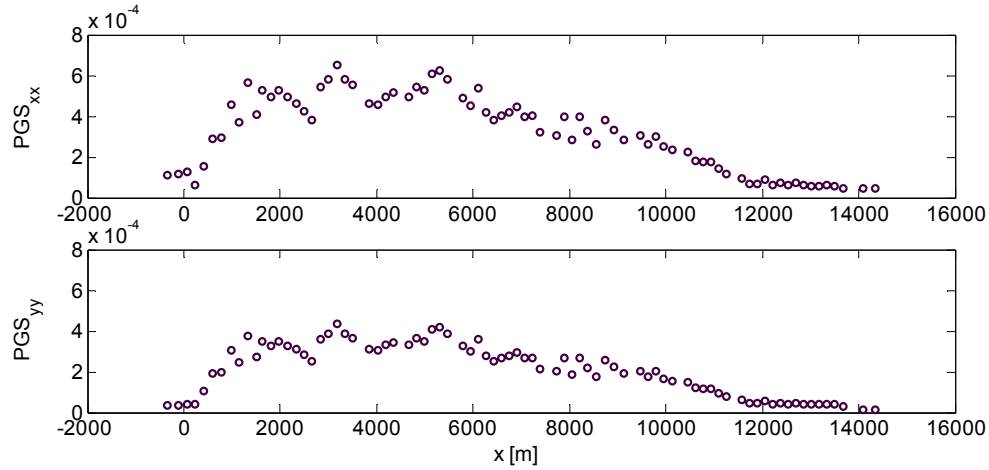
### SURFACE GROUND RESPONSE

The NS cross-section is characterized by a distinct horizontal transition from low to higher velocity values at the basin borders, especially at the Southern side. It is interesting to analyze the spatial variation of peak ground displacement, velocities and accelerations (Figure 9) and strains ( $PGS_{xx}$  and  $PGS_{yy}$  for the longitudinal and vertical direction respectively in Figure 10) at the surface.





**Figure 9. Spatial variation of peak ground displacement (PGD), velocity (PGV) and acceleration (PGA) along the NS cross-section**



**Figure 10. Spatial variation of peak ground strains in the horizontal (PGS<sub>xx</sub>) and vertical (PGS<sub>yy</sub>) directions along the NS cross-section. PGS<sub>xy</sub> is not reported because its value at the surface is negligible**

Note that the origin of the x-axis in these figures denotes the Southern basin edge, and the prevailing wave propagation direction is South to North, in agreement with the location of the earthquake epicenter with respect to Düzce. While there is a smooth variation with horizontal distance of PGD and PGV, both PGA and PGS are strongly influenced by the lateral discontinuities, which imply a significant increase of values between around 1 km and 3 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.

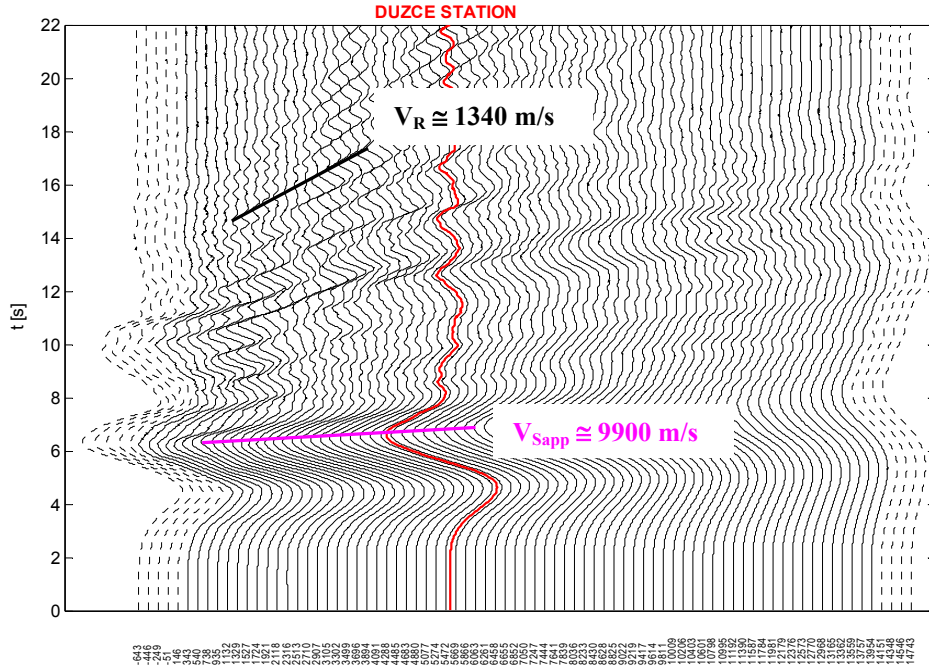
Focusing on ground response in the horizontal direction, it is interesting to evaluate how peak ground strains are related to peak ground velocities and check the performance of simple formulas useful in engineering practice. Simple solutions for ground strain evaluation (Newmark, 1967) relate the peak horizontal strain to the peak horizontal particle velocity PGV by the relationship:

$$PGS = \frac{PGV}{C}, \quad (1)$$



where  $C$  denotes either the apparent propagation velocity of S-waves in the horizontal direction ( $V_{\text{Sapp}}$ ) or the prevailing phase velocity of Rayleigh waves ( $V_R$ ).

In Figure 11  $V_{\text{Sapp}}$  and  $V_R$  have been visually evaluated on the basis of the displacement patterns along the NS cross-section, by connecting the peaks of the most relevant phases. Note that we are only interested in rough estimates of the apparent velocities and that a precise evaluation is out of the scope of this work.



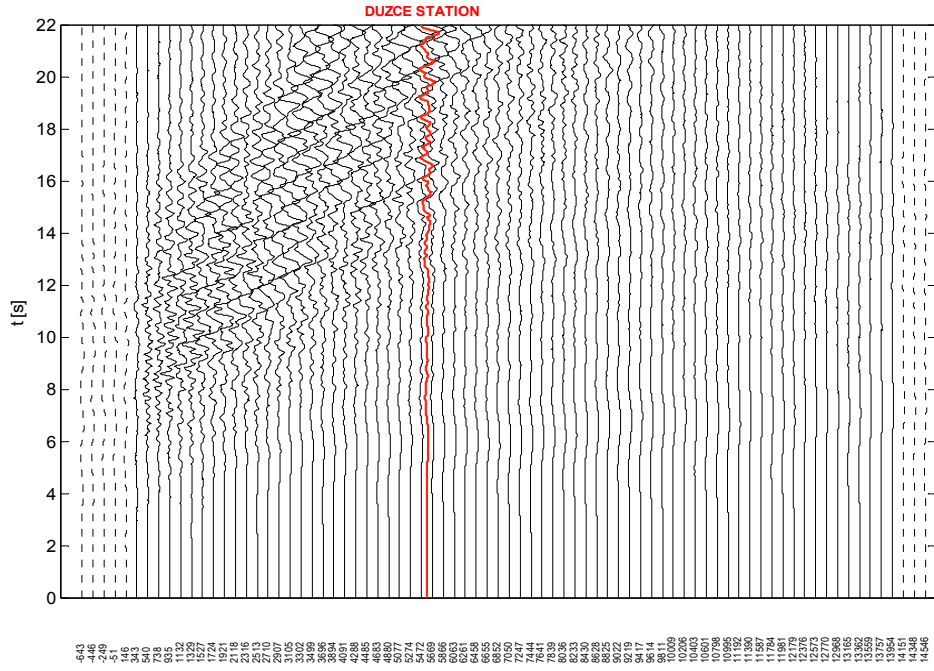
**Figure 11. Horizontal (in plane) displacement time sections with equally spaced receivers, with estimation of wave propagation velocities for S and Rayleigh waves. The abscissa indicates the receiver location on the surface along the NS cross-section. The dotted lines refer to points out of the basin, the thick one refers to the site of the Düzce station**

Since the velocity contrast between the basin and the underlying bedrock is sharp, S-waves propagate nearly vertically in the basin, yielding a very high value of  $V_{\text{Sapp}}$ , the use of which in (1) would lead to strongly underestimating PGS.

For the purpose of highlighting the possible limitations of use of equation (1), it is interesting to compare in Figure 11 and Figure 12 the waveforms of displacement and longitudinal strain respectively, evaluated along equally spaced receivers at ground surface.

It is evident that the nearly in phase S-arrivals do not give rise to any significant ground strain, while the highest values of strain are associated to the later Rayleigh wave arrivals. In fact there is an evident lack of correlation between the phases that carry the peak values of velocity, associated to S-waves, and those carrying the highest values of strain, associated to surface waves.

This proves that the use of (1) stemming from 1D wave propagation assumptions in a homogeneous soil, should be considered with care in the presence of strong lateral soil irregularities that may give rise to horizontally propagating waves.

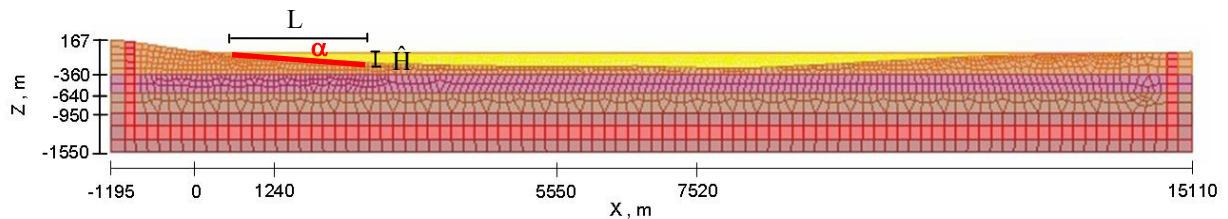


**Figure 12. Horizontal (in plane) strain time section with equally spaced receivers. The abscissa indicates the receiver location on the surface along the NS cross-section. The dotted lines refer to points out of the basin, the thick one refers to the site of the Düzce station**

In this case, an alternative approach to ground strain evaluation is the formula proposed by Scandella & Paolucci (2006):

$$PGS = r \frac{PGV}{\beta} \left[ F_1(x/L, \alpha) + F_2(x/\hat{H}, \alpha) \right]. \quad (2)$$

where  $r$  is the reflection coefficient,  $\beta$  is the  $V_{S30}$  shear wave velocity, the functions  $F_1$  and  $F_2$  between square brackets depend on the dip angle  $\alpha$  of the underlying bedrock, the normalized position  $x/L$  of the site with respect to the soil-bedrock contact, while the geometrical meaning of  $L$  and  $\hat{H}=L \tan \alpha$  is illustrated in Figure 13.

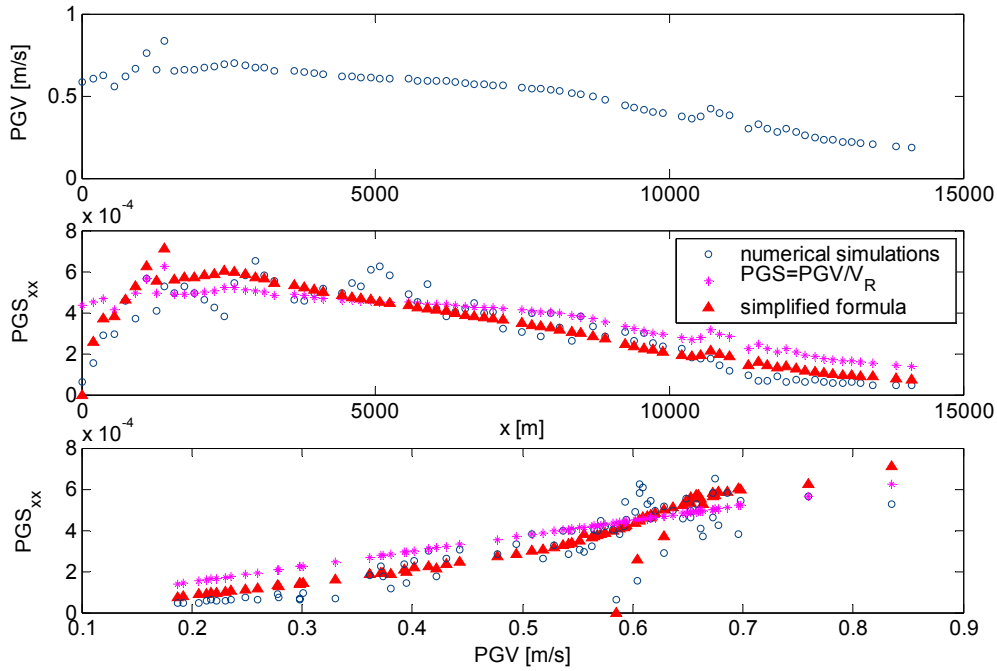


**Figure 13. SE model of the NS cross-section with the meaning of the geometrical parameters used in the simplified formula (2)**

Note that equation (2) has the advantage of not introducing the introduction of an apparent wave propagation velocity, the evaluation of which is one of the main problems for application of (1). To apply (2) to the present case, we have considered an average value of shear velocity for the uppermost 30 m,  $\beta=325$  m/s, an average dip angle of the bedrock  $\alpha=4^\circ$ ,  $L=2000$ m and  $r=0.89$ . The latter parameter has been evaluated using an impedance contrast of 0.12 between the basin surface layer and the rock layers outside the basin.

In Figure 14 the different PGS evaluations are compared. Note that we have omitted the case where  $C=V_{sapp}$ , leading to unrealistically values of strains. The best agreement with the results of the

numerical simulations is obtained using (2), if we consider both the PGS-PGV relationship and the position where the maximum value of  $PGS$  occur. Equation (1), with  $C=V_R$ , leads to an acceptable agreement with numerical results, but it does not capture the details of the spatial variability of  $PGS$  as in the case of application of equation (2).

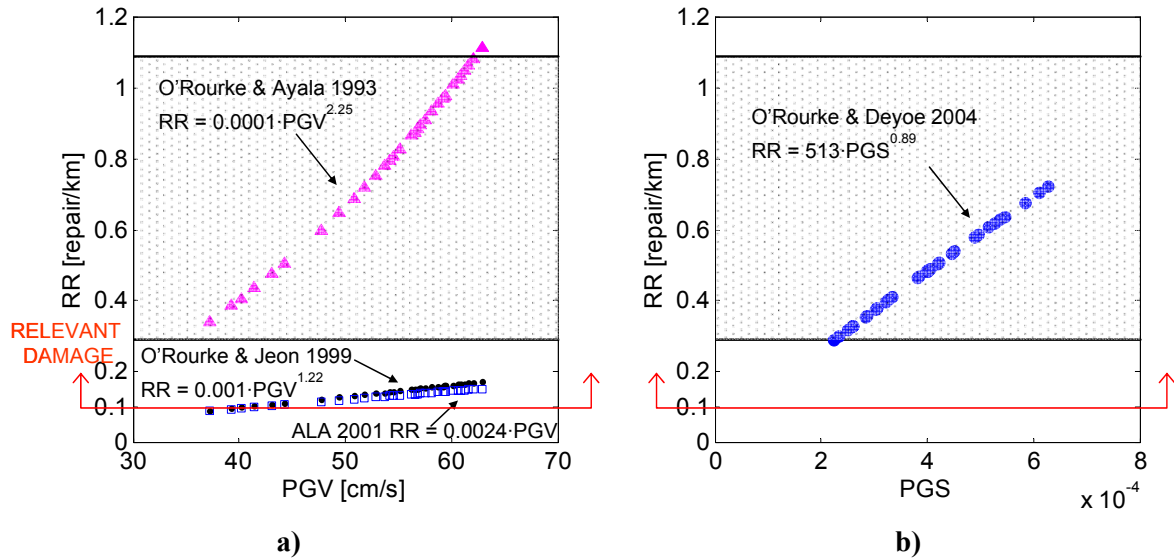


**Figure 14. Horizontal PGS vs. PGV for the Düzce case, obtained by numerical simulations, application of (1) with  $C=V_R$ , and application of equation (2)**

### DAMAGE ESTIMATION BY VULNERABILITY CURVES

An important requirement for assessing the seismic performance of a lifeline system is the ability to evaluate the potential damage as function of the level of seismic hazard intensity. The vulnerability is usually given in terms of a fragility relation which relates the damage state to a measure of the intensity of the earthquake hazard. For water pipelines the predicted damage is given in terms of Repairs/km (RR) and the intensity parameter is usually given in terms of peak ground velocity (PGV). O'Rourke and Deyoe (2004) showed that the scattering in the estimation of repairs due to wave propagation becomes much smaller when the seismic shaking is characterized by ground strain (PGS) as opposite to PGV. Figure 15 shows a comparison between the repair rates evaluated in the town of Düzce using different vulnerability relations and the PGV – PGS values estimated by the numerical simulations. It turns out that the application of different vulnerability functions in terms of PGV, such as ALA (2001) and O'Rourke and Ayala (1993), provides very different predictions of RR, as already noted by Pitilakis et al. (2005) who estimated for the area of Düzce RR varying from 0.117 to 0.884 according to the relation used. The O'Rourke and Deyoe (2004) relationship in terms of PGS provides intermediate values ranging from 0.13 in the Northern part of the town to 0.7 in the Southern one.

If we superimpose in Figure 15 the range of RR observed in different sectors of the town of Düzce and reported by Tromans (2004), although the scatter and uncertainty of the evaluation is quite large, we note that both the O'Rourke and Ayala (1993) and the O'Rourke and Deyoe (2004) relationships provide a reasonable agreement with the observed values, using the simulated range of either PGV or PGS in the most built-up part of the town.



**Figure 15. Repair Rate evaluation in Düzce using different vulnerability relations: a) RR vs. PGV; b) RR vs PGS. The threshold RR=0.1 repairs/km associated to significant damage to pipelines in large urban area is shown. The dotted strip highlights the range of observed repairs/km (Tromans, 2004)**

### CONCLUDING REMARKS

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 during the November 12, 1999 earthquake and its consequences in terms of estimation of damage to the underground lifeline network. Due to the near field conditions, the problem has been tackled by a numerical approach involving seismic wave propagation including the source, the propagation path, and the amplification effects induced by the Düzce basin. To this end the key has been the use of the Domain Reduction Method developed by Bielak et al. (2003). Based on the numerical results, we have tested different simplified relationships for peak ground strain estimation as a function of peak ground velocity. Furthermore, we have verified the level of damage predicted by different vulnerability functions, and observed that it may vary by up to one order of magnitude, depending on the function used and on ground motion severity parameter the vulnerability function is based on, either PGV or PGS. Comparing the estimated damage with the observed one, both the O'Rourke and Ayala (1993) and O'Rourke and Deyoe (2004) relations fit reasonably well the range of observed RR with the simulated range of either PGV or PGS.

### ACKNOWLEDGEMENTS

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