13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 2916

SPATIAL DISTRIBUTION OF PIPELINE DAMAGE IN DÜZCE CAUSED BY THE 1999 KOCAELI AND DÜZCE EARTHQUAKES

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SUMMARY

Results are presented of an investigation into water pipeline damage in Düzce, Turkey, following the 1999 Kocaeli and Düzce earthquakes. Temporal variations in pipeline repairs are analysed to identify earthquake-related pipe breaks. GIS-based analysis reveals no clear correlations between spatial distributions of pipeline damage and site conditions, as characterised by microtremor measurements. A reasonable correlation *is* observed between pipeline damage and building damage. The spatial distribution of peak ground velocity during the Kocaeli earthquake is approximated using pipeline damage data. Interpretation of pipeline damage caused by the Düzce earthquake is obscured by the effects of the earlier Kocaeli earthquake.

INTRODUCTION

In 1999, the town of Düzce, Turkey suffered extensive damage from two earthquakes separated by fewer than 90 days. The first event, the 17 August 1999 Kocaeli (M_w 7.4) earthquake, was associated with a surface fault rupture of approximately 140 km, whose eastern-most segment terminated within 15 km of the centre of the town (Omer [1]). A map published by the Turkish Government (Ozmen [2]) indicated resulting MSK intensities in Düzce as high as IX in the south west of the town. Düzce's strong-motion station (DZC) recorded peak accelerations and velocities of 0.36g and 54 cm/s respectively. The second event, the 12 November 1999 Düzce (M_w 7.1) earthquake, although smaller, occurred even closer to the town, with the surface fault rupture passing within 8 km (Figure 1). At DZC, ground acceleration reached 0.51g and ground velocity reached 84 cm/s.

Field trips were conducted in May 2000 and May 2001 to investigate earthquake-induced damage to Düzce's water pipelines. The investigation can be broken down into three areas:

1. Analysis of temporal variations in pipeline repairs before and after the earthquakes in order to identify earthquake-related breaks.

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2. Comparison between the spatial distributions of water pipeline damage and building damage.
3. Investigation into the influence of site conditions on damage distribution based on ambient noise measurements

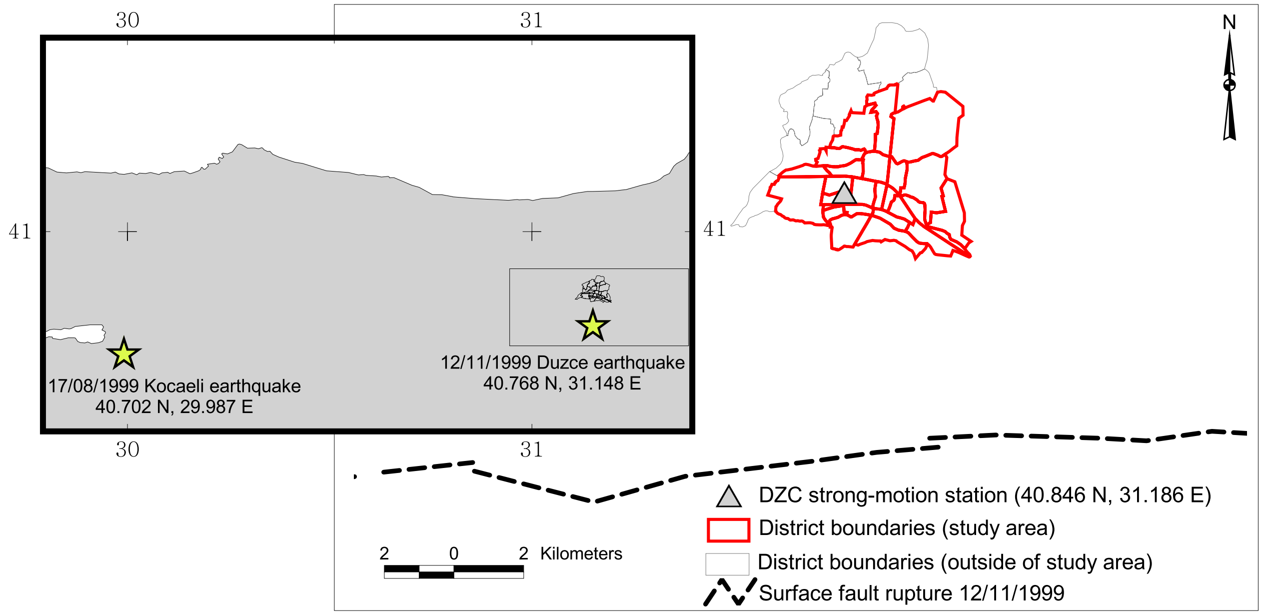

Figure 1 Location of study area. Inset shows geographical context and earthquake epicentres.

Data were collected relating to each of these areas and digitised onto a GIS. To facilitate spatial analysis, each dataset was aggregated at the town district level, as summarised in Table 1. For reasons of statistical reliability, GIS-based analysis was restricted to the most built-up districts of Düzce (i.e. those districts having at least 100 buildings per km^2). These districts are bounded in red in Figures 1, 4, 6, 8 and highlighted in grey in Table 1.

WATER PIPELINE DAMAGE

The water supply system in Düzce dates back to the 1940's. The only known maps available are those created by the Engineering Department of the Bank of the Provinces (Iller Bankası), which has been responsible for design, finance and construction of Düzce's water supply system since 1985. Düzce Municipality's Water Division provided copies of the most recent Iller Bankası maps, covering the whole town at a scale of 1:2000. These maps, dated July 1997, are design drawings for a new network and therefore differ somewhat from the existing system. Out of a total length of 435 km of pipe, approximately 280 km had been laid by September 2000 (Tadday [3]), although there is no indication which pipes these are. The pre-existing network is thought to be about 500 km in length, although no maps exist to confirm this (Tadday [3]). This older network was still in use at the time of the field work and was connected to the new system via a series of bypasses. The total length of the pipe network at the time of the August 1999 earthquake was estimated to be around 780 km (assumed equal to the September 2000 figure).

For the purposes of the current study, the full 435 km network as designed by Iller Bankası was assumed to be representative of the whole network (new and old combined) and was therefore digitised onto the GIS database. Pipeline repair rates calculated from lengths based on this network could then be multiplied by a pipe length adjustment factor, C_{PL} = 435/780 to account for the difference. Such uncertainty relating to buried infrastructure is common. In the absence of reliable maps, one study of earthquake damage to buried pipelines took road length (multiplied by a factor of 0.75) as a surrogate measure of pipe length (Shih [4]). In another study (Trifunac [5]), the variation of pipeline damage across a city relied on the assumption that the spatial density of pipes was constant within the area under investigation. For the town of Düzce, it was decided that the new network would better represent the actual system than either of these estimation methods.

Table 1 Data summary covering pipeline and building damage and site conditions. All data are aggregated at the district level. Notation is described in the main text.

				Pipeline damage rates (per km)			Building damage data							
District ID	District Name	District area (km^2)	Pipe length, L_p (km)	R_pK3	R_pD2	R_pK5	N_{D4}	N_{D3}	N_{D2}	N_{D1}	ΣN_{Di}	Building damage Index, D	$\bar{f}_p$	σ_{fp}
1	Çamköyü	3.093	36.9	0.000	0.000	0.000	69	54	183	2	308	0.263	-	-
2	Sarayyeri	1.802	8.1	0.000	0.000	0.000	17	20	63	0	100	0.244	-	-
3	Arapçifliği	2.667	11.0	0.000	0.000	0.000	4	33	124	0	161	0.183	-	-
4	Sancaklar	1.241	35.4	0.028	0.000	0.028	36	108	387	9	540	0.198	0.80	0.019
5	Çavuşlar	1.117	16.1	0.062	0.124	0.187	-	-	-	-	-	-	-	-
6	Akınlar	1.711	7.5	0.133	0.000	0.133	16	17	124	2	159	0.199	-	-
7	Körpeşler	1.392	18.8	0.053	0.000	0.053	9	43	169	1	222	0.187	0.81	0.018
8	Beyciler	3.625	54.5	0.551	0.257	0.808	29	114	411	5	559	0.193	0.96	0.061
9	Fatih	0.443	16.8	0.417	0.476	0.893	9	31	95	1	136	0.203	0.76	0.059
10	Karacahacımusa	0.715	8.3	0.000	0.000	0.000	11	2	74	7	94	0.185	0.84	0.043
11	Yeni	0.443	14.6	0.000	0.000	0.000	12	6	165	1	184	0.175	0.84	0.039
12	Hamidiye	0.715	33.6	0.951	0.119	1.070	122	141	298	0	561	0.272	0.83	0.089
13	Karaca	0.493	24.2	0.620	0.248	0.868	71	23	302	1	397	0.227	1.01	0.172
14	Koçyazı	1.932	52.6	0.266	0.019	0.285	42	51	281	3	377	0.209	1.02	0.191
15	Dereli	1.297	44.7	0.000	0.000	0.000	12	13	203	0	228	0.174	1.13	0.122
16	Mergic	1.052	11.7	0.000	0.000	0.000	10	20	59	0	89	0.223	-	-
17	Aziziye	2.098	83.9	0.751	0.191	0.942	160	130	512	1	803	0.251	0.76	0.091
18	Uzunmustafa	0.487	24.3	0.864	0.288	1.151	109	124	231	1	465	0.281	0.75	0.033
19	Kültür	0.901	36.7	2.042	1.089	3.131	280	381	208	7	876	0.341	0.80	0.156
20	Şerefiye	0.257	16.2	1.174	1.050	2.224	106	100	125	2	333	0.321	1.06	0.176
21	Burhaniye	0.221	13.7	1.315	0.584	1.899	92	116	101	0	309	0.324	1.01	0.118
22	Nusrettin	0.379	18.2	1.486	0.550	2.037	128	175	207	1	511	0.299	1.05	0.124
23	Cumhuriyet	0.618	25.0	0.400	0.080	0.481	18	28	137	1	184	0.206	1.07	0.209
24	Camikebir	0.331	17.7	1.356	0.452	1.808	163	125	127	0	415	0.354	0.77	0.110
25	Cedidiye	0.367	19.7	0.610	0.966	1.576	114	146	107	4	371	0.329	0.96	0.190
26	Fevzicakmak	0.768	30.1	0.531	0.597	1.128	27	84	163	0	274	0.229	1.16	0.151
27	Kiremitocağı	0.232	10.8	2.126	0.277	2.403	49	45	116	1	211	0.272	0.65	0.071
28	Çay	0.978	47.8	0.481	0.293	0.774	189	172	524	2	887	0.262	0.89	0.074
29	Azmimilli	1.074	38.5	1.402	1.064	2.466	158	236	533	1	928	0.252	0.87	0.088

The full digitised network is illustrated in Figure 2. No distinction is made between different pipe materials or diameters as this information was not systematically available. However, it is known that most of the new network consists of PVC pipes with diameters between 100 and 200 mm. The old network is mainly CI (cast iron), with some AC (asbestos cement) pipes. A 600 mm diameter AC pipe conveys raw water from the main source, the River Ugur, to the water treatment plant which lies to the south of the town. A 1m diameter steel pipe then carries the treated water to the distribution network, joining the town in the Azmimilli District (district ID 29). Twin CI pipes, of diameter 125 mm, transport water from a well-field and reservoir to supplement the main river water supply; these pipes join the town in the north-east. Both main water sources are illustrated in Figure 2, although the precise connection point of the 125 mm CI pipes to the distribution network is not known.

Düzce Municipality's Water Division summarises work carried out on the water network in the form of a daily logbook. This logbook system had been used by the Municipality since the 1970's. Following the earthquakes, as part of an initiative to improve record keeping, UNICEF worked with Municipality staff to summarise this data digitally in the form of a spreadsheet. A computer file summarising the period 25 January 1999 – 20 January 2001 (726 days) was obtained. Entries made in the water supply system logbook do not include any information on the nature or cause of pipeline damage. The amount of time required to restore a water network following an earthquake varies from event to event and depends on the amount of damage caused and the availability of the workforce. In deriving fragility relations using pipeline damage data obtained from the 1989 Loma Prieta earthquake, Eidinger [6] used repairs made in the two weeks following the earthquake. Repair of earthquake-related pipeline damage in Mexico City following the 1985 Michoacan earthquake, however, took several months (Ayala [7]). The situation in Düzce is complicated by the fact that two destructive earthquakes occurred within three months, the second event occurring whilst repairs of damage from the first event were still underway. In order to identify earthquake-related pipeline repairs in Düzce, it is therefore necessary to plot a time-line of the available data.

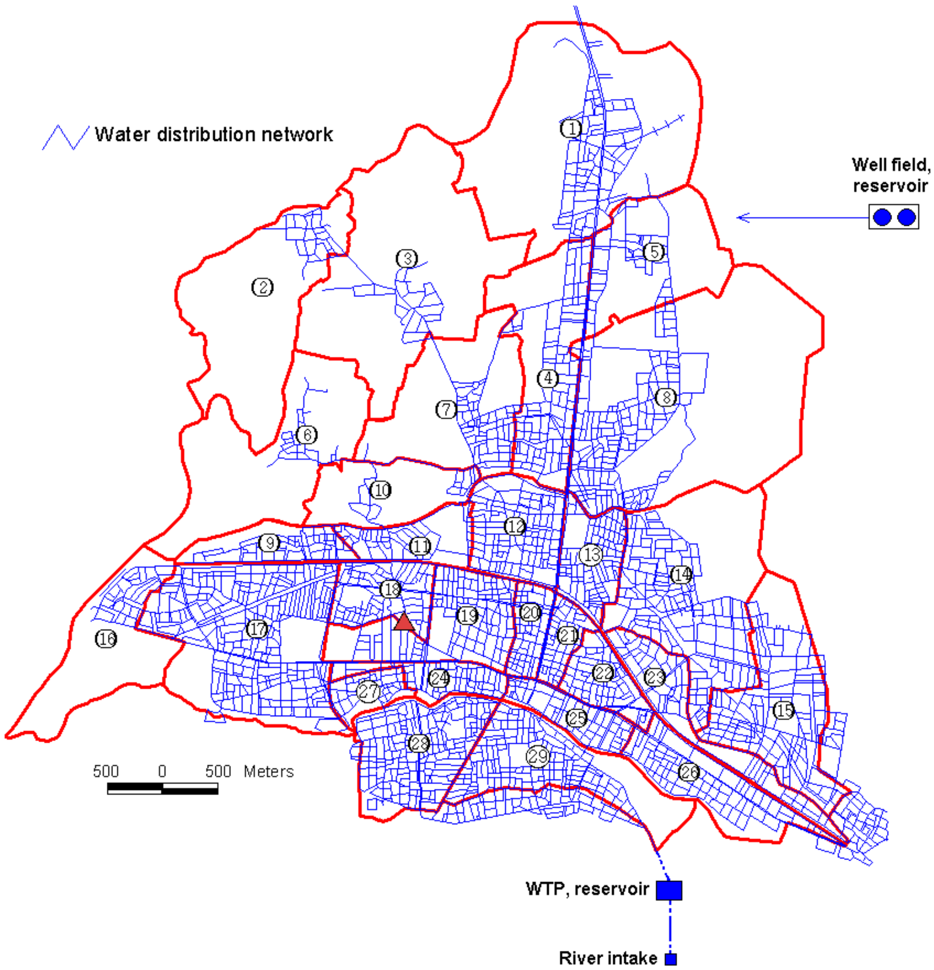

Figure 2 Düzce's water supply system, digitised from the 1:2000 scale maps of the Bank of the Provinces. District IDs are specified in Table 1. The red triangle shows the location of the DZC strong-motion station.

It was decided to aggregate the pipeline repair data according to nominal monthly periods. As time between the Kocaeli and Düzce earthquakes corresponds to exactly three 29-day periods, this was taken as the nominal month length. The temporal variation in network repairs for the whole of Düzce is plotted in Figure 3. Prior to the Kocaeli earthquake, the network repair rate is seen to be very stable from month to month. Immediately after the earthquake, there was a marked increase in pipeline repairs. A monthly repair rate about twice the pre-earthquake level was sustained for 2 months, which reflects the response of the Municipality to the extensive earthquake damage to the water network. A sharp drop in repair rates to almost pre-earthquake levels occurred in the month immediately following the Düzce earthquake. This corresponds to the two week period during which the majority of water division staff were repairing the 600 mm diameter AC transmission line which suffered extensive damage where it crossed the Düzce fault zone (ASCE/TCLEE [8]). Once this work had been completed, attention was returned again to the water distribution network, evidenced in the sharp increase in numbers of repairs carried out in the period ending 9 January 2000. This was followed by a sharp decrease for a period of four months to an average repair rate around a quarter of pre-earthquake levels. A UNICEF field report dated 13 March 2000 (UNICEF [9]) stated that 90% of mains pipes in Düzce were reported to be functioning following the extensive post-earthquake repair works. The trend observed in the repair rate suggests that the majority of repairs to the most important pipes had already been completed some time between 9 January and 7 February 2000. This conclusion is also supported by the trend observed in the time line of service connections. The sharp reduction in mains repairs between January and February coincided with a sharp increase in service connection jobs. Such a shift in focus in work carried out by the Water Division staff is only likely to have happened once the mains network had been largely re-established.

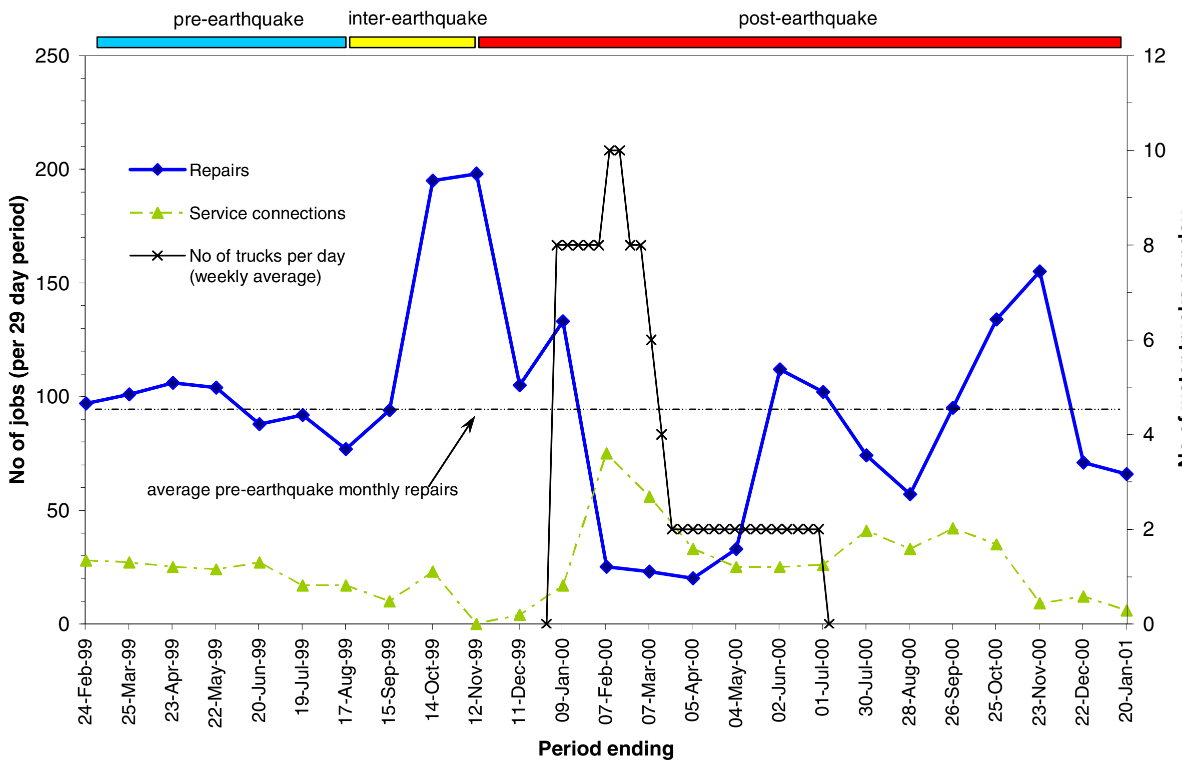

Figure 3 Temporal variations of network repairs, service connections and provision of potable water by truck within Düzce.

Figure 3 also includes data relating to the provision of water by truck, which formed part of the UNICEF-funded post-earthquake rehabilitation of Düzce (UNICEF [9-13]). Potable water was provided by truck as long as Düzce's water demands were not being met by the town's water distribution network. The UNICEF programme made use of private truck contractors in order to release the Municipality staff to attend to network repairs and service connections. Trucked water supply began on 30 December 1999 with the provision of 600 m^3 water per day (equal to 8 trucks each supplying 75 m^3), enough for 30,000 of Düzce's 75,000 inhabitants (assuming 20 litres per person per day). This provision rose to a maximum of 10 trucks per day for a short period at the start of February 2000, with a graduated reduction over the following five weeks corresponding to a reduction in the number of service connections. Trucked water provision, at 150 m^3 per day, was sustained until July. UNICEF reports indicate that many people in Düzce continued to use trucked water in preference to piped water due to concerns about water quality, even in areas where piped water had been restored.

From the trends observed in the time lines, it was decided to aggregate the monthly post-earthquake repair data from the log books according to three time-frames. These datasets, along with the pre-earthquake repair data, formed the basis of the spatial analysis. The time-frames and descriptions of the quantities are summarised in Table 2. Values for each quantity for each district are summarised in Table 1. The spatial distribution of the post Kocaeli repairs, *R_pK3*, is illustrated in Figure 4.

Table 2 Summary of time frames used for aggregation of pipeline repair data

Time frame	Explanation	Quantity mapped (incl. description)
18 Aug 1999 – 12 Nov 1999	Damage caused by Kocaeli earthquake	*R_pK3* - Post-earthquake repair rate per km length of pipe (data aggregated post Kocaeli earthquake 3 months)
13 Nov 1999 – 9 Jan 2000	Damage caused by Düzce earthquake	*R_pD2* - Post-earthquake repair rate per km length of pipe (data aggregated post Düzce earthquake 2 months)
18 Aug 1999 – 9 Jan 2000	Combined damage caused by both earthquakes	*R_pK5* - Post-earthquake repair rate per km length of pipe (data aggregated post Kocaeli earthquake 5 months)

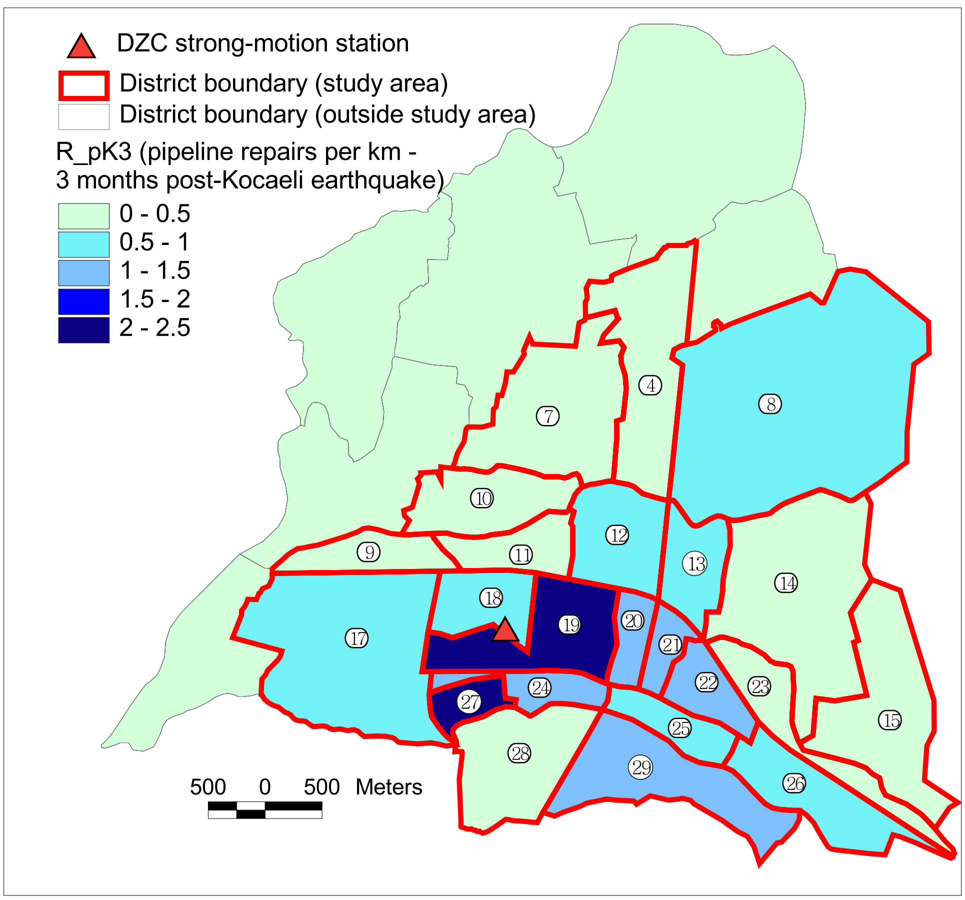

Figure 4 Post-earthquake pipeline repairs (per km of pipe) summed over the 3 months immediately following the Kocaeli earthquake, *R_pK3*.

In Table 3, observed pipeline repair rates are compared with values predicted from the HAZUS (FEMA [14]) pipeline fragility relation for brittle pipes. Quantities *R_pK3*, *R_pD2* and *R_pK5* are summarised for District 18 (which contains the DZC strong-motion station), and for the whole study area. The HAZUS predictions are calculated from PGV values recorded at DZC during the Kocaeli and Düzce earthquakes (54 cm/s and 84 cm/s respectively).

Table 3 Comparison of observed and predicted pipeline repair rates for Düzce following the Kocaeli and Düzce earthquakes

	Repairs per km pipe		
	Kocaeli earthquake *R_pK3*	**Düzce earthquake *R_pD2***	**Both earthquakes *R_pK5***
Observed repair rate for district 18	0.86	0.29	1.15
Observed repair rate (average for whole study area)	0.71	0.34	1.05
Estimated repair rate (from HAZUS fragility relation)	0.79	2.14	2.93

The results indicate that pipeline repair rates observed in district 18 were typical of those experienced across the whole town, for all three post-earthquake time-scales. The HAZUS prediction for damage caused by the Kocaeli earthquake is within 10% of the observed values. However, whereas the predictions indicate 2.7 times more damage as a result of the Düzce earthquake than as a result of the Kocaeli earthquake, observed values show the opposite trend. From a closer inspection of the strong-motion records, the Düzce earthquake would be expected to produce greater levels of damage than the Kocaeli earthquake. Husid plots are presented in Figure 5 to compare the time variation in Arias intensity between the two earthquakes at the DZC strong-motion station. The Arias intensity associated with the Düzce earthquake is more than twice the value associated with the Kocaeli earthquake, for both horizontal components of motion.

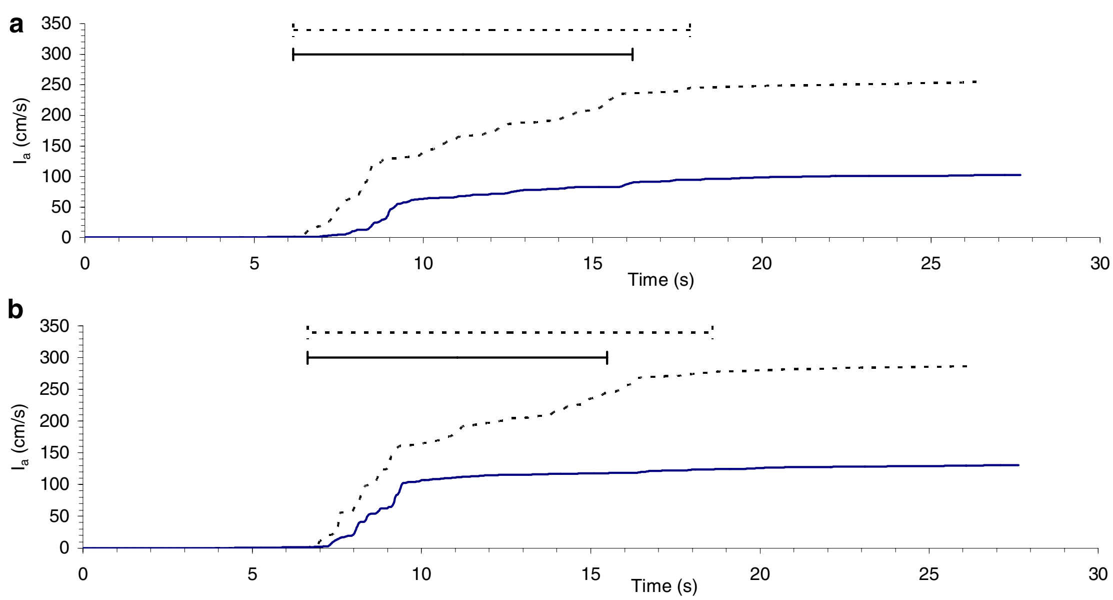

Figure 5 Comparison between Husid plots for accelerograms recorded at DZC strong-motion station during the Kocaeli and Düzce earthquakes. Figure (a) shows NS components for both earthquakes. Figure (b) shows EW components for both earthquakes. Data from the Kocaeli earthquake is indicated with a solid line; data from the Düzce earthquake is indicated with a dashed line. For each Husid plot, the effective duration (Bommer [15]) is indicated.

The rate of arrival of energy at DZC, as indicated by the gradient of the Husid plot, was also much higher during the Düzce earthquake, again indicating greater damage potential. Finally, longer duration of ground shaking during the Düzce earthquake (as indicated in Figure 5) is another factor likely to have contributed to greater damage levels. Energy-equivalent velocity spectra presented by Sucuoglu [16] also support the assertion that strong motion during the Düzce earthquake caused greater damage in Düzce than strong motion during the Kocaeli earthquake.

The most likely explanation for the lower levels of pipeline damage observed following the Düzce earthquake is incomplete documentation of repairs carried out in the period immediately after the earthquake. Restoration of an adequate water supply will have taken precedence over systematic record keeping at this time. Some of the repairs carried out by third parties assisting in the post-earthquake restoration (eg. Iller Bankası, as reported in Efendioglu [17]) may not have been recorded in the Municipality logbook used in the current study.

BUILDING DAMAGE

Data relating to Düzce's building stock and damage caused to buildings as a result of the Kocaeli and Düzce earthquakes were obtained from the Municipality's GIS Division, a summary of which is included in Table 1. The data are given in terms of the number of buildings in each district, N_{Di} having a certain level of damage, i. Building damage was defined according to a four-level classification scheme, details of which are presented in Table 4. These data refer to the situation following the second earthquake. Unfortunately, the available data do not make any distinction between damage caused by the two earthquakes.

Table 4 Building damage classification for Düzce (translated from Kajitani [18]). Approximate equivalence to EMS-98 (Grunthal [19]) damage grades is also from Kajitani [18].

Damage grade	Description	Details	Approximate equivalence to EMS-98 (Grunthal [19]) damage grade
1	No damage	No visible damage.	-
2	Light damage	No damage to main supporting system of building (foundation or main pillars). Cracks visible in non-structural walls. Building habitable.	1 & 2
3	Medium damage	Some damage and weakening of main supporting system. Cracks visible in beams or shallow cracks visible in columns. Partial collapse of non-structural walls.	3
4	Heavy damage	Significant destruction of main supporting system. Columns or structural walls split or collapsed. Building toppled or partially or totally collapsed.	4 & 5

In order to quantify total building damage, data for each damage grade was combined into a single damage index, D, using a weighted average scheme, as expressed below:

$$D = \frac{\sum_{i=1}^{n}\left(W_i N_{Di} / N_{Btot}\right)}{\sum_{i=1}^{n} W_i}$$

where: W_i are damage grade weighting coefficients. Values used were those used by the Municipality $[W_1, W_2, W_3, W_4] = [0, 0.25, 0.5, 1]$

N_{Di} is the number of buildings at a given damage grade for a particular district,

N_{Btot} is the total number of buildings in a particular district

Values of D for each district in Düzce are summarized in Table 1.

SITE CONDITIONS FROM MICROTREMOR MEASUREMENTS

A desk study conducted prior to the fieldwork threw little light on the dynamic properties of soils in the Düzce area. In order to investigate the influence of site conditions on the spatial distribution of pipeline damage, it was therefore decided to carry out a microtremor survey in the study area. Over one hundred measurements were taken throughout Düzce using Guralp CMG-40TD-1 and CMG-3ESP seismometers sampling at 100 Hz. For each location, the average horizontal-to-vertical spectral ratio (HVSR) of ambient noise measurements was calculated from 20 x 40.96 s sample windows. Prior to calculation of spectral ratios, Fourier spectra were smoothed using an adjacent averaging algorithm with a smoothing window half-width of 0.098 Hz. For each sample window, the HVSR was calculated from the root-mean-square average HVSR for the two horizontal components.

Site conditions were characterized by the predominant frequency of the ground (f_p) obtained from the HVSR and the average HVSR amplification over various frequency bands. As has been found in other microtremor investigations, the average HVSR amplification at any given site was considerably less reliable than the predominant frequency. In the current paper, therefore, only the f_p dataset will be considered. The full microtremor dataset, together with methodology and analysis, is presented in Tromans [20].

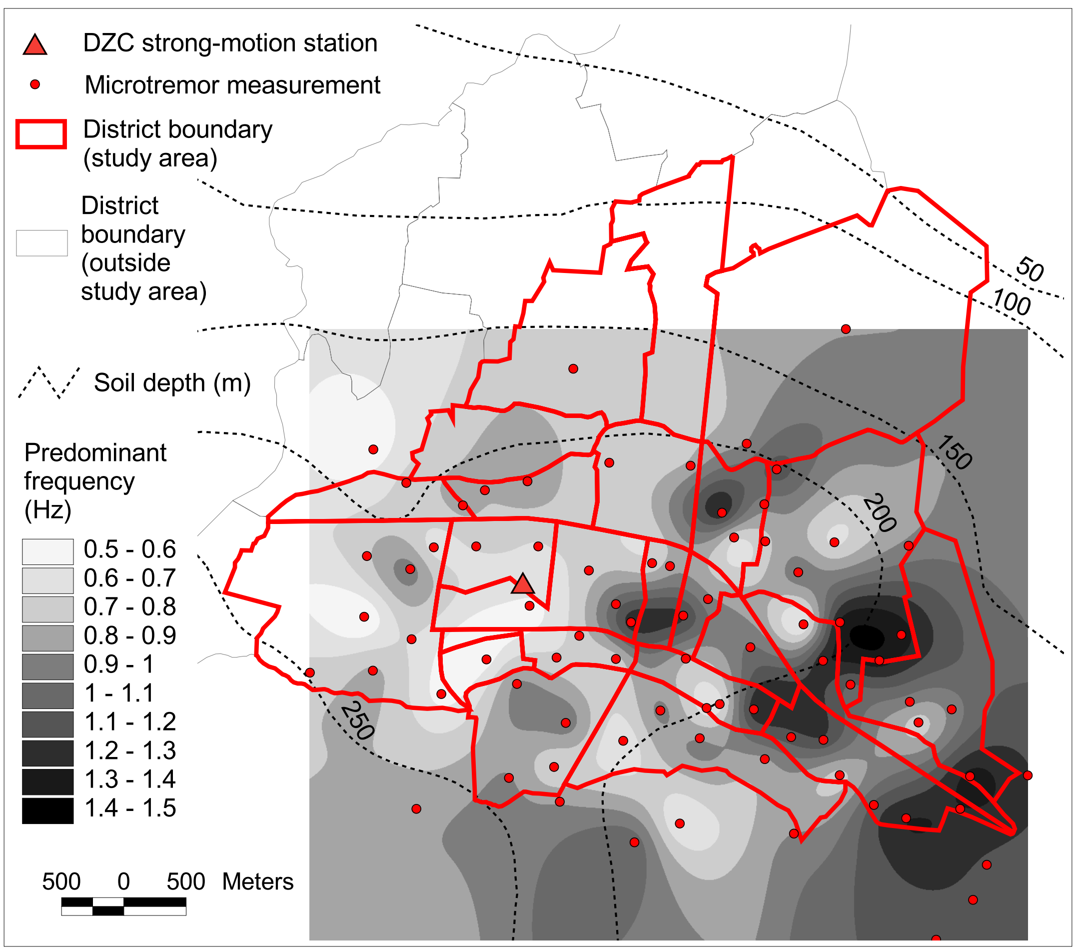

Figure 6 Contours of predominant frequency, f_p (Hz).

In order to help identify spatial trends in the f_p dataset, a parameter surface was defined extending over the whole study area. Interpolation between measurement locations was carried out within the GIS environment using the ArcView 3D Analyst Extension. A tension spline interpolation algorithm (based on a 5 m grid spacing, a weighting parameter of 20 and a fit to the nearest 6 grid points) was judged to give the best results, which are presented in Figure 6.

Contours of soil depth (surface-to-bedrock) have been superimposed on Figure 6. This information is from a geophysical investigation carried out by the Turkish General Directorate of Mineral Research and Exploration and Ankara University (MTA/AU [21]), as presented in Aydan [22]. There appears to be a general trend of increasing f_p from the western and central parts of the town towards the east and northeast. This observation is interpreted as the influence of soil depth on the ground response since a reduction in soil depth is generally expected to lead to an increase in f_p.

In order to investigate the influence of f_p on pipeline damage rates, its mean value, $\bar{f}_p$ was computed for each district from the interpolated parameter surface (5-m grid spacing) using the ArcView Spatial Analyst Extension. These values are expressed in Table 1.

SPATIAL ANALYSIS

Influence of f_p on damage distribution

For a fixed value of PGV, ground strain will generally be greater in soft soils than stiffer soils. This has been confirmed by Nakajima [23] in a series of field measurements using strain gauges and accelerographs. For the same value of PGV, maximum ground strain observed in a location in soft ground was on average 3 to 4 times that observed in a location on hard ground. In this case, the predominant frequency of the soft ground was 0.8 Hz whilst the predominant frequency of the hard ground was around 2.5 Hz. It was therefore anticipated that in the case of Düzce, districts having low average values of f_p would experience greater pipeline damage rates than districts with higher average values of f_p.

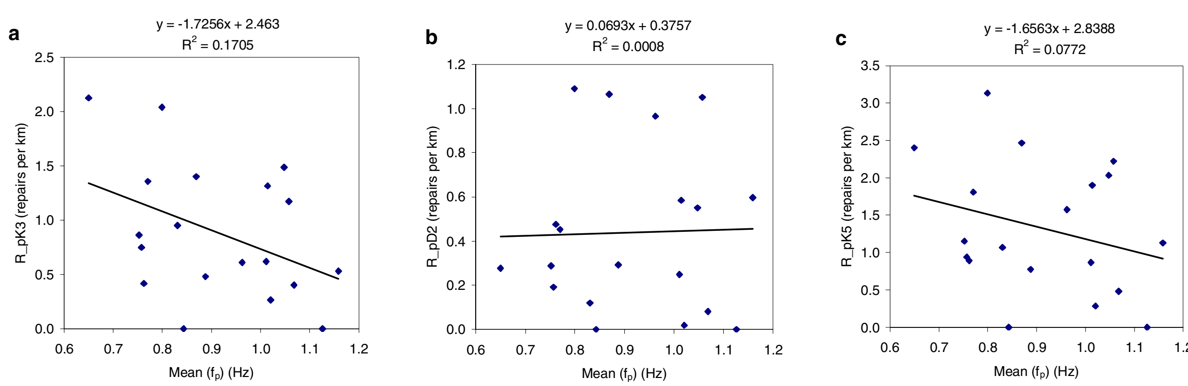

Figure 7 Relationship between mean f_p and various pipeline damage parameters

The relationships between various damage parameters and the mean value of f_p are presented in Figure 7. Regressions excluded data from districts outside of the central part of Düzce (as explained in the Introduction) and additionally, districts 4, 7, 8 and 10, which had very sparse microtremor survey coverage. Figure 7 (a), which represents damage from just the Kocaeli earthquake, appears to show decreasing pipeline damage rates for higher values of mean f_p, as anticipated. However, the r^2 value for this dataset is very low (approximately 0.17), calling into question the significance of any apparent trend. The correlation between mean f_p and the quantity *R_pK5* is even less significant. Any dependency of pipeline damage on site conditions in Figures 7(b) and (c) is obscured by uncertainties in pipeline damage statistics following the Düzce earthquake.

Clearly, the mean value of f_p calculated at the district level is a poor predictor of pipeline damage rates observed across Düzce. Aggregating microtremor data at the district level smoothes over spatial variations in site conditions which are likely to have been of significance to the earthquake behaviour of buried pipelines. However, the resolution of data in the investigation was limited by the availability of damage data and economic constraints on the extent and detail of the microtremor survey.

The relationship between peak ground strains (which are responsible for pipeline damage) and the predominant frequency of the ground needs further investigation. The variations in f_p observed across Düzce are brought about by a combination of changes in soil depth and changes in the shear-wave velocity structure of the ground. It is expected that shear-wave velocity profiles in each district would help in the interpretation of the pipeline damage data, although such data was not available for the current study.

It is likely that some of the variation observed in f_p across Düzce is a result of uncertainty in the identification of the predominant peak obtained from the HVSR of microtremor data. As explained by Bard [24], the distinctiveness of f_p is affected by the impedance contrast between the surface soil layers and the underlying stiffer formations. Shear-wave velocity profiles coinciding with microtremor measurement locations could also be used to validate the microtremor dataset.

It is worth noting that Trifunac [25] investigated the spatial distributions of severely damaged buildings and of breaks in the water distribution system following the 1994 Northridge earthquake and found no simple correlations with various generalised categories of surficial geology.

Comparison between pipeline damage and building damage

Comparisons between measures of pipeline damage and the building damage index, *D*, are presented in Figure 8. All three measures of pipeline damage are seen to correlate reasonably well with building damage, with r^2 values ranging from 0.51 – 0.69. It is notable that the best correlation is seen for *R_pK5*, which includes the combined effects of both the Kocaeli and Düzce earthquakes (as is the case for the building damage statistics).

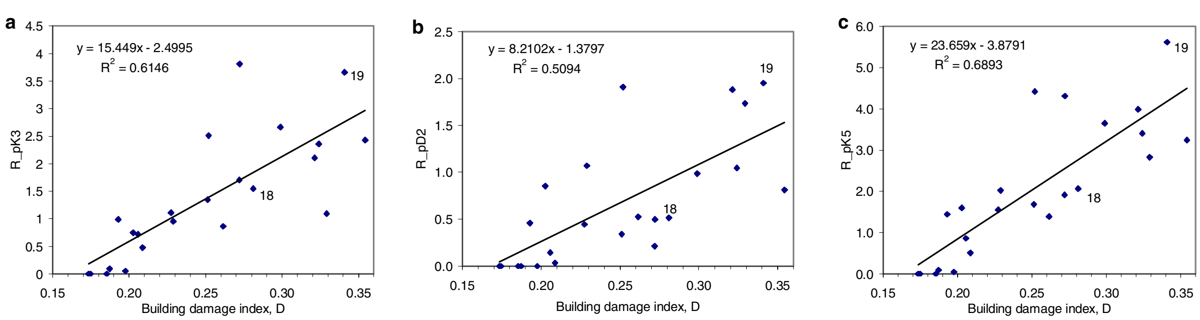

Figure 8 Comparison between pipeline damage rates and building damage rates for all districts of Düzce. Data points referring to districts 18 and 19, in the vicinity of DZC strong-motion station, are highlighted.

The fact that districts experiencing a high level of pipeline damage also experienced a high level of building damage is taken to imply that damage patterns were dominated by the influence of variations in strong motion from district to district. It is assumed that there was no strong regional correlation between pipeline vulnerability and building vulnerability, which is reasonable at the district level, although would not be so reasonable if considering damage variations between individual town blocks. The significant range in levels of damage observed across the districts of Düzce (as evidenced in Figure 4) is therefore believed to be the result of significant variations in the intensity of ground shaking.

One factor which might have contributed to the close correlations observed between pipeline and building damage levels is the effect of building collapse on buried structures. Some pipes may have survived the passage of seismic waves only to have been damaged by the collapse of a nearby building. It is known from discussions with Municipality Water Division staff that some pipe damage was caused during post-earthquake reconstruction works. The toppling of a damaged minaret, for example, resulted in damage to buried water pipes leading to 10,000 people being without water for three days (Tadday [26]).

None of the trends shown in Figure 8 passes through the origin. This implies that a greater level of ground motion is required to cause pipeline damage than building damage. O'Rourke [27] observed no pipeline damage in areas with PGV < 10 cm/s as a result of the 1994 Northridge earthquake. Isoyama [28], in deriving pipeline fragility relations based on data from the 1995 Hyogoken-nanbu earthquake, suggested strong-motion thresholds of PGV = 15 cm/s and PGA = 100 cm/s^2 for pipeline damage to occur.

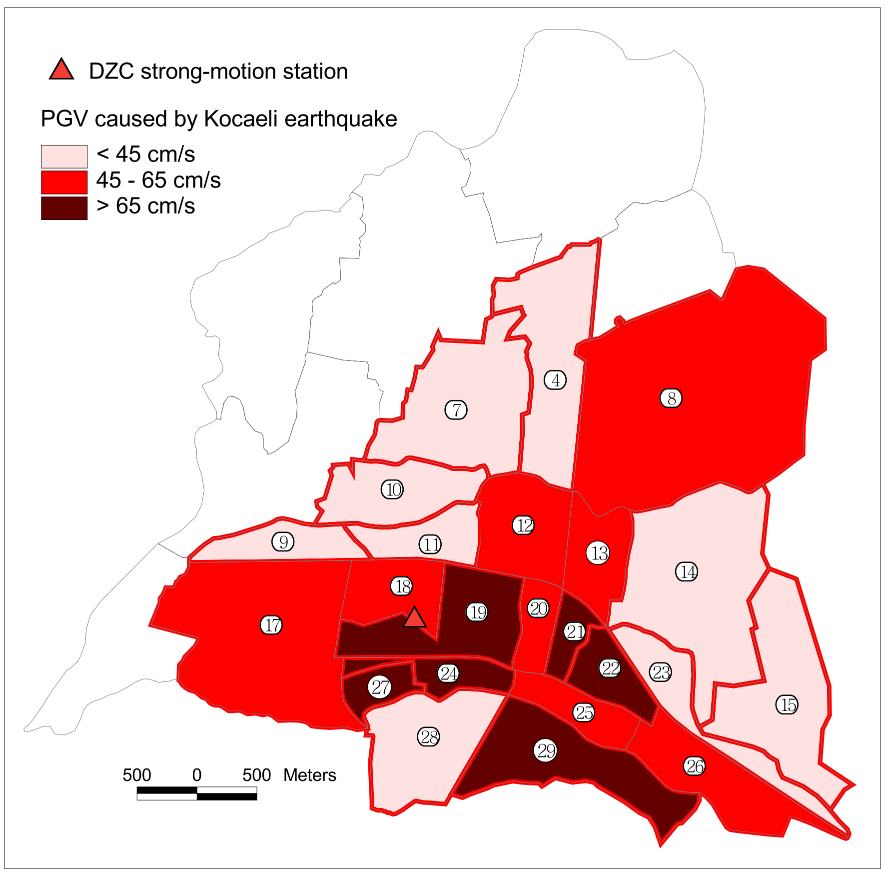

Figure 9 Estimated distribution of PGV in Düzce as a result of the Kocaeli earthquake, inferred from pipeline damage distribution. Predictions are in terms of PGV_L, the largest of the two horizontal components of PGV.

The DZC strong-motion station is situated in district 18 (Uzunmustafa). As indicated in Figure 8, this district experienced average levels of both pipeline and building damage (regardless of the pipeline damage parameter considered). The average strong ground-motion in other districts could be scaled according to the level of damage relative to this district. It is, however, possible that the strong-motion recorded at DZC was more representative of the ground motion experienced in district 19 (Kültür) as the strong-motion station is very close to the boundary of this district. In this case, the values recorded at DZC would have been amongst the highest experienced anywhere in the town, as inferred from the high levels of pipeline and building damage in district 19.

Figure 9 shows the distribution of PGV as a result of the Kocaeli earthquake, inferred from pipeline damage data. This map is based on the assumption that the strong-motion experienced at DZC was representative of the district in which it is located (district 18). PGV was calculated using the HAZUS fragility relationship, which predicted a pipeline damage rate in district 18 very similar to the observed value (see Table 3). Due to the uncertainties associated with the data, predictions have been restricted to three levels of PGV:

1. Districts with PGV similar to the value recorded at the DZC strong-motion station (defined by the range 45–65 cm/s, which is approximately 10 cm/s either side of the recorded value).
2. Districts with PGV less than the value recorded at DZC (PGV < 45 cm/s).
3. Districts with PGV greater than the value recorded at DZC (PGV > 65 cm/s).

CONCLUSIONS

- Time-line analysis of pipeline repair data following the Kocaeli and Düzce earthquakes was used to identify earthquake-related pipe breaks. Pipeline repair rates caused by the Kocaeli earthquake are similar to the values predicted from the HAZUS pipeline fragility relation. Consideration of the damage potential of strong-motion recorded at DZC calls into question the completeness of the repair log in the period immediately following the Düzce earthquake.

- No significant correlation was found between the spatial distributions of pipeline damage and the mean value of f_p. Further investigation is needed to identify the influence of local variations in the shear-wave velocity structure of the ground on the relationship between f_p and peak earthquake-induced ground strains. It is suggested that shear-wave velocity profiles at a selection of microtremor measurement sites would also improve validation of the microtremor dataset.

- A reasonable correlation was observed between the spatial distributions of pipeline damage and building damage. This is interpreted as evidence that damage patterns were dominated by the influence of variations in strong motion from district to district. Building damage data, aggregated over both the Kocaeli and Düzce earthquakes, obscured earthquake-specific damage patterns. However, the variation in pipeline damage levels from district to district assigned to the Kocaeli earthquake was used to infer the spatial distribution of characteristics of the strong motion, based on the existing HAZUS pipeline fragility relation.

- Anecdotal evidence suggests that the close correlation between the spatial distributions of pipeline damage and building damage may have been influenced by the impact of building collapse on buried pipelines. Further investigation is required to quantify the significance of this effect in Düzce.

- Comparison between building damage rates and pipeline damage rates across Düzce implies that the onset of pipeline damage requires a greater level of ground motion than the level needed to cause building damage. This confirms the findings of previous studies in Japan and the US.

ACKNOWLEDGEMENTS

This research was jointly funded by EPSRC, WRc Plc and Kubota Corporation under the British Government Department of Trade and Industry's PTP (Postgraduate Training Partnership) initiative.

The authors wish to thank Hitoshi Inada of Kubota Corporation for his close involvement throughout the project. We thank colleagues at Imperial College and WRc; in particular, Dr John Douglas, Dr Ian Walker, Dr Stephen Russell and staff in the GIS section. Dr Cansen Guralp and his colleagues at Guralp Systems Ltd provided us with seismometers and technical support for the microtremor survey. Municipality staff in Düzce supplied us with data relating to pipeline and building damage and gave much practical assistance in the field, as did Murat Şahin and Klaus Tadday of UNICEF. Professors Amr Elnashai, Mustafa Erdik, Haluk Sucuoğlu, Özer Kenar and Hasan Sarikaya and their respective colleagues all gave of their time to assist in the fieldwork. We also benefited from the local geological expertise of Dr Chris Menkiti of Geotechnical Consulting Group and Roberto Rossetti of Astaldi S.p.A.

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