

## A GIS Approach for Seismic Analysis of Pipeline Networks

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### Abstract

As part of an extensive study which involves a TUBITAK (The Scientific and Technological Research Council of Turkey) funded Project entitled “Evaluation of Earthquake Effects on Buried Pipeline Systems Using Geographical Information Systems (GIS)”, a software program development has been undertaken. The objective of this study is to develop a new methodology for the assessment of earthquake effects on buried pipeline systems by integrating geographical information systems (GIS) with numerical methods such as finite element analysis. The software works with GIS. The software performs first Stage 1 checks by evaluating whether the given pipeline system satisfy certain seismic design and code requirements such as Earthquake Resistant Design Codes in Japan (JSCE, 2000) and international standards such as Earthquake-and-Subsidence-Resistant Design of Ductile Iron Pipelines (ISO, 2006). Some inputs to the program are seismic information (e.g., ground shaking maps) and soil data (e.g. soil type maps, liquefaction hazard maps, etc.). Both transient and permanent ground deformation effects are considered. The program provides and shows users the pipelines that need further seismic evaluation. At Stage 2 state, the program utilizes the results of finite element analysis which are integrated into GIS and evaluates the pipeline network in detail. DIANA program is used in finite element analysis. Denizli, Turkey is selected as a primary pilot area for the application of the software and methodology.

*Keywords: Earthquake; DIANA; Finite Element Analysis; Geographical Information Systems (GIS); Pipelines*

### 1 Introduction

Evaluation of pipeline systems against future earthquakes is very important for the efforts to build earthquake-resistant infrastructures. Continuous service of drinking water and natural gas pipeline systems or getting their functionality quickly back right after an earthquake is very important and crucial for urban societies. It was observed in the past earthquakes that pipeline damage density was much higher at locations where permanent ground deformations (PGD) were observed. Hence, this paper deals with especially PGD effect evaluations. PGD occurs as a result of surface faulting, liquefaction, landslides and differential settlement from consolidation of cohesionless soils. It is important for utility companies to evaluate their existing systems against PGD effects as well as to design their new systems resistant to these effects. The aim of this study is to provide a geographical information system (GIS)-based tool and methodology for evaluating PGD effects on buried lifeline systems. GIS for pipeline systems gained wide acceptance in the last decade (e.g., O’Rourke and Toprak, 1997; O’Rourke et al., 1998). Denizli was selected as a primary pilot area for the application of the software and methodology. The general characteristics of buried lifeline systems in Denizli City as well as in other urban areas of Turkey were presented herein. The finite element results from the case studies and Denizli lifelines will be utilized in GIS-based software developed in this study. Primarily, ARCGIS software was used in the GIS applications (ESRI, 2001).

## 2 Buried Lifeline Systems In Denizli

### 2.1 Gas

The gas market in Turkey is regulated by Republic of Turkey Energy Market Regulatory Authority (EPDK) according to Natural Gas Market Law No. 4646, dated 18/4/2001 and the Natural Gas Market Distribution and Customer Services Regulation. The Regulation sets forth the principles and procedures pertaining to the selection of the companies to be issued a natural gas city distribution licenses, and natural gas distribution activity to be conducted and customer services to be provided by the distribution licensees. Distribution license tender is conducted by the Authority and announced in the Official Gazette of Turkey. Distribution license is issued and the ownership of the distribution network shall be transferred to the company which wins in the tender, taking into account issues such as the level of development and consumption capacity of and the number of users in the city, for the duration of the license term determined by the Authority in the tender announcement. The Authority may break the city into more than one distribution regions with defined boundaries, depending on the density of population, and tender each region separately. The city distribution company obtaining the distribution license from the Authority must offer a partnership at a rate of 10% to the municipality or the municipal company within the city in which it is authorised without the need to provide any capital. Such capital rate may be increased at a rate of maximum 10% provided that the equivalence has been paid.

KENTGAZ Denizli Dođal Gaz Dađitim A.Ş got the tender for Denizli City in 2006 and became responsible company for the construction, operation, expansion, improvement of distribution network, and delivery of natural gas in Denizli for the following 30 years (<http://www.kentgazdenizli.com.tr>). The first gas was delivered to parts of Denizli in October 2006.

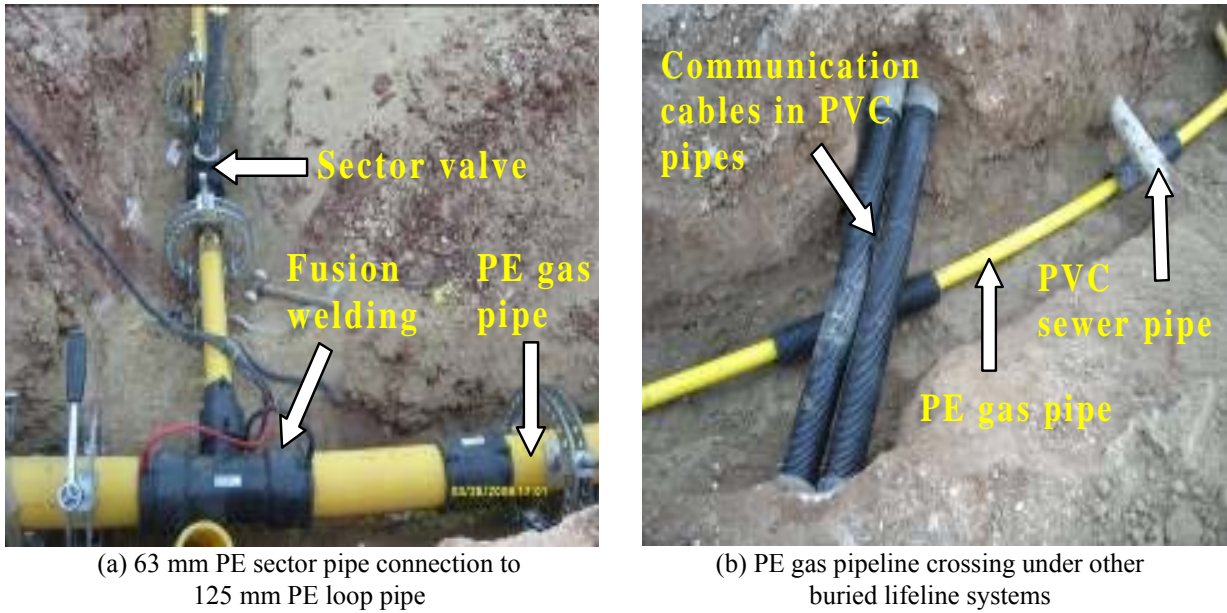
Denizli is divided into 23 regions for the gas distribution network construction. For each region, high pressure gas coming from steel pipelines is transferred to lower pressure polyethylene (PE) pipelines via gas regulating stations. Steel pipelines have the diameter of 8 inch (about 200 mm) with a wall thickness of 5.2 mm. The coating of pipes is PE and the length is 12 m. PE pipelines are composed of PE80 SDR11 with two different diameters: 125 mm (11.4 mm wall thickness) and 63 mm (5.8 mm wall thickness). Distribution network within the City is constructed as a ring system. PE pipelines of 125 and 63 mm, respectively form the ring and distribute gas to the sector. There exist loop and sector valves to cut off the gas to the certain parts of the system in case of emergency and repair situations. Loop valves located on 125mm diameter pipelines with certain intervals whereas sector valves are located where the 125 and 63 mm diameter pipelines are connected (Figure 1a).

Steel pipelines are connected by welding. First, two 12 meters pipes are welded outside before placing in the trench. Then, they are welded with other connected pipes in the trench. Quality of the welds is tested via ultrasonic methods and x-ray films. Furthermore, the coating of the pipes is also controlled against any damages. Any damaged locations discovered during the controls as well as the welded parts of the pipes covered by isolation materials.

PE pipelines are brought to the field as 130 m (for 125 mm diameter) or 148 m (for 63 mm diameter) continuous rolls. They are placed in the trenches and welded by electro-fusion technique. The trenches are 1.3 to 1.9 m deep and about 50 to 60 cm wide. During the placement of pipelines, it is possible to encounter other buried utility systems and if this is the case then the pipeline may pass under those utilities (Figure 1b).

### 2.2 Drinking water

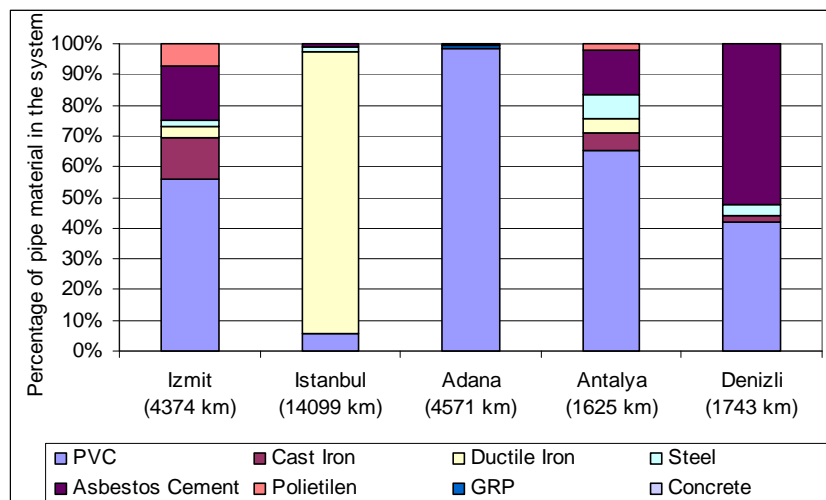
In Turkey, primarily municipalities are owners of the water distribution networks in urban areas and they control and sell water to the consumers. However, the Bank of Provinces (İller Bankası) in Turkey had historically great influence in establishment of water distribution networks in urban areas. The Bank of Provinces is an affiliated institution of the Turkish Ministry of Public Works and Settlement. The Bank of Provinces was first established under the name of “Municipalities Bank” in 1933 and later it was renamed with its current name in 1945 (İller Bankası, 2008). With the restructuring, its authority and responsibility expanded from municipalities to villages and provincial administrations. Its major function was to provide financial and technical assistance to local authorities for settlement development besides banking operations. Among others its main duties included to carry out technical works, to develop projects for urban developments such as water distribution networks, and to implement the projects for the infrastructural investments on behalf of the local governments. A new law in 1968 limited the water related services of the Bank of Provinces to urban areas with populations between 3,000 and 100,000. However, regulations changed later in 1983 which allowed the Bank of Provinces to cover



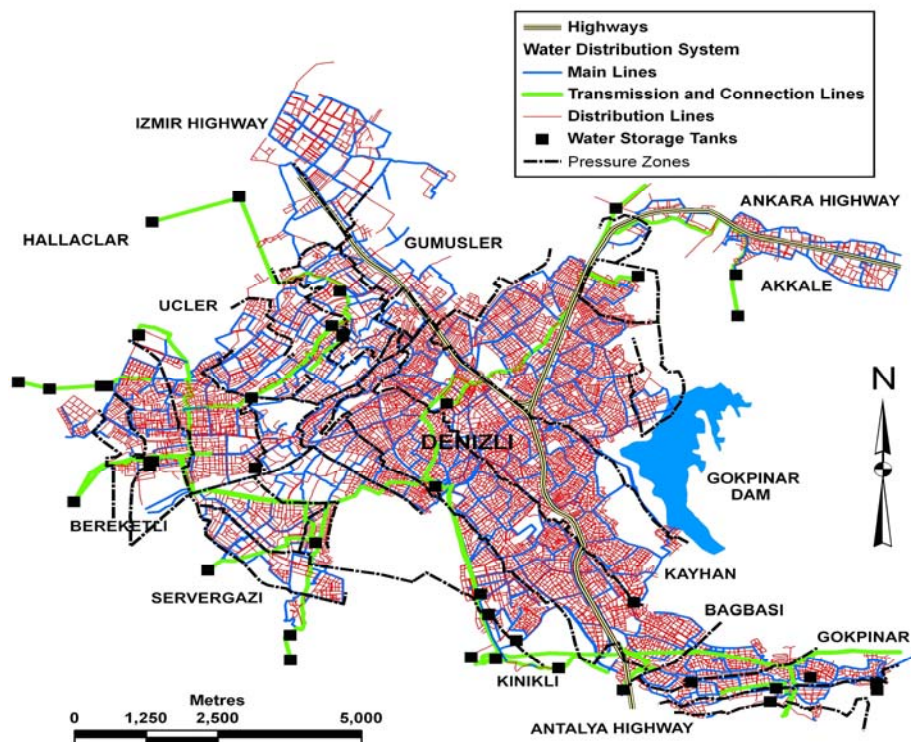
**Figure 1.** PE gas pipelines

Municipalities having a population less than 3,000 and cities with a population higher than 100,000 if their Municipality Committees give the authorization. According to the Bank of Provinces statistics, the total amount of pipelines placed in Turkey by its support between the years 1969 and 2005 was about 175,000 km.

Municipalities have Water Works departments who deal with daily operations of their water distribution systems. Some of these departments, especially in metropolitan municipalities (populations greater than 750,000) have relatively big independent budgets, hence they can plan and organize large investments to their systems (e.g., ISKI for Istanbul). Others mostly depend on the technical and financial support of the Bank of Provinces. Hence, the policies of the Bank of Provinces have direct impact on the composition of water distribution networks in small and mid-size cities. One such policy was the use of primarily asbestos cement (AC) pipes in water supply systems until about mid 1990s. Hence, many water supply systems including the systems at the earthquake regions were built using primarily AC pipe material. In recent years, however use of polyvinyl chloride (PVC) pipes (especially for diameters between 100-200 mm) was increased in the distribution systems. Figure 2 shows the distribution of pipe materials in the water supply system of 5 cities in Turkey (Toprak et al., 2009). Istanbul water distribution system is remarkably different than others as ductile cast iron is the principal



**Figure 2.** Composition of water distribution systems in selected cities of Turkey (Toprak et al., 2009)



**Figure 3.** Map of Denizli City water supply system (Toprak et al., 2009)

pipe material used in the system. Also high proportion of PVC pipes in other distribution systems is clearly noticeable. Discussions with experts from the Bank of Provinces indicated that composition of Denizli water distribution system is more representative of other mid-size cities in Turkey.

The GIS database of the water supply system and its details are provided in Toprak and Taskin (2007) but for convenience, Figure 3 shows the details of the water distribution system in Denizli City. The total length of pipeline is about 1745 km with some 95% of the transmission and connection lines made of steel. The main and distribution lines are asbestos cement AC (54%), PVC (44%) and cast iron (CI – 2%). The diameter of the distribution lines is between 65 and 200 mm whereas the main lines are between 100 and 600 mm in diameter. The CI pipelines are the oldest in the system and primarily serve the more well-established parts of Denizli which include important local business districts with a high population density.

A new comprehensive design project for the water distribution system in the service area of Denizli Municipality was prepared recently in 2007. And construction work for the water distribution pipeline replacements started in 2008. It is intended that drinking water network of all City will be replaced by ductile iron (DI) pipelines at the completion of the ongoing infrastructure project. Two types of DI pipes are used in current construction: K9 and C40.

The internal and external coatings of K9 pipes are cement and zinc, respectively whereas the internal and external coatings of C40 pipes are cement and zinc-aluminum. Figure 4 shows the placement of K9 pipeline. Although both pipes are capable of operating at pressures more than 40 bars, the design pressure is 10 bars for the system.

### 2.3 Waste water

Sewer system of the Denizli city was designed in engineering sense first time in 1986. Previously, sewer system was constructed without any complete project and additions were made when needed. Sewer system was working as a combined system (sanitary and storm) based on the old rectangular cross sectional area open channels. Many problems were observed because there was no separate storm water drainage system. In 2007, Denizli Municipality decided to renew the whole sewer system. A separate storm sewer system was designed.



(a) Compacting the DI pipe bed



(b) Gasket installment for DI pipe

**Figure 4.** The placement of K9 drinking water pipeline**Figure 5.** Construction of new sewer system in Denizli

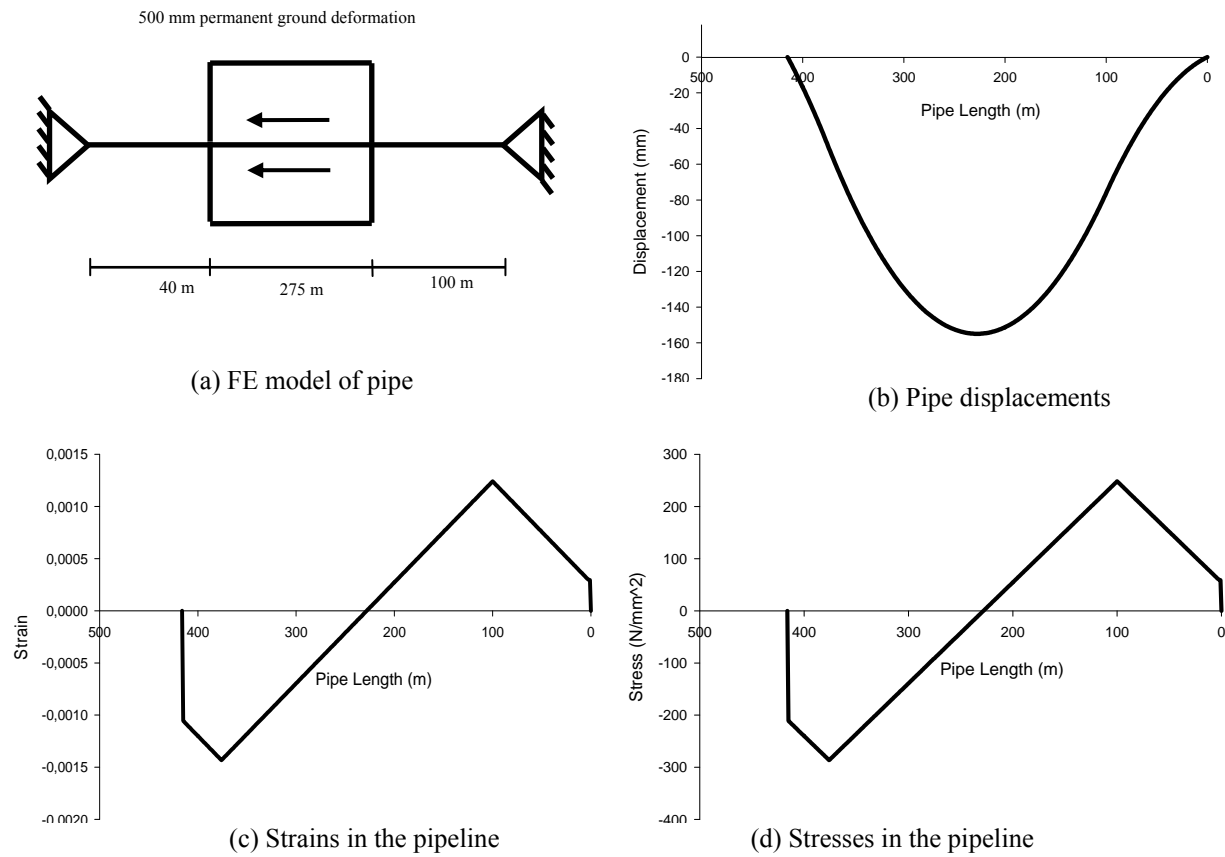
Construction started in 2008 and primarily concrete pipes are used in the sanitary and storm sewer systems (Figure 5). Some large diameter corrugated high-density polyethylene (HDPE) pipes were used in storm sewer system because of their superior specifications to the concrete pipes in large diameters. According to the 2007 project, the total sewer pipe length of Denizli city is 1964 km.

### 3 Analysis of the Lifeline Systems

During the 1994 Northridge earthquake, permanent ground deformation (PGD) occurred in Holocene alluvial sediments along Balboa Blvd. Permanent ground deformations on Balboa Blvd. and adjacent McLennon Ave. affected four gas transmission, one oil transmission, and two water trunk pipelines.

Three of the pipelines failed with serious consequences, and four of the pipelines were not damaged. Accordingly, a case history evaluation of this incident is important for understanding factors contributing to the vulnerability of buried lifelines, calibrating analytical models, and taking corrective measures to improve performance. As discussed by various researchers (Toprak, 1998; O'Rourke and Toprak, 1995; and O'Rourke and O'Rourke, 1995) there were six pipelines which crossed both the tensile and compressive ground rupture zones, including the Mobil Oil Line, Granada Trunk Line, and the Rinaldi Trunk Line, Old Line 120, Line 3000, and New Line 120. Line 3003 crossed only the tensile ground rupture zone. Toprak (1998) presented the analytical assumptions and results for each of the pipelines by using a PGD of 500 mm, which is consistent with the measurements in the field.

In this study, a finite element program, DIANA was used for the analysis (DIANA, 2007). Initial results show consistency with observed and published results. As an example, Figure 6 shows the results for the new line 120.



**Figure 6.** The FE results for the new line 120

This pipeline has a nominal diameter of 610 mm with a wall thickness of 6.4 mm. The external coating of the pipe is epoxy and burial depth is 1.5 m. The yield stress of the pipe material is 415 MPa. The pipeline has almost 90° bends at 100 m away from the tensile zone and 40 m away from the compression zone. These points are modelled as supports in FE model because the pipe movement is constrained by the bends. FEM results show that pipeline displacement as high as 155 mm occurred as a result of 500 mm displacement of 275 m soil block. Maximum pipe strains of % 0.124 and 0.143 were calculated at tensile and compression zones, respectively. The maximum tensile and compressive stresses in the pipeline are 248 MPa and 286 MPa, respectively. The strains and stresses experienced by the pipeline during the earthquake loading are much lower than the yield values and in accordance with the observed behaviour.

FEM analysis of Denizli lifelines for PGD effects from future earthquakes will be performed using the predicted lateral spread displacements caused by liquefaction in the events of M6, M6.3, M6.5 and M7 earthquakes associated with the Pamukkale and Karakova-Akhan faults. Lateral displacements were calculated at each Standart Penetration Test (SPT) sounding location where liquefaction was predicted according to approach recommended by Youd et al. (2002). Liquefaction analysis was performed using the “simplified procedure”. This methodology was first introduced by Seed and Idriss (1971) and later modified by various researchers. Youd et al. (2001) provide a state-of-the-art summary of the consensus recommendations from 20 experts in workshops held in 1996 and 1998. The method requires SPT data and index test results. In this study (related to M6, M6.3, M6.5, and M7 earthquakes associated with the Pamukkale and Karakova-Akhan Faults), Campbell and Bozorgnia (2003) were followed as their attenuation relationship can be used to calculate both peak ground acceleration (PGA) and velocity (PGV). Figure 7 shows predicted lateral ground displacements for M6.3 and M7.0 earthquakes.

The FEM results from the case studies and Denizli lifelines will be utilized in the GIS-based program which is under development in this study. Denizli is selected as a primary pilot area for the application of the software and methodology.

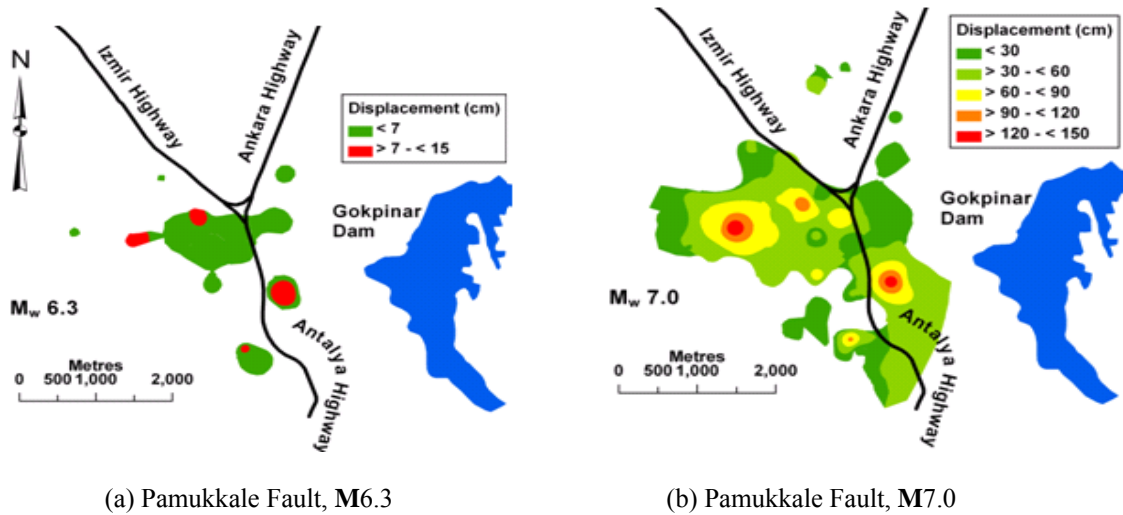


Figure 7. Predicted lateral ground displacements for M6.3 and M7.0 earthquakes (Toprak et al., 2009)

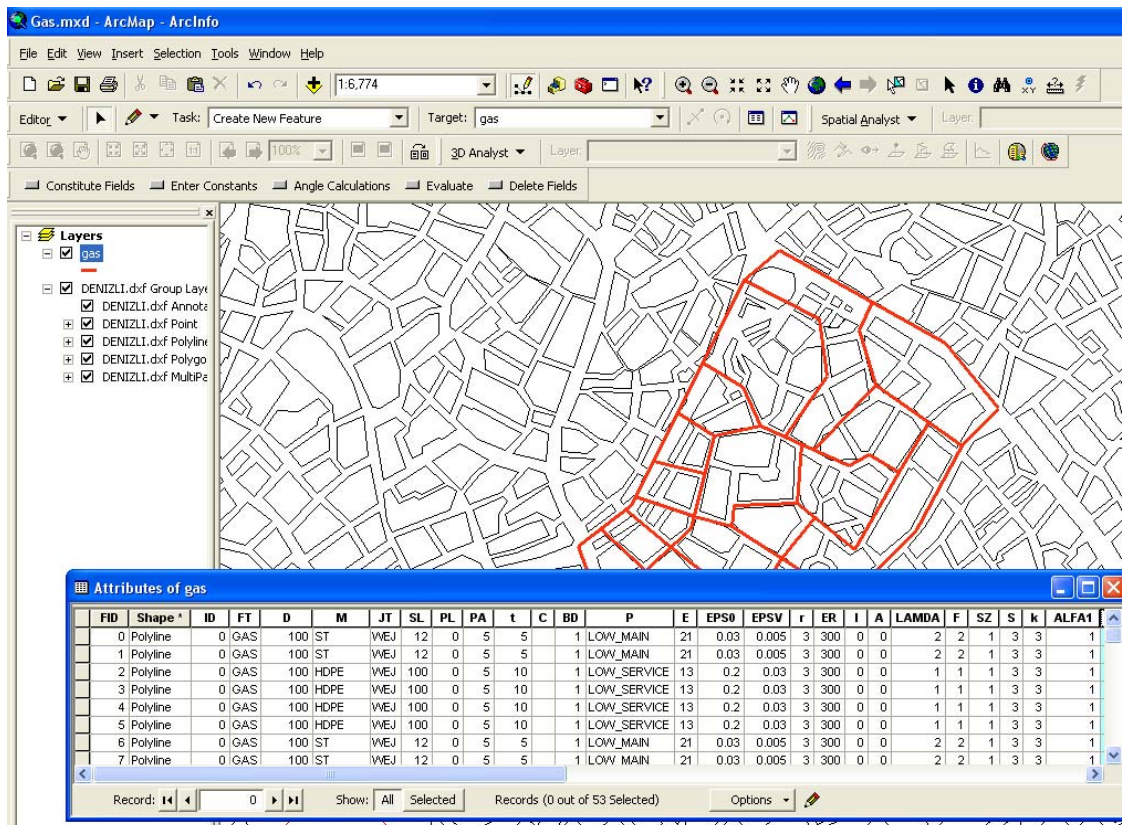
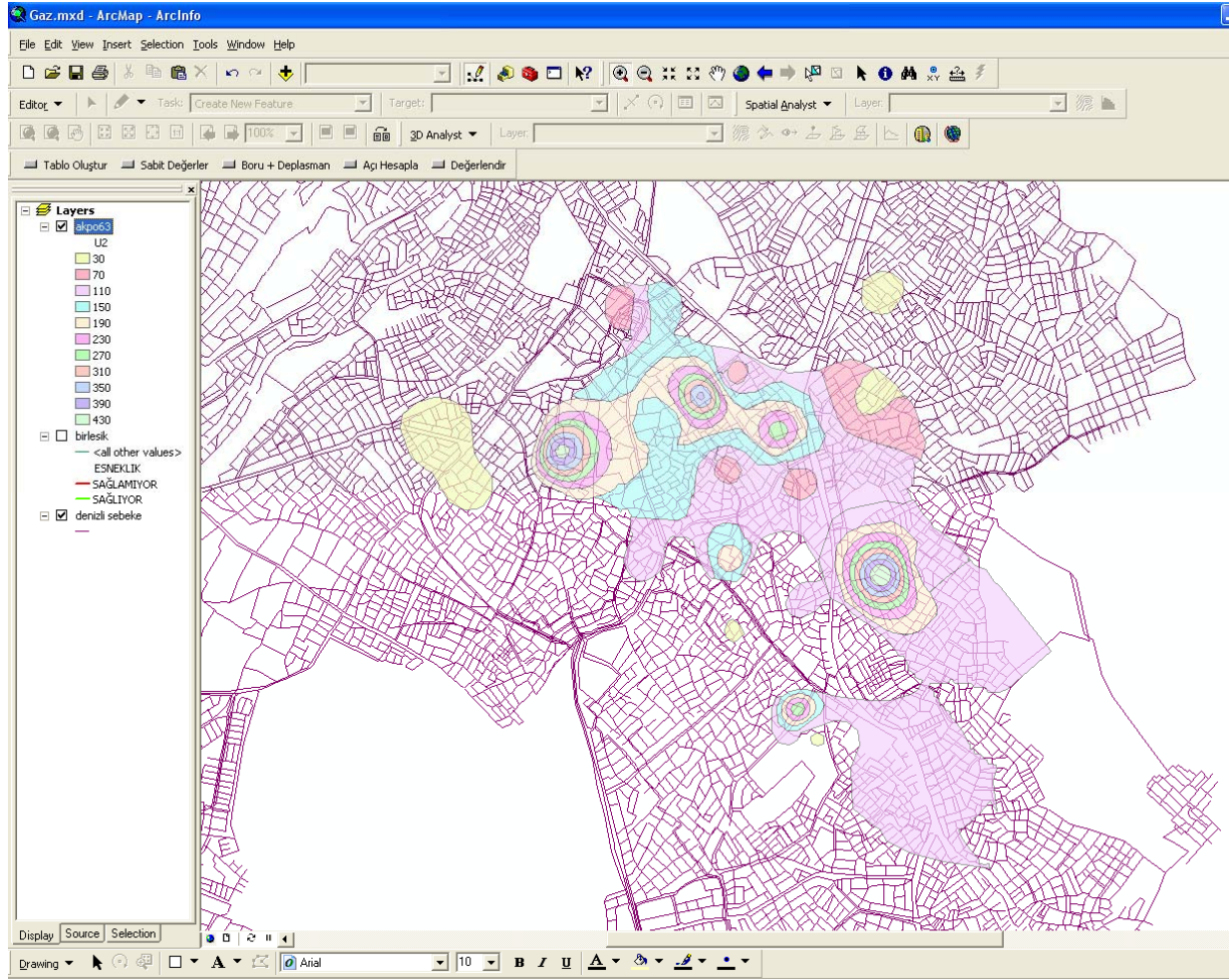


Figure 8. An input and analysis screen from the software

ARCGIS was used in the applications. The user can choose two different levels in the analysis. In the first stage, the software performs basic checks and conformity with the existing codes such as Earthquake Resistant Design Codes in Japan (JSCE, 2000) and international standards such as Earthquake-and-Subsidence-Resistant Design of Ductile Iron Pipelines (ISO, 2006) e.g., evaluates whether the given pipeline system satisfies certain seismic design and code requirements. It generally uses default parameters. In the second stage, the software utilizes more detailed information and FEM results and models. It identifies the pipelines that require further evaluation.



**Figure 9.** Pipelines superimposed on the ground displacement polygons

Some inputs to the program are seismic information (e.g., ground shaking maps) and soil data (e.g. soil type maps, liquefaction hazard maps, etc.). Figure 8 shows an input and analysis screen from the software. Fig. 9 shows pipelines superimposed on the predicted lateral soil displacement given in Fig. 8b. Fig. 10 shows the preliminary evaluation results from the software developed in this study. The software calculates the displacement components from the input map in parallel and transverse direction to any pipeline and checks the response of pipelines with respect to flexibility criteria.

## 4 Conclusions

This study presents the results of an ongoing study on the evaluation of earthquake effects on buried pipeline systems using geographical information systems (GIS). It primarily aims to provide a GIS-based tool and methodology for evaluating seismic effects on buried lifeline systems. Special emphasis was given to integration of geographical information systems (GIS) and finite element method. DIANA finite element program was utilized in the studies. Case study of pipelines around Balboa Blvd from 1994 Northridge earthquake was used for calibration purposes. Denizli was selected as a primary pilot area for the application of the software and methodology. The general characteristics of buried lifeline systems in Denizli City as well as in other urban areas of Turkey were described herein and assessment of these systems against future earthquakes was discussed.

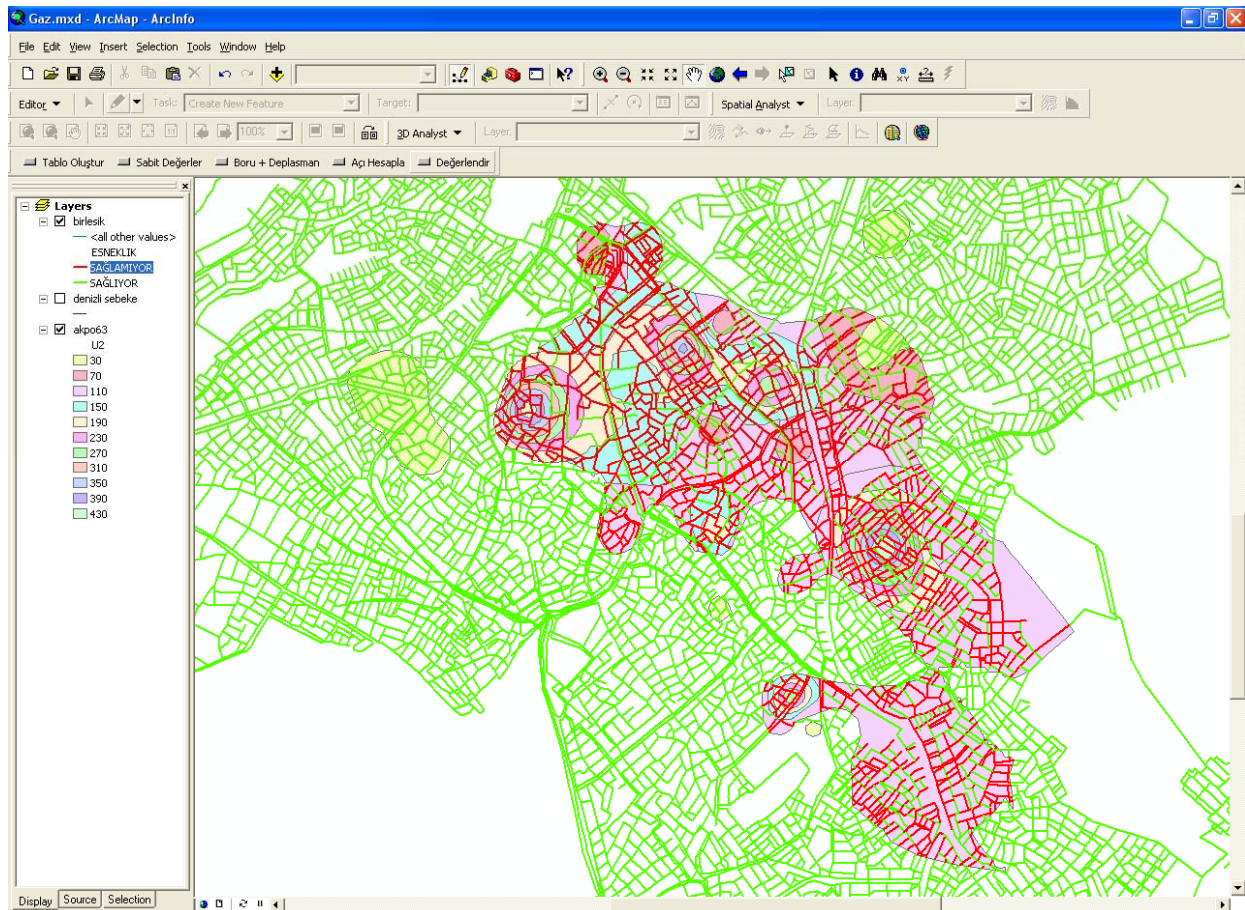


Figure 10. Results of the evaluations

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