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THE ROLE OF GEOTECHNICAL FACTORS ON DAMAGE MODES AND DISTRIBUTION: LESSONS LEARNED FROM ADAPAZARI

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ABSTRACT

The city of Adapazarı, located at the edge of an alluvial basin and in the near field of the causative fault, experienced substantial damage during the 17 August 1999 Kocaeli, Turkey earthquake (M_w 7.4). Two distinct and mutually exclusive modes of building damage were observed at deep alluvium sites: structural system failures due to excessive vibrations and foundation bearing failures apparently associated with the soft and liquefiable surface deposits.

A comprehensive investigation program was undertaken to develop a predictive understanding of the role of geotechnical factors over the building damage observed in the city. The research consisted of the following three major phases: i) site response studies conducted utilizing representative one-dimensional soil response models to investigate the variation of ground motion characteristics in the city, ii) the series of monotonic and dynamic triaxial tests performed to investigate the undrained shear and deformation behavior of silt-clay mixtures which dominated the sites of foundation failure, and iii) characterization of the sites as "stiff" and "soft" on the basis of respective ground attributes to identify the localities of occurrence of the two damage modes.

Results of the one-dimensional soil response studies were found to be highly correlated with the general trends observed in the intensity and distribution of building damage. The laboratory tests showed that the dynamic stiffness and strength of the silt-clay mixtures did not display any trends that could be interpreted as "liquefaction" under means of loading comparable to that imposed by the earthquake. Outcome of the site characterization consistently predicted the respective sites of occurrence of the two distinct damage modes. It was concluded that the buildings over soft sites benefited from significant reductions in seismic demand owing to the strong nonlinear soil response, and escaped from pancake-type collapse.

Keywords: Cyclic triaxial test, Foundation failure, Kocaeli earthquake, Nonlinear soil response, Silt-clay mixtures, Site effects

INTRODUCTION

The City of Adapazarı (Pop. 190 000), located in northwestern Turkey and at a mere average distance of 5 km from the surface rupture of the causative North Anatolian Fault, was among the worst affected urban centers during the 17 August 1999 İzmit (Kocaeli) earthquake (M_w 7.4). About 2% of the city's population was killed and 12% of the buildings (over 2800) either collapsed or were heavily damaged during the earthquake. Extent and patterns of damage to building structures in Adapazarı was peculiar in several ways and continues to draw worldwide researcher interest.

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Distribution of the building damage throughout the city, which is sited at the edge of a sedimentary basin, was highly non-uniform. The overall damage was strikingly low in the southern section, underlain by stiff and shallow residual soils, despite the closer proximity to the fault. As a general trend, damage concentration increased rapidly to the north over the soft and thick alluvial deposits, with four- to seven-story RC buildings receiving the greatest impact. The sharp variation in the distribution of damage clearly indicated the existence of well-known local site effects such as motion amplification and low frequency enhancement associated with the alluvial basins which are particularly unfavorable to structures with higher periods. More remarkably, however, two strongly contrasting modes of building damage occurred in reinforced concrete (RC) buildings with similar characteristics over the alluvial deposits: structural system failures due to excessive vibrations and foundation bearing capacity failures apparently associated with the weak or liquefiable surface deposits. As these two modes of damage were observed to be strictly mutually exclusive, the weak or liquefiable surface soils evidently provided a means of natural base isolation for numerous buildings in the city. Due to this remarkable phenomenon the number of structural collapses, and hence loss of life, can be argued to have been reduced significantly, considering that the pancaked reinforced concrete buildings were primarily responsible for nearly 3700 lives being lost in the city. Subsequent field investigations indicated that the foundation failure sites predominantly consisted of fine-grained surface soils of low plasticity (silt-clay mixtures), defined as CL or ML according to the Unified Soil Classification System, the seismic liquefiability of which has yet been a controversial issue.

A comprehensive research program, partly in progress, was undertaken to develop a predictive understanding of the role of geotechnical factors over the building damage in the city by the Civil Engineering Department of the Middle East Technical University. The effort consisted of three major complementary phases. In the first of these, geotechnical characteristics of the ground structure underling the city were identified on the basis of available borehole information, and representative one-dimensional ground response models were constructed. These models were calibrated utilizing a series of aftershock records and used for site response studies to estimate the variation of ground motion characteristics in the city. The results were contrasted to the general trends observed in the intensity and distribution of the building damage. In the second phase, an answer was sought to the question, whether the deposits of silt-clay mixtures underlying the sites of bearing capacity failures had liquefied during the earthquake. For this purpose, the undrained behavior of these soils was investigated through a series of parallel monotonic and dynamic triaxial tests performed over natural soil samples. In the final phase, characteristic attributes of the alluvium sites were identified on the basis of amplification or de-amplification of the strong motion. Subsequently, distribution of the sites thus categorized was contrasted to that of the collapsed buildings in the city with known location coordinates to elucidate the occurrence of distinct damage modes.

The paper aims at a unified assessment of the critical role the geotechnical attributes played on the building damage in Adapazarı. Following a review of each of the three major research phases, significance of the results, which were generally contradictory to the early presumptions, are discussed. The case of Adapazarı is unique in several ways from the viewpoint of geotechnical earthquake engineering and, no doubt, the lessons derived will be vastly influential in understanding and mitigation of the seismically induced damage.

OVERVIEW OF GEOTECHNICAL CONDITIONS AND BUILDING DAMAGE

Older and relatively smaller part of Adapazarı is situated on the stiff and shallow soils on the south, while the greater part rests over the alluvial basin on the north, which is a former lake bed. Figure 1 presents the geological highlights of the area of interest. Bedrock formation descends sharply through

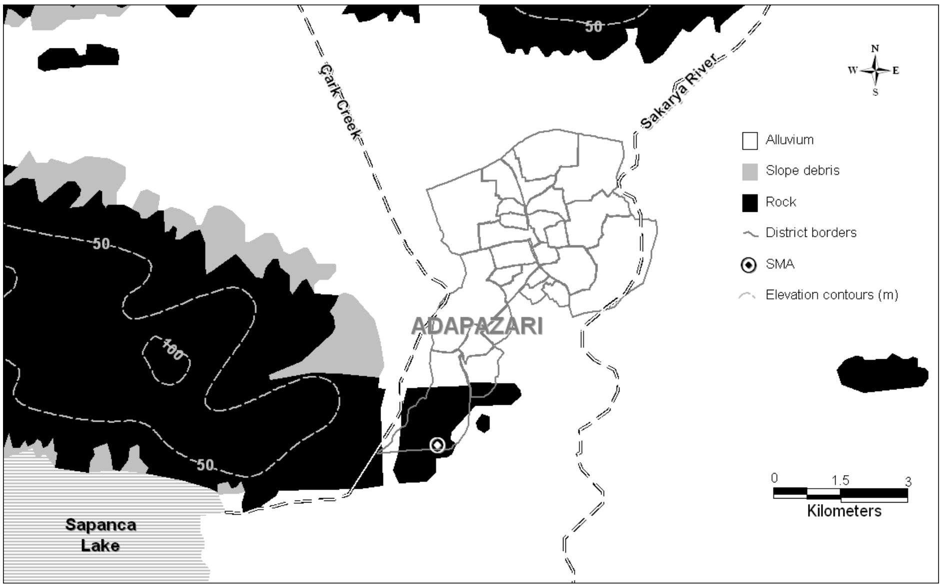

Figure 1. Main geological features of Adapazarı

north, reaching depths in excess of 200 m within the city limits. On the basin, Quaternary stream deposits of about 15 m thickness overlay the deep clay layers that are lake sediments. Within this range the soils dominantly consist of normally consolidated mixtures of fine sand, silt and clay of variable proportions with occasional bands of sand and gravel. Figure 2 depicts the central municipality districts and the variation of depth to bedrock.

Damage was heavily concentrated at the central part of the city on the basin, where alluvial soil thickness varies from about 125 m to over 200 m. In several central districts the ratio of collapsed and heavily damaged buildings exceeded 20%. The worst affected building class constitutes relatively new 4- to 7-story apartment buildings with reinforced concrete load bearing systems and hollow brick infill walls. These buildings, almost without an exception, were constructed over shallow rigid mat foundations due to the rather weak surface soils and consistently high levels of ground water on the alluvial basin.

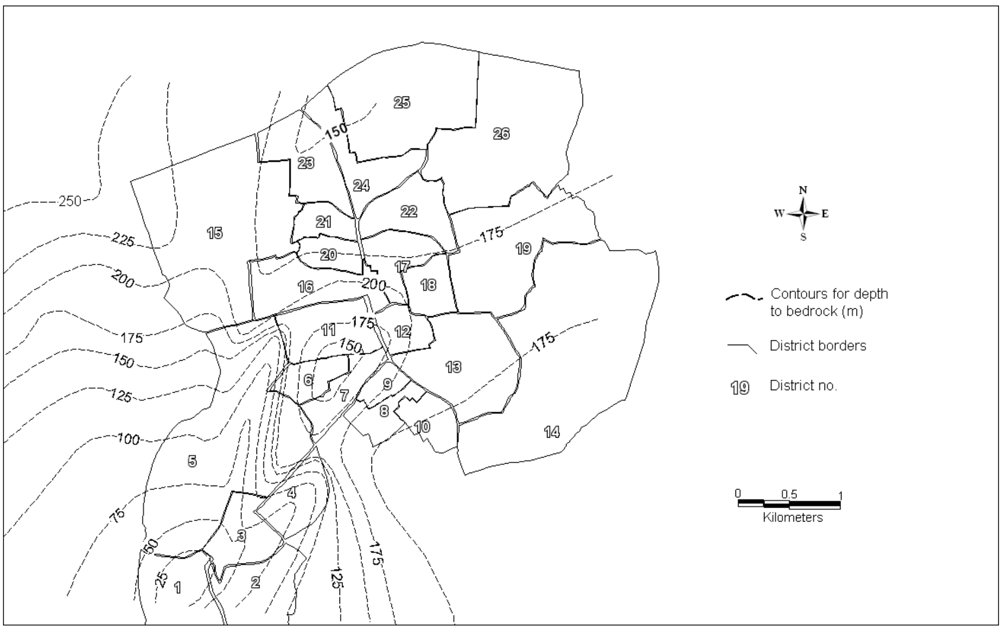

Figure 2. Central municipality districts and variation of depth to bedrock

Two distinct and mutually exclusive modes of building damage were observed in the city: structural system failures and foundation displacements (failures) in the forms of settlement, tilting and lateral movement (Figures 3 and 4). Occurrence and severity of foundation displacements were evidently associated with factors such as strength of foundation soils, building height, foundation aspect ratio and presence of adjacent buildings. Displacements were more pronounced in the case of taller buildings with poor foundation aspect ratios and in general decreased with decreasing story number. In the blocks of adjacent buildings, the displacements were relatively less and commonly in the form of uniform settlements up to about 25 cm, whereas the buildings at block ends typically experienced excessive tilts. Foundation displacements exceeded tolerable limits in numerous buildings; the mat foundations however, remained intact even in the cases of extreme tilting and settlement. Remarkably, those buildings which were subjected to foundation displacements did not sustain any structural damage, irrespective of the form and extent of the displacements.

Clear surface manifestations of soil liquefaction were rare throughout the city. In some cases ground heaving accompanied the foundation failures generally within 1- 2 m strips nearby the buildings, whereas large settlements occurred in several others without apparent ground heaving.

Figure 3. Building damage in the form of bearing system failures at stiff sites

Figure 4. Building damage in the form of foundation bearing failure at soft sites

Building Damage Data

The structural damage in Adapazarı is correlated with the local site conditions through two sets of data, both based on the collapsed building cases. One of these data sets is acquired through reduction of the data surveyed by the General Directorate of Disaster Affairs of Turkey (GDDA), covering damaged buildings in the city comprehensively. The reduced set consists of statistics expressing the ratio of collapsed buildings to that of total number of damaged on the basis of municipal districts. Also, the buildings with three and fewer stories were eliminated during the reduction process, as the majority of such buildings were relatively old and non-engineered. The preference of collapse statistics is due to the initial confusion regarding evaluation of foundation displacements and the associated misinterpretations during the damage assessment surveys. The other set, which is a subset of the first, consists of 241 collapsed buildings all of which had reinforced concrete frame load bearing systems with known location coordinates. This set is utilized to contrast the positions of the collapsed buildings with the variation of surface deposit characteristics within the city. Both of the data sets are presented and discussed in detail by Yakut et al. (2005).

SITE RESPONSE STUDIES

The main event of the 17 August earthquake was recorded in Adapazarı by a strong-motion station located only about 3 km north of the observed surface rupture. Due to a malfunction, the only registered lateral accelerogram was the east-west component, which is almost fault parallel. The record is representative of the ground motion in the southern section of the city, which is underlain by stiff and shallow residual soils and the intensity of damage was low. The ground motion characteristics, however, are to be significantly altered over the deep alluvial soils as manifested through the sharp variation observed in the concentration of damage.

Bakir et al. (2002) investigated the local site effects on the distribution of ground motion intensity and the associated building damage in Adapazarı. The variation of ground motion over the deep alluvial soils of the basin was estimated through one-dimensional site-response analyses. For this purpose, a soil column representative of the profile at deep alluvial sites was constructed combining the highly consistent stratifications observed in the deep borehole logs with the highly variable stream deposited surface soils encountered in the top 15 m. Data from aftershocks with magnitudes varying between 4.2 and 5.8, recorded simultaneously over stiff shallow soils and deep alluvium were utilized to calibrate the model through adjustment of shear-wave velocities of deep clay deposits dominating the profile. Figure 5 presents the idealized soil column utilized in site response analyses and the corresponding shear-wave velocity variation along with the logs of deep boreholes.

The east-west lateral component of the mainshock recorded in the city was deconvolved and assigned as the rock motion. Analyses were conducted using the computer program SHAKE (Schnabel et al., 1972). Ground surface acceleration time histories computed for various thicknesses of alluvium as dictated by the variation of bedrock and that of the recorded lateral component are presented in Figure 6. Corresponding 5% damped response spectra are given in Figure 7.

Evaluation of the Analyses Results

In Figure 6 the peak horizontal acceleration is observed to be amplified by a factor up to 1.2 depending on the depth of alluvium. More importantly, however, the high frequency components are effectively eliminated from the time histories representative of ground motions at deep alluvium sites, as would be expected. The particularly adverse effect of this elimination over the relatively higher building structures in the city is obvious in Figure 7. In the period range between 0.25-0.5 s, typical of three- to four-story buildings, the spectral accelerations of the computed motions on the alluvium exceed that of the mainshock record (representative of shallow residual soils) up to about 0.5g, depending on the depth to bedrock. Spectral differences exceed 0.8g in the period range of 0.5-0.7 s, typical of five- to six-story buildings, with corresponding amplification ratios ranging between 1.5 and 3. Besides, the dependency of spectral accelerations over the alluvium depth is rather pronounced in this period range. Hence, it can be concluded that the buildings with three or more stories, and particularly those of five- to seven-stories, located over alluvial sites in Adapazarı were subject to considerably larger seismic forces during the 17 August earthquake, compared to those over favorable ground in the southern part of the city.

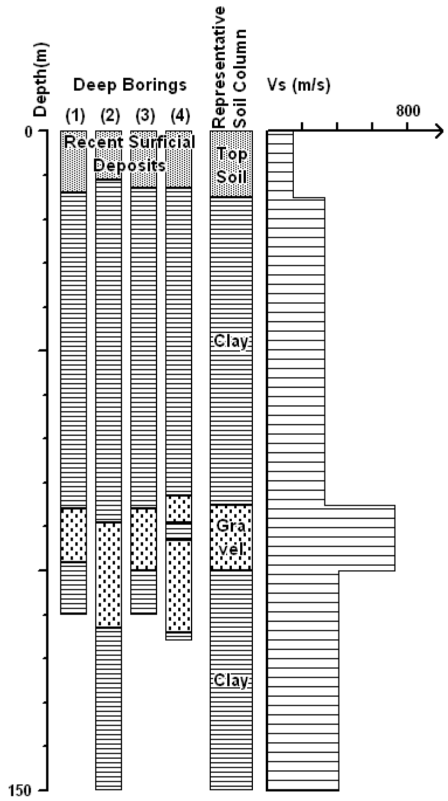

Figure 5. Deep borehole logs, idealized soil profile and variation of shear wave velocity

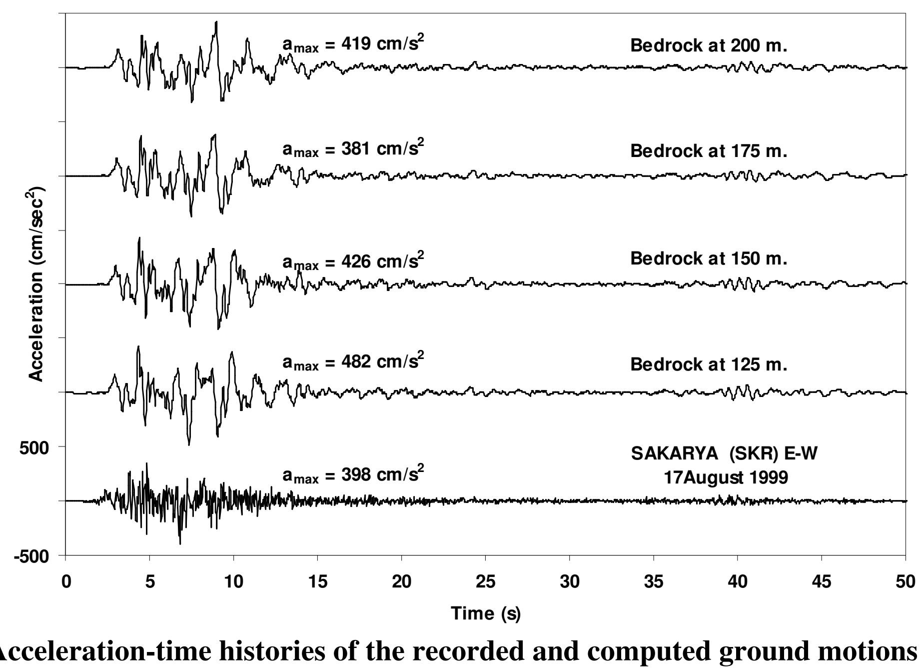

Figure 6. Acceleration-time histories of the recorded and computed ground motions for various depths of alluvium

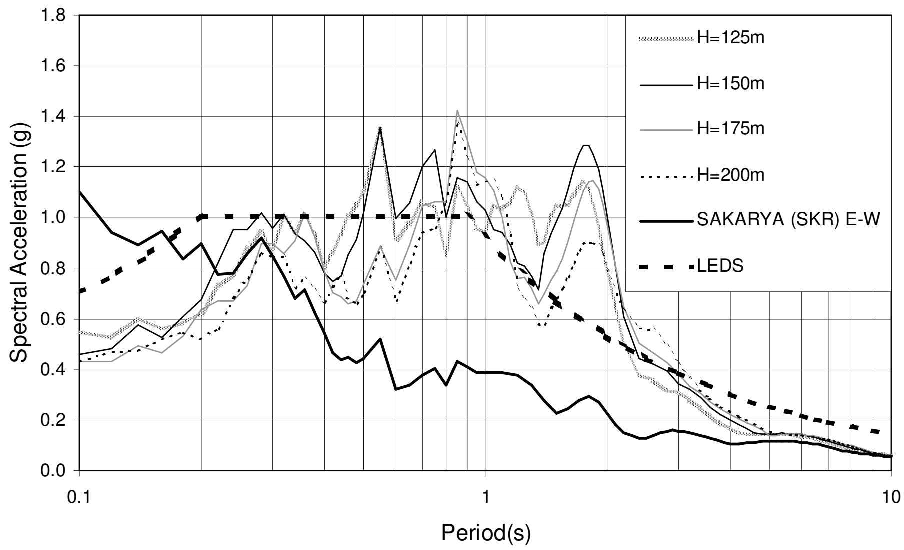

Figure 7. Acceleration response spectra (5% damped) of the Adapazarı record and computed ground motions for various depths of alluvium (thick dashed line is the associated linear elastic design spectrum specified in the Turkish Seismic Code)

SHEAR AND DEFORMATION BEHAVIOR OF ADAPAZARI SILT-CLAY MIXTURES

Widespread bearing failures of shallow mats in Adapazarı were particularly remarkable from the geotechnical engineering perspective. Generally shared point of view in the preliminary evaluations made by independent reconnaissance teams that visited the city following the earthquake was that these failures were likely to be liquefaction induced. Surface soils in the part of the city overlying the alluvial basin were known to consist of commonly loose to medium stiff sand layers with apparent potential for liquefaction. Interestingly, however, subsequent ground investigations conducted at the sites of observed foundation displacements revealed that the sand layers, if existed, were consistently too deep and had quite high penetration resistance to liquefy. Within top 10 m of the profile the soils were predominantly fine grained and of low plasticity (silt-clay mixtures), classified as CL/ML. As of present, the cyclic behavior of such soils is relatively less studied compared to those of sands and their seismic liquefiability has yet been a controversial issue. Yilmaz et al. (2004) studied the undrained cyclic shear and deformation behavior of Adapazarı silt-clay mixtures to investigate the likely mechanism(s) that led to the collapse of foundation soils during the 17 August earthquake, and discussed implications of the findings with relevance to the seismic performance of building foundations in the city.

Testing Methodology

Undisturbed soil samples were retrieved from 2 to 4.5 m depths at the sites of foundation failure in the city. Test specimens were extruded side by side from the same level in a sampling tube to form consistent sets of test with identical material. Samples in each set were consolidated under similar initial isotropic and subsequent anisotropic stress conditions so as to follow the representative stress paths to the long-term pre-earthquake state of stress of the foundation soils. Following consolidation, one sample in each set was subjected to triaxial monotonic compression test, while the remaining samples were tested cyclically. All the tested samples were transition material between ML and CL type soils on the plasticity chart (Figure 8)

In cyclic tests the samples were subjected to one-way (compression only) and two-way (i.e. deviator stress cycled between negative and positive values) loading. Based on the frequency characteristics of the calculated surface motion of 17 August earthquake on the alluvial basin, sinusoidal cyclic axial loads were applied with frequencies of 1 Hz and 0.5 Hz. Following dynamic loading, the samples were brought back to the initial anisotropic stress-state and were monitored for about 5 min for existence of an imminent state of failure or any deformations due to possible substantial loss of strength induced by cyclic loading. Finally, the samples were sheared under rapid monotonic loading (in about 2 s) with a range of stress rates between 10 and 160 kPa/s, to observe the effect of more pronounced viscous soil response on the apparent strength.

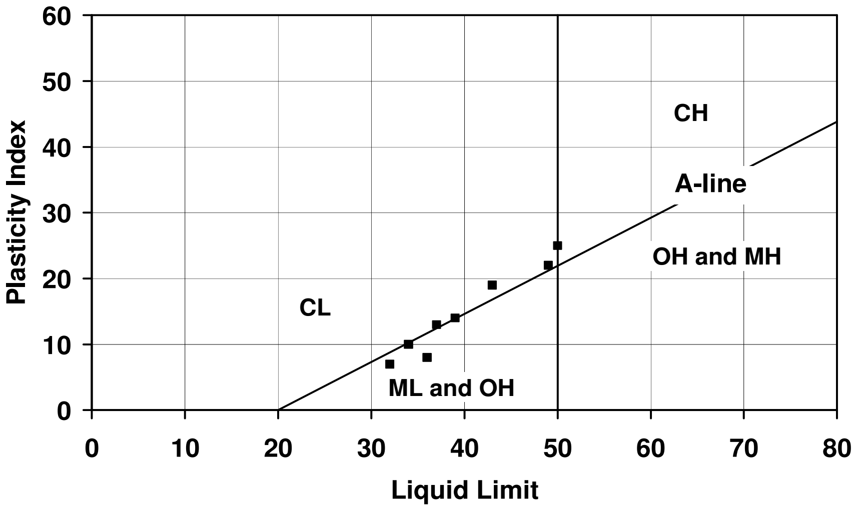

Figure 8. Plot of tested samples on plasticity chart

Test Results and evaluation

Distinct trends were observed in the cyclic tests depending on the type of loading (one-way or two-way), as well as the respective levels of applied minimum and maximum deviatoric stress. The results representative of the general trends are presented in Figure 9a-d, where monotonic compression, cyclic and consequent rapid loading responses are superposed for each set of test.

For one-way loading with the peak stress exceeding monotonic strength, plastic strains are observed to accumulate with almost a constant rate for each cycle (Figure 9a). Whereas in the case of peak cyclic stress remaining below monotonic strength, plastic strains still occur in each cycle; the incremental strain amplitudes, however, are much smaller, and tend to decrease rapidly with increasing number of cycles (Figure 9b). No cyclic degradation was observed in stiffness of the samples tested under one-way loading condition, even in cases the monotonic strength is exceeded. In the case of two-way loading, based on the maximum and minimum levels of deviatoric stress applied, the specimen can develop incremental cyclic strains in compression and/or extension, corresponding representative plots of which are presented in Figure 9c and 9d.

Despite demanding cyclic load combinations applied in several of the test, none of the samples in the series displayed a state of failure, or even any limited deformations following cyclic loading. The other noteworthy observation from Figure 9a-d is that the apparent strength increase with reference to monotonic strength is significant in the rapid loading stage. Such behavior, which is associated with cohesion, can be attributed to the pronounced viscous response induced by the increased speed of loading.

An overall evaluation of the test results indicate that the relatively large permanent displacements of the building foundations situated over the fine surface deposits in the city would not be possible, unless the capacity defined by monotonic strength is significantly exceeded during seismic shaking. Test results also indicate that the viscous behavior dominates the strength and plastic deformation accumulation response of these soils under loads with increased rates of loading.

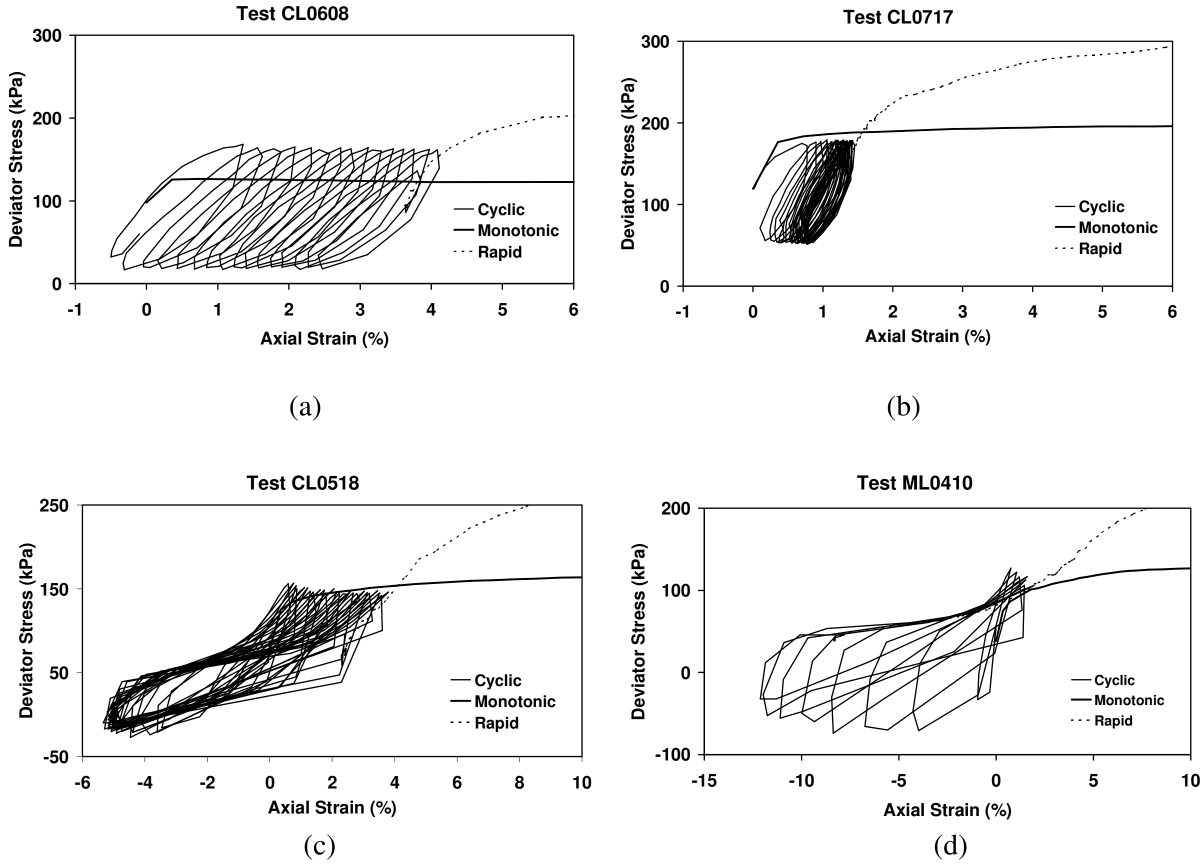

Figure 9. Stress-strain responses representative of distinct trends observed in cyclic triaxial tests with corresponding monotonic and rapid compression triaxial test results: (a) one-way compressive loading with peak axial stress exceeding monotonic strength, (b) one-way compressive loading with peak axial stress remaining below monotonic strength, (c) two-way loading with specimen cyclically failing in compression and (d) two-way loading with specimen cyclically failing in extension

BENEFICIAL EFFECTS DUE TO NONLINEAR SOIL RESPONSE

The peculiar damage patterns emerged in Adapazarı were re-examined in an effort to understand whether they are indicative of a consistent trend in terms of the building attributes and/or site conditions. Part of this extensive study consisted of a reevaluation of the available databases comprising buildings surveyed in the city following the earthquake. Buildings were rated from the viewpoint of conventional seismic performance using accepted parameters to confirm the observed damage. An examination based solely on structural attributes, however, showed that the building collapses in Adapazarı were too involved to be reduced to a few simple deficiency factors and the site effects were likely to have played a major role in the observed damage (Yakut et al., 2005). Geotechnical attributes were combined subsequently by Bakir et al. (2005) to identify whether, all other factors related to structural characteristics being uniform as they were in the urban center of Adapazarı, the geotechnical factors could have played the critical role.

Regarding the two distinct modes of damage emerged in Adapazarı, while collapsed or structurally heavily damaged buildings had no foundation displacements, those sustained bearing failures had no structural damage, irrespective of the form or extent of the foundation displacement. Hence, the nonlinear soil response manifested by the widespread foundation displacements evidently provided means of natural passive base isolation for numerous buildings in the city during the 17 August earthquake.

Although recognized for quite a long time, the phenomenon of seismic demand reduction due to strong nonlinear response of soft or liquefiable soil deposits, contrary to the traditionally held idea that the seismically induced structural damage is greater on “poor” ground, has been receiving greater attention more recently. The evidence of such beneficial effects comes from field surveys that contrast structural damage distribution during major earthquakes with the large strain capability of soil deposits (Trifunac and Todorovska, 1999; Trifunac, 2003; Tokimatsu et al., 1994) and strong motion records captured in vertical arrays, as well as from laboratory studies with dynamic centrifuge model tests (Liu and Dobry, 1997; Hausler and Sitar, 2001). Soils responding nonlinearly during strong shaking can provide beneficial effects over structural performance through two possible modalities: first, seismic wave energy reaching to the ground surface may be partly absorbed by the deposit; and second, foundation – soil interaction may become more pronounced during seismic shaking, shifting to the nonlinear range. Either way, the seismic demand can be reduced in the short period range.

Site classification and idealized spectra

A site-specific geotechnical classification methodology, aiming at estimation of surface response and simplified interpretation of building damage in Adapazarı associated with the 17 August earthquake was developed and implemented over central municipality districts of the city. Within this context, the reduction of seismic demand over RC building structures due to soft and liquefiable surface deposits were investigated through contrasting the spatial variability of local soil characteristics and estimated surface response to the distribution of structural damage. Available geotechnical information is utilized to classify the sites as “stiff” or “soft”, considering amplification and de-amplification characteristics of surface deposits encountered in the city. Accordingly, based on the results of preliminary analytical and numerical site response studies, the soft sites for potentially liquefiable deposits (loose sands and silty sands) and non-liquefiable fine deposits (silt-clay mixtures) were characterized on the basis of uncorrected Standard Penetration Test (SPT) blow counts as follows:

(1) Sands and silty sands with SPT-$N_{45} \leq 30$
(2) Silt-clay mixtures with SPT-$N_{45} \leq 10$

Sites with surface deposits complying with the above criteria for at least 50% of the 10 m were referred as “soft sites”. Significant reductions are presumed to have occurred in seismic demand on typical RC building structures at such sites in the city. Conversely, the sites not confirming to the above definition are referred to as “stiff sites”, at which the ground motion is anticipated to have amplified to some degree.

An idealized set of spectra representative of the ground shaking during 17 August earthquake within city limits were constructed through compilation of the results of a series of 1-dimensional response analyses based on alluvium depth, as well as a characterization of the sites according to the criteria specified above. Effects of local sites on the building damage were interpreted utilizing two sets of damage data, as explained earlier: i) through comparison of the spectral acceleration distribution to the collapsed building statistics on the basis of municipal districts, and (ii) through contrasting variation of surface deposit characteristics with the distribution of available collapse cases with known location coordinates. A set of sample spectra generated utilizing the codification developed is presented in Figure 10 together with the smoothed response spectrum of the Adapazarı record.

Correlation of site conditions and damage

As observed in Figure 10, in the period range representative of three- to five-story buildings, differences between the spectrum of the main shock seismogram and the spectra of the computed ground motions on stiff sites over deep alluvium increase with increasing period, approaching 0.3g, depending on the alluvium thickness. In the period range of 0.5-0.7 s, representative of five- to seven-story buildings, spectral differences reach 0.5g. Accordingly, it is concluded that during the 17 August earthquake, disregarding any de-amplification potential of surface deposits, buildings with three or more stories located on deep alluvial soils in Adapazarı were subjected to considerably larger seismic forces compared to those over shallow residual soils in the southern section of the city. This is consistent with the general trend of building damage distribution observed in the city. At those sites classified as "soft", however, substantial decreases are expected to have occurred for all categories of buildings in Adapazarı.

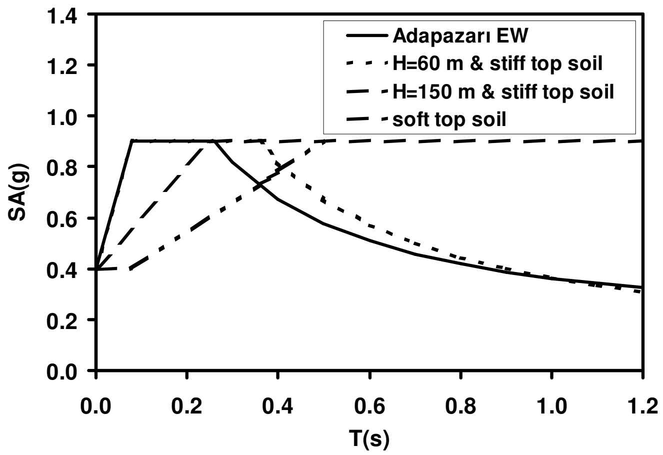

Figure 10. Sample spectra for soft and stiff sites (outcrop spectrum is the smoothed spectrum of Adapazarı record

To ascertain the effects of local sites on damage, collapsed building statistics for buildings with four and more stories on the basis of municipal districts are contrasted in Figure 11 with the variation of surface deposit characteristics in the top 10 m of the borehole logs. The percentages of liquefaction susceptible soils (sand and silty-sand) encountered within the depth of interest are indicated by gray scale circles at borehole locations. The circles are enclosed in squares in case the site soils complied with the soft site criteria. Collapse rates are observed to be reduced in general in the central part of the city (districts 11, 12, 16, 17, 18 and 20) where surface deposits are predominantly liquefaction prone or classified as soft site, despite the concentration of taller buildings with potentially higher seismic vulnerability in the area. Conversely, the rates are generally increased in the districts where surface deposits are mainly stiff or less sensitive to liquefaction (districts 15 and 22).

Utilizing the idealized spectra (Figure 11) and variation of depth to bedrock (Figure 2), distribution of spectral accelerations is computed corresponding to the 0.5 s period, representative of the range of fundamental periods of 3 – 7 story RC buildings, and contour mapped in Figure 12. Distribution of the areas identified as soft sites are superimposed on the same figure, together with the positions of collapsed buildings for which the location coordinates were available. Spectral accelerations range over 0.6g – 0.9g and are observed to increase with increasing alluvium depth. Almost all of the collapsed buildings are located within the highest spectral acceleration zone, clearly indicating the influence of alluvium depth over seismically induced force levels imposed over building structures during the earthquake. The striking observation from Figure 12, however, is that the indicated locations of 4 – 7 story collapsed buildings, with few exceptions, lie outside the patches marking soft sites, over which substantial reductions in the seismic demand are anticipated to have occurred. This outcome is consistent with the post-earthquake observations relating to certain zones in the city where buildings with substantially reduced levels of structural damage were commonly accompanied by foundation displacements of various forms and levels, an apparent indication of strong nonlinear response of surface soils.

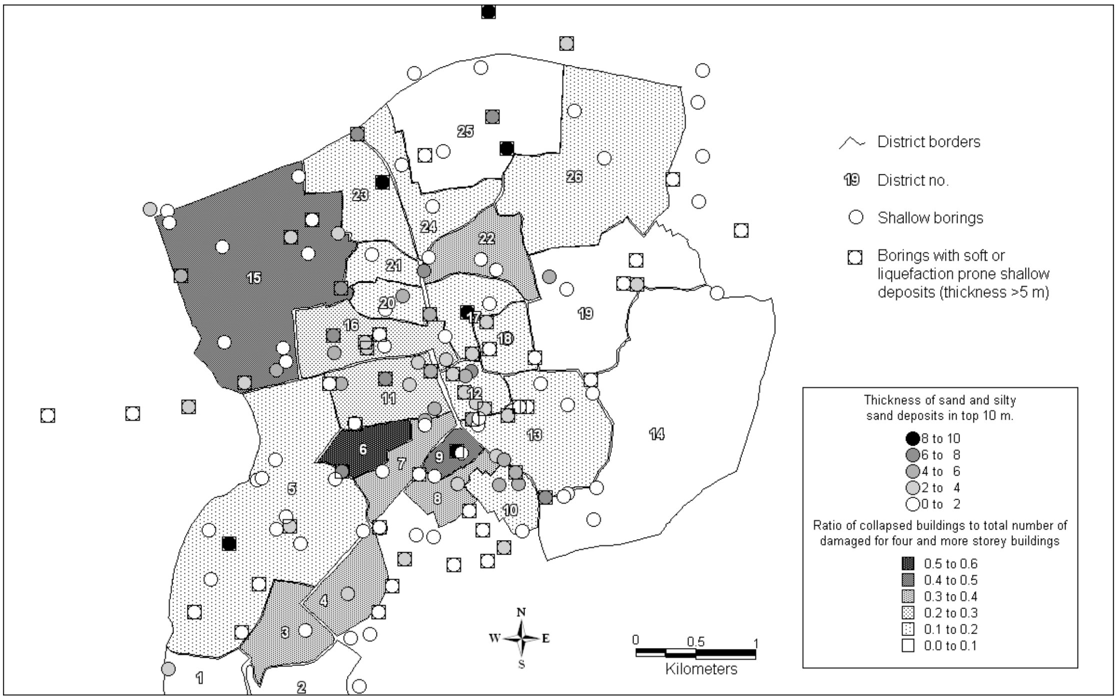

Figure 11. Collapsed building statistics for buildings with four and more stories in Adapazarı on the basis of municipal districts compared to the variation of surface deposit characteristics in the upper 10 m of the profile

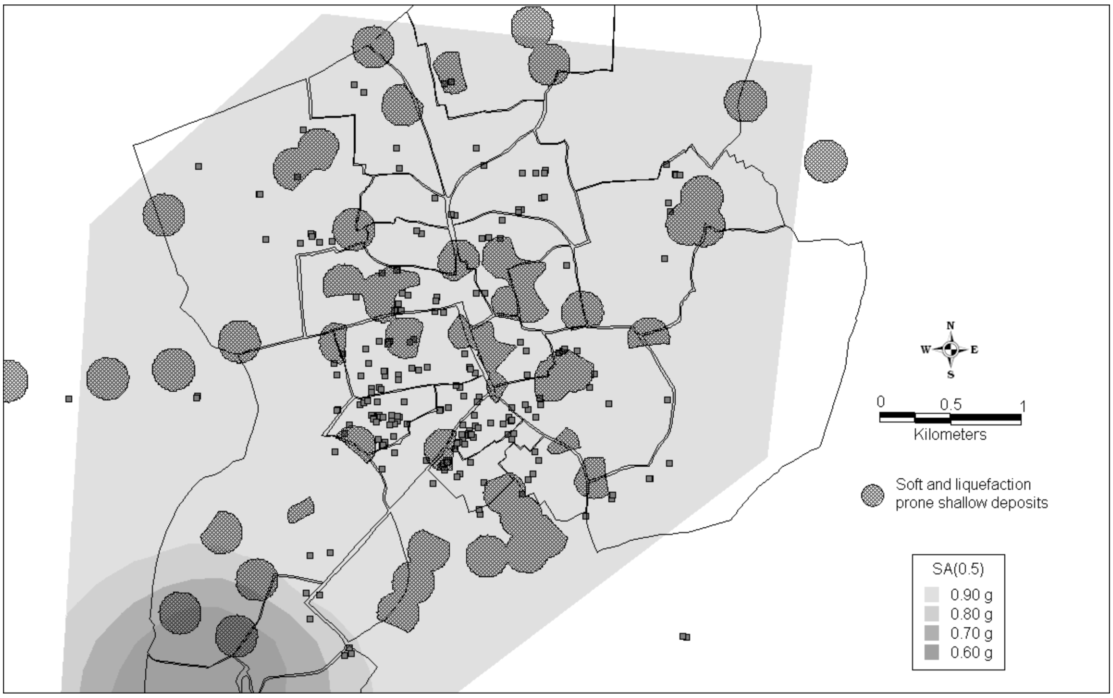

Figure 12. Variation of spectral acceleration corresponding to 0.5 s period (squares indicate locations of collapsed buildings and dark gray patches mark the soft sites)

DISCUSSION AND CONCLUSIONS

The highly variable ground characteristics underlying the city of Adapazarı played a dominant role on the extent and distribution of ground motion intensity and on the subsequent building damage during the 17 August 1999 Kocaeli earthquake. The effect of geotechnical factors over damage to building structures was investigated through a comprehensive study consisting of three major phases, the results and implications of which are briefly discussed in the following.

One-dimensional soil response analyses yield consistent results with the post-earthquake observation of general trends in the distribution and extent of damage in Adapazarı. It is also to be recognized that the presented site response analyses do not involve site-dependent effects due to strong nonlinear soil behavior, which may result in substantial reductions over spectral acceleration response for certain period intervals.

Results of the series of monotonic and dynamic triaxial tests performed over silt-clay mixtures forming the surface deposits at the sites of foundation displacements show that, under means of dynamic loading estimated to have acted during the 17 August earthquake, these soils do not display any trends that can be interpreted as "liquefaction", regarding stiffness and strength response. Their cyclic strain characteristics, however, critically depend on the relative level of peak cyclic stress with regard to the monotonic shear strength: while plastic strains can rapidly accumulate at practically constant rates per cycle in case the monotonic strength is exceeded, they tend to remain insignificant otherwise. The pronounced viscous response of these soils under rapid monotonic loading is reflected through significant increases of apparent strength.

Regarding seismic response of shallow mat on soils with comparable characteristics, these findings imply that excessive permanent displacements would not be possible unless the bearing capacity defined by monotonic strength is significantly exceeded during seismic shaking; while the residual strain accumulation response beyond capacity would depend on viscous soil behavior. These implications explain the observed dependency of existence and severity of foundation displacements on the clay content of foundation soils that relate to viscous soil response. In consistence with the laboratory observations, Bakir and Yilmaz (2006) have shown that the ultimate capacities of shallow mat foundations situated over silt-clay mixtures at alluvial sites in the city were, in general, substantially exceeded under seismically induced forces estimated to have existed during 17 August earthquake.

The most intriguing aspect regarding damage in Adapazarı was perhaps the significant reductions in seismic demand over building structures due to nonlinear soil response, which contravened the established paradigm that seismic damage is inherently greater over "poor" ground. On the basis of presented results in this article, the obvious consequence of this phenomenon in the case of Adapazarı was an overall reduction in the extent of structural damage, and particularly in the collapse rates of typical mid-rise RC buildings constituting the bulk of building stock. In view of the tragic consequences of the collapse of multistory RC buildings from the viewpoint of life safety, we conclude that the loss of life in the city must have been significantly reduced during the 17 August earthquake.

Examples of other studies presenting systematic field evidence of structural damage reduction induced by strong nonlinear response of soft or liquefiable surface deposits are reported from California (Trifunac and Todorovska, 2006 and 1994; Trifunac, 2003). Notably, the buildings that have profited from seismic demand reduction in Adapazarı and in California have entirely different attributes (Bakir et al., 2006). This difference is of significance because it validates the notion that reduced effects due to nonlinear soil behavior is not limited to a particular building class. The other point we would like to draw attention is that field penetration testing appears for being a viable tool to identify the local sites of potential seismic demand reduction, as it was in the case of chaotic alluvial depositions in Adapazarı.

Reduction of seismic demand due to nonlinear soil response displays an obvious potential that can be exploited for innovative engineering solutions. Eventual incorporation in seismic microzonation and design codes is also possible, provided that the geotechnical peculiarities leading to strong de-amplification of ground motion are appropriately identified. Hence, the need is clear for a practical methodology through which the seismically induced ultimate foundation displacements can be estimated with a reasonable accuracy, so that it can be checked whether they are acceptable from the viewpoint of post-earthquake serviceability. Accordingly, the available beneficial effects can be retained, while any unnecessary counter measures are avoided. On the basis of field evidence, a strong foundation, such as a mat, appears to be the fundamental requirement to remove the potential detrimental effects on the load bearing system due to uneven settlements.

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