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Seismic assessment results and actual application in the complex ground conditions of Bolu tunnels after the 1999 Duzce earthquake

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ABSTRACT: The Anatolian Motorway Gümüsova-Gerede Section, a portion of the Trans-European Motorway (TEM) network, will link Ankara to Istanbul and Turkey to Europe. Stretch-2 of the Gumusova-Gerede motorway, a portion of which is under construction comprises twin tunnels of 2790 m and 2963 m. The tunnels are being excavated in a faulted and heavily tectonised sequence. Being in the first degree seismic environment in of the North Anatolian Fault Zone, the tunnels were significantly affected by Duzce Earthquake of 12th Nov. 1999. This paper describes the detailed studies undertaken as part of the re-assessment of the effects of the 1999 Düzce earthquake having the magnitude of Mw = 7.2 on the 18 m diameter highway tunnels. Following the earthquake, detailed seismic design studies have been carried out. The aim of the seismic design is to allow for serviceability of tunnels for emergency usage and easy repair within a short period after a new seismic event. The new design strike a balance between too stiff a lining and too soft a lining (which might attract excessive grounds loads). To verify the new design, a comprehensive instrumentation program was implemented to monitor the actual tunnel performance. Some instrumentation results are presented here which provide an insight into tunnel behaviour in such poor ground conditions.

1 INTRODUCTION

The construction of the Gumusova-Gerede section of the Trans-European Motorway (TEM) commenced in 1988 with various stretches completed and opened to the public traffic at intervals between December 1992 and August 1996.

Bolu mountain crossing twin highway tunnels, are 18 m in excavated diameter and lengths of 2963 m and 2790 m according to the new alignment. The ground pillar between two tunnels is approximately 50 m. Overburden above the tunnels is up to maximum 250 m, with the majority of the tunnels under a cover of 80–150 m. Ground water levels were 45%–95% of the overburden cover above the tunnel crown along the new alignment. The face excavation area of twin tunnels varies between 133 m^2–260 m^2, depending on ground conditions, lining thickness and deformations. Each tube comprises 13.00–8.2 m excavation diameter for an equivalent circle.

The twin tunnels are being excavated in a faulted and heavily tectonised sequence. Tunnel design was prepared based on standard Austrian Rock Classification system (1992–1994). The original tunnel design was performed according to NATM principles, with shotcrete, rock bolts and light steel sets. The highway tunnels are located in a first degree seismic environment in to the North Anatolian Fault Zone, and were significantly affected by the Duzce earthquake of 12th November 1999. The epicenter of the Duzce earthquake was approximately 20 km from the northern Asarsu portals of the tunnels. The peak ground acceleration (PGA) at the project site was measured as 0.81 g. The performance of Tunnels have been assessed at different stress levels arising from excessive loading in different seismic hazards caused by the earthquake using the intrinsic characteristic structure of soil. The findings have been used in developing the basic method and philosophy in determination of main lines for re-designing the tunnel. This also plays a significant role in ground water pressure. Following Turkey earthquakes of 17 August and 12 November 1999 detailed site investigation and seismic design studies have been carried out. Two seismic hazards affecting the tunnels have been considered.

Table 1. Measured strength and stiffness parameters

	Peak		Residual		
Unit	φ[6]	c[6](kPa)	φ[6]	c[6](kPa)	$G_o/'^{7}_{v}$
High PI[5] flysch clay (clayey matrix 80% to 100%)	15°–17°	100	9°–12°	50	500[1]
Blocky flysch clay (clayey matrix 60% to 65%)	20°–25°	100	13°–17°	50	650[1]
Area 3 FG[3] clay	13°–16°	100	9°–12°	50	700[1]
AS/EL FG[3] clay	18°–24°	100	6°–12°	50	NA[4]
Metasediments	25°–30°	50	20°–25°	25	825[1]
Crushed MCB	20°–25°	50	15°–20°	25	950[1]
Sound MCB[2]	55°	1500	NA[4]	NA[4]	High

[1]From high quality pressure meter tests; [2]Metacrystalline basement rock; [3]Fault gouge; [4]Not available; [5]Plasticity index [6]ϕ', c' = effective stress friction angle and cohesion, respectively; [7]G_o/σ'_v = ratio of max shear modulus to initial vertical effective stress.

2 GROUND CONDITIONS

The tunnels are excavated through highly tectonised and faulted sequences of rocks, and intermixed series including flyschoid of mudstones, siltstones-limestones and amphibolite, with stiff heavily slickensided, highly plastic fault gouge clay. The proportion of the clayey matrix by volume varies from about 30% to 100%. In some zones, the ground consisted of uniform fault gouge with no hard inclusions forming the least favorable conditions. To date such zones have been encountered in thickness of up to 50 m along the tunnel alignment, which also extend sub-vertically up to ground level (i.e. overburden cover 80 m to 120 m of poor material). The mixed ground conditions have made tunneling difficult. Along some sections of tunnel the dip of the slickensided surface has been toward the face with the potential for large blocks to slide into the work area. Face bolting was used to reduce this risk. In 1998/99, a detailed characterization of the ground ahead of the tunnel faces was implemented via a pilot tunnel test program (Geo Consult 1998). The mechanical properties are given in Table 1.

The geology at and near the fault zone consists of highly tectonised and intermixed series of mudstones, siltstones and limestones with stiff heavily slickensided highly plastic pure foult gouge clay. This fault gouge clay layer is between metasedimentary rocks (and quartzic rocks and amphibolite of the Metacrystalline basement strata (MCB). The meta sedimentary rocks comprise metasiltstone, metalimestone, quartzic limestone, crystallized limestone, blocks with bedded and slickensided low to medium plastic firm to stiff sandy silty to clay fault gouge matrix). This fault gouge material is at the interface between Asarsuyu – Elmalik geological formation. The proportion of the clayey matrix varies substantially between the different geotechnical units, such that the worst ground comprises wide zones of uniform pure fault gouge clay (Ozben 2003). Figure 1 shows the location of some of the more extensive fault gouge zones.

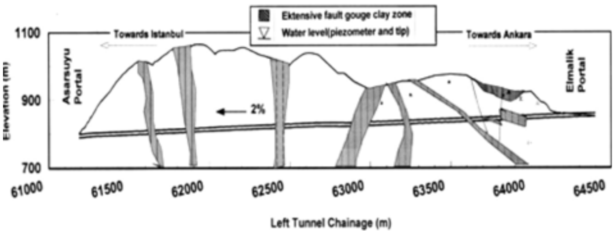

Figure 1. Tunnel geology-fault zones and ground water tables.

3 EARTHQUAKE PERFORMANCE OF TUNNELS

Site inspection of the tunnels was carried out after the Duzce earthquake. The damage patterns discovered are summarized below.

3.1 *Relevant site observations*

The epicentre of the Mw 7.2 earthquake was approximately 20 km (Erdik 2001) from Asarsu portals of the tunnels. The surface rupture of the fault was within 3 km of these portals. Peak acceleration and velocity recorded at the nearest strong motion station at Bolu were 0.81 g and 66 cm/s, respectively. It was initially concluded that this damage was due to ground shaking alone since no surface ruptures had been observed to cross the tunnel alignment and no fault offset displacements were evident within the accessible parts of the tunnels. In the main Asarsu tunnels within the metasediments, slight-moderate damage was observed as slabbing and spalling of shotcrete, and also longitudinal cracking and deformation of the potentially weak Top Heading-Bench joint.

In the Asarsu Left Tunnel Bench Pilot Tunnels (BPT) in fault gouge clay, moderate – severe damage was observed. Invert heave of 0.5 to 1.0 m occurred, together with damage to the shotcrete arch lining comprising shotcrete concrete (S/C) slabbing, spalling,

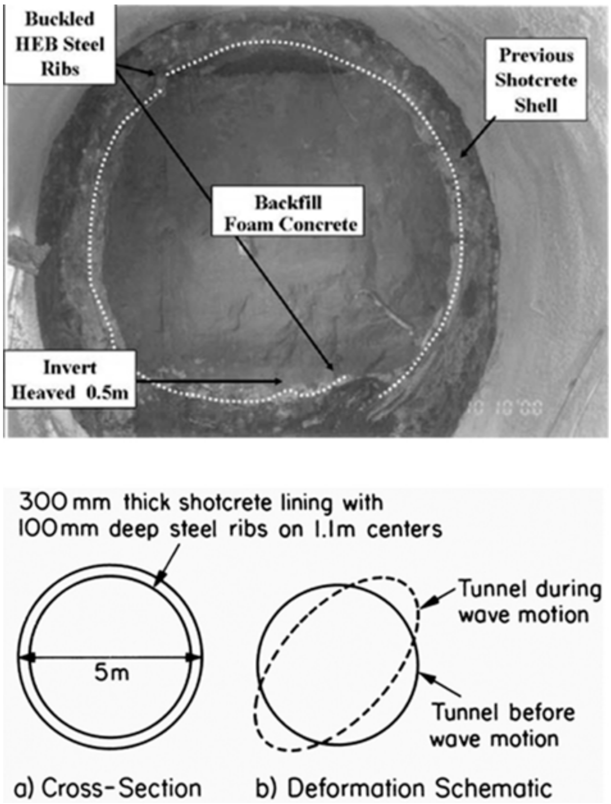

Figure 2. Picture during re-mining of Bench Pilot Tunnels (BPT) showing typical floor heave and buckled steel rib + shotcrete shell. (a-b) BPT Cross-Section and Seismic Distortion.

S/C compression crushing and associated steel rib buckling at crown, shoulder and knee areas (Figure 2) (O'Rourke, Goh, Menkiti, Mair 2001)

In both Asarsu main tunnels, cracking of the monolithic concrete invert was observed as longitudinal tensile-type cracks. Running close to the centerline and occasional shear-type cracks deviating away from the centerline towards the sides. Crack widths were 0.5 cm–5 cm, depending on ground conditions, invert thickness and reinforcement levels. In the Asarsu Right (ASR) tube in fault gouge clay, various levels of reinforcement bar had been installed in the invert – allowing a quantitative assessments to be made. It was found that 51 cm^2/m shear steel cages installed at the sides of inverts in clayey metasediments successfully prevented shear-type cracks. However, 25 cm^2/m tensile reinforcement mats placed near the top of the invert similar to the ground could distribute and limit (but not prevent) tensile cracking.

Inspection pits in this area showed a steel-concrete bond failure mechanism, rather than tensile failure/necking of the 36 mm diameter ribbed bars. Most critically, it was noted that the reinforcement for the Option 3 support system lead tunnel successfully prevented the development of any tensile or shear cracks in inverts within the low strength Asarsu/Elmalik (AS/EL) main fault gouge clay.

In general, the site observations confirmed that the observed damage pattern is consistent with loading induced by vertically propagating earthquake shear waves. This supports the basic assumptions of the dynamic analyses that are being conducted.

Severe damage in the form of complete collapse of two parallel 16.5 m diameter main tunnels occurred during the earthquake near the southern Elmalik portals. The tunnels were excavated in main fault gouge clay, at a center-to-center separation of 54 m and supported by 45 cm–75 cm of shotcrete (f_{cu} = 20/30 MPa). Large deformations necessitating re-profiling works had occurred in this area before the earthquake. During the earthquake itself, the right tube lining was breached with inrush of clayey material and complete blockage of the tunnel so that miners had to escape through a cross-adit and via the left tube. At this time the left tube was collapsing with falling blocks of shotcrete and clay. Within 1–2 hours of the main shock, the left tube too had become blocked by clay debris. The collapse in the right tube propagated upwards through 50 m of cover to cause a 5 m diameter sinkhole and concentric ground cracks at the surface during the earthquake. Progressive failure occurred, confirmed by the generation of another 8 m diameter sink hole over the left tube, through 122 m of cover, some 4.5 months after the earthquake (Menkiti, 2000).

3.2 *Instrumentation results*

Following the earthquake; concrete crushing, shear cracking and offset displacement of the lower footing were observed in Bernold No.2, near the face excavations in the surviving Asarsuyu drives. Pre and post earthquake deformation readings are available which allow an assessment of the induced deformations in Bernold blocks 1&2. Figure 3 shows the 3-D optical deformation reading for Bernold 1. It is acknowledged that the accuracy of this system is limited to several millimetres. It can be seen that a settlement of about 10 mm and a convergence of about 14 mm is indicated as having being induced by the earthquake. Rigid body offset displacement of 150 mm is also indicated by the 3-D data. Pre and post-earthquake measurements were available at 5 different sections in the inner lining within clayey metasediments. Figure 4 shows the typical configuration with pressure cells and embedded strain gauges at various points around the inner lining. The lining hoop stress changes at the crown of Block 54 are also shown, as typical results. Figure 4 shows also the earthquake induced radial stresses on inner lining from pressure cells and embedded strain gauges. Peak values of up to 10 MPa (equivalent to about 17% of the overburden) are induced at the crown and feet of the arch lining, representing a significant proportion of the strength reserve (O'Rourke, Goh, Menkiti and Mair 2001). The results of geotechnical instrumentation show that permanent increases in bending moment and compressive hoop stress equivalent to about 17% of the overburden were induced by ground shaking.

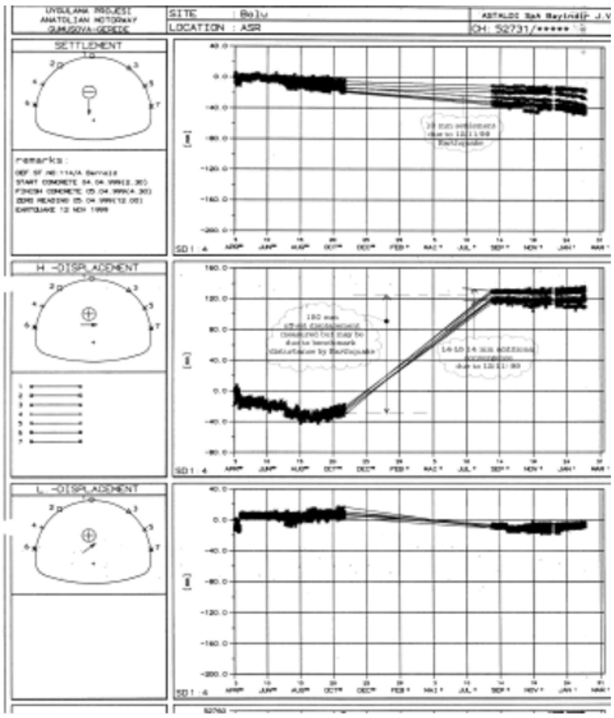

Figure 3. (3D) optical deformation reading for Intermediary Lining (B40 MPa, ds = 60 cm) from station 114/A in ASR tunnel on before and after earthquake.

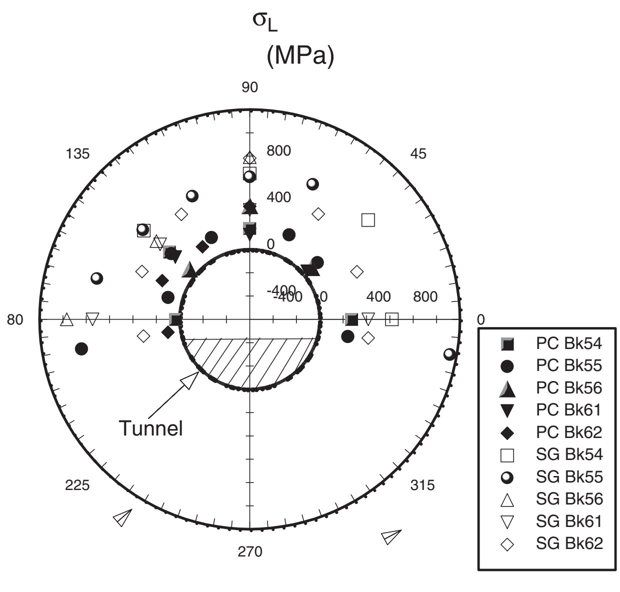

Figure 4. Earthquake induced radial stresses (kPa) on inner lining from pressure cells and embedded strain gauges.

4 SEISMIC CONSIDERATION AFTER 17 AUGUST GOLCUK AND 12 NOVEMBER DUZCE EARTHQUAKES

Following the 17 August and 12 November Duzce earthquakes of 1999, the Client (KGM) instructed an upgraded seismic criteria. Before the 12.11.99 earth quake the Contractor was asked to review the seismic design of the Bolu tunnels utilising detailed dynamic analyses to quantify earthquake effects. Following the 1999 earthquakes, the Client instructed a higher design earthquake design together with stringent performance requirements for the motorway immediately after the design event.

As a consequence, detailed dynamic analyses have been conducted to estimate the tunnel seismic loading and to provide a basis for determining the lining reinforcement. As input into this assessment a site specific seismic hazard assessment study had been carried out. The study was divided into two parts:

- A probabilistic site specific assessment of earthquake ground shaking (Erdik and Yilmaz 2000).
- An assessment of the fault rupture hazard in the site vicinity (Barka and Lettis 2000)

The project's philosophy is that the primary support may become over stressed during the design earthquake, but the inner lining remains undamaged. The new design earthquake was defined as a 2000 year return period event. Based on a probabilistic site specific seismic hazard update study conducted by Erdik, M. and Yilmaz, C. (2000), this design event was calculated to correspond to a peak ground acceleration of 0.81 g (Figure 5).

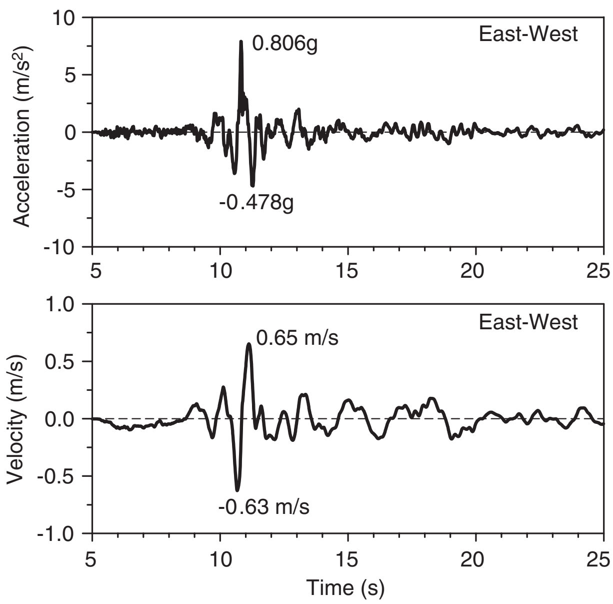

Figure 5. Strong Motion Time Records. Bolu Station Records for 12/11/99 Mw = 7.2 Earthquake E-W Records.

The motorway tunnel is located in within the Anatolian through region. The review assessed the potential of faults in the vicinity of the project site to rupture within the design life of the motorway. Two potential active faults that may cross the tunnel alignment were identified. The Bakacak Fault is one of these active faults. In the event of rupture along these faults the associated earthquake was determined to be of (Mw = 6¼ to 6½) moderate level. The associated fault system is called the North Anatolian Fault Zone (NAFZ). The NAF is a right-lateral transformation fault, representing the boundary between the Black Sea and the Anatolian Plates. It extends a total length of about 1500 km running east-west. The Bakacak fault is identified as a short secondary fault in the step-over region between the two major NAF branches in the Bolu region (i.e. the northern Düzce branch and the southern Mudurnu branch). The location of the Bakacak fault is stated by the authors to cross left tunnel between Ch.62 + 800 and 63 + 000. This layer of fault gouge is at the interface between the Asarsuyu and Elmalik geologic domains identified in tunnel face logs (included 4 associated Bench pilot tunnels BPTs) and through vertical boreholes. According to the results of tunnel seismic design studies performed two potential earthquake hazards affecting the tunnels have been considered (Menkiti, Mair, O'Rourke and Russo, 2000). The hazards are:

- Strong Ground Shaking
- Fault Rupture Displacement

Seismic lining design loads have been derived for static loading and ground shaking, consistent with the Client's seismic performance specifications. The most severe loads from a pool of 11 earthquake records reflecting site conditions and including near field effects, were adopted for design (Menkiti, Kurzweil, Golser, 2000). It was found that the continuous zones of poor fault gouge clays required Option 3&4 support were the most critical. The Bakacak fault of this size may generate an Mw = 6¼ to 6½ earthquake with up to 30 to 50 cm of fault rupture. Conservatively a design value of 0.5 m has been adopted. Therefore high ground loads would be applied to the lining due to fault displacement.

A solution incorporatinf seismic displacement joints has been adopted (Lombardi, May 2001). A fault crossing design and retrofit strategy that addresses the above points has been developed. It consists of wide closely spaced seismic joints (every 4.4 m) to accommodate the fault rupture by slip and/or rotation. Seismic Joints would be created in the complete lining (BPTs, Bernold lining, Inner lining and Invert) at 4.4 m intervals in order to allow articulation. Figures 6 & 7 shows the typical inner lining and invert with seismic joints.

Inner lining block length of 4.4 m was chosen to suit the existing construction round length of invert and Bernold lining. This design strategy is ideally suited to accommodate the low probability event of distributed slip without significant damage to the tunnel. Concentrated slip and large relative movements may be concentrated at 1 or 2 seismic joints, necessitating local speed reductions prior to repairs. The rupture of the Mw = 7.2 12th November 1999 Düzce earthquake was about 5 km from Bolu Mountain crossing. In the Bakacak fault crossing the design has considered the following load cases.

a) Static loading plus severe ground shaking (design 2000 year return period of earthquake)
b) Static loading plus moderate ground shaking (M_w = 6–6.5) plus permanent fault offset.

Figure 6. Seismic joints of 4.40 m spacing and 0.50 m spanning are currently being constructed at the Bakacak Fault crossing.

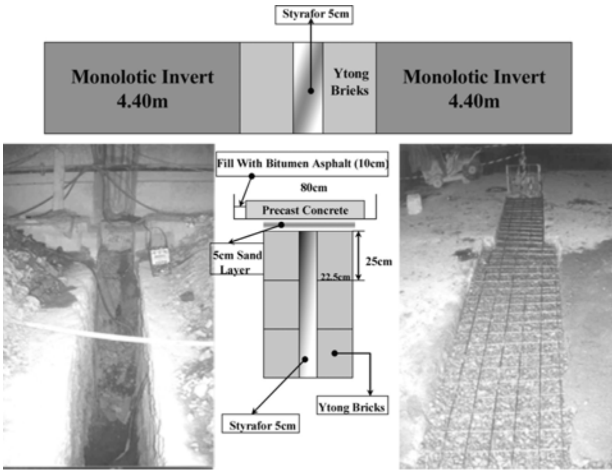

Figure 7. Detailed seismic joints in the monolithic invert.

It is intended to cross the Bakacak fault zone using Option 4 design. Some modifications of the Option 3 and Option 4 design have been necessary to account for the new earthquake design criteria, imposed after the 1999 Golcuk and Düzce earthquakes. From the suite of 11 records the 3 most adverse have been selected as input into detailed Flac analyses to generate design lining loads. The momentary peak load, therefore considers the maximum peak load from the worst of the 11 accelerograms a severe loading condition. For the locked-in load, present after the earthquake the average lining loading derived from the 3 most severe earthquakes is used. As a result of dynamic analyses and following detailed dynamic analyses of the load case of severe ground shaking (Mw = 7.2) for Option 3 and Option 4 it was noted that Bakacak fault rupture was more critical than a medium size earthquake event. Weak ground conditions mean that the static loads would be high and a robust basic design would be required. The high dynamic strains are dissipated and attract the high dynamic loads on the existing tunnel support system under the seismic ground shaking. Therefore, negative dynamic loading is exerted on the already existing static load. For that reason, extra amount of steel reinforcement was required for the Bakacak fault crossing section of the tunnels. The dynamic analyses indicate that large quantities of steel are necessary for Option 3. Lower reinforcement is predicted for Option 4, which is inherently more resistant to earthquake loading. In both cases upgrade of the inner lining and Bernold lining concrete from B30 to B40 is required. Steel fibre has also been used in Bernold lining. These represent significant support upgrades relative to that required for static loading alone.

This design strategy is ideally suited to accommodate the low probability event of distributed slip without significant damage to the tunnel. This is done by concentrating concentrated slip, large relative movements may at 1 or 2 seismic joints, necessitating local speed reductions prior to repairs.

5 CONCLUSIONS

With 1999 earthquakes, very good earthquake performance experience was gained from completed tunnel section. Despite very high level seismic loading and fault displacement, very good earthquake performance of the tunnels was observed.

Following the earthquake, The Client asked for a higher design earthquake resistance (2000 year return period) together with stringent performance requirements for the motorway immediately after the design event. As a consequence detailed dynamic analyses have been conducted to estimate the tunnel seismic loading and to provide a basis for determining the lining reinforcement. Also, for the active faults crossing, articulations have been provided to accommodate the main part of the lateral displacement in the fault.

In conclusion, Bolu tunnels are very important with regard to the validity and practicality of the models developed for the seismic performance of tunnels.

Comparison of the damage observed and geological conditions and also design followed has indicated that these could be the basis for assessing the performance of tunnels and identifying the potentially hazardous zones.

REFERENCES

Geo Consult, (May 28,1998), *Experimental Investigations During Construction of Pilot Tunnel, Gümüsova-Gerede Motorway* project report No.45110/R/2148.

William Lettis & Asssociates Inc. & A.Barka, (September 30, 2000), *Geologic Characterisation of Fault Rupture Hazard*, Gümüsova-Gerede Motorway project report.

Tokgozoglu, F. & Isik, S. (October 6, 2002), *Seismic Consideration Of Bolu Tunnels After Duzce Earthquake and Possibile oluation Proposal*, International Conference/ Workshope & Exhibition on Tunnelling & Underground Space Use.

Geo Consult, (July 15, 1998), *Design Methodology Unexcavated Sections Gümüsova- Gerede Motorway*, project report, No.45110/R/2149.

Ozben, M. (2003), *Engineering Geology of Bolu Mountain Tunnel and Encountered Geological and Geotechnical Problems During Excavation and Their Effect on Tunnel Excavation and Support System,* Ph.D. Thesis.

Menkiti, C.O. & Mair, R.J. & Miles, R. (April 2001), "*Tunnelling in Complex Ground Conditions in Bolu, Turkey*" for Publication in the Proceedings of Underground Construction 2001.

Menkiti, C.O. & Işık, S. (April 7, 2001), *Investigation of Toughness, Energy Absorption Capacity and Modulus of Elasticity Observations of Tunnel Steel Fibre Reinforced Shotcrete and Intermediate (Bernold) Lining Concrete in Bolu Tunnels* of The Gümüsova-Gerede Motorway by Yüksel & Rendel JV.

Menkiti, C.O. & Işık, S. (June 8, 2000) *Stiffness-Strain Relationships From Pressuremeter Tests, Interface Fault Clay in Bolu Tunnels of* The Gumusova-Gerede Motorway by Yuksel & Rendel JV

Menkiti, C.O. (December 5, 2000), *Review of Deformations of Bernold Lining Blocks in Asarsuyu Right Tube, Originally Damaged By the 12/11/99 Earthquake and Then Further Deformed By Recent Construction Works.*

Lombardi, (May 2001), Gümüsova-Gerede Motorway *Asarsuyu Tunnels, Detailed Seismic Analysis-Op.3 + Op.4 and Active Fault Crossing-Design Philosophy and Joint Requirements*.

O'Rourke, T.D., Goh, S.H., Menkiti, C.O. & Mair, R.J. (2001), *Highway Tunnel performance during the 1999 Duzce earthquake.*

Menkiti, C.O., Mair, R.J., O'Rourke, T. & Russo, M. (Octobor 9, 2000), *Minutes of Meeting on The Seismic Design Review of Bolu Tunnels.*

Menkiti, C.O. & Kurzweil, H.C. & Golser, W. (November 14, 2000), *Minutes of Meeting on The Seismic Design Review of Bolu Tunnels (Fault Crosing).*