# EVALUATION OF THE SEISMIC PERFORMANCE OF TUNNELS DURING EARTHQUAKES IN TURKEY

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***SUMMARY***

In 1999, Turkey has experienced two major earthquakes; Kocaeli Earthquake with magnitude of Mw=7.4 on 17 August 1999, and Düzce Earthquake with magnitude of Mw=7.2 on 12 November 1999. During the Kocaeli Earthquake, bored tunnels in good rock conditions on Anatolian Motorway, Korutepe and Gültepe Tunnels, which are near to the earthquake epicenter, performed well. During this earthquake, geotechnical measurements showed that Bolu Tunnel, in which excavation is continuing in difficult geological conditions and located far from the epicenter, was not effected. During the last Düzce earthquake, Bolu Tunnel, located very near to the epicenter to the earthquake, is highly effected , collapse and damages occurred in the tunnel. In this paper the general procedure for evaluation of seismic performance of tunnels are reviewed and history of static and seismic performance of the Bolu tunnel is given. The seismic design works, carried our after the earthquake, such as the preliminary seismic design works considering simplified analysis , detailed dynamic analysis considering ground shaking and fault rupture crossing the tunnel are evaluated in this paper. For Turkey, importance of this evaluation is high for tunnels which will be constructed in regions with high seismicity and poor rock/soil conditions. For tunnels located in poor rock/soil conditions subjected to major earthquakes, additional loads are induced to the tunnel lining and reinforcement with considerable amount is required.

## 1-INTRODUCTION

In 1999, Turkey has experienced two major earthquakes; Kocaeli Earthquake with magnitude of Mw=7.4 on 17 August 1999, and Düzce Earthquake with magnitude of Mw=7.2 on 12 November 1999. During the Kocaeli Earthquake, tunnels on Anatolian Motorway, Korutepe and Gültepe Tunnels, which are near to the earthquake epicenter, performed well. These tunnels are bored tunnels in good rock conditions. During this earthquake, geotechnical measurements showed that Bolu Tunnel, far from the epicenter, was not effected. During the last Düzce earthquake, Bolu Tunnel, located very near to the epicenter to the earthquake, is highly effected , collapse and damages occurred in the tunnel.

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## 2-EVALUATION OF SEISMIC PERFORMANCE OF TUNNELS

In general, tunnels have performed well during earthquakes compared to above structures, because they are embedded, tends to move with the ground and magnitude of the ground motion decreases with depth. But there are damages in tunnels during earthquakes. The possible causes for the damages are ground shaking, fault rupture through the tunnel, landslide( especially on portals), liquefaction.

## 3- BOLU TUNNEL AND PROBLEMS ENCOUNTERED DURING THE CONSTRUCTION

Bolu Tunnel on Gümüşova-Gerede Motorway is located on an area, affected by Düzce Fault, which is one strand of North Anatolian Fault , Elmalık faults and Aşağı Bakacak Faults, which are secondary faults of NAF. Map showing the main fault alignments affecting Bolu Tunnel is given in Figure 1. Geological conditions of the tunnel alignment is very complicated. Ground conditions vary in short distances as seen in Figure 2. Asarsuyu side of the approximately 3300 m long tunnel is located mainly in metacrystalline basement, heavily fractured in some parts, and sheared metasediments. This part of the tunnel is in fair rock conditions compared to the Elmalık side of the tunnel with poor soil conditions. Elmalık side of Bolu tunnel is located on flyshoid series with low and high plasticity and main fault gauge consisting high plasticity clay

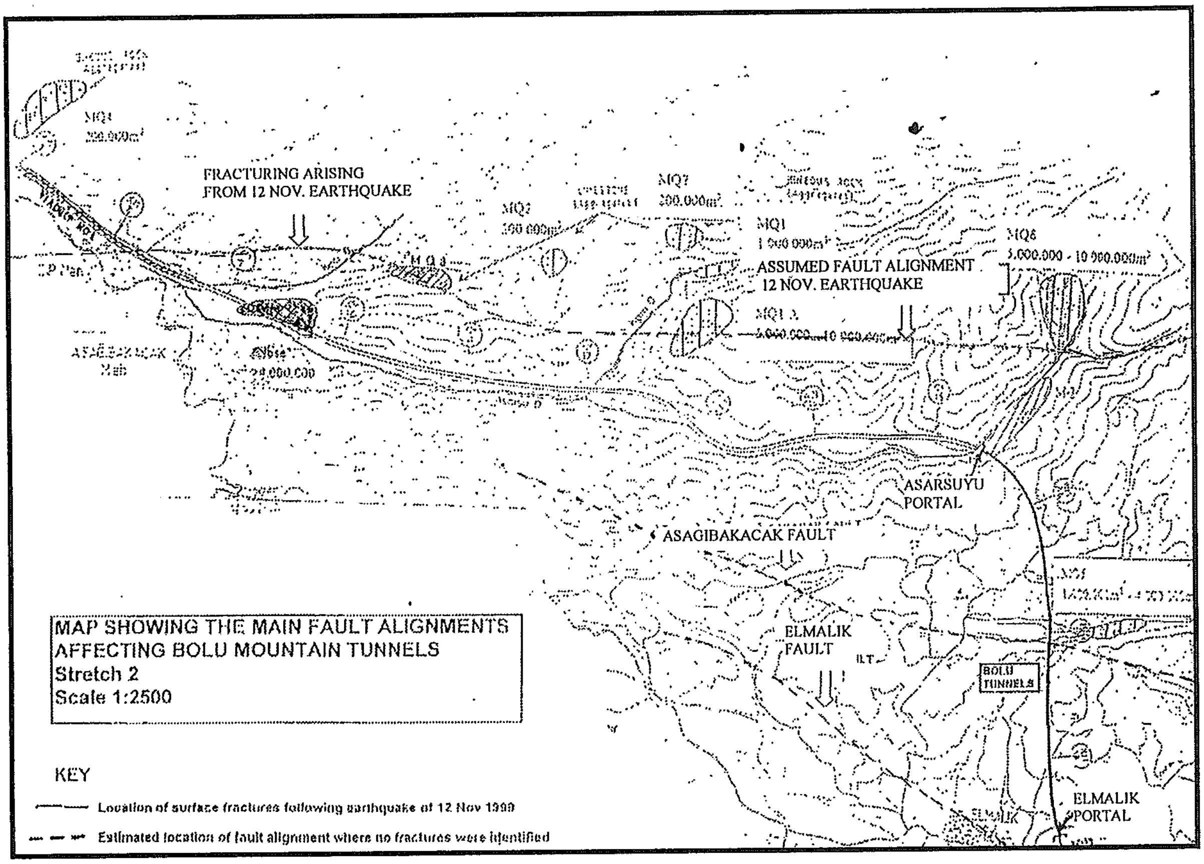


**Figure 1:** Map showing the main fault alignments affecting Bolu Tunnel

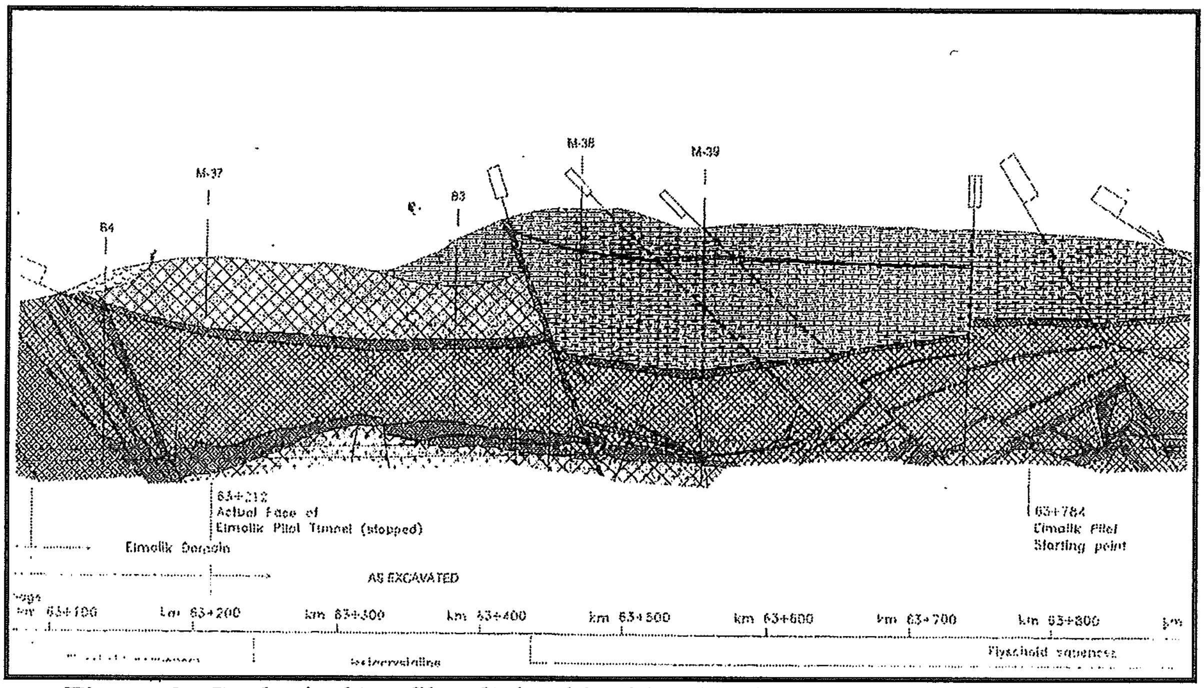


**Figure 2:** Geological Profile of Elmalık Side of Bolu Tunnel

Tunnel excavation was started on 1993 according to New Austrian Tunneling Method and progressed mainly on Asarsuyu side. During excavation on Elmalık side of the tunnel support system was modified because high deformations occurred on fault zones. The modifications consisted deep monolithic invert, increased shotcrete and concrete quality and thickness, using steel ribs with higher performance etc.

Because Bolu Tunnel is located on an area with varying soil conditions, site investigations such as boreholes on excavation face, lab. test and design works were carried out with excavation. In 1998 to obtain more data related to nonexcavated parts of tunnel and speed up the construction works driving a pilot tunnel was decided. Pilot tunnel with a diameter of 4.6 m and length of 826 m was driven. Geological conditions were evaluated with the geological mapping at face . Lab test were done on samples from boreholes driven on tunnel wall and block samples taken from pilot tunnel and geotechnical measurements were carried out. Evaluating all data obtained from pilot tunnel two support types, Option 3 and 4 (Figure 3 and 4), are designed to apply in poor soil conditions in main fault gouge, flyshoid series with low and high plasticity. These support types are designed to construct a rigid lining to carry loads due to high deformations .

During the tunnel construction records such as geological mapping and geotechnical measurements (borehole extensometers, strainmeters in shotcrete and invert) were taken continuously. This enables to evaluate the suitability and performance of the support system and also the seismic performance of the tunnel. Sections of tunnels, where damages and collapse occur during earthquake, are located on the part of the tunnel, where problems encountered at statical conditions.

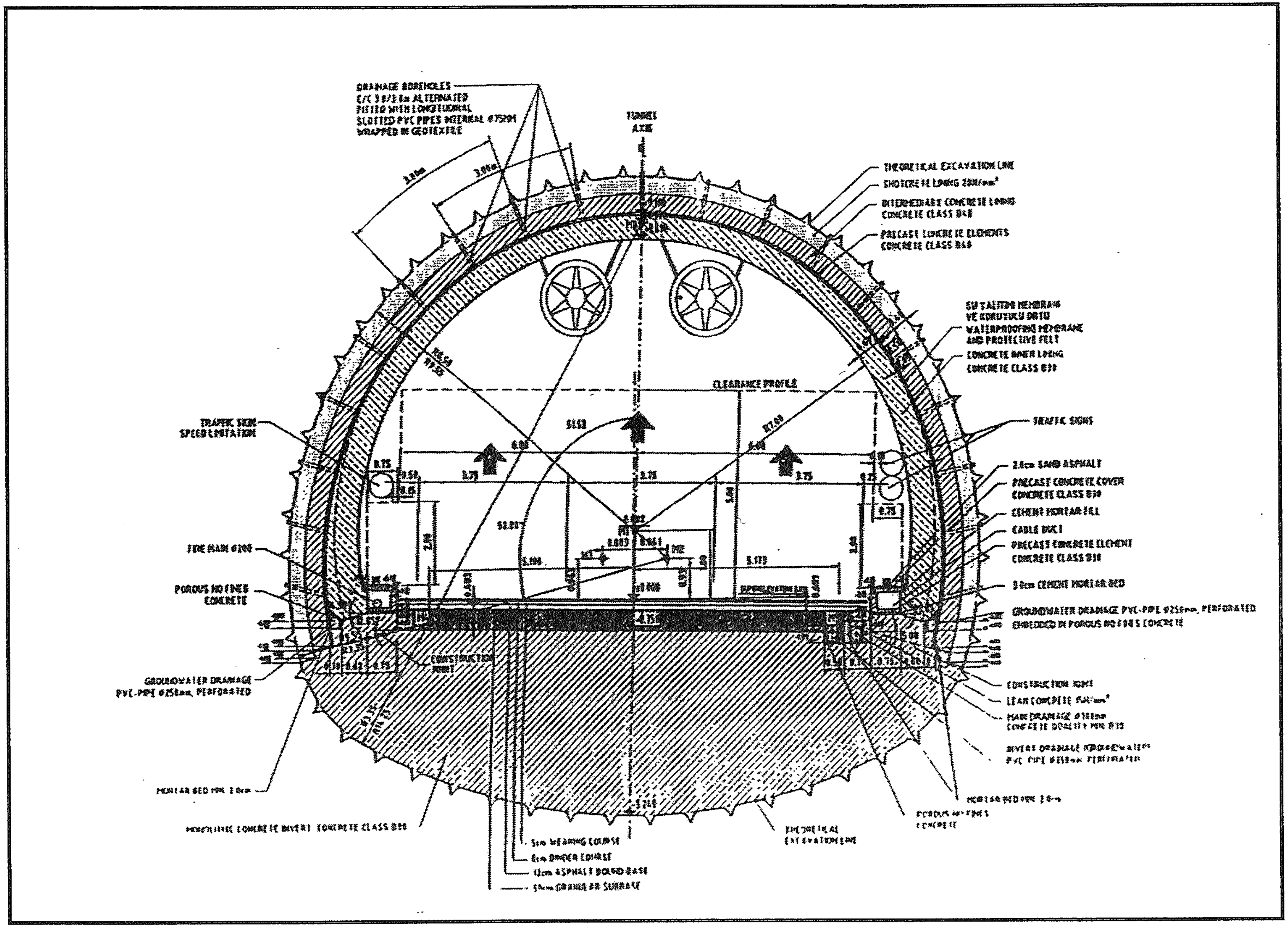


Figure 3: Crossection of Option 3

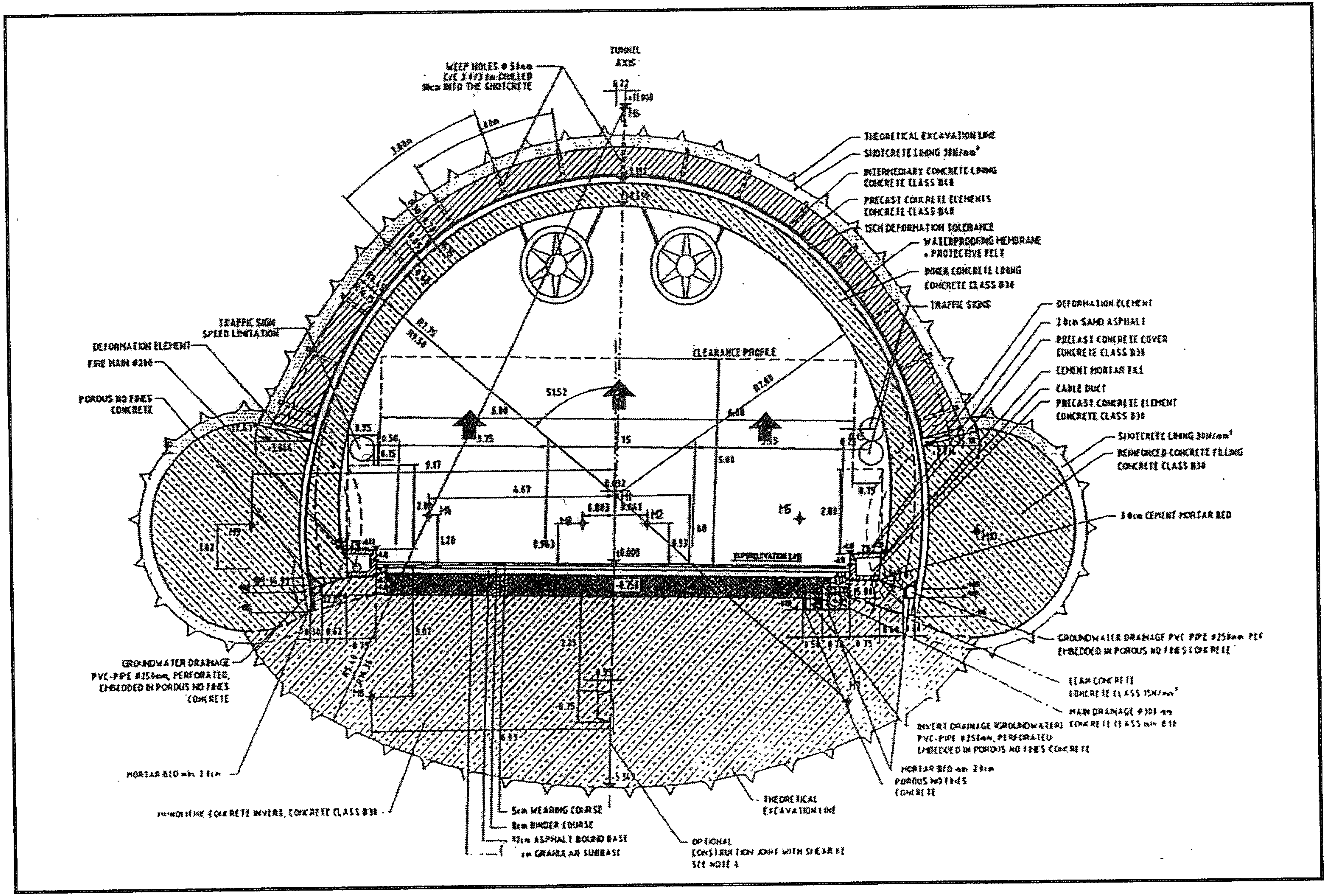


**Figure 4:** Crosssection of Option 4

## 4-SEISMIC PERFORMANCE OF THE BOLU TUNNEL

After the earthquake on Düzce Fault on 12 November 1999 collapse and damages occurred at Elmalık side of the tunnel. Before the earthquake ,at his part of the tunnel, during the excavation and applying supports high deformation and settlement problems occurred and inner lining was not completed yet.

Collapse occurred at the Elmalık side near to portal. To determine the extend and mechanism of the collapse, site above the tunnel was examined, cracks and other features such as sink holes were mapped . Horizontal boreholes from collapse face and vertical boreholes above the tunnel were driven (Figure 5). Considering those investigations the possible mechanism of the collapse was defined as: Because of high ground shaking, ground failure occurred as sinkholes, those sinkholes are extended with time the collapse extended approximately 500 m of the tunnel.

At sections, where the support was completed, on Elmalık side , there are cracks on invert, which can be repaired. At Asarsuyu part of the tunnel local cracking is seen in shotcrete.

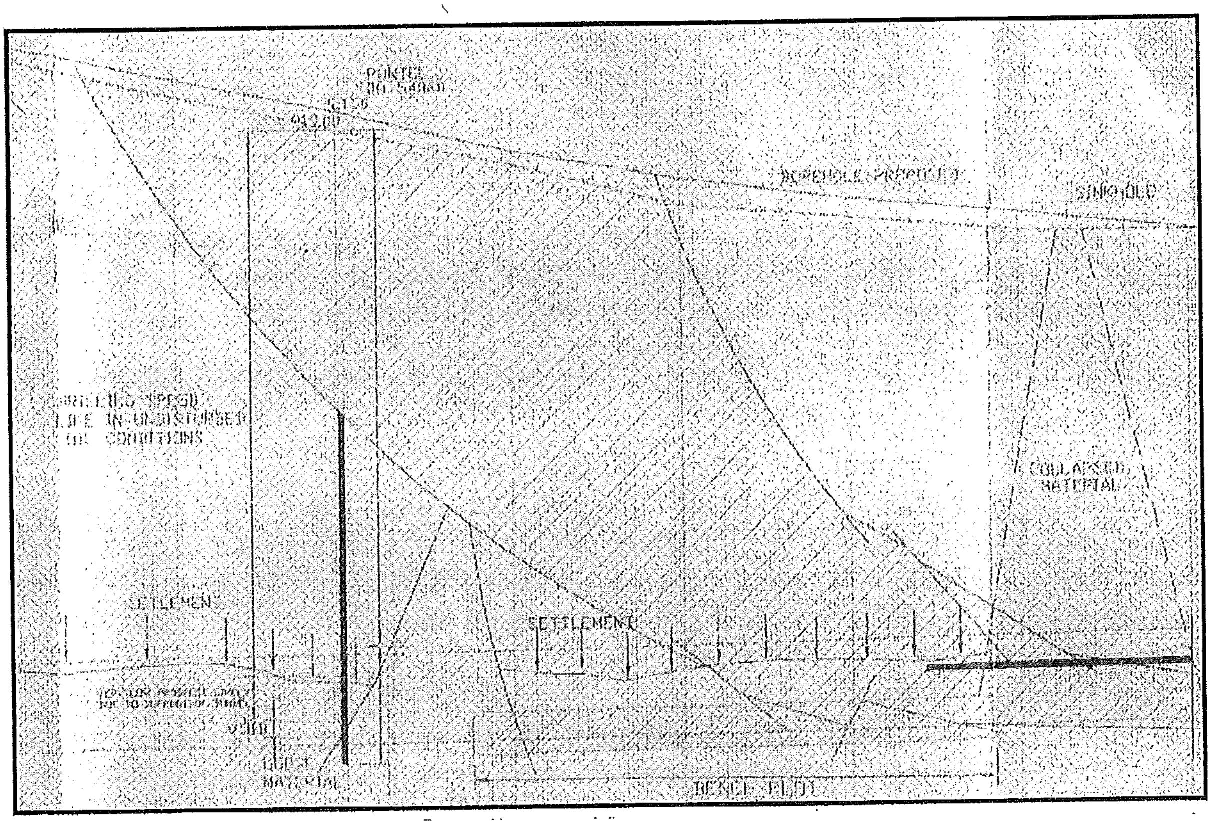


**Figure 5:** Profile of Collapse Area

## 5-SEISMIC DESIGN OF BOLU TUNNEL

### 5.1 Preliminary Seismic Design

In the preliminary seismic design , nonexcavated and excavated parts of the tunnel except collapse zone was considered , because the design works related to reexcavate of the tunnel or change the alignment are going on . For the parts with support class CM, Option 3 and Option 4 the tunnel simplified analysis were done according to FHWA Manuel. (Lombardi Engineering Ltd)

In these analysis the effect of ground shaking and ovaling deformation , which is more critical, were considered . After the Reassesment of Site Specific Seismic Study by Yılmaz and Erdik peak ground acceleration (PGA) was determined as 0.81 g for a 2000 year return period. For the simplified analysis it is reduced to by a factor of 0.7 because of the tunnel depth.. Peak particle velocities were defined as function of type of soil, moment magnitude , distance to the source and PGA .

For the geotechnical data used in the simplified analysis pressiometer tests were evaluated by the Engineer (Yüksel Rendel) for seismic requirements.

Using the lining (shotcrete, bernold, inner) properties, geotechnical data, seismic input, overburden seismic loadings were determined for each support systems. Two loading phases are considered. In the first phase it is assumed that seismic thrust forces are shared by different part of linings by cross section ratio, bending moments are shared by the moment of inertia ratio of each lining. Considering the results from first phase, in the second phase the intact linings are supposed to carry seismic bending and stresses in inner lining are determined.

The results of simplified analysis showed ;

1- For CM, Option 3 and Option 4 support classes the stress in inner lining increases due to seismic loading that inner lining should be reinforced.

2- For Option 3 and 4 detailed dynamic analysis should be done

### 5.2 Detailed Seismic Design

#### 5.2.1Detailed dynamic analysis for Option 3 and 4

Detailed Dynamic Analysis were carried out using Finite Element Method considering ground shaking. For the analysis three ground motion records were used; Bolu station record, a synthetic accelerogram, Loma Prieta earthquake records with similar directivity effect and site geology. Ground motion data was used with a correction factor of 0.6 for a depth of 200 m.

Firstly one dimensional analysis were done by SHAKE to estimate shear strains in soil. Then one dimensional analysis were done by FLAC to asses compatibility with SHAKE. Finally two dimensional analysis were done by FLAC modeling construction sequences for Option 3 and Option 4 applications; initialization of static stress state, excavation, installation of shotcrete lining and invert, installation of intermediate lining, installation of final lining, allowance of drainage, dynamic analysis using three ground motion records. The philosophy of the design is that outer lining may reach yielding threshold but inner lining will be able to withstand earthquake forces.

Dynamic analysis showed that there will be permanent loads on inner lining due to earthquake and it should be reinforced. Option 4 is less affected by earthquake but Option 3 requires additional reinforcement at bench.

### 5.2.2 The effect of fault rupture on tunnel

There are two active faults crossing tunnel alignment; Bakacak fault with expected displacement of 50 cm, Zekidağ fault with expected displacement of 15-25 cm. The philosophy of the design is that displacement shear displacement will take place entire fault extension, damage in some segments due to fault rupture

As result of analysis, steel fibre will be used in lining to allow accommodating displacement, seismic mesh in final lining to prevent debris falling on road, length of cast segments (L= 5m) and create seismic joints (t=50 cm) to accommodate larger part of fault displacement.

## 6- CONCLUSION

Effect of ground motion on tunnels are less than that compared to above structures. Factors effects the seismic performance of tunnels are seismicity of tunnel region, rock/soil behavior through which tunnel is driven , quality of support and lining system of tunnel. Evaluating these factors, seismic requirements for tunnels should be considered. For Turkey importance of this evaluation is high for tunnels which will be constructed in regions with high seismicity and poor rock/soil conditions.

REFERENCES:

1-Seismic Retrofitting Manuals Of Highway Systems, Volume III, Draft,1999, FHWA
2-Yılmaz, Erdik, "The Reassessment of Site Specific Seismic Study", Report, February 2000
3-Barka "Düzce Earthquake and Effect to Bolu Mountain Motorway", Report,2000
4-Yüksel Rendel , "Stiffness-Strain Relationships From Pressuremeter Tests", Report, June 2000
5-Lombardi, Report "Seismic Design , Seismic Screening", Report, June 2000