IZMIT BAY BRIDGE: IDENTIFYING FAULTS AND EVALUATING THEIR IMPACT ON THE THIRD LONGEST SUSPENSION BRIDGE IN THE WORLD

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ABSTRACT:

The Izmit Bay bridge, a 3-km-long suspension bridge crossing of Izmit Bay, Turkey is planned to be constructed in one of the most seismically active places in the world. The site, which has the potential to experience significant earthquakes associated with the relative motion accommodated on the North Anatolian Fault, is underlain by deep deposits of soft soils, and areas of unstable and liquefiable soils. Characterizing the seismotectonic setting, foundation soil conditions, potential fault locations, as well as other geohazards was a critical component for the project concessionaire to finance the project and obtain meaningful bids for bridge design and construction. Given the Build Operate Transfer (BOT) funding mechanism, executing this work in the least possible time was critical to the concessionaire's financing scheme. Fugro was retained to provide geotechnical, geological, and seismological evaluations for the project region, and to generate data for contractors to develop reliable designs and bids. A sophisticated and extensive site investigation program of the Izmit Bridge was designed to address the uncertainties associated with these issues with emphasis in characterizing the fault setting at the third longest bridge in the world. Fugro also performed probabilistic fault displacement hazard analyses to estimate surface displacements associated with direct fault rupture during an earthquake on the North Anatolian Fault. Subsequently, numerical analyses were conducted to evaluate the fault rupture-induced demands on a bridge pier foundation in terms of displacements and rotations.

KEYWORDS : Suspension bridge, fault rapture, geohazard, North Anatolian Fault Zone

1. INTRODUCTION

The Izmit Bay bridge, a 3-km-long suspension bridge that crosses Izmit Bay in Turkey, is planned to be constructed in one of the most seismically active places in the world. The bridge is the critical link of the 420km Gebze – İzmir Motorway (Figure 1) awarded through a Build Operate Transfer (BOT) mechanism to the NÖMAYG Joint Venture in 2009. NÖMAYG intend to execute the bridge construction through an EPC (Engineering, Procurement and Construction) contractor. The bridge will be constructed in an area where Izmit Bay narrows from its typical >8km width to about 3 km, and will connect the Diliskelsi peninsula to the North with the Hersek peninsula on the south.

The fundamental unknowns for the design and execution of major bridges are related to the selection of appropriate substructures and the environmental loads of the region. Reducing the uncertainties related to these issues significantly reduces bid contingencies and reduces both schedule and cost risks to the owner. In the case of the Izmit Bridge, the site spans the plate boundary between the Anatolian plate on the south and the Eurasian plate on the north (Figure 1) and will experience significant earthquakes on the North Anatolian Fault Zone (source of the 1999 Magnitude Mw 7.4 Izmit and Mw 7.2 Düzce earthquakes). Moreover, the site is underlain by deep deposits of soft soils, and areas of unstable and liquefiable soils. Characterizing the geological, seismological and geotechnical setting, foundation soil conditions, fault locations, as well as other geohazards

and developing appropriate design criteria was a critical component for the project concessionaire to finance the project and obtain meaningful bids for bridge design and construction. Given the BOT funding mechanism, executing this work in the least possible time was critical to the concessionaire's financing scheme.

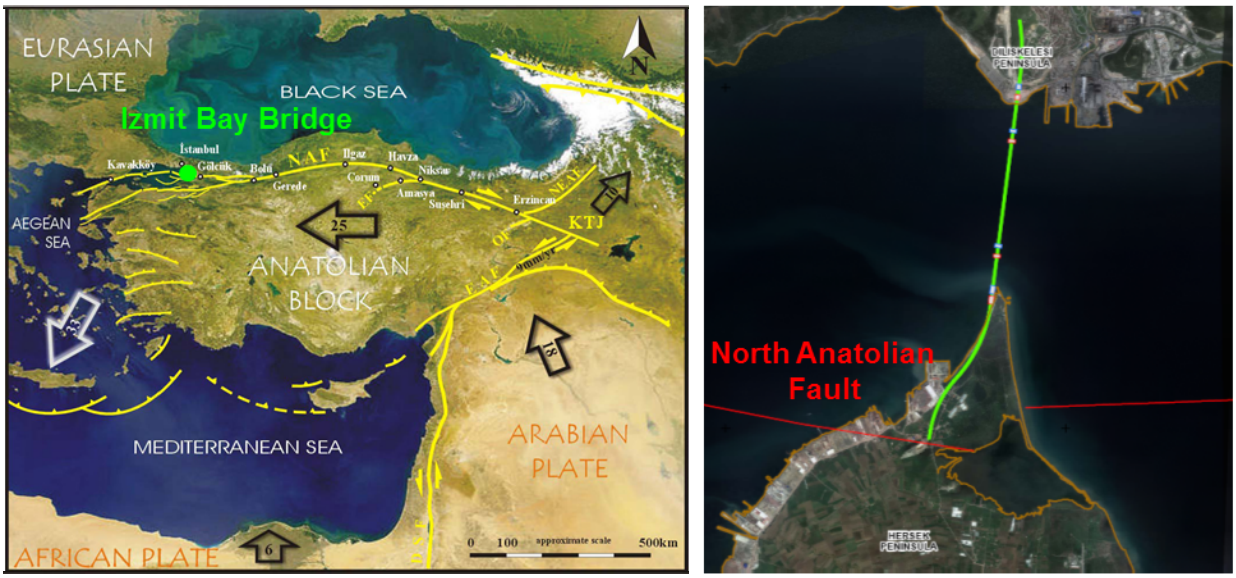

Figure 1. Project location and tectonic setting

2. SITE INVESTIGATION PROGRAM

Fugro worked with NÖMAYG's technical team to mutually develop an appropriate work scope for the project that met their schedule and addressed their risk mitigation goals. The extensive site investigation was designed to address the following issues:

- Regional fault setting with a focus on locating the North Anatolian Fault in the project vicinity. Studies that focused on regional fault characterization included offshore bathymetric and geophysical surveys using a suite of tools; as well as onshore geophysical surveys and trenching on the Hersek peninsula.
- Alignment area geology and site conditions, with a focus on evaluating variations in near-surface site conditions near the bridge alignment, and potential shallow geohazards that may impact the bridge. These studies included primarily a grid of offshore and nearshore CPT soundings, as well as a dense grid of intermediate penetration offshore geophysical survey within a ~ 700 meter corridor along the bridge.
- Foundation stratigraphy in an area around the proposed bridge foundations. These studies included: 1) offshore borings/ CPT soundings at the two tower locations; 2) nearshore and onshore borings/CPT soundings at the south anchorage area; 3) vertical and inclined borings at the north anchorage locations; and 4) CPT soundings and a few borings along the southern approach structures alignment.

To address the above issues, equipment and personnel were mobilized (Figure2) from 14 different execution centers in Europe and North America to provide the following:

- Deep water geophysical surveys covering an area of about 80 square km of 2D multichannel reflection surveys. The offshore geophysical surveys were designed to cover two specific areas: 1) an approximately 8-km by 10-km region centered on the bridge alignment to understand the regional geology and map the North Anatolian Fault, and 2) a more focused 750-meter wide corridor centered on the bridge alignment to obtain the necessary topographic, bathymetric and subsurface data for design and construction of the proposed bridge alignment. These surveys included seafloor surveys using multibeam echo sounder and side scan sonar that cover the regional survey area. Additionally, laser line

scan surveys of the northern and southern shoreline were conducted to image shoreline topography. Three sets of subbottom geophysical surveys including: 1) a high frequency subbottom profiler to image the very shallow (<10 meters) sediment; 2) intermediate penetration multichannel boomer reflection surveys (< than 100 to 200 meters); and 3) deeper penetration multichannel airgun geophysical surveys (<500 to 1000 meters);

• Shallow water geophysical surveys designed to use bottom laid cables and very shallow draft vessels in order to obtain good quality near-surface seismic reflection data near the South Anchorage. The principle of reciprocity applied to collecting seismic reflection data allows for multiple receiver lines to be replaced by a single receiver line and multiple source lines. The use of a bottom laid cable eliminated the operational problems associated with towing a surface cable in shallow water. Both air gun and boomer data were obtained for most of the shallow water survey lines. Approximately 70 lines of either boomer or air gun data were collected using 15 bottom cable lays. An additional 5 lines were obtained using a towed cable from a small skiff for shallow water areas.

• Deepwater and nearshore geotechnical investigations including 19 borings drilled to depths of about 120 to 200 meters and 46 CPT soundings advanced to depths ranging from 20 meters to 80 meters, with a typical depth of 40 meters. Each boring included extensive sampling interspersed with downhole, in-situ CPT soundings and vane shear tests. In addition, OYO P-S Suspension Logging was performed on all the borings. A field laboratory was provided to support each of the geotechnical site investigation operations such that samples could be extruded and preliminary index and strength testing conducted within a few hours of sample collection. The focus of the geotechnical program was to collect detailed stratigraphic data in the vicinity of the bridge as well as high-quality material properties to be used for static and dynamic design;

• Onshore geophysical surveys including approximately 9 km of onshore seismic reflection surveys using a vibroseis truck to help map fault crossings along Hersek Peninsula;

• Onshore paleoseismic investigations including trenching and surveys of Byzantine aqueducts that were offset by faults and geologic mapping. The purpose of the investigation was to assess the presence or absence of active faulting in order to characterize the hazard posed by future surface-fault rupture generated by a large magnitude earthquake on the North Anatolian Fault. The trenching activities involved an initial screening trench along much of the alignment at the northern portion of the Hersek Peninsula to evaluate ground conditions and shallow features, followed by detailed and deeper trenches in areas where fault traces may be visible;

• Onshore geotechnical investigations including 54 CPT soundings and 11 borings to depths of about 50 to 120 meters. These investigations were focused both on characterizing subsurface conditions at the North Anchorage on the Diliskelesi peninsula, the approach structures to the bridge along the Hersek peninsula, and to help with fault delineations on the Hersek peninsula.

3. FAULT CHARACTERIZAZATION ALONG THE BRIDGE ALIGNMENT

3.1. Integrated Site Characterization

An integrated approach to site characterization was adopted for the project. In this approach, the stratigraphy observed in the borings and CPT soundings was compared and integrated with stratigraphic relationships imaged by the geophysical surveys. All of the data in the geotechnical explorations, i.e. borings and cone penetration test (CPT) soundings, were captured in a Geographic Information System (GIS) database to allow synthesis, comparison, analyses and output of the data. . The GIS was used to shorten the overall timeframe for the site characterization and allowed project Tender design to proceed concurrently with the geotechnical and earthquake engineering interpretations.

The basic data sets used for the integrated site characterization included:

• Surficial seafloor data from the bathymetry and sidescan sonar surveys;

• Near-shore topography from the LIDAR survey;

- Subsurface seismic reflection data from subbottom profiler, boomer, and airgun marine surveys;
- Geotechnical exploration data from marine and land borings and cone penetration tests; and
- Results from the onshore seismic surveys.

A key element of the integration of geophysical and geotechnical data was the conversion of reflection times observed in the geophysics to depth. Compressional and shear velocities were measured in the geotechnical borings using an OYO down-hole suspension logger. The processed seismic reflection data were analyzed and mapped using the Kingdom Suite 2D PAK seismic interpretation program by Seismic Micro Technology that contains many of the attributes of the seismic work stations used for petroleum exploration.

Figure 2. Site Investigation equipment

3.2. Fault Identification and Characterization

The bridge spans the plate boundary between the Anatolian plate on the south and the Eurasian plate on the north. Fault movement and seismic hazard potential are primarily associated with the North Anatolian Fault (source of the 1999 Izmit and Düzce earthquakes) whose northern strand projects across the bridge alignment.

Both onshore and offshore site investigation data were used for the identification and mapping of the traces of the North Anatolian Fault along the bridge alignment. Onshore data included analyses of tectonic geomorphology, geotechnical investigations using borings and cone penetration tests, seismic refraction and reflection surveys, and paleoseismic investigations including trenches and analysis of offsets on a Roman aqueduct. Offshore investigations included a multibeam bathymetry survey, multichannel marine seismic reflection surveys using multiple sensors and marine geotechnical borings and CPTs.

Possible fault traces were interpreted on the geophysical data from several characteristics including: abrupt termination of bed forms, sudden changes in dips of reflected horizons, apparent offsets of reflection patterns from a sequence of horizons, vertical or near vertical alignment of diffraction patterns, offsets of subsurface fold axis, bathymetric features, gas plumes, and for low-angle faults (thrusts), reflections off of the fault plane. All of

these features (anomalies) may be caused by other geologic or noise sources as well as faults. However, it is the line-to-line correlation of similar anomaly patterns over a distance of a kilometer or more that are indicative of a continuous structural feature. The seismic data were also used to identify areas where there is a lack of evidence of recent faulting. In many parts of the offshore survey area shallow unconformities representing continuous reflectors can be mapped over areas of several square kilometers. Where these reflectors are not apparently offset by traces of the North Anatolian Fault polygonal areas of "no-apparent-faulting" were created and the thickness of the unfaulted sediment section between the sea floor and the unfaulted horizon was calculated (Figure 3). The age of these unfaulted horizons were checked against age dating tests on samples using the radiocarbon age dating technique. Additionally, existing age dating results from ESR-dating analyses (Dolu et al, 2007; Meric et al, 1995) were used in the comparisons. The stratigraphic relationships derived from the integrated site characterization were found to be in general agreement with the sample ages estimated using the two age dating techniques. Those data thus allowed for estimation of the age of the unfaulted horizons to confirm the faulting had not occurred in the Holocene.

The results of the fault studies were to identify the main trace of the North Anatolian fault in the project vicinity, a zone of deformation around the main fault trace, and zones of tertiary deformation (i.e. folded but not faulted). As shown on Figure 3, the main zone of deformation is located approximately 2.1 km south of the South Anchorage for the bridge. In this area, approximately 14-meters of offset were observed in a Byzantine aqueduct that crosses the fault. The zone of secondary deformation however extends out to the north to the area between the south Anchorage and the South Tower.

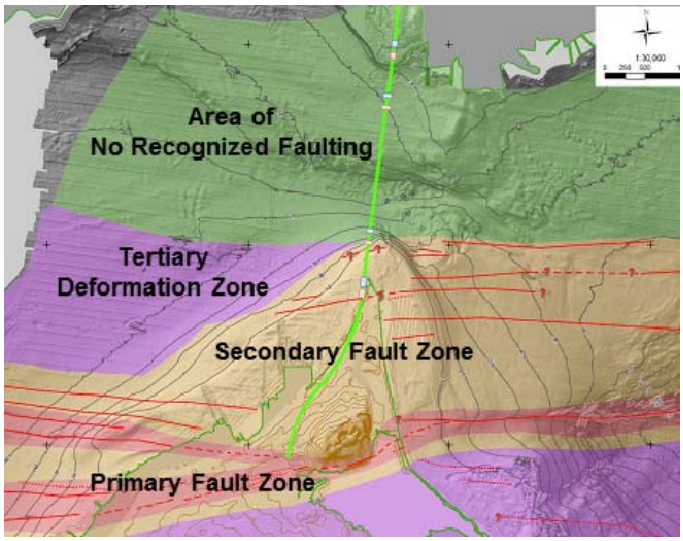

Figure 3. Mapped faults and "no-apparent-faulting" areas along the alignment

In particular, the shallow water geophysical and geotechnical survey data appear to identify the presence of several secondary faults within the area and the south anchorage of the main bridge was moved approximately 150 m north from the originally proposed location to an apparent area of no recent faulting. This shift to the North necessitated the extension of the South Approach Viaduct by about 150 meters to the North into an area of identified secondary faults. As shown on Figure 4, several fault traces were identified between the South Approach Viaduct Piers P01 and P02 that illustrate the hazard to the South Approach Viaduct. Farther to the south, data were not available to map specific faults in detail. This was primarily because it is difficult to collect seismic reflection data in the shallow section while the shallow groundwater and relatively young sandy near surface soils preclude practical paleoseismic trenching. In the offshore section at least one apparently active fault was mapped as projecting towards the Approach Viaduct, and crosses the structure near the shore landing. Faulting is also apparent in the geotechnical data collected during Fugro's offshore site investigation. The

stratigraphy between Piers P01 and P02 appears to be significantly impacted by faulting (Figure 4). From south to north, the deeper soil layers appear to sequentially step down across each mapped fault. While these differential movements maybe due to in part reverse or normal faulting, they are more likely the result of right-lateral strike slip or oblique movements that offset westward or northwest dipping soil horizons.

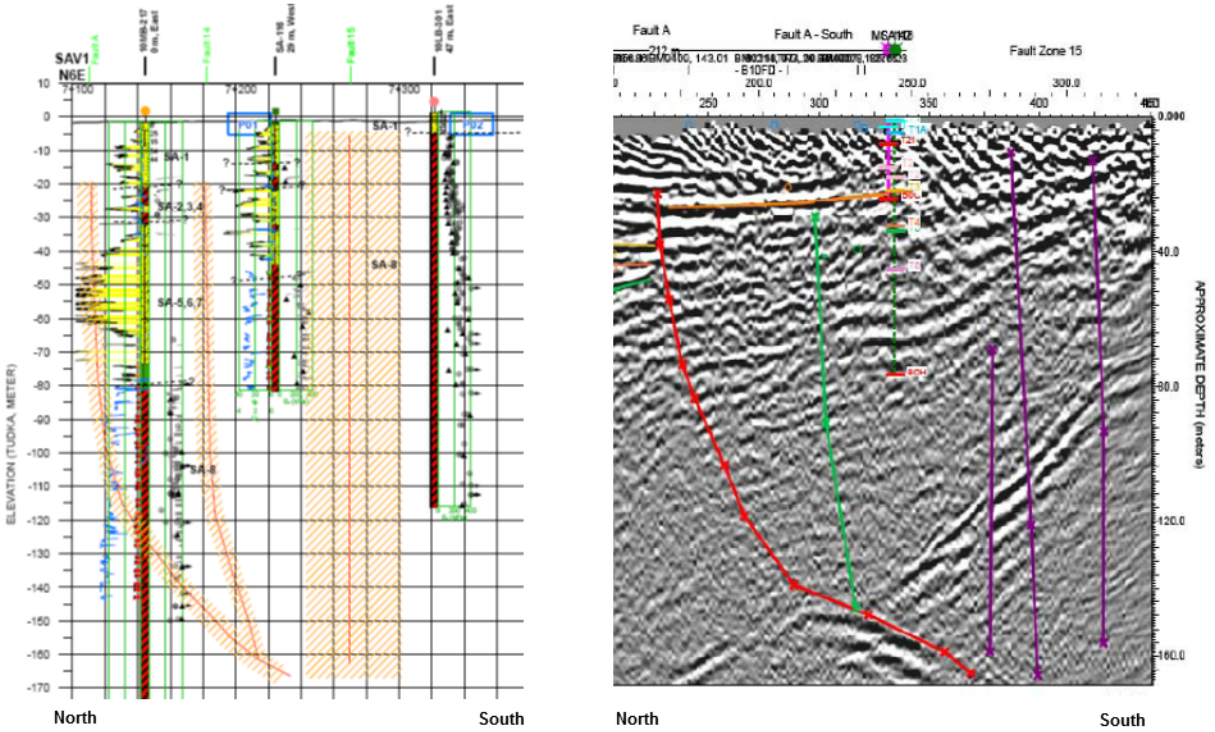

Figure 4. Fault Identification in Geophysical and Geotechnical Data: (a) Subsurface conditions based on CPT and SPT results, (b) Geophysical Data (Boomer)

4. EVALUATION OF FAULT HAZARD ALONG THE BRIDGE ALIGNMENT

4.1. Probabilistic Fault Displacement Hazard

Probabilistic fault displacement hazard analyses (PFDHA) were performed to estimate surface displacements associated with direct fault rupture on the NAF and provide design values of relative displacement that the bridge and approach structures should accommodate (Travasarou et al 2013).

PFDHA were initially performed for a crossing point identified by the intersection of the primary NS-NAF trace and the southward extension of the bridge alignment. Fault displacement estimates at this crossing location were considered to represent the total relative displacement on the primary trace of the NS-NAF. A fraction of the total displacement was then assumed to occur in the secondary and tertiary zones of deformation mapped near the approach structures and between the South Anchorage and South Tower.

PFDHA was conducted based on: a) a displacement approach relying primarily on estimates of fault displacement during earthquakes from in-situ observations, and b) an earthquake approach using the regional source model which relates the fault displacement to earthquake magnitude (Youngs et al., 2003).

The design horizontal displacement on the NS-NAF was based on the average of the two approaches and was estimated approximately 4.5 meters and 6.9 meters for the 1,000- and the 2,475-year return periods, respectively. Vertical displacement was estimated to be 0.25 and 0.5 meter, for the two return periods. Surface displacement is assumed to be negligible for the 150-year level. Interpretation of geological data suggests that approximately

15% of the surface displacement along the fault's main trace is also triggered on the secondary faults. It was recommended that the approach structures be designed to withstand 0.7 meter and 1 meter of relative horizontal displacement anywhere along their length. For the vertical displacement it was recommended that the total vertical displacement estimated for the primary zones be accommodated in the secondary and tertiary zones of deformation.

4.2. Engineering Evaluations For Fault Rupture Through A Foundation

The south approach structures are located within a zone of secondary deformation around the primary trace of the North Anatolian Fault. The viaduct design consists of 10 spans with lengths varying between 136 m and 100 m and two back spans one of 125 m, attached to the South Anchorage of the main bridge and the other of 74 m attached to an embankment at the south end of the structure. The South Approach Viaduct (SAV) is located within the secondary fault zone of NAF, which includes a number of active fault traces. While, it was possible to image near-surface fault features offshore, this was not possible in the onshore areas, where high ground water table and large thicknesses of very recent sediments hampered paleoseismic trenching, and geophysical techniques could not image the near-surface. Consequently, it was not possible to preclude the potential for faults being present at the individual foundation locations. In recognition of the very active tectonic setting, and the constraints on fault characterization, the project design criteria required that Soil-Structure Interaction analyses be performed to evaluate fault rupture effects originating from the relative motion accommodated on the secondary faults in the southern approach structures area.

Recent research combining field studies, and centrifuge and numerical modeling resulted in the development of a validated methodology for analysis and design of foundation–structure systems against surface fault rupture (Anastasopoulos et al, 2008). Fugro applied this methodology, to evaluate the demands on the SAV foundations from a secondary fault rupture through one Pier location (Giannakou et al, 2012). Analysis of the bridge–foundation system subjected to faulting–induced deformation is conducted in two steps. In Step 1, the response of a single bridge pier foundation subjected to fault rupture deformation is analyzed where a detailed 3D model of the structure and surrounding soil is subjected to fault rupture induced displacement at its base. In Step 2, a global structural model is subjected to the computed displacements and rotations of Step 1. The foundation system plays a key role in the response of structures subjected to fault induced ground movement (Faccioli et al., 2008, Anastasopoulos et al. 2008). Depending on the relative stiffness of the foundation, the superstructure will either rotate as a rigid-body without being substantially distressed (i.e., rigid and continuous foundation systems), or will follow the faulting-induced deformation profile of the ground surface, usually sustaining substantial structural damage (i.e., pile foundations). Two foundation systems were evaluated for the SAV: a large, relatively stiff reinforced foundation block with a plan area on the order of 26 by 36-meters and approximately 6-meters thick, and a caisson-type foundation with a plan area on the order of 8 by 21-meters comprising1-meter thick slurry walls and a 3-meter thick concrete cap. Three dimensional nonlinear numerical analyses were performed to evaluate the demands on a pier foundation in terms of displacements and rotations due to fault rupture (both strike slip and dip slip with dip angle of 80o). Fault rupture propagation through the soil will induce large shear strains, therefore consideration of the post-peak strain softening behavior of soils is essential in these types of problems (Bray et al., 1994; Anastasopoulos et al, 2008). A Mohr Coulomb failure criterion that allows for strain softening was used to model the soil layers. The ability of the numerical model to capture the fault rupture propagation through soil was verified against centrifuge experiments (Giannakou et al, 2012). Parametric analyses were performed with respect to the relative position of the foundation to the fault rupture outcrop, the dip angle of the dip-slip fault-component and the fault rupture orientation relative to the foundation. Since both foundation systems are rigid and continuous, they are capable of achieving a satisfactory performance against fault rupture induced deformations. Both systems force the fault rupture to divert around the footing, although rotation and torsion of the footing does occur (Figure 5). The differential displacements and rotations of the shallow footing are larger (i.e., 1 to 2 degrees rotation) than in the case of the slurry wall caisson foundation system (i.e., 0.5 to 1 degree rotation) due to the larger stiffness of the latter.

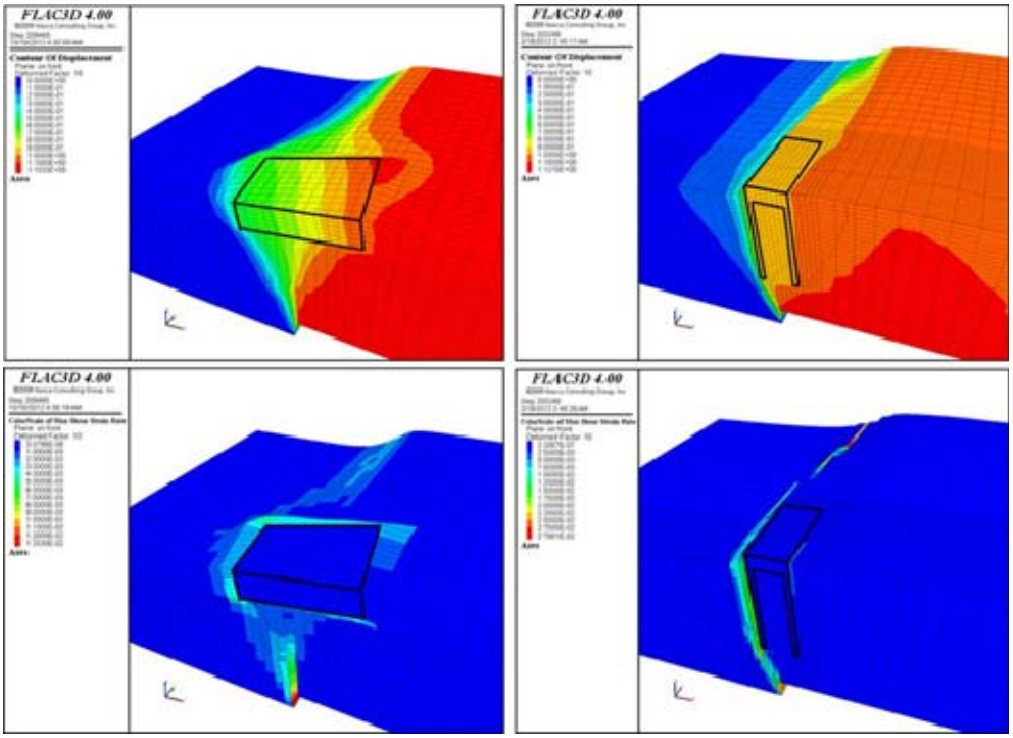

Figure 5. Total Displacement and Maximum Shear Strain Rate Contours of the two Foundation Systems subjected to the 2,475-year Secondary Fault Rupture Scenario (magnified 10 times)

5. CONCLUSIONS

In general, when designing structures in seismically active areas, foundations of critical structures are typically located away from known faults. However, for long structures such as bridges, tunnels and pipelines, a fault maybe unavoidable, and fault rupture risk impossible to preclude. Fugro performed geological, geophysical and geotechnical site investigation for the Izmit bBay Bridge project and an integrated site characterization was conducted. The geophysical survey data provided valuable insight into the geologic conditions in this area. Paleoseismic trenching was performed on the Hersek Peninsula to locate fault traces near the bridge alignment. Interpreted geotechnical and geophysical data collected during site investigation revealed numerous traces of the North Anatolian Fault zone on both sides of the Hersek Peninsula and possible traces on the peninsula interpreted from the onshore investigations. In recognition of this, the entire area near the south anchorage of the main suspension bridge and the south approach viaduct was classified as a secondary fault zone, indicating the potential for secondary faults through the area. Foundation design for the approach structures was optimized by performing probabilistic fault displacement hazard analyses in combination with advanced numerical soil structure interaction studies. Similar methodologies can be adopted for quantifying near-source seismic hazards for important projects.

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