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IZMIT BAY BRIDGE SOUTH APPROACH VIADUCT: SEISMIC DESIGN NEXT TO THE NORTH ANATOLIAN FAULT

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ABSTRACT

This paper presents the various geotechnical issues considered during the seismic design of the South Approach Viaduct. Due to the very close proximity to the North Anatolian Fault, advanced numerical models and state-of-the-art methodologies were adopted for the seismic design of the viaduct. Key aspects include the development of design ground motions at the base of the structure incorporating soil-structure interaction effects, and the consequences of fault deformations passing through the foundation on both the foundation and the superstructure. Similar methodologies can be adopted for the seismic design of important structures located close to large faults.

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Introduction

The Izmit Bay bridge, a 3-km-long suspension bridge that crosses Izmit Bay in Turkey, is being constructed in one of the most seismically active places in the world, spanning the plate boundary between the Anatolian and the Eurasian plates. The South Approach Viaduct (SAV) of the Izmit Bay bridge along the western side of the Hersek peninsula brings the bridge down from the anchorage of the main suspension bridge to an elevated embankment approximately 1.3 km farther south and is located within a zone of secondary deformation around the primary trace of the North Anatolian Fault (Fig. 1). The viaduct consists of eleven piers and an abutment at the south end of the structure.

Due to the very active tectonic environment of the project and the constraints on fault characterization, the design criteria required that the structure be designed to withstand: (i) the fault rupture effects through any one of the viaduct pier foundations and (ii) the strong ground motions originating from the fault rupture on the North Anatolian Fault located approximately 2 km south of the viaduct.

Due to the very close proximity to the North Anatolian Fault (NAF), the viaduct design against near-source seismic hazards for the SAV was a challenge. Advanced numerical models and state-of-the-art methodologies were adopted for the seismic design of the viaduct. This paper presents key seismic design aspects that include soil-structure interaction evaluations for the development of design ground motions at the base of the viaduct piers, and the consequences of fault rupture passing through the foundation.

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Viaduct Design to Withstand Fault Rupture Demands

Design Approach

Recent research efforts combining field studies, centrifuge model testing, and numerical modeling have 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 in order to evaluate the demands on the SAV foundations from a secondary fault rupture that passes through one Pier location. The analysis of the bridge–foundation system subjected to faulting–induced deformation is conducted in two steps (Fig. 2), in which the interaction between rupture, soil, foundation and superstructure is taken into account. 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.

Foundation Selection

The foundation system has been found to play 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 of foundation with a plan area on the order of 8 by 21-meters consisting 1-meter thick slurry walls and a 3-meter thick concrete cap.

Figure 1. Project location and regional tectonic setting

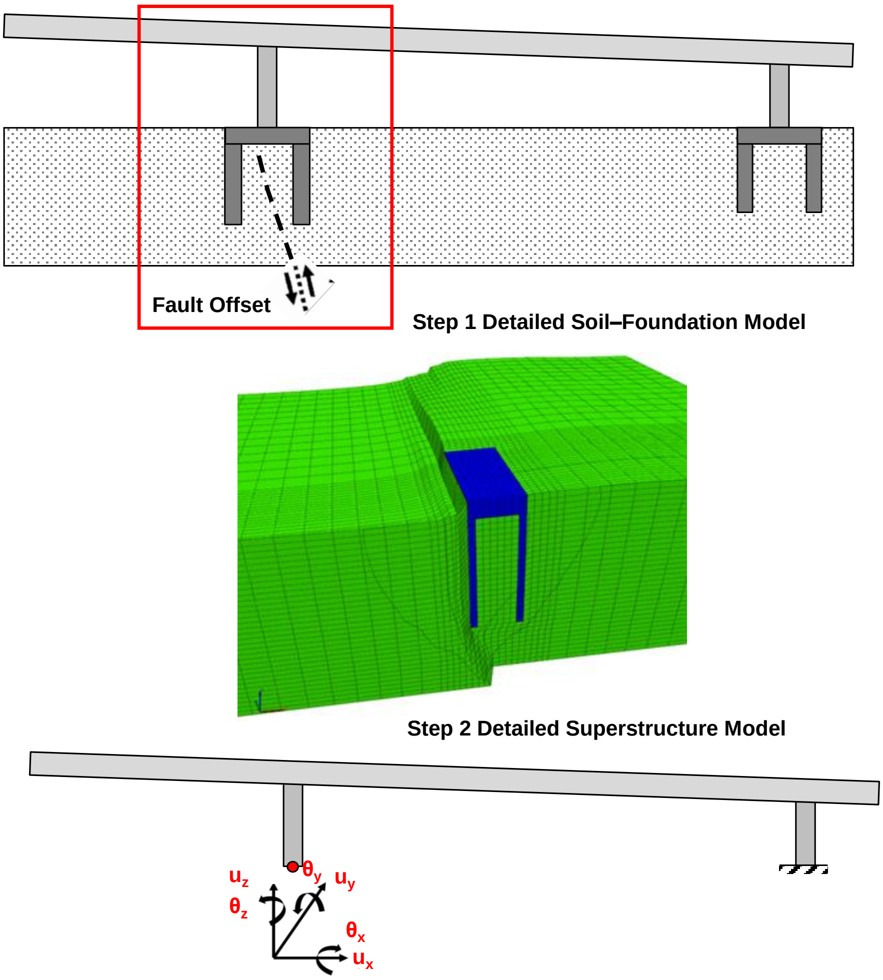

Figure 2. Overview of Design Approach Against Fault Rupture: (a) Step 1: Detailed Soil Foundation Model, (b) Step 2: Detailed Superstructure Model.

Fugro performed probabilistic fault displacement hazard analyses to estimate surface displacements associated with direct fault rupture during an earthquake on the North Anatolian Fault. Design values of relative displacement that the suspension bridge and approach structures should be able to accommodate were provided for return periods of 1,000 and 2,475-years. It was recommended that the approach structures be designed to withstand 0.7 meter and 0.3 meter of relative horizontal and vertical displacement anywhere along their length for the 1,000-year event and 1 meter and 0.5 meter for the 2,475 -year event.

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 80^{o}). 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 (Fig. 3). The differential displacements and rotations of the shallow footing were found to be 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. The slurry caisson system was selected for the pier foundations.

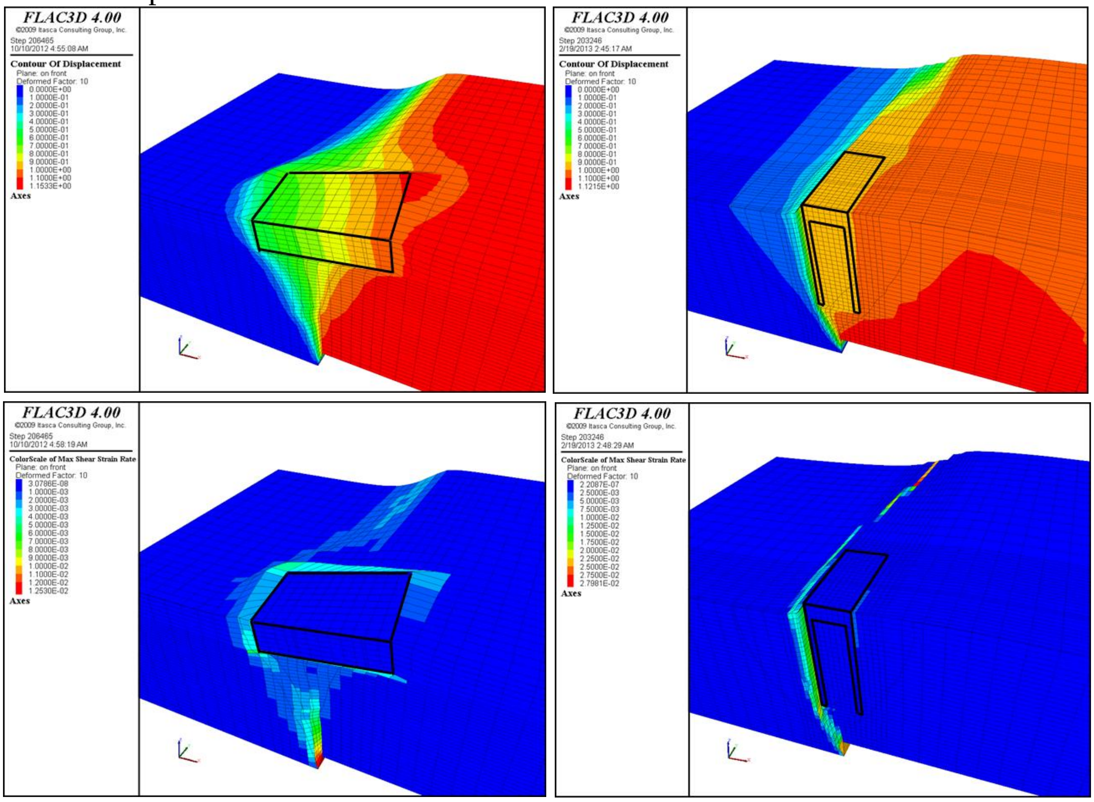

Figure 3. Total Displacement and Maximum Shear Strain Rate Contours (magn. 10 times)

Evaluating the Effects of Strong Ground Motions on Viaduct Response

Design Approach

A substructuring approach was adopted for the dynamic nonlinear time history analyses analyses of the SAV. A 3D finite element model of the viaduct was developed that was connected at the base of each pier to a set of 3 translational and 3 rotational nonlinear springs through a rigid vertical link of varying length. The nonlinear springs represent the load-deflection characteristics of the soil surrounding the foundation, while the rigid link is there to capture the effects of the embedment depth of the slurry wall on the rotational and translational stiffness of the springs. Since the length of the slurry walls varies from pier to pier the length of the rigid link will also vary.

Development of Nonlinear Foundation Springs

Three dimensional finite element analyses were conducted to develop the backbone curve representing the nonlinear load-deflection relationships. The backbone curves were developed by numerically "pushing" the slurry wall foundation in all three directions and calculating the resistance offered by the surrounding soils (Fig. 4). Because these nonlinear relationships are incorporated in the global model with a Massing unload-reload criterion, they also provide hysteretic damping during time history analyses.

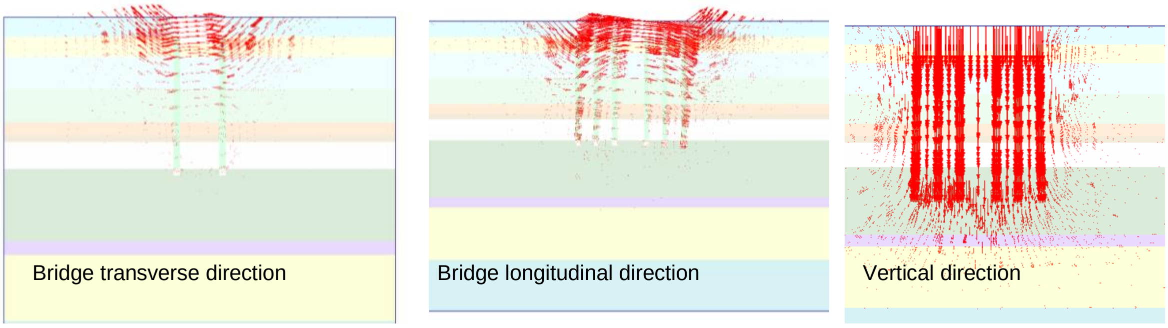

Figure 4. Development of Nonlinear Foundation Springs for Use in Structural Analyses

Development of Kinematic Ground Motions

The presence of the foundation tends to “resist” and, hence, modify soil deformations generated by the passage of propagating seismic waves. As a result the motion at the foundation (also called kinematic motion) differs from the free-field ground motion.

Finite difference models were developed at each foundation location. The soil elements were modeled using nonlinear elements that capture the finite strength of the soil as well as its nonlinear stress-strain relationships. No superstructure is included in these analyses. Due to the high levels of shaking at the project site, significant non-linearity and relatively high shear strains (in excess of 1 percent) are induced in the soil by the ground motion propagation. Accordingly, the soil behaves according to a nonlinear stress-strain law implemented through a "hysteretic" model that allows for the modeling of the reduction of the shear modulus with increasing shear strain and corresponding increase in hysteretic damping. The slurry wall foundation elements were modeled as elastic.

The Fault Normal (FN) and Fault Parallel (FP) directions of the motion that were developed from Probabilistic Seismic Hazard Assessement (PSHA) analyses (Travasarou et al 2013) were rotated to coincide with the longitudinal (X-axis) and transverse (Y-axis) SAV axes and were input at the base of the finite element models and propagated upwards. Motions were input as “outcrop” motions at a depth of about 50 meters where a competent soil horizon was assumed to be present.

Kinematic acceleration time histories were developed in the two horizontal directions (longitudinal and transverse to the bridge axis) at each foundation location for seven motions and three design events (i.e. corresponding to 150-year, 1,000-year and 2,475-year return periods). Vertical components of design ground motions were also developed by applying vertical-to-horizontal (V/H) ratios to the horizontal component of ground motions derived from site response analyses at the South Approach Viaduct foundation locations.

Fling effects were also incorporated in the kinematic ground motions due to the vicinity of the structure to the NAF. Fling pulse was added in the fault parallel component and was idealized as a single cycle sinusoidal wave with a specified peak acceleration and period. The fling arrival time and the polarity of the ground motion were selected such that the fling velocity interferes constructively with the velocity of the transient ground motion (Fig. 5). For the 1000-year return period the fling displacement was estimated to range between about 1.6 to 1.8 meters between Pier 1 and South Abutment.

Due to variations in the soil conditions at each of the foundation locations, differential site response effects were observed in the transient time histories at each of the Pier locations. The differential responses occur due to variations in the soil conditions, as well as different levels of nonlinearity that develop within each of the soil profiles. The peak transient relative displacements in the Fault Normal and Fault Parallel direction for all motions were 0.25 and 0.1 meter, respectively, for the 1000-year event. Given the very high shaking levels, the abrupt transitions in soil conditions across fault locations, the SAV structure had to be able to accommodate these types of relative displacements within the performance requirements specified for each of the project design earthquakes.

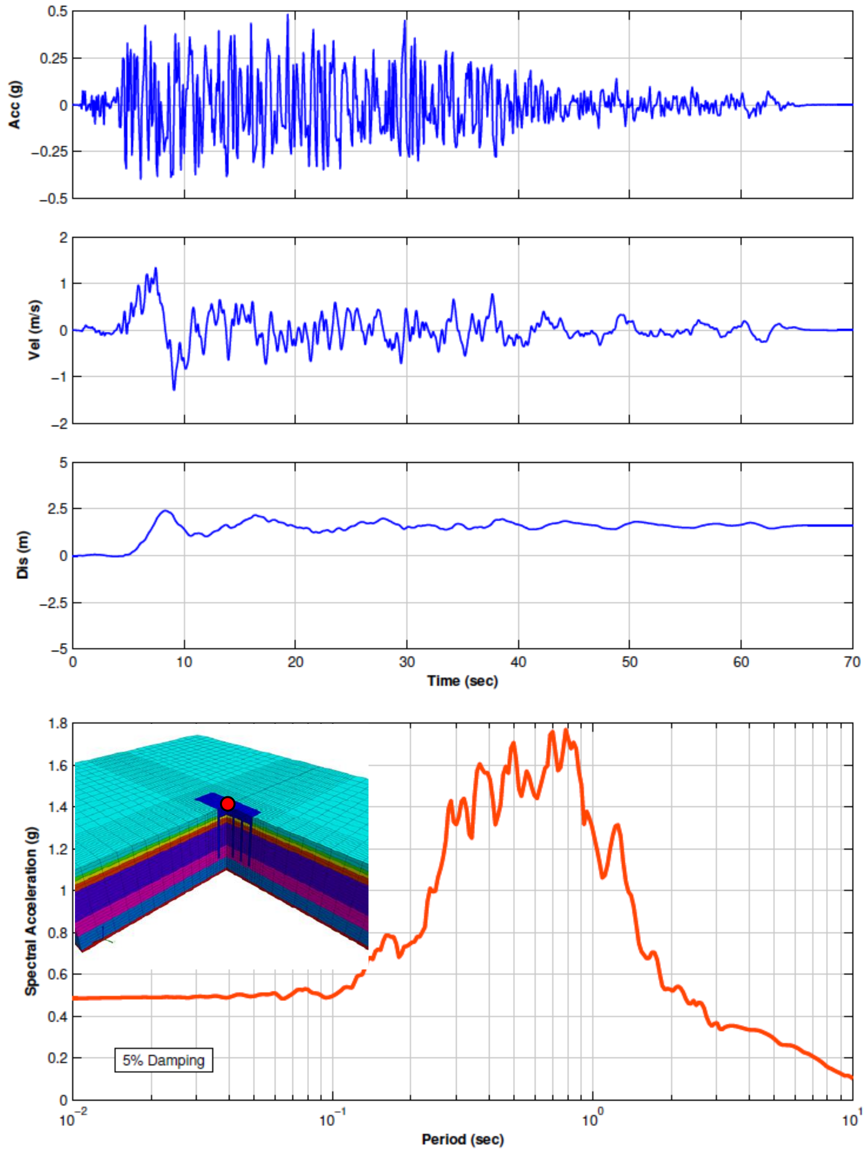

Figure 5. Acceleration, velocity and displacement time histories and acceleration response spectra bridge longitudinal kinematic ground motion component with fling.

Conclusions

The design of foundations systems to withstand near fault motions and fault displacements is a complex subject. 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. The current case history illustrates the use of site investigations to characterize the fault setting, displacement hazard analyses to develop design displacements and advanced numerical modeling to evaluate design structural demands and develop design ground motions at the base of the structure. Similar methodologies can be adopted for quantifying near-source seismic hazards for important projects.

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