DESIGN AND CONSTRUCTION OF LRT VIADUCT ALIBEYKOY

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Abstract

Alibeykoy Viaduct is a 410 meters long double track LRT viaduct located in Istanbul, Turkey. Yuksel Proje is the designer of the viaduct. The superstructure system consists of a post-tensioned concrete box-girder cast on scaffolding system with platform widths of 12.60 meters and 16.10 meters. In the wider part, there is a LRT station on the viaduct having a total length of 170.3 meters with span lengths of 48.65m+73m+48.65m. The superstructure was constructed with span by span method. High seismicity of Istanbul combined with soft soil conditions consisting of alluvial mud up to 40 meters from the surface necessitated detailed soil-structure analyses including subsurface basin effects. Nonlinear 2D analyses including both subsurface basin and the whole structure were also performed to design the substructure. Barrette piles with dimensions of 1.50m×2.80m were selected in the substructure to resist dominant kinematic forces resulting from soft soil conditions. A hybrid seismic isolation system consisting of hysteretic dampers, spherical bearings and rubber bearings were selected to provide service load horizontal rigidity as well as high energy dissipation capacity and restoring force capability during earthquakes. The construction of the viaduct was recently completed.

1. GENERAL

Alibeykoy Viaduct was designed and constructed in scope of İstanbul Light Rapid Transit Project and have a total of 410 meters with double tracks. The superstructure system consists of a post-tensioned concrete box-girder cast on scaffolding system with platform widths of 12.60 meters and 16.10 meters. In the wider part, there is a LRT station on the viaduct having a total length of 170.3 meters with span lengths of 48.65m+73m+48.65m. The superstructure was constructed with span by span method. High seismicity of Istanbul combined with soft soil conditions consisting of alluvial mud up to 40 meters from the surface implied a special design methodology for the bridge. General Layout of the bridge is presented in Figure 1. In Figure 2, a recent general view of the viaduct under construction is presented.
Figure 1: General Layout of the Alibeykoy Viaduct (Dimensions in cm)

Figure 2: View of the Bridge under Construction in December 2017
2. SUPERSTRUCTURE

The superstructure is composed of single-cell (E=12.60 meters) and double-cell post-tensioned concrete box girder (E=16.10 meters), built by span-by-span method on scaffolding. On the viaduct, there is a LRT station with a total length of 170.3 meters having a continuous span arrangement of 48.65m+73m+48.65m. The platform width of this section is E=16.10 meters. Depth of the box girder varies from 3.5 meters to 2.5 meters as the mid-span is approached.

Apart from the LRT station part, typical span length is 58.65 meters with a platform width of E=12.60 meters. This part of the viaduct has two span continuous modules with a variable girder depth of 2.5 meters and 3.75 meters at the mid-span and piers respectively. In Figure 3, typical mid-span cross-sections are presented.

![Figure 3: Cross-Section of the Superstructure (Dimensions in cm)](image_url)
Train to be utilized in the line is ABB train with an axle weight of \( W_{axle} = 13.5 \text{ tons} \times 1.30 = 17.5 \text{ tons} \). Typical axle spacing is 1.8 meters. In design of the superstructure and substructure, mainly AASHTO LRFD of 2007 and AASHTO LRFD Seismic of 2011 specifications were used (AASHTO 2007, AASHTO 2011).

Uniform settlement limit for scaffoldings of concrete bridges is limited to 2.5 cm during construction and more severe conditions apply for differential settlement (FHWA 1994). Due to very loose soil conditions, some site tests were performed at the site for determination of the settlement, before finalizing the construction method. The recorded settlements were always below 2.5 cm with a formwork deflection of 0.22 cm under the weight of the fresh concrete. No camber deflection was specified for the superstructure.

3. SUBSTRUCTURE AND SEISMIC DESIGN

Istanbul is an earthquake prone city and a major earthquake with a magnitude of \( M_w = 7.5 \) is expected within the next 50 years. The seismicity of the bridge was studied in detail and site specific design spectrums for the bridge were developed for different earthquake return periods.

The design of the substructure and seismic isolation system were performed by taking 475 year return period earthquake as basis (DBE). Life safety performance level was targeted at this EQ level. During Maximum Credible Earthquake (MCE) with a return period of 2475 years, plastic hinging in the piles was allowed per requirements of AASHTO LRFD Seismic clauses for piles in liquefiable soils. Design spectrum for the bridge for DBE level EQ for Soil Class E is presented in Figure 4.

![EQ Design Spectrum for DBE Level Earthquake](image)

The soil conditions at the bridge consists of alluvial mud with SPT values in the order of \( N_{60} = 2-5 \), starting from about 4-5 meters from the surface and extending to sandstone-siltstone at the bottom. At the top of the alluvial mud, there is a stiffer crust composed of gravel, sand etc. The depth of the alluvial mud varies from 0 m at the abutments to approximately 40 m at the intermediate piers. The geotechnical profile of the bridge is presented in Figure 5. The groundwater level can be practically assumed to be at the top. Subsurface topography reveals well known basin edge effect during a major earthquake (Adams et al. 1999). Amplification of the seismic waves is expected at the basin edges, corresponding to Axes 2 and 7 of the Alibeykoy Viaduct.
Forces acting on a foundation system can be divided into groups as kinematic and inertial. Inertial forces result from the weight of the superstructure and substructure. Kinematic forces result from the soil surrounding the foundation.

To be able to reduce inertial seismic forces during an earthquake, a hybrid seismic isolation system consisting of sliding spherical bearings, rubber bearings and hysteretic dampers was selected. Spherical bearings resist vertical forces and rubber bearings provide restoring force capability during a seismic event. Hysteretic dampers provide service load rigidity during braking & acceleration of the trains as well as wind load resistance. Moreover, during a major seismic event, hysteretic dampers provide very high energy dissipation capacity to reduce seismic forces transmitted to the substructure. General view of the bearing + damper system is presented in Figure 6. Horizontal displacement limit of the system is ± 350 mm. Effective vibration period of the seismic isolation system is about 2.7 sec.

Piers are quite short and massive so they behave elastically during a seismic event. Kinematic effects are quite dominant and they are the determinant factor in design of the pile system. The alluvial mud over the bedrock becomes mobilized at a horizontal acceleration of about 0.08g, indicating the dominating role of the kinematic effects.

To be able to design pile system, some 1D pseudo-static analyses (Elahi et al. 2010) were performed using DEEPSOIL software (Deepsoil 2016). As the first step in Pseudo-static analyses, site response analyses were performed using DEEPSOIL to determine horizontal displacement and shear strain level at every pier location using nonlinear soil properties. Site specific 7 times history records were utilized in the analyses. Maximum free-field displacements were in the order of 7 cm to 17 cm for DBE (475 year) EQ level.
In the next step, a 2D Plaxis model was used to get kinematic forces resulting from soil displacement during an earthquake. Free field displacements were put as input load into the model. This was done by determination of pseudo-static acceleration resulting in the same free-field displacement level. Pile caps and piles were also included in the model by condensing their properties into 2D. Soil was modelled by equivalent elastic approach (effective stiffness) and associated values were taken from DEEPSOIL model. These analyses were again performed separately for each pier.

Barrette piles with dimensions of 2.80 m ×1.50 m were selected due to their higher inertia as compared to commonly used circular piles, especially in their stronger direction. A checkboard arrangement of barrette piles was adopted in order to provide similar horizontal stiffness in both transverse directions. View of the barrette pile layout is presented in Figure 7. The depth of the piles is in between 16.00 meters and 52.00 meters.
After getting Pseudostatic analysis results, they were combined with inertial forces by the combinations reported in CALTRANS (Caltrans 2012). Structural analyses were performed using Larsa 4D analysis software, using time dependent material properties (Larsa Inc. 2007). Construction stage wizard of the software program was utilized with predicted and planned construction stages. General view of the Larsa model is presented in Figure 8.

[1] 100% Kinematic Effects + 50% Inertial Effects

[2] 100% Inertial Effects + 50% Kinematic Effects

Basin effects were studied with another PLAXIS model, as presented in Figure 9 (Brinkgreve et al. 2006). In this model, bridge itself was also included with a condensation to 2D. Moment-Curvature relationships of the barrette piles were also included in the model to able to see potential plastic hinging of the piles. Bearing system and dampers were modelled by an equivalent elasto-plastic spring. Site specific time-history records were used in the analyses. Analyses were performed for 475 year and 2475 year EQ levels.
For 475 year EQ level, analysis results indicated drastic differences in pile forces between 1D Pseudo-static approach and 2D Model at axes close to the basin edges. 2D analyses resulted in approximately four-to-five times higher forces at axes 2 and 7. For axes at the middle of the basin (5&6), both approaches were in coherence with each other. Maximum bending moments are listed in Table 1. All piles were designed to behave elastically during 475 year level EQ.

Dynamic analyses were also performed for 2475 EQ level (MCE). For this EQ level there was plastic hinging at some barrette piles, as presented in Figure 10. Low plastic rotations indicated limited damage to piles during MCE level earthquake. Plastic hinging was observed at pile-pile cap connection and at alluvial mud-bedrock interface. Pile regions at the interface of alluvial mud and bedrock were detailed as a potential hinge region per requirements of EN 1998-2 (Eurocode 1998-2 2003).

Table 1: Summary of Analysis Results for 1D Pseudo-static and 2D Dynamic Methods

<table>
<thead>
<tr>
<th>Axis No</th>
<th>Pseudostatic Analysis</th>
<th>2D Dynamic Analysis</th>
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<tr>
<td></td>
<td>M\text{_weak} \text{(kN.m)}</td>
<td>M\text{_strong} \text{(kN.m)}</td>
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<td>4328</td>
<td>10466</td>
</tr>
<tr>
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</tr>
<tr>
<td>7</td>
<td>5268</td>
<td>14054</td>
</tr>
</tbody>
</table>
Figure 10: 2D Dynamic Analyses Results for MCE (2475 year) Level EQ
4. CONCLUSION

In Alibeyko LRT Viaduct, subsurface basin combined with deep alluvial mud necessitated a special design for the substructure and the pile system. Pseudo-static 1D and Dynamic 2D analyses resulted in sharp differences in barrette pile forces at the basin edges, due to well-known basin edge effects. In the mid part of the basin, 1D and 2D analyses were in correlation with each other. Very high kinematic forces resulted in a foundation system consisting of 2.80m×1.50m barrette piles. Approximately, 75% percent of the pile shear forces and bending moments resulted from the kinematic effects.

In order to reduce inertial seismic forces, a hybrid bearing + damper system consisting of sliding spherical bearings, hysteretic dampers and rubber bearings was selected. Hysteretic dampers provide service load horizontal rigidity under braking, acceleration and wind loading as well as providing high energy dissipation capacity during a major earthquake. Rubber bearings provide restoring force capability to the system. Therefore, post-yield period of the seismic isolation system was mainly controlled by the rubber bearings. Spherical bearings resist vertical forces.

Span-by-span construction method on a scaffolding system was selected for the post-tensioned box girder superstructure. Some settlement tests were performed to assure that the settlements shall remain under 2.5 cm during the deck construction.

Construction of the viaduct was recently completed.

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References

Larsa Inc. 2007. Larsa 4D. USA.