

Dynamic analysis of an immersed tunnel in Izmir

Análisis dinámico de un túnel sumergido en Izmir

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Abstract

The original design of the planned Izmir Bay Immersed Tube Tunnel, considered it to be a continuous subsea tunnel for the whole length of about 7.6 km. But this was later changed into having 2 shorter tubes of 2.7 km long each connected thru' a 2.2 km long artificial island created in the middle of the bay from the excess dredged material, a concept which also reduces costs and increases efficiency. This island will serve as a venue for the 2025 Expo Exhibition, which Izmir city will apply to organize in the future. Reason for the research study was to provide a preliminary design, using a dynamic analysis, during the current pre-feasibility stage, of the immersed tunnel to show whether it can be built across the Izmir Bay. This paper takes into account the new alignment and presents the results of a 2-D dynamic analysis conducted of the prefabricated 100m long tunnel elements, sitting within a backfilled dredged ditch, dug after the recommended ground improvement was carried out. Analyses considered staged construction and the results showed that: Tunnel units and its surrounding soils inside the dredged ditch act together to provide a better earthquake response with a damping effect of the earthquake force; Tunnel units do not float to the sea surface, but continued to stay inside the dredged ditch and applied positive stresses to the foundations during the design earthquakes. As there was no floating, there was no need for anchoring the tunnel to ditch bottom; Tunnel units and immersion joints (made of specified strong elastomer material) continued to stay in compression longitudinally and provided a superb water-tightness level; There were no risky (un-tolerable) ground deformations during, after striking of the design earthquakes. Total vertical and differential displacements of the tunnel units and in the surrounding soils were all at acceptable levels; Concrete surface crack widths occurring in the tunnel units, during striking of the design earthquakes were also found to be allowable. Study results show that the tunnel elements can withstand Mw=7 short duration (<10 sec) or Mw=6 long duration (>10 sec) earthquakes without major damages to their structure.

Keywords: Immersed Tube Tunnel, Dynamic 2-D Analysis, Soil-tunnel interaction, earthquake response of subsea tunnels.

Resumen

El diseño original del Túnel de Tubo Inmerso en la Bahía de Esmirna, considerado como un túnel submarino continuo para toda la longitud de aproximadamente 7.6 km. Pero más tarde se cambió a 2 tubos más cortos de 2,7 km de longitud conectados cada uno a través de una isla artificial de 2,2 km de longitud creada en el medio de la bahía por el exceso de material dragado, un concepto que también reduce los costos y aumenta la eficiencia. Esta isla servirá como sede para la Exposición Expo 2025, que la ciudad de Izmir aplicará para organizar en el futuro. La razón del estudio de investigación fue proporcionar un diseño preliminar, utilizando un análisis dinámico, durante la etapa actual de prefactibilidad, del túnel sumergido para mostrar si se puede construir a través de la bahía de Izmir. Este documento toma en cuenta la nueva alineación y presenta los resultados de un análisis dinámico bidimensional realizado de los elementos de túnel prefabricados de 100 m de largo, asentados dentro de una zanja de dragado rellena, excavada después de que se llevara a cabo la mejora de suelo recomendada. Los análisis consideraron la construcción por etapas y los resultados mostraron que: Las unidades de túnel y sus suelos circundantes dentro de la zanja de dragado actúan en conjunto para proporcionar una mejor respuesta a los terremotos con un efecto amortiguador de la fuerza sísmica; Las unidades de túnel no flotan en la superficie del mar, sino que permanecieron dentro de la zanja de dragado y aplicaron esfuerzos positivos a las cimentaciones durante los terremotos de diseño. Como no había flotación, no había necesidad de anclar el túnel para dejar el fondo; Las unidades de túnel y las juntas de inmersión (hechas de un material de elastómero fuerte especificado) continuaron comprimiéndose longitudinalmente y proporcionaron un excelente nivel de impermeabilidad; No hubo deformaciones de terreno arriesgadas (no tolerables) durante, después de golpear los terremotos de diseño. Los desplazamientos verticales y diferenciales totales de las unidades del túnel y en los suelos circundantes se encontraban en niveles aceptables; Anchuras de grietas superficiales de concreto que ocurren en las unidades del túnel, durante el golpeo de los terremotos de diseño también se encontraron permitidas. Los resultados del estudio muestran que los elementos del túnel pueden soportar Mw = 7 terremotos de corta duración (<10 segundos) o Mw = 6 de larga duración (> 10 segundos) sin daños importantes en su estructura.

Palabras clave: túnel de tubo sumergido, Análisis dinámico en 2-D, Interacción suelo-túnel, Respuesta a terremotos de túneles submarinos.

Introduction

Izmir city is the 3.rd biggest city in Turkey with a population of about 4 millions and is home to significant industrial, agricultural manufacturing, export and tourism activity. The residential, industrial areas are located around the Izmir Bay, which is a very shallow inland sea bay (having <20 m water depth). The planned Izmir Bay Immersed Tube Tunnel

(IBITT) Project will ease traffic flow in the north-south direction, due to shortening of a 46 km long highway around the Bay with a straight 7.6 km long crossing (Figure 1) (Egeli & Kartaltepe, 2012).

The tunnel is expected to consist of twin immersed sections, each 2700 m long, placed in their dredged ditches and a 2200m long artificial island in the middle. Each immersed section will have 27 no.s of 100 m long precast concrete units, whose outside dimensions will be 39.8 m (widths) and 10.0m (heights). Each unit interior will be 6.5 m high and cross-section will contain twin 3-lane highways at the ends and dual railway section in the middle (Figure 2).

The longitudinal (S-N) cross-section (from left to right) of IBITT is shown in Figure 3, after its proposed ground improvement by the compaction-grouting method. The slopes for the 4 sloping 1200 m long sections will be at 2.5%. The maximum seawater depths in the middle of the immersed portions will be about 20 m.

Figure 1. The route of the planned IBITT. Source: Egeli & Kartaltepe (2012).



History of Immersed Tunnels, Advantages and Disadvantages

Immersed tunnels are around nearly for 100 years, started mainly in the USA having prefabricated, short length, round steel tunnels, but in the last 50 years, they've developed as being prefabricated, long length, single-storey, wide-width, rectangular-sectioned concrete tunnels having many transportation lanes, used mostly in the Europe and in the Far-East. Some examples constructed in the last 50 years with their locations and important aspects in brackets are; a) Marmaray tunnel (world's deepest at 60 m, 2 section rail tunnel, 1.4 km length, Turkey); b) Fehmern Belt link (The largest cross-sectioned tunnel, Denmark); c) Oresund Link (world's earlier longest tunnel, 4 km, Denmark-Sweden); d) Busan-Geoje Link (world's latest longest tunnel, 4 km, South Korea); e) Caland Tunnel (1.1 km, city tunnel, Holland); f) Western Harbour Crossing (2 section short city tunnel, Hong Kong), etc.

Figure 2. The cross-section of the planned IBITT. Source: Egeli & Kartaltepe (2012).

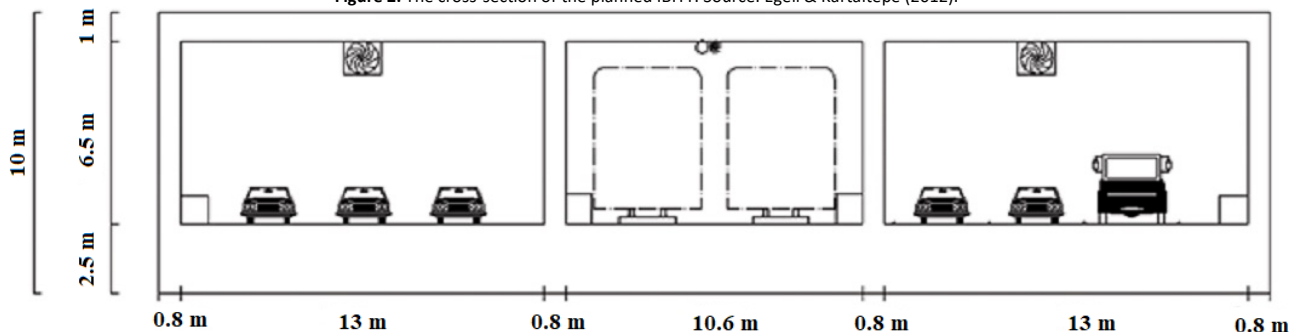
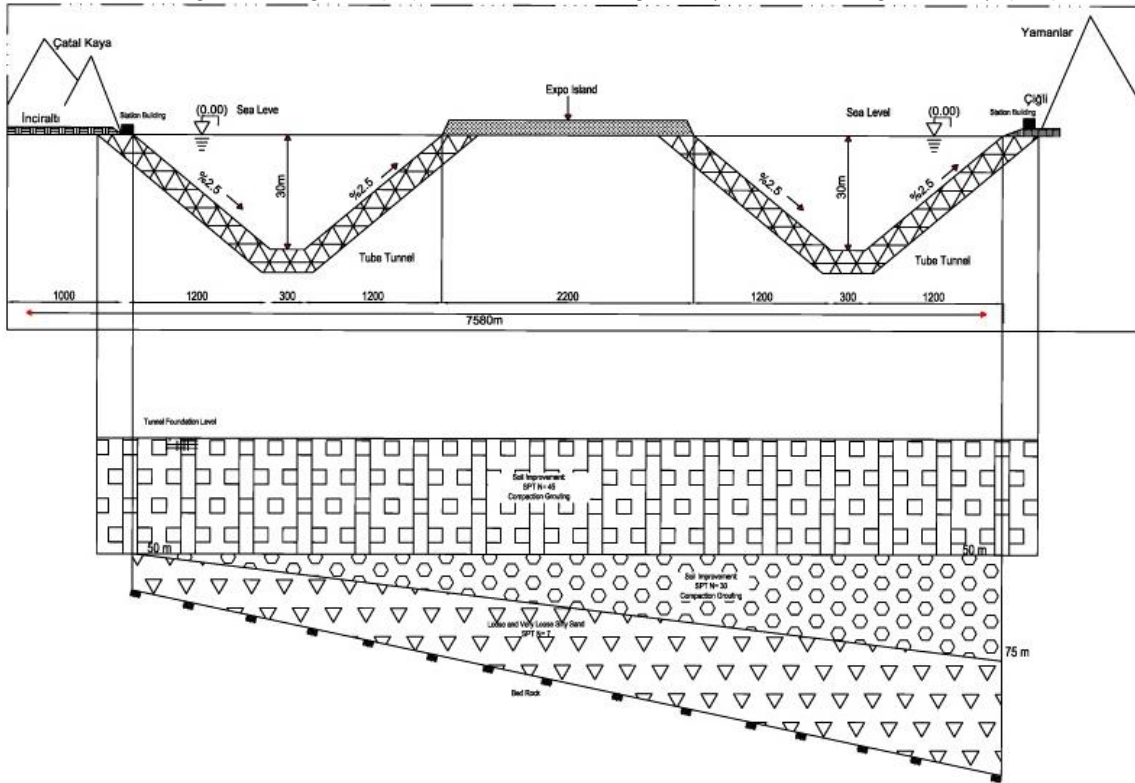


Figure 3. The longitudinal (S-N) section of the IBITT after its ground improvement. Source: Egeli & Kartaltepe (2012).



The Advantages of the immersed tunnels are as follows:

- They are very cost effective for large widths having many transport lanes (road, rail),
- They can be applied to poor seabed soils, only after doing a proper ground improvement, as they apply reduced stresses to improved foundation soils, due to buoyancy force of water (by Archimidis principle),
- Although earthquake response of immersed tunnels inside dredged ditches, surrounded by selected backfilled soils placed in sea may require some further research with laboratory work, observations made from our calculations regarding this issue will be noted in further sections.

The Disadvantages of the immersed tunnels are as follows:

- The deepest water depth that they can be used is 60 m (e.g. Marmaray Tunnel),
- They require straight or nearly-straight (with large radius of curvature) alignment, to allow concrete units and immersion joints stay in longitudinal compression during and after the earthquakes, to provide continuous water-tightness,
- They should not float during and after operation and any earthquakes and their foundations should not have any tensional stresses,
- If the tunnel length is greater than 4 km, portal (end) ventilation may become insufficient and a tall ventilation shaft (upto atmosphere) may be needed for each minimum 2 km, which is costly and provides hindrance to marine traffic.

The IBITT project fulfills all these conditions, needing no ventilation shafts in the middle of each tunnel alignment (2.7 km.) and the middle railway section will be used as an escape route for the people from the other road lanes, during any emergency or accidents, with imposed tight fire and smoke control measures.

Site Geology, Ground Improvement and Tunnel Suitability to site

Izmir Bay has a V-shaped bedrock level variation. At the apex point of V-shape, Izmir fault is present. This fault line produced mostly weak, short-durationed earthquakes, (up to; M=6, in the Richter Scale). As, the large earthquakes happening in the Aegean region had large recurrence intervals and the region was home to many short faults, it was proper to assume M=7 short-durationed (<10 sec.s) or M=6 long-durationed (>10 sec.s) earthquakes in the design analyses (Sezer, 2004).

Izmir fault makes a curvature towards left and lands onshore (Inciralti) sooner, in the south of the IBITT tunnel alignment, whose nearest point is within 5 km distance to the fault line. Deep drill holes done in the past near the tunnel alignment (up to 100 m depths below the existing seabed levels) have shown that Kartaltepe (2008) Izmir Bay seabed deposits consist of mixtures of very loose silt, sand and alluvial deposits, which are either non-cohesive or have very low cohesion values. Moreover, the rock head level (i.e. depth to bedrock) was found to be at approximately 50 m depth below the seabed level in the south (Uçkuyular site) and at about 280m depth below the seabed in the north (Çiğli side). A very low to low allowable bearing capacity values of the existing seabed soils upto bedrock levels necessitate that a controlled ground improvement 'by the compaction grouting process' must be applied at the site, before dredging and placing the tubes in their dredged ditches.

Because of above explained site geology, attempts to replace the northern immersed tunnel (near Çiğli) by a 'high viaduct bridge on piles' to provide a better visual effect, are not supported neither recommended. Because bridge, which will carry dual 3-lane highway and dual twin railway lines (with their traffic) will transfer all their weights in-air to the friction piles, whose maximum lengths will be 100 m and will be short of bedrock levels up to about 280 m. Whereas the immersed tunnel will apply much reduced due to buoyancy, but they will be still positive stresses to the improved poor seabed soils. The vertical extend and the quality (ie. soil stiffness to be achieved) of the ground improvement will be at a much higher level for the 'bridge-on piles'. The piles will be short of bedrock and rely only on the side-friction to carry the all the weights of viaduct bridge and piles. Compared to the immersed tunnel case, bridge-option costs will increase by at least about 3-4 times, to provide enough support for the piles. Even so done, big risk for the pile settlements still exist, especially during earthquakes and during its operation for the design life of 50 years. If this happens, bridge may be closed, as being rendered 'unsafe', until the situation is rectified by the experts, most probably by spending more money on the quality and the extend of the 2nd. Stage ground improvement or by enlarging piles (or both), to increase the pile side friction and to minimize pile settlements.

Dynamic analysis of the immersed tunnel units

Even though; immersed tube tunnels are designed and constructed all over the world, special design codes for immersed tunnels do not exist. Standard codes for highway structures are often used, although these codes are related to structures designed for different structural behavior and external impact. The design of an immersed tube tunnel is very much related to construction method and site conditions. The seismic analysis of an immersed tunnel usually includes 3 main aspects, which are ground shaking (seismic motion), geotechnical ground failures and their effect on the tunnel structure. The sectional force and displacement along the immersed tunnel should be estimated by the dynamic analysis for tunnel units including the site conditions at the planned tunnel sites. Also, soil-structure interaction can be considered for the design and analysis.

Finite-Element Modeling of the IBITT

A non-linear Plaxis 2-D Dynamic FEM model was used to predict the most probable values of settlement and displacement of tunnel elements. In this context, higher-order 15-node triangular elements was utilized to achieve good numerical quality for the calculations. Further 'hardening soil with small strains '(Hs Small)' soil model was used to represent the behavior of the granular marine soils. In the tunnel cross-section, analyzed section around the tunnel included 50 m depth and 120 m horizontal section (Figures 4-5 and Table 1). Tube tunnel and sand concrete protection elements were modeled using the 'Linear Elastic' (LE) Model and this materials were assumed as 'non-porous'. Armor stone was modeled using the 'Mohr Coulomb' (MC) Model. Geometry of the model is limited to a 640 m long wide, 65 m deep section. Tunnel has settled in the middle of the model, because of boundary conditions. Earthquake motion was applied from the bottom of the model. Absorbent boundaries were used to obtain more realistic results. Material models and parameters adopted in the analyses are given in Tables 1-2.

Figure 4. Cross-Section of the IBITT used in the Plaxis 2-D FEM model. Source: Egeli & Kartaltepe (2012).

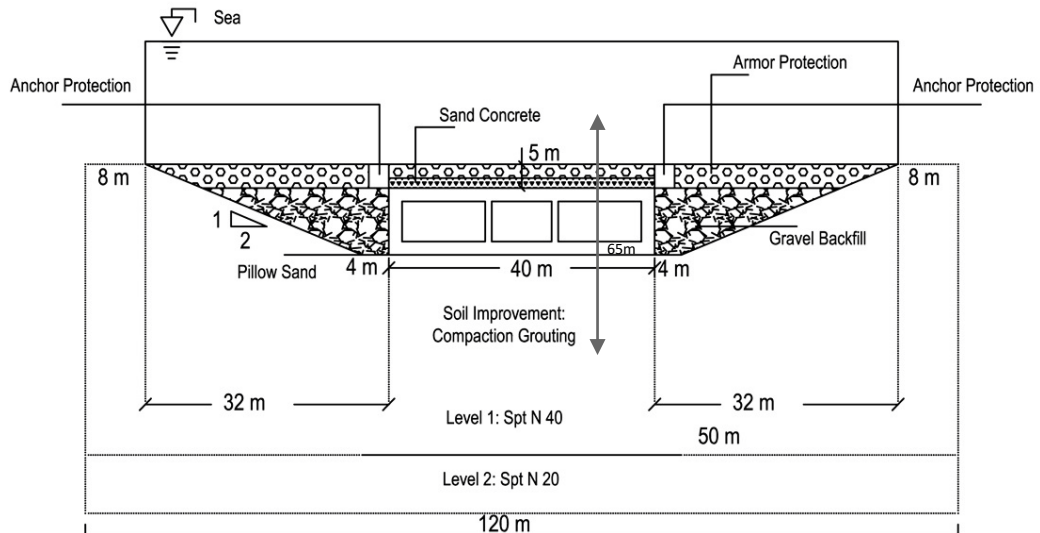


Figure 5. FEM Mesh used in the Plaxis 2-D Analyses. Source: Egeli & Kartaltepe (2012).

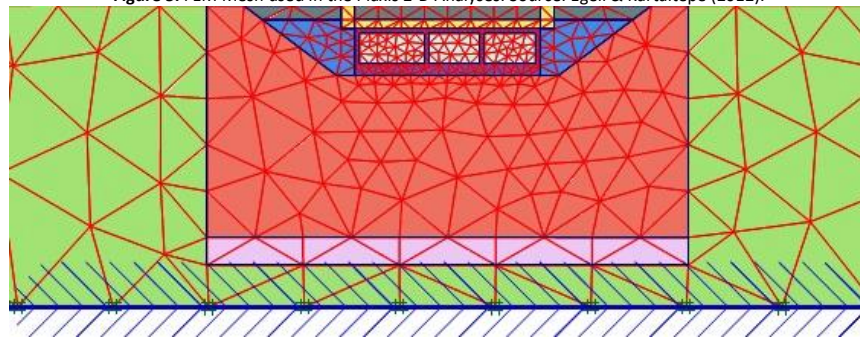


Table 1. Material models and parameters used. Source: Egeli & Kartaltepe (2012).

Model	Type		γ_{unsat} (kN/m ³)	γ_{sat} (kN/m ³)	k_x (m/day)	k_y (m/day)	E_{50}^{ref} (kN/m ²)
Gravel	Hardening Soil-Small strain	Drained & Undrained	19.00	22.00	0.86	0.86	7.67E+04
Imp. Silty Sand N'=40 deg.	Hs Small	Drained & Undrained	18.00	20.00	1.037	1.37	1.66E+04
Imp. Silty Sand N'=20 deg.	Hs Small	Drained & Undrained	17.50	19.50	1.037	1.37	9.36E+03
Loose Silty Sand	Hs Small	Drained & Undrained	16.00	18.00	8.64	8.64	3.74E+03
Armor Stone	MC	Drained	29.00	29.00	8.64E+04	8.64E+04	5.00E+04
Tube Concrete	LE	Non-Porous	25.00	-	-	-	2.80E+07
Sand Concrete	LE	Non-Porous	21.00	-	-	-	2.65E+07

γ_{unsat} : Unsaturated Unitweight; γ_{sat} : Saturated Unitweight; k_x : Permeability in x direction; k_y : Permeability in y direction; E_{50}^{ref} : Secant Stiffness.

Static design and settlement analyses

The static geotechnical design for the immersed tunnel elements focused on time-settlement behavior of the tunnel elements during the following construction stages considered: 1. Dredging of the trench. 2. Installation of the tunnel elements and covering work. 3. Discharging water inside the tunnel elements. 4. Operation of the tunnel for the Design Working Life of 100 years. Construction stages are given in Table 3 below.

Table 2. Other material parameters used Source: Egeli & Kartaltepe (2012).

	E_{oed} (kN/m ²)	E_{ur} (kN/m ²)	m (-)	c (kN/m ²)	Φ' (°)	Ψ (°)	$\Delta_{0.7}$ (%)	G_0 (kN/m ²)	R_{inter}	ν (-)
Gravel	7.67E+04	2.44E+05	0.5 0	2.00	45.00	12.00	-	-	0.68	
Impr. Silty Sand, N'= 40	1.51E+04	4.97E+04	0.5 0	1.00	48.30	0.00	1.00E-05	7.39E+04	1.00	
Impr. Silty Sand, N'= 20	9.36E+02	2.81E+04	0.5 0	1.00	40.00	0.00	1.00E-05	1.94E+05	1.00	
Loose Silty Sand	3.74E+03	1.21E+04	0.5 0	1.00	26	0.00	2.00E-05	1.43E+04	0.7	
Armor Stone	-	-	-	1.00	45	0.00	-	-	1.00	0.20
Tube Concr.	-	-	-	-	-	-	-	-	0.67	0.30
Sand Concr.	-	-	-	-	-	-	-	-	0.67	0.20

E_{oed} : Tangent Stiffness; E_{ur} : Unloading /Reloading stiffness; m : Power for stress-level; c : Cohesion; Φ' : Friction Angle; Ψ : Dilatancy Angle; $\Delta_{0.7}$: Shear Strain at $G_s=0.722G_0$; G_0 : Shear Modulus; R_{inter} : Interface Parameter; ν : Poisson's Ratio.

Table 3. Construction Stages considered for the static analyses and results obtained. Source: Egeli & Kartaltepe (2012).

Construction Phases	Static Conditions	
	Total Vertical Displacement (mm)	Relative Displacement (mm)
1 Dredging Stage	181	-
2 Placing Tube and Side Filling	81	100
3 Placing Sand Concrete	60	21
4 Placing Armor Stone	(-)17	77
5 After pumping out water	16	33

Calculations showed that during placement of the armor stone, some swelling of ground has occurred, but after pumping out of water from the tunnel unit the net result was 16mm of total vertical settlement (Kartaltepe, 2008).

Dynamic design and earthquake analysis

The dynamic soil-structure interaction analysis (between a tunnel unit and its surrounding soil) is assessed by the two-dimensional (2D) plane-strain analysis. The calculated displacements of the tunnel considered that; transverse sections are used as input, e.g. as 'prescribed displacements', in the subsequent structural analyses of the tunnel elements. The soil movements around the tunnel to lead to a relative displacement between concrete and soil are checked. Relative displacements can cause to introduction of shear stresses into the concrete elements. Also, tensile forces can trigger cracks on the concrete shell of the tunnel element. Because of the relatively high axial stiffness of the concrete elements and the more flexible immersion joints between them, displacements will be concentrated in the joints. During an earthquake, the primary function of the joints is therefore to be able to follow the imposed tolerable displacements, without failure (ie. opening of the flexible joint) to ensure water tightness. Secondly, the joints should absorb a considerable part of the earthquake energy, a process limiting the existence of high tensile forces in concrete.

Discussion of the Results

In the 2D Dynamic Analyses (2017), earthquake force produced by the nearby Izmir fault was assumed to reach the tunnel from south at 45° oblique angle to N-S direction. In this study two important earthquake scenarios were considered. These are 1) 2005 California Offshore and 2) 2008 Utah Wells earthquake records. Utah Wells earthquake magnitude was 6.0 (ML), fault was a normal fault. California Offshore earthquake magnitude was 7.2 (ML), fault was a strike-slip fault. Numerical results are given in Table 4 and some in Figures 6-8. This data were used in the dynamic (2D) analyses, during which following observations were made:

- 1) During the dynamic analyses conducted by using the Plaxis 2D program, it was observed that the Tunnel units and its surrounding backfilled soils inside the dredged ditch in sea, act together to provide a better earthquake response for the tunnel, due to providing a damping effect of the earthquake force,
- 2) Tunnel units do not float to the sea surface, but continued to stay in the dredged ditch and applied positive stresses to the foundations, as no tensional stresses are would be allowed. As there were no floatation of the units to sea surface, there was no need for anchoring them to ditch bottom, which was only assumed to be smoothed by 0.1m thick sand cushion, after laying the tunnel in its place, to allow uniform stress concentration at the outer bottom surface of the tunnel unit.
- 3) Tunnel units and immersion joints between them (made of strong elastomer) continued to stay in compression longitudinally and did not fail, allowing good water-tightness.

Table 4. Cases considered for the dynamic analyses performed and results obtained. Source: Egeli & Kartaltepe (2012).

Dynamic Conditions		
E/Q Magnitude	Vertical Displacements(mm)	Horizontal Displacement(mm)
1 Mw= 7	32.72	41.41
2 Mw= 6	32.75	21.5
Differential Displacement		
	At the Bottom Slab (mm)	At the Lateral Shell (mm)
1 Mw= 7	6.3	1.57
2 Mw= 6	6.4	2.2

Figure 6. Vertical total displacements in the dynamic analysis of the IBITT. Source: Egeli & Kartaltepe (2012).

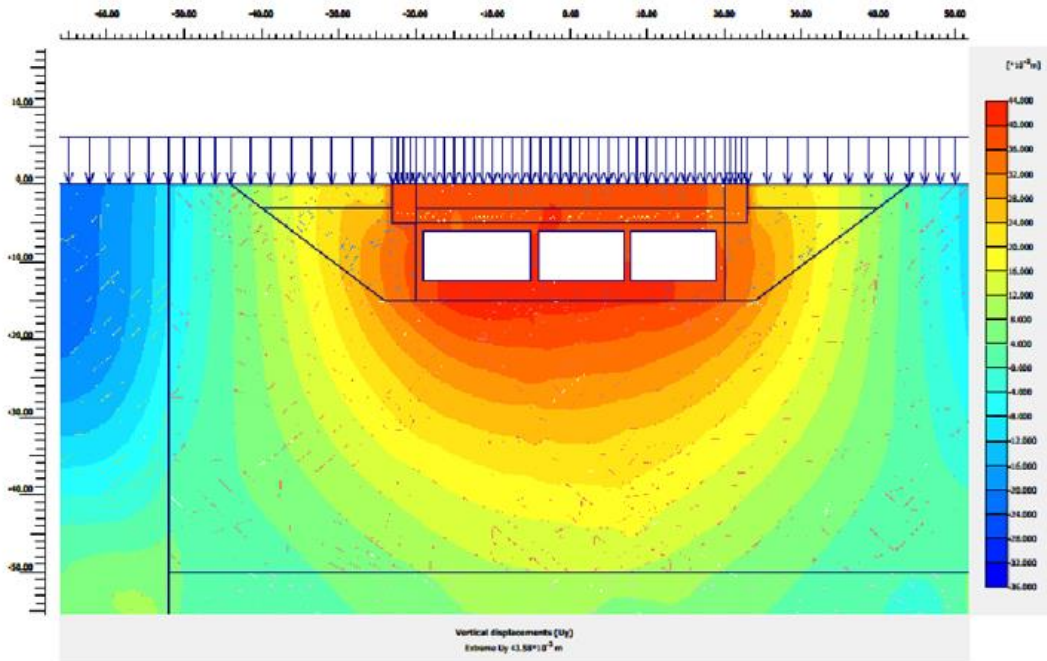


Figure 7. Vertical differential displacements in the dynamic analysis of the IBITT. Source: Egeli & Kartaltepe (2012).

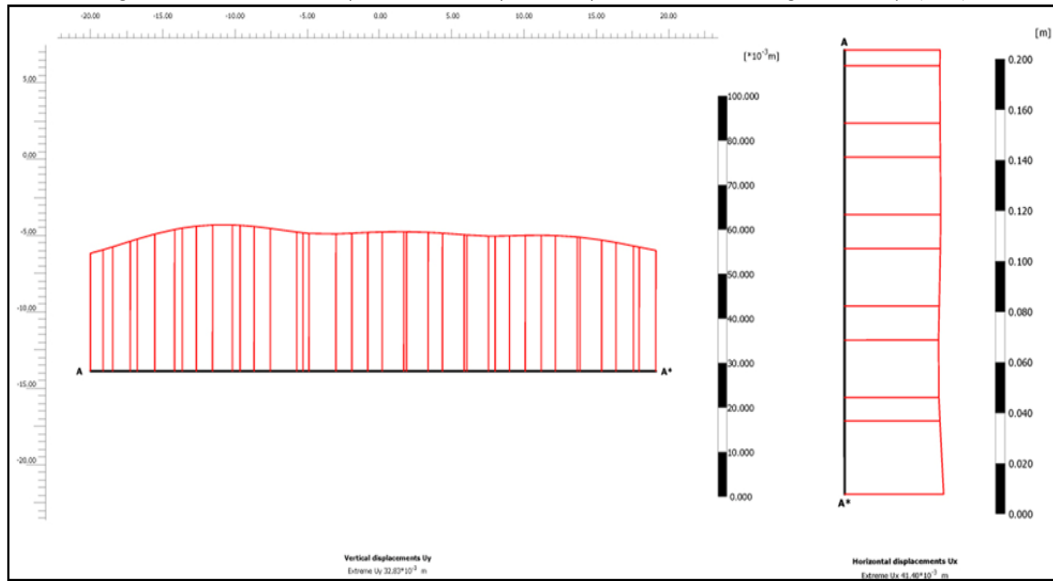
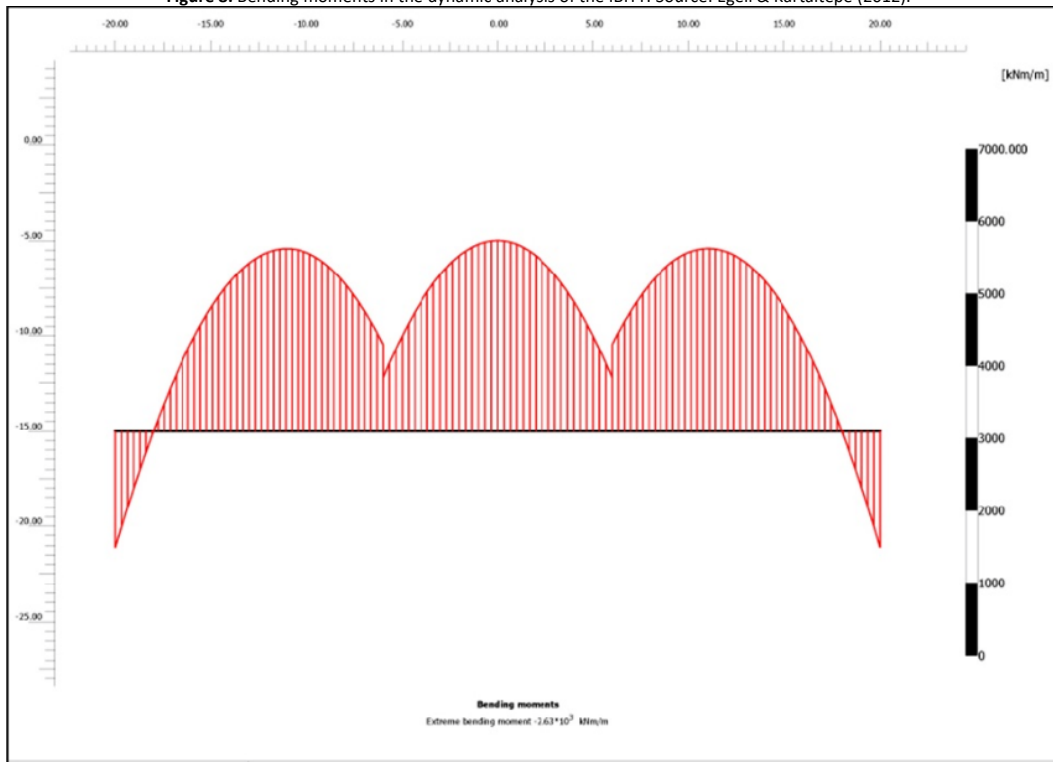


Figure 8. Bending moments in the dynamic analysis of the IBITT. Source: Egeli & Kartaltepe (2012).



Flexural cracking is controlled for the reinforced concrete structures by to ensuring to provide the required level of durability for the structure. Because of the saline seawater providing a highly corrosive marine environment for the tunnel units, it is common practice to impose tight limits for the flexural crack widths, particularly in the water-retaining external surfaces of the structure. Typically, maximum crack-widths on the external face will be limited to 0.15–0.2 mm, and on the inside faces, between 0.2 mm and 0.25 mm (ACI 318-11, 2011). The Post-earthquake displacements were used for the calculations of concrete crack-widths, using the formula given in the equation 1 below (ACI 224.2R-92, 2004).

$$w_{max} = 0.0145f_s \sqrt[3]{d_c A} \times 10^{-3} \quad [1]$$

Results of crack-width calculations are given in Table 5, which indicates that crack widths in the dynamic analysis of IBITT are found to be tolerable (0.15 mm) and less than 0.2 mm, the maximum value allowed for the inside and outside faces of the tunnel units (ACI 318-11, 2011).

Table 5. Result of crack-width calculation after the dynamic analysis of the IBITT. Source: Egeli & Kartaltepe (2012).

f_s (Mpa)	200	w_{max} (mm)
d_c (mm)	40	0.15
s (mm)	40	0.15

Finally, it's noted that analyses assume that ground improvement is done beforehand and then construction of the tunnel units are carried out successfully. Analysis considered staged construction and it was observed that there were no risky deformations. Analysis included to check the results for 2 cases of post-earthquake deformations and stresses. Earthquake cases studied were for Richter magnitude, $M_w = 6.0$ long duration (>10 sec) and $M_w = 7.1$ short duration (<10 sec) earthquakes. However all these results should be reviewed and re-evaluated, after obtaining additional sea-borehole data from the tunnel alignment during the next full feasibility study and design-construction stages.

Conclusions

The planned Izmir Bay Immersed Tube Tunnel (IBITT) Project will ease traffic flow in the north-south direction, due to shortening of a 46 km long highway around the Bay with a straight 7.6 km long crossing. Even though immersed tube tunnels are designed and constructed all over the world for long time, special design codes for them do not exist. The dynamic analysis (for preliminary design) of an immersed tunnel in earthquake regions usually includes 3 main study areas, which are; response to a seismic motion, geotechnical ground analyses to check displacements are tolerable and checking to see the performance of the tunnel structure and immersion joints are acceptable, during and after the selected seismic-motions. However, during the detailed design stage, sectional shear forces, moments, displacements and reinforcements should also be checked for acceptability.

Analysis performed assume that "compaction-grouting type" ground improvement was done successfully, before tunnel construction and selected design earthquake strikes afterwards.

Analyses considered staged construction and the results showed that:

1. Tunnel units and its surrounding soils inside the dredged ditch act together to provide a better earthquake response with a damping effect of the earthquake force.
2. Tunnel units do not float to the sea surface, but continued to stay inside the dredged ditch and applied positive stresses to the foundations during the design earthquakes. As there was no floating, there was no need for anchoring the tunnel to ditch bottom.
3. Tunnel units and immersion joints (made of specified strong elastomer material) continued to stay in compression longitudinally and provided a superb water-tightness level.
4. There were no risky (un-tolerable) ground deformations during, after striking of the design earthquakes. Total vertical and differential displacements of the tunnel units and in the surrounding soils were all at acceptable levels.
5. Concrete surface crack widths occurring in the tunnel units, during striking of the design earthquakes were also found to be allowable.

Lastly, it's noted that this analysis only serves for the pre-feasibility study stage or for the preliminary design stage. All these results should be reviewed/re-evaluated, after obtaining the additional sea-borehole data along the alignment, during the next full feasibility-study or the detailed design stages.

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